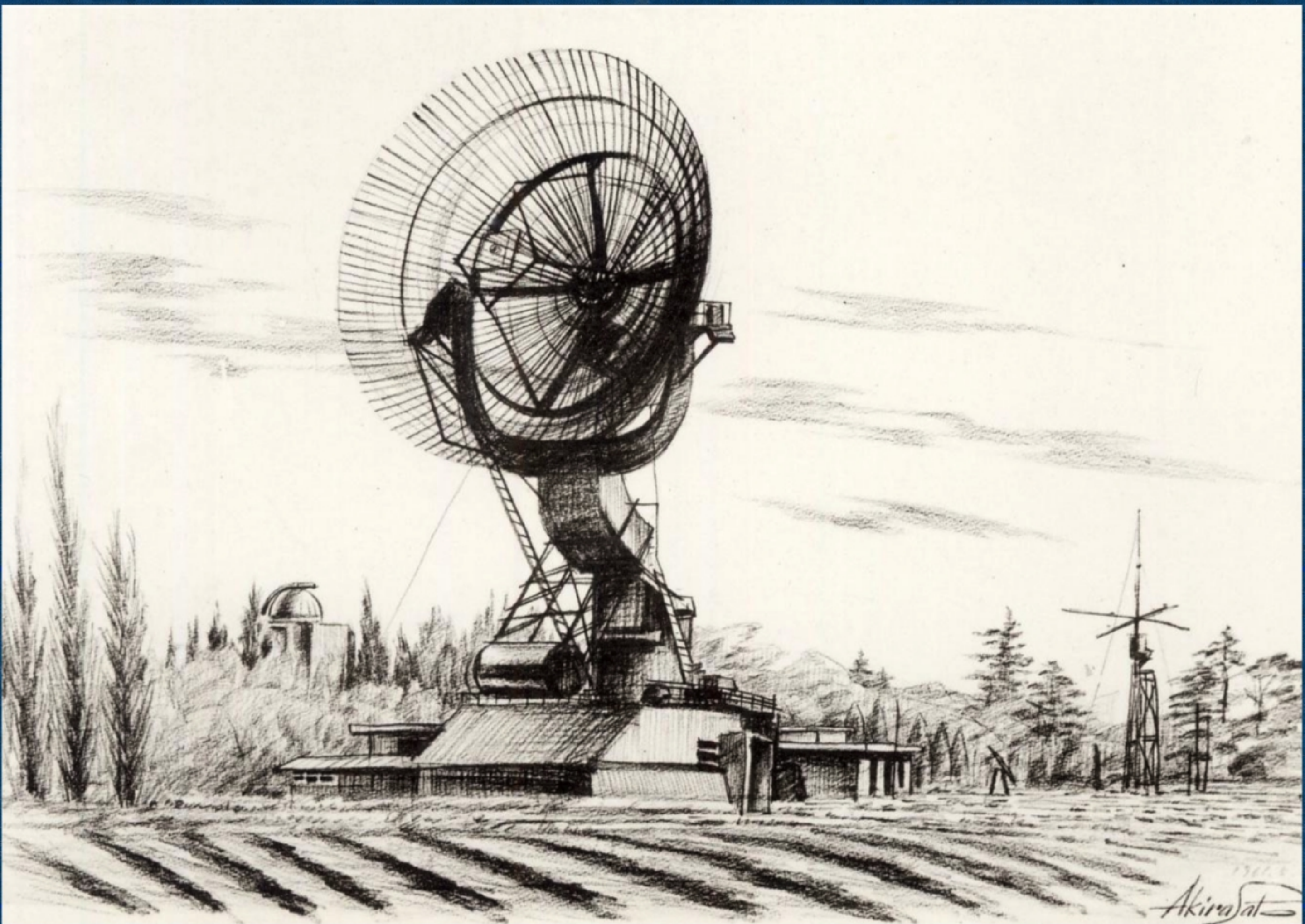
JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE



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COVER IMAGE

A sketch by Akira Sato showing the rhombic antenna of the 100–140 MHz dynamic spectrograph (on the tower above and slightly left of the artist's signature) and the 10-m parabolic antenna. In the background, and to the left of the parabolic antenna, is the TAO's distinctive 'Einstein Tower' solar telescope. This image appears in the third article in the series, Highlighting the history of Japanese radio astronomy, by Kenji Akabane, et al., which starts on page 2 of this issue (courtesy: NAOJ Archives)

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HIGHLIGHTING THE HISTORY OF JAPANESE RADIO ASTRONOMY. 3: EARLY SOLAR RADIO RESEARCH AT THE TOKYO ASTRONOMICAL OBSERVATORY

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Abstract: The radio astronomy group at the Tokyo Astronomical Observatory was founded in 1948 immediately after WWII, and decided to put its main research efforts into solar radio astronomy. The first radio telescope was completed in 1949 and started routine observations at 200 MHz. Since then, the group has placed its emphasis on observations at meter and decimeter wavelengths, and has constructed various kinds of radio telescopes and arrays operating at frequencies ranging from 60 to 800 MHz. In addition, radio telescopes operating at 3, 9.5 and 17 GMHz were constructed. In parallel with the observationally-based research, theoretical research on solar radio emission also was pursued. In this paper, we review the instrumental, observational and theoretical developments in solar radio astronomy at the Tokyo Astronomical Observatory in the important period from 1949 through to the 1960s.

Keywords: Japan, Tokyo Astronomical Observatory, solar radio astronomy, solar radio telescope, solar radio emission.

1 INTRODUCTION

The first deliberate attempts by Japanese scientists to detect radio emission from an extraterrestrial object can be traced back to the Tokyo observations at 3 GHz by Koichi Shimoda (b. 1920) of the partial solar eclipse on 9 May 1948 and observations of solar noise at 3.3 GHz by Minoru Oda (1923–2001) and Tatsuo Takakura (b. 1925) in November 1949 from Osaka (see Ishiguro et al., 2012; Ishiguro and Orchiston, 2014). However, these observations were experimental. In 1948, the radio astronomy group led by Professor Takeo Hatanaka (1914–1963; see Figure 1)[1] was founded at the Tokyo Astronomical Observatory (henceforth TAO) at Mitaka, Tokyo, with strong support from the Director of the Observatory, Professor Yūsuke Hagiwara (1897–1979). Other members of the group were Fumio Moriyama (b. 1927) and Shigemasa Suzuki (1920–2012). At that time, the TAO did not have the electronics technology which was necessary to observe radio emission from non-solar sources. In addition, the period after World War II was a very difficult one in which to get suitable equipment and stable power supplies for radio telescopes. So Hatanaka's group decided initially to put its main research efforts into solar radio astronomy, which they believed would be more easily carried out than non-solar radio astronomy.

In 1949, the first solar radio telescope at the TAO was constructed with help from the Radio Research Laboratories of the Ministry of Posts and Telecommunications at Hiraiso, which already was deeply involved in research into the ionosphere and had an excellent background in radio astronomical instrumentation and techniques. Since then, new radio telescopes for solar observations at meter and decimeter waves were constructed one after another at the TAO, as the staff there developed their own technologies and ideas. As a result, the TAO group was able to make important contributions to solar observational radio astronomy and theory. Hatanaka's group, and the vibrant solar research group at the Toyokawa Observatory led by Haruo Tanaka from the Research Institute of Atmospherics at Nagoya University, were to play a key role in researching solar radio emission during the 1950s and 1960s, and ensure Japan's international visibility in this area of astronomy. For Hiraiso, Tokyo, Toyokawa and other Japanese localities mentioned here and elsewhere in this paper see Figure 2.

Figure 1: A meeting of the Japanese National Commission V of URSI held at the Toyokawa Observatory in 1954. Professor T. Hatanaka is the 'larger than life' figure on the extreme right, in the back row. Others from the TAO in this photograph are: K. Akabane (back row, second from the left), T. Takakura (back row, third from the left), S. Suzuki (beside Hatanaka), and TAO Director, Professor Y. Hagihara (front row, right) (adapted from Tanaka, 1984: 345).

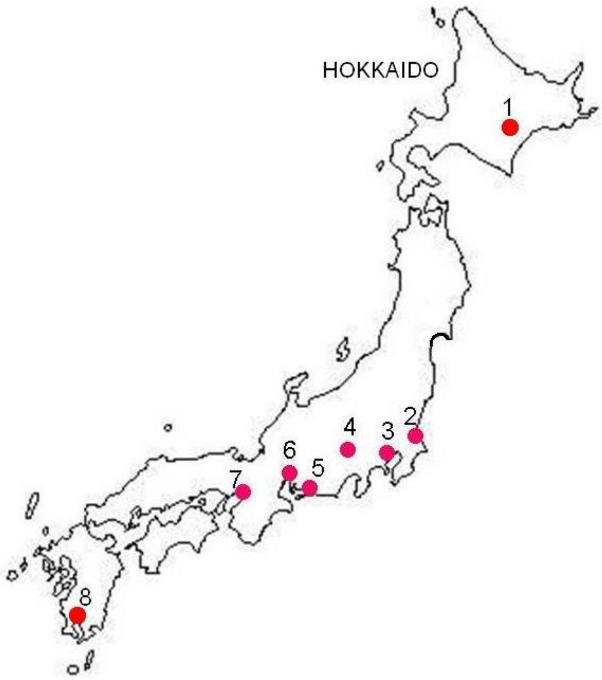


Figure 2: Japanese localities mentioned in the text. Key: 1 = Obihiro; 2 = Hiraiso; 3 = Akihabara, Tokyo; Tokyo Astronomical Observatory (Mitaka); Tokyo University; 4 = Nobeyama; 5 = Toyokawa Observatory; 6 = Nagoya; 7 = Osaka; 8 = Kagoshima.

From the summer of 1960, the future plans in radio astronomy were discussed at the TAO. One was to start non-solar radio astronomy. Another was to construct a large solar radio interferometer in order to carry out spatially-resolved observations. Later, construction of a 160 MHz compound interferometer at Nobeyama was planned. Preliminary observations for it started at Nobeyama in 1965, construction began in 1967 and this new radio telescope was completed in 1970.

In this paper, we review the early solar radio research at the TAO from 1948 to 1965 for instrumentation and from 1948 to 1967 for observational and theoretical research.

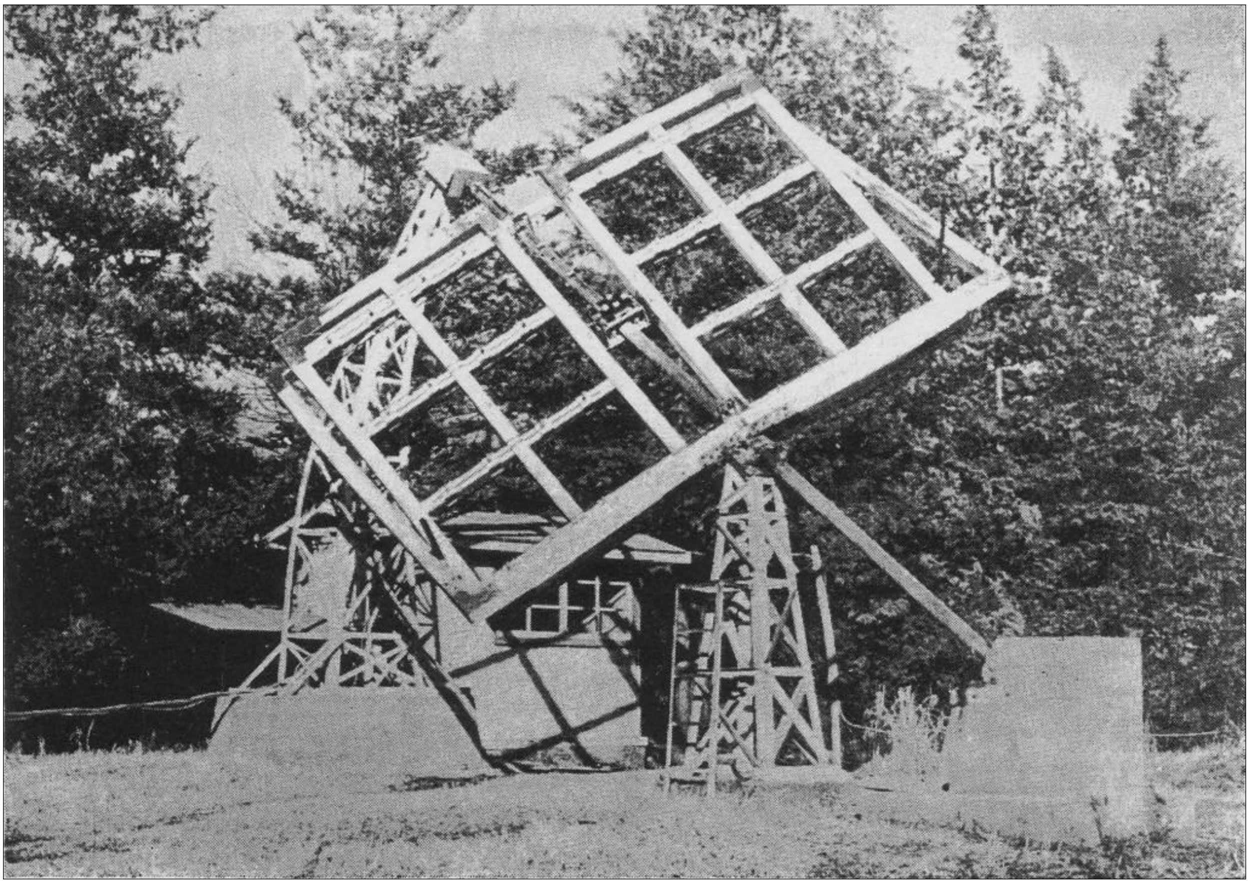


Figure 3: The 5 m × 2.5 m equatorially-mounted 200 MHz broadside array which began routine solar observations as the first radio telescope at the TAO in 1949 (after Suzuki and Shibuya, 1952).

2 INSTRUMENTATION

A 5 m × 2.5 m equatorially-mounted broadside array at 200 MHz was constructed as the first solar radio telescope at Mitaka in cooperation with the Radio Research Laboratories of the Ministry of Posts and Telecommunications (Suzuki and Shibuya, 1952), and daily observation of solar radio emission started in September 1949. The equatorial mount was a recycled mounting for a refracting telescope that was taken to Hokkaido (Japan's northern-most main island—see Figure 2) and used to observe a solar eclipse in 1936. A 4-stage 4 column beam antenna was arranged on a wooden frame which was attached to the iron polar axis (which was about 7 m long), as shown in Figure 3. The antenna was manually driven every 30 minutes in hour-angle, and the declination by about 4° every week. The antenna gain is estimated to have been 17 dB. A super heterodyne receiver was used, and the RF (radio frequency) amplifier (shown in Figure 4) used a Wallman cascode connection that gave a low noise figure and the resultant overall receiver noise figure was about 10 dB, including cable loss of 1.8 dB. The IF frequency was 10.7 MHz, and the bandwidth was about 100 KHz. The IF (intermediate frequency) signal was followed by a linear detector. There were two DC amplifiers. One was a nearly-log amplifier which used a semi-remote cutoff pentode that covered a wide dynamic range, from radio emission from the quiet Sun to intense bursts. The outputs were recorded on a chart recorder with a chart speed of 240 mm/hr. The time constant was determined by the response speed (about 0.5 s) of the chart recorder. The AC component of the detector was monitored by a speaker. Another DC amplifier was appended in order to observe the fine structure of solar radio bursts and also radio emission from the Galaxy. In this DC amplifier, the DC component was eliminated by a bridge circuit. The gain of the DC amplifier could be selected from 1, 2, 3, 10, 20. The speed of the chart recorder was 60 mm/min. The absolute flux density of solar radio emission and the receiver stability were calibrated using the difference between the open sky and a standard noise generator which used a 2-pole tube saturator (Sylvania 5722). Here, we would like to add the personal recollections of one of the authors of this paper (KA):

> A coaxial resonator attached to a miniature vacuum tube was used as each tuned circuit in the RF circuit. We could buy the miniature vacuum tube only from electrical parts discharged from the US Army in Akihabara, Tokyo. The tuned circuits had frequently poor contacts, but we could reactivate the RF receiver by knocking it by hand! In addition, the power condition at that time was very bad, i.e., the power voltage and power cycle fluctuated greatly with time beyond the standard level, such as from 60 to 90 volts and from 42 to 49 cycles, respectively. Therefore, we always had to manually adjust for these power fluctuations.

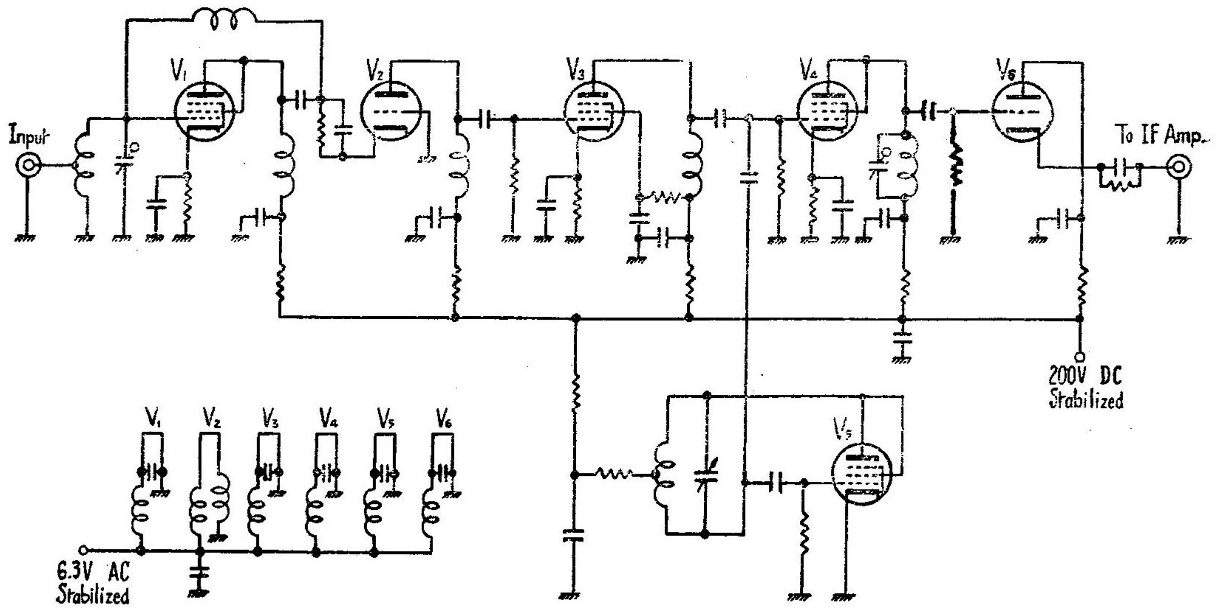
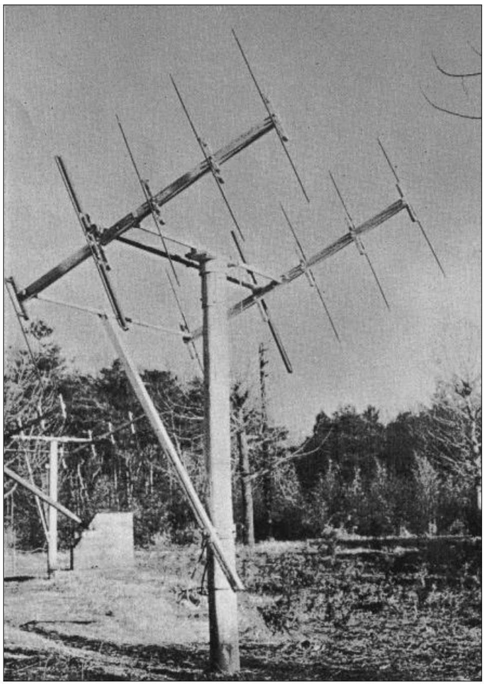


Figure 4: The RF amplifier of the first telescope at the TAO (after Suzuki and Shibuya, 1952).

Later, 100 MHz and 60 MHz total flux radiometers were installed and began routine observations of solar bursts in September 1950, and a further 60 MHz polarimeter also started trial observations in May 1951 (Suzuki and Shibuya, 1952). As a result, routine operation at three frequencies, 200, 100 and 60 MHz, became possible. It also was possible to study the circular polarization of solar bursts. The 100 MHz and 60 MHz total flux radiometer antennas, which were on alt-azimuth mounts, consisted of double Yagi antennas each with five elements, as shown in Figure 5. The polarization plane was perpendicular to the horizontal plane. The antenna gain was 13 dB. The receiver used a double super heterodyne circuit, and the first and second intermediate frequencies were respectively 10.7 MHz and 1.6 MHz. The bandwidth was 40 KHz. Since the directivity of the antenna was wide, it was difficult to point to the open sky. Therefore, the receiver was calibrated using only the reference resistance. On the other hand, the 60 MHz polarimeter antenna consisted of two dipoles with reflectors which were separated by a quarter wavelength and orthogonal to each other, as shown in Figure 6. Right- and left-handed circular polarization signals could be obtained by adding or subtracting the outputs from the two antennas. Actually, both circularly-polarized signals were observed alternately every five minutes. An example of the total flux and the polarized radiation of an outburst is shown in Figure 7.



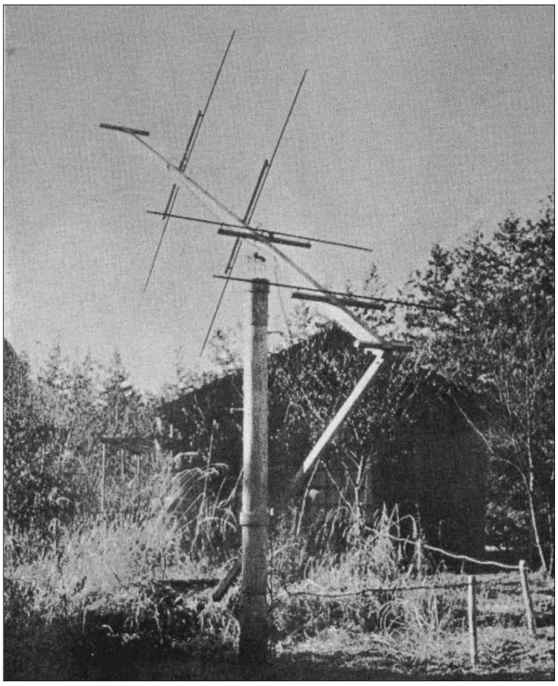


Figure 5 (left): The double Yagi antennas of the 100 MHz total flux radiometer (after Suzuki and Shibuya, 1952).
Figure 6 (right): The antenna of the 60 MHz polarimeter. The two dipoles with reflectors are separated by a quarter wavelength and orthogonal to each other (after Suzuki and Shibuya, 1952).

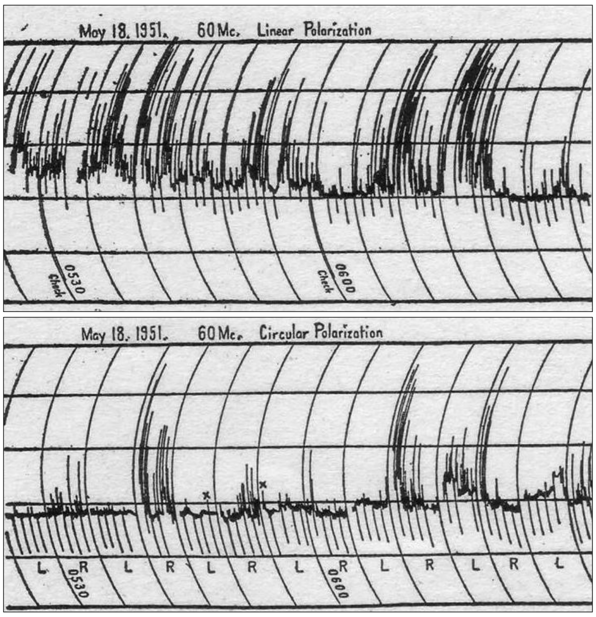


Figure 7: An example of the total flux and the circularly polarized radiation from an outburst which were respectively observed with the 60 MHz total flux radiometer and the 60 MHz polarimeter (after Suzuki and Shibuya, 1952).

At the URSI General Assembly in 1950 it was resolved to organize an international collaborative network in which continuous global solar observations at 200 MHz and 3 GHz would begin in January 1951, and the TAO participated in this program using the 200 MHz broadside array. Responding to the requirement from the URSI General Assembly, a 2-m parabolic transit type antenna operating at 3 GHz was temporally assembled by Akabane, and after some experimentation routine observations began in August 1952. The paraboloid consisted of copper plates nailed onto a parabolic wooden framework. The receiver was mostly assembled from electrical parts released by the US Army in Akihabara. Akabane's next targets were: (1) to somehow get a mounting that would allow the antenna to automatically track the Sun; and (2) to attach the existing, but improved, receiver to that new mounting. He decided to use the 2 m equatorially-mounted parabolic antenna which Koichi Shimoda from the University of Tokyo had used to observe the partial solar eclipse of 9 May 1948 (see Shimoda et al., 2013). This mounting was able to be driven by clockwork. As a result, Shimoda's antenna was transferred to the TAO and stored in its warehouse. Then in 1955, about two years later, Akabane completed the new 3 GHz radio telescope, which had much better sensitivity and stability than the previous system (Figure 8).

Figure 8: The new 3 GHZ radio telescope that used Shimoda's old parabolic dish (courtesy: K. Akabane).

In 1952, a 100–140 MHz dynamic spectrometer was constructed using a rhombic antenna, and this is shown in Figures 9 and 10.

A large parabolic antenna had been needed since 1951 in order to promote international cooperation and also pursue new research in solar radio astronomy, so construction of a 10-m parabolic antenna was planned by TAO staff. The TAO began building this antenna in 1951 and it was completed in 1953 (see Figures 9 and 10). Regular solar monitoring at 200 MHz then was taken over by the 10-m antenna, using the old broadside array receiver, until a new receiver was built for the new antenna. At that time, this was the second largest steerable radio telescope in the world. The parabolic reflector was made from square copper mesh with a spacing of 5 mm which allowed operation down to wavelengths of less than 6 cm. This radio telescope used an equatorial mounting. The polar axis was driven by a synchronous motor whose power was supplied by a 50 Hz power inverter with an accuracy of 10^{-8}. The antenna also could be driven by high-speed motors for fast slewing. The pointing of this antenna was controlled to an accuracy of 1 arcmin from the observing room.

Initially, the polarization of Type 1 bursts at meter wavelengths was thought to be circular, although no detailed investigation had been carried out. When Hatanaka was at Cornell University during 1952 and 1953, he analyzed the polarization of Type I bursts at 200 MHz based upon the data obtained at Ithaca (linear components) and Sacramento Peak (two circularly-polarized components switched every ten minutes) and reached the conclusion that the polarization of these bursts was elliptical in general, but that the shape and orientation depended on the position of the source on the solar disk. He felt it was necessary to simultaneously measure the four Stokes paramet-

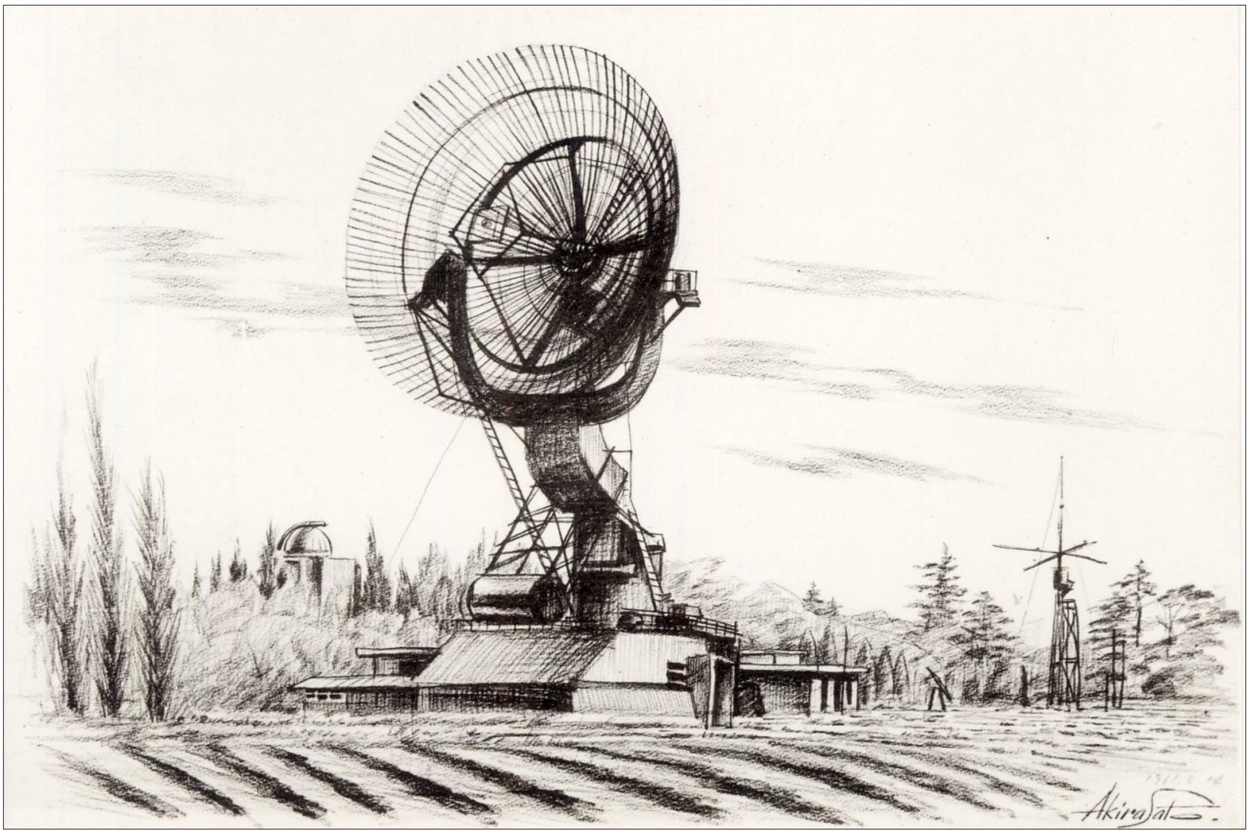
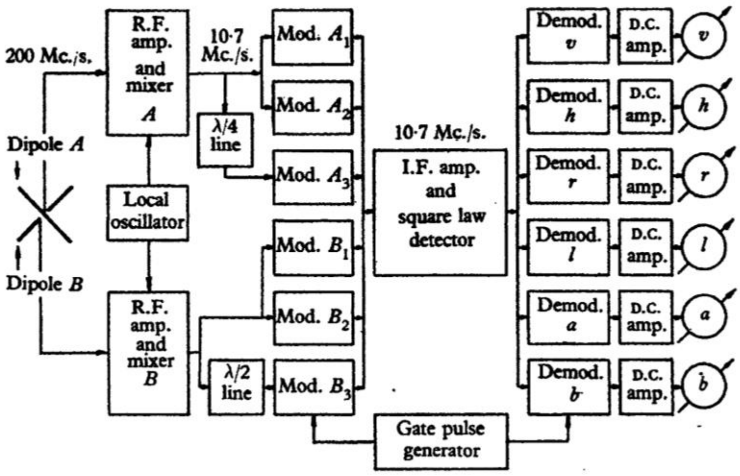


Figure 9: A sketch by Akira Sato showing the rhombic antenna of the 100–140 MHz dynamic spectrograph (on the tower above and slightly left of the artist's signature) and the 10-m parabolic antenna. In the background, and to the left of the parabolic antenna, is the TAO's distinctive 'Einstein Tower' solar telescope (courtesy: NAOJ Archives).

Figure 10: A panoramic view of the TAO radio astronomy precinct taken in about 1966 showing (from left to right) the rhombic antenna of the dynamic spectrograph, the 10-m parabolic antenna, a 612 MHz 3-element Yagi antenna, the 9.5 GHz equatorially-mounted 1.1-m parabolic antenna, the 17 GHz 8-element grating interferometer, and behind it a 17 GHz 0.8-m parabolic antenna and a 612 MHz 3-element Yagi antenna. The two Yagi antennas constitute the 612 MHz interferometer (courtesy: NAOJ Archives).

ers of the solar bursts in order to determine the precise nature of the polarization. Thus, construction of a new 200 MHz radio telescope, termed 'a time-sharing polarimeter', was started immediately after Hatanaka returned to Tokyo. This polarimeter was completed and began routine solar observations around the end of 1954. Details of the antenna-receiver are described by Hatanaka, Suzuki and Tsuchiya (1955a; 1955b), Hatanaka (1957b) and Suzuki and Tsuchiya (1958a; 1958b). The block diagram of this system is shown in Figure 11. In this antenna, a pair of crossed half-wavelength dipoles, which were orthogonal to each other with a degree of coupling of –35 dB, were placed at the focus of the 10-m antenna. Two outputs from the pair of dipoles were independently amplified by the RF amplifier (NF = 6 dB) and converted to two IF signals at 10.7 MHz (with bandwidths of 100 KHz). Here, the phase and gain difference between both electronic channels were corrected. These two output voltages were combined after inserting phase retardations of 0, π, π/2, and –π/2 in one of them by time sharing (repeating frequency = 1/200 s). Note that the crosstalk between the two antenna channels was kept to –50 dB. The combined signal passed through an IF amplifier and a square-law detector, and then generated four audio outputs (outputs v, h, r, and l) by demodulators. Note that the square-law detector was newly-developed by Suzuki (1955) and eliminated the disadvantages of the conventional square-law detectors, such as slow response, low output voltage, and drift. Since each output voltage also generated two other audio outputs (outputs a and b), a total of six outputs was obtained and recorded by a six-channel pen recorder at a speed of 4 mm/min (which, if necessary, could be changed to 60 mm/min). The four Stokes parameters could be calculated from these six outputs, including two redundant equations. In order to equalize the intensities of the polarization channels, the calibration signals from standard noise generators (Sylvania 5722) were inserted into the coaxial cables connected to the crossed dipoles by quarter-wave switches. Note that in addition to regular solar monitoring, the 10-m antenna was temporarily used at 3 GHz to observe the 20 June 1955 partial solar eclipse, and the Moon.

Several new radio telescopes, such as 67 and 100 MHz interferometers to detect the total radio emission, a 250–900 MHz dynamic spectrometer (using the rhombic antenna originally constructed for the 100–140 MHz dynamic spectrometer) and a 9.5 GHz polarimeter (using a 1.2-m paraboloid), were constructed during 1955 and 1957 in preparation for the International Geophysical Year (1957–1958). Some of these telescopes are now described in more detail.



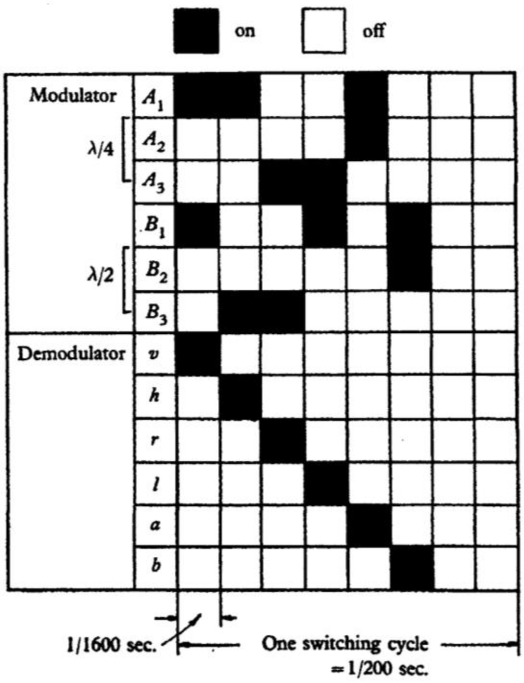


Figure 11 (top): The block diagram of the 200 MHz time-sharing polarimeter. Bottom: The combination of the modulators and the demodulators (after Hatanaka, 1957b).

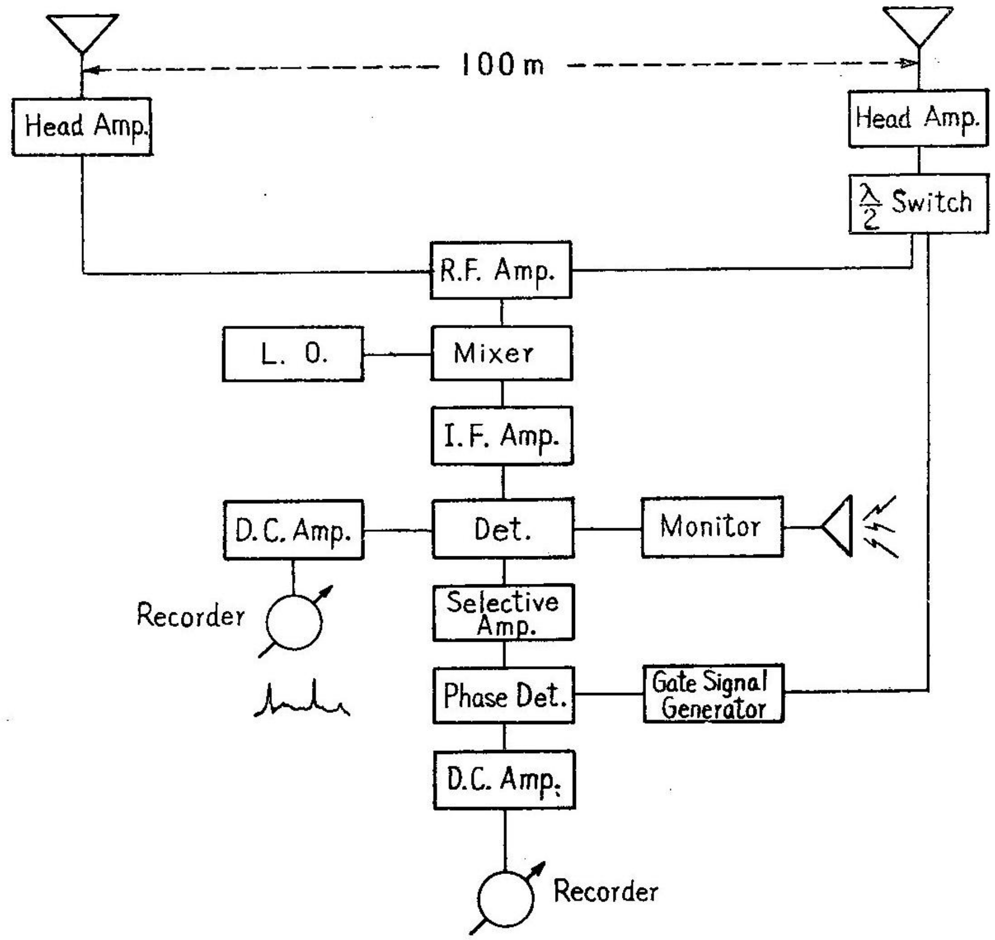
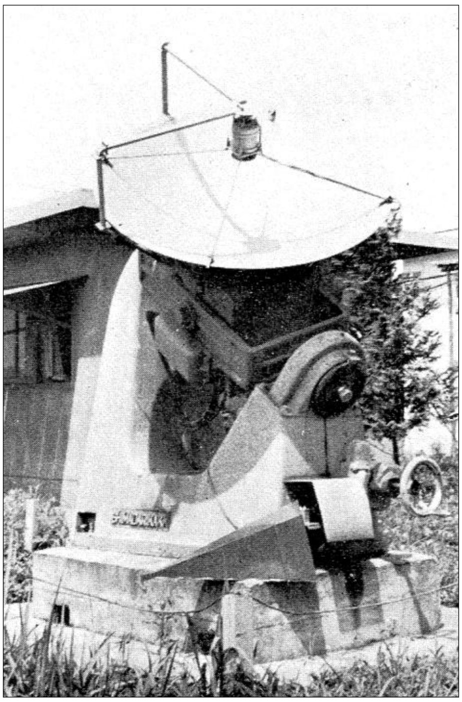


Figure 12: The block diagram of the 67 MHz interferometer. The block diagram of the 100 MHz interferometer is essentially the same as this (after Moriyama and Misawa, 1956).

A two-antenna interferometer with a longer baseline has lower sensitivity for a broad source such as the quiet Sun but higher sensitivity for compact sources such as those associated with solar bursts. Therefore, a two-antenna interferometer with a longer baseline is better than a radiometer for identifying the sources of weak bursts and distinguishing them from the background emission from the solar disk. Initially 60 MHz was selected as the observing frequency, and construction of the interferometer began in the autumn of 1954 (Moriyama and Misawa, 1956; Moriyama, 1958). However, interference from terrestrial communications was very severe, so the observing frequency was shifted to 67 MHz, resulting in successful detection of the quiet Sun and the stronger discrete radio sources in the autumn of 1955. The 67 MHz interferometer began daily solar monitoring in the spring of 1956, but unfortunately observations frequently were blocked by strong terrestrial interference. On the other hand, a 100 MHz interferometer also was constructed, and modeled on the 67 MHz interferometer (Moriyama, 1958). The 100 MHz interferometer started routine solar observations in July 1957. Details of both interferometers are provided by Moriyama (1958). Each antenna of both two-antenna interferometers consisted of a pair of five-element double Yagi antennas. The polarization plane was perpendicular to the horizontal plane. The antenna baselines of the interferometers were 60 m and 30 m in an east-west direction for the 67 MHz and 100 MHz interferometers, respectively. The receiver systems used super heterodyne circuits with phase-switching systems, as shown in Figure 12, essentially the same for both interferometers. The noise figures of the receivers were 4–5 dB. The bandwidth of the IF at 10.7 MHz was 80 KHz. The RF signal in one arm was modulated at the speed of 500 Hz using a λ/2 switch. The RF signals from both antennas were added, converted to the IF signal, and demodulated by the phase-sensitive detector to produce a multiplier output. There were two output signals. In one, just after the square-law detector the DC signal was recorded with a time constant of less than 0.1 s as the total radiation from the Sun (e.g. from solar bursts). In the other one, after the phase-sensitive detector the low frequency signal was recorded with a time constant of about 20 s as the interference pattern due to the diurnal motion of the Sun. At the end of each day's observations, the absolute value of solar radiation was determined by comparison with the flux density of the Cassiopeia A discrete radio source. Although the overall sensitivity was quite good, generally within 0.1 sfu (solar flux units) of the theoretical value, the actual sensitivity was determined by interference from city noise, which varied on a daily basis, often resulting in lower sensitivity of only 2 sfu (note: 1 sfu = 10^{-22} W/m^{2}Hz).



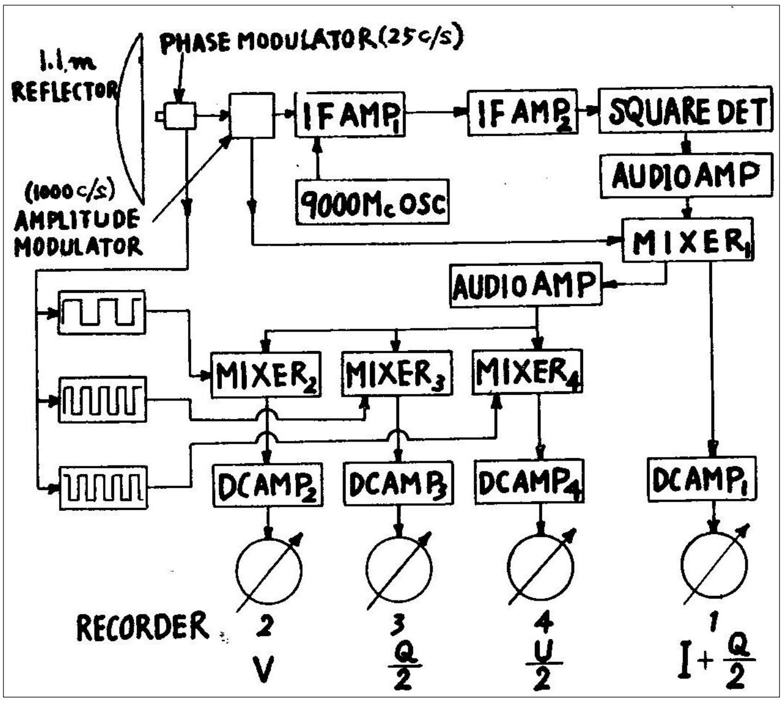


Figure 13 (left): The 1.1-m parabolic antenna of the 9.5 HGz polarimeter (after Akabane, 1958c).
Figure 14 (right): The block diagram of the 9.5 GHz polarimeter (after Akabane, 1958c).

Although the polarization of the solar radio emission had been observed in meter wavelengths, no detailed observations had been made in microwaves at the TAO, so a new type of 9.5 GHz polarimeter was constructed, and this began routine observations in May 1957 (Akabane, 1958a; 1958c). This equatorially-mounted polarimeter used a 1.1-m parabolic reflector, and is shown in Figure 13, while the block diagram of the receiver system is shown in Figure 14. The feed at the focus of the reflector was a cylindrical wave-guide used in the H_{11} mode. The phase modulator, which used a rotating λ/4 phase shifter, rotated with a velocity of about 25 Hz, and was connected to the rectangular waveguide. The amplitude modulator also operated with a ferrite-switching system at a frequency of 1,000 Hz which was independent of the frequency of the phase modulator. The intermediate frequency was 60 MHz, with a bandwidth of 8 MHz, and both the signal and the image bands were received. The noise figure of the overall receiver was about 12 db. The output of the square law detector was mixed with the reference signal from the amplitude modulators to obtain output 1. The output from mixer 1 was mixed again with the fundamental, second and fourth harmonics of the reference signal from the phase modulator to obtain outputs 2, 3 and 4. Thus, the Stokes parameters (I, Q. U, and V) could be obtained from the four outputs. The time constants of the DC amplifiers were 0.3 s for output 1 and 1 s for each of the other three outputs. The minimum detectable fluxes were 3 sfu and 6 sfu for output 1 and the other three outputs, respectively. The flux calibration of the daily measurements was carried out using the two output levels which were obtained by pointing daily at the empty sky and by inserting a carefully-matched load between the phase modulator and the amplitude modulator. The absolute flux calibration was done using a standard horn with an aperture of 205 × 255 mm.

During the International Geophysical Year (1957–1958), a narrow-band dynamic spectrometer operating at meter wavelengths also was constructed for experimental purposes and to carry out observations of Type I bursts between November 1957 and March 1958 (Tsuchiya, 1962). The observing frequency was selected to be 199–207 MHz, which was rather free from interference caused by city noise. The antenna was a 32-element transit type beam-antenna. Each element was a one-wavelength dipole. The RF signal was converted down to the IF at 50 MHz with a bandwidth of 100 KHz using a swept-frequency local oscillator. The receiver output was displayed on a cathode-ray tube, and was photographed on 35 mm film using a speed of 150 mm/min.

A new type of radio telescope referred to as a ‘multiplying multiphase interferometer’ (see Figure 15) was developed by Suzuki to locate the east-west position on the Sun of 200 MHz solar bursts (see Suzuki, 1959; Suzuki and Morimoto, 1960). The new interferometer was able to minimize the ambiguity and simplify the reduction procedure in locating the position of the radio burst sources, as compared with the amplitude ratio method which had been used up to that time. Construction of the multiplying multiphase interferometer started as an initial concept in 1957, and the final system was completed after certain improvements, such as the addition of phase-tracking electronics. The new interferometer started routine observations of both solar bursts and enhanced regions on the Sun in 1959. The block diagram of the system is shown in Figure 16. The system was composed of

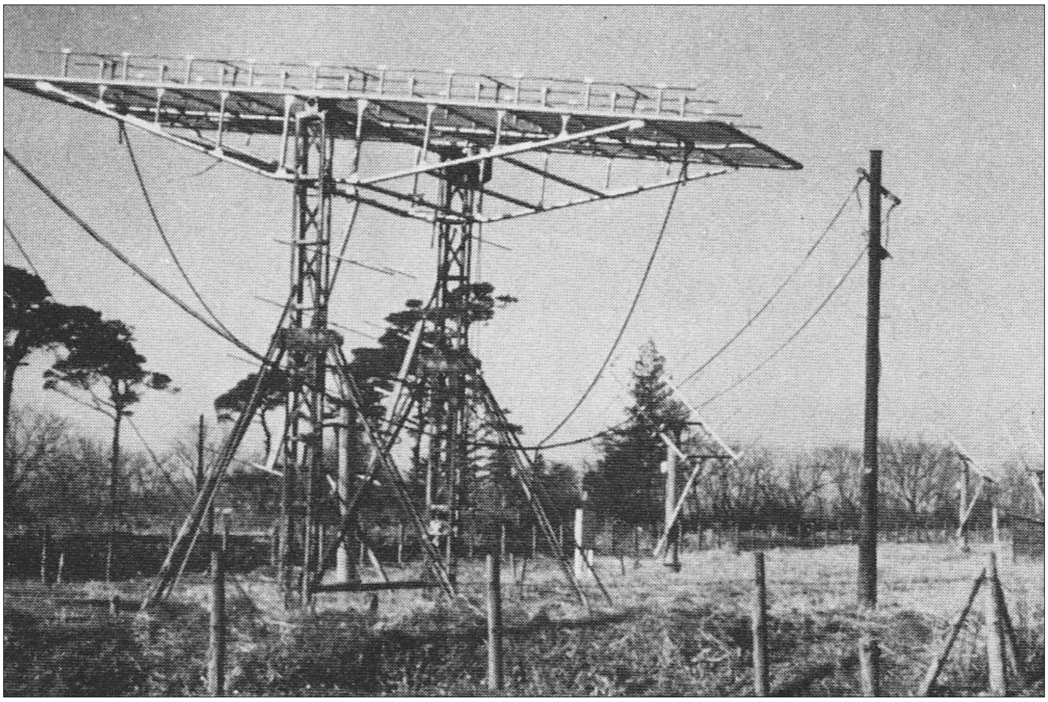


Figure 15: One of the broadside antennas used by Suzuki for his E-W position interferometer (courtesy: NAOJ Archives).

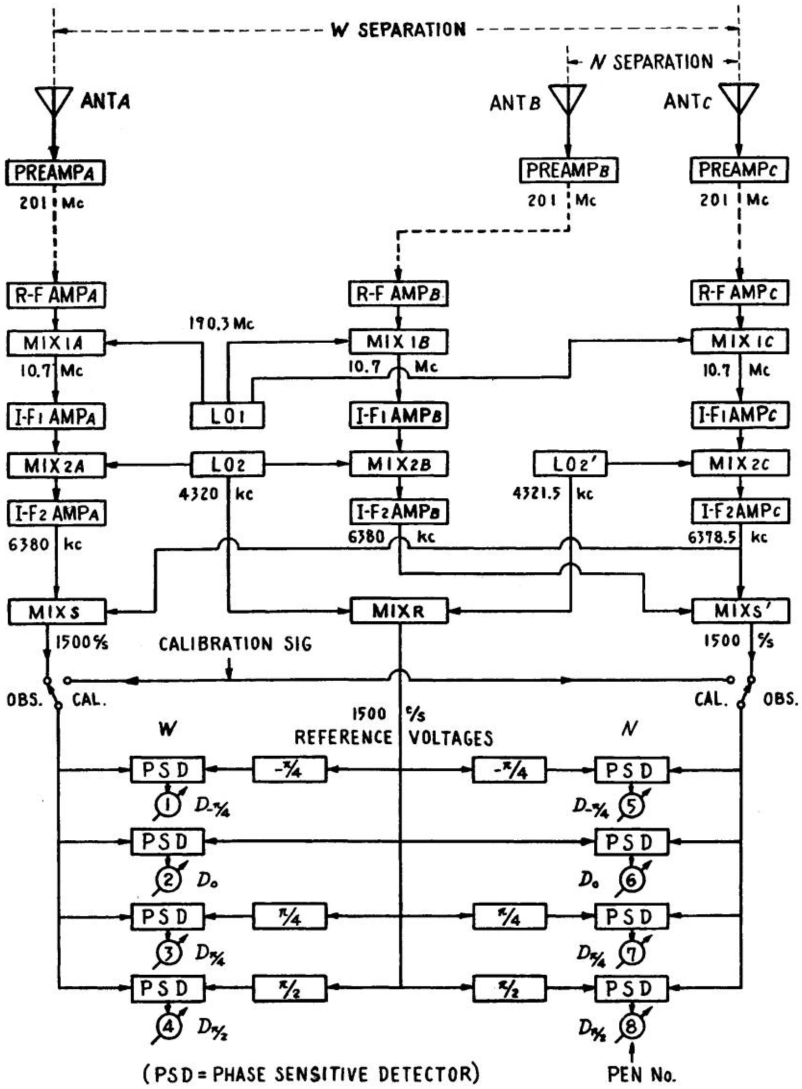


Figure 16: The block diagram of the 200 MHz multiphase interferometer (after Suzuki, 1959).

three antennas consisting of twin two-antenna interferometers arranged along an east-west baseline, one with a 338 λ baseline length and the other with a 50.5 λ baseline. The latter system was used to complement the former one only to remove the ambiguity of position-determination on the Sun of solar bursts and was similar to the former system. Each antenna was a vertically-polarized broadside array with forty dipoles (four in the horizontal direction by ten in the vertical direction). Detailed descriptions of the receiver system are given only for the former system in the following. The RF signals at 201.0 MHz from the two antennas were converted to the IF signals at 10.7 MHz by mixing with the common first local oscillator. The

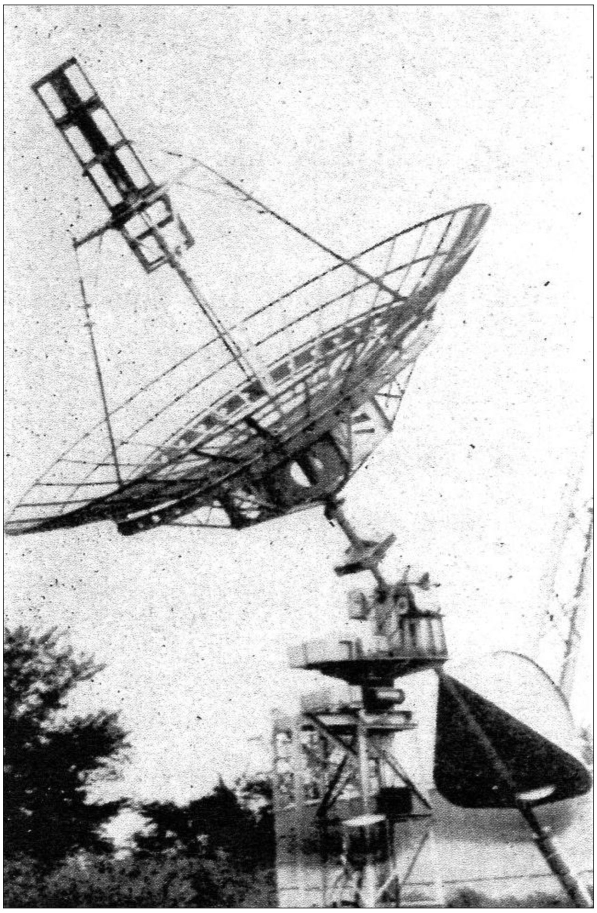


Figure 17: The 6-m parabolic antenna which was used with the 300–800 MHz dynamic spectrometer (courtesy: NAOJ Archives).

The first IF signals were again converted to the second IF frequencies at 6,380 and 6,378.5 KHz by using two second local oscillators at frequencies of 4,320 and 4,321.5 KHz, respectively. Then, the two second IF signals were mixed in a multiplier to produce the beat frequency of 1,500 Hz. On the other hand, the two second local oscillator signals were also combined in another multiplier to produce another beat frequency. The beat frequency between the two local oscillators was fed to the phase-sensitive detectors as reference signals with phase retardations of –π/4, 0, π/4, and π/2 to produce the four outputs, i.e., 1, 2, 3, and 4, respectively. The outputs were recorded simultaneously on a chart using an eight-pen recorder with a chart speed of one millimeter per second. The overall bandwidth was about 100 KHz and a time constant of 0.25 s was used. Radio sources on the Sun could be located by simple eye-estimation with an accuracy of about 6 seconds of arc under favorable conditions.

An alt-azimuth mounted 6-m parabolic antenna with a focal length of 2.5 m was constructed in 1959, and was able to automatically track the Sun. An improved receiver system for a new 300–800 MHz dynamic spectrometer was attached to the parabolic antenna (see Figure 17), and routine observations of solar bursts commenced in August 1959 (Takakura, 1960a). The parabolic antenna was illuminated by a double-tapered ridged horn. The RF amplifier consisted of a one-stage ground-grid amplifier whose plate circuit was tuned by a butterfly resonator, and a crystal mixer was attached to the resonator. The local oscillator was tuned also by a butterfly resonator and the instantaneous frequency was equal to that of the RF amplifier. By using a 1.5 MHz IF amplifier, both side bands were received. The IF bandwidth was 500 KHz. The detected output was fed to the brightness-modulation grid of a cathode-ray tube through a one-stage quasi-logarithmic DC amplifier. The tube was photographed with a CANON 35-mm continuous recorder in which the film moved about 2 cm or 1 cm per minute

A new 150–300 MHz dynamic spectrometer and 408 MHz and 800 MHz radiometers were completed and started routine observations in 1960. The primary feeds of these instruments were attached to the 6-m parabolic reflector, together with that of the 300–800 MHz dynamic spectrometer. This was because multi-frequency simultaneous observations, which were achieved by putting several different dipoles at the primary focus of a parabolic antenna, only became technically possible around 1960. Regarding observations with the 150–300 MHz dynamic spectrometer, unfortunately it was almost impossible to detect solar bursts at frequencies below 220 MHz due to terrestrial interference caused mainly by television stations and communication signals. On the other hand, 160, 200, and 300 MHz patrol radiometers, which used dipole antennas, also were constructed to monitor intense solar bursts and were put into routine operation. As a result, quantitative studies of solar bursts over a wide frequency range became possible by combining data obtained using these new radio telescopes with information obtained from previously-constructed ones.

In 1961, a north-south array was added to the 200 MHz multiphase interferometer and both arrays started solar radio observations.

In 1962, 300 MHz crossed dipoles were attached to the 10-m antenna and a new 300 MHz polarimeter started routine observations (Tsuchiya, 1963a). The primary feeds at 300 MHz shared the 10-m antenna with those of the 200 MHz time-sharing polarimeter. The block diagram of the

300 MHz polarimeter is shown in Figure 18. The RF signals from the crossed dipoles entered a polarization-switching network which consisted of coaxial cables and two variable capacitors. By switching alternately the variable capacitors placed at both ends of the two λ/4 cables at a switching speed of 50 Hz, right- and left-handed polarization components were obtained on a time-sharing basis. Cross-talk between the dipoles was about –38 dB, and insertion loss of the polarization-switching network was about 6 dB. The RF signal from the polarization-switching network passed through a quarter-wave switch and was converted down to the IF frequency of 21.4 MHz with a bandwidth of 1 MHz in the mixer. The IF signal was detected by the square law detector, and then the total flux (R+L) and difference signal (R-L) of the polarization fluxes generated by using a phase-sensitive detector were obtained. The receiver system of the 300 MHz polarimeter was different from that of the 200 MHz time-sharing polarimeter. In the 200 MHz polarimeter, the two output signals from both dipoles were converted independently to the two IF signals and then combined after passing through appropriate phase-shifters. Variations of gain and phase of any electronic circuit on the way to the combined point caused errors in measurements of Stokes parameters. Therefore, observers had to balance phases and gains among electronic passages every day. This defect became more severe in the UHF band. In the 300 MHz polarimeter, this defect was overcome by using the polarization-switching network composed of λ/4 coaxial cables which was put on the RF transmission lines placed just after the outputs of the dipoles.

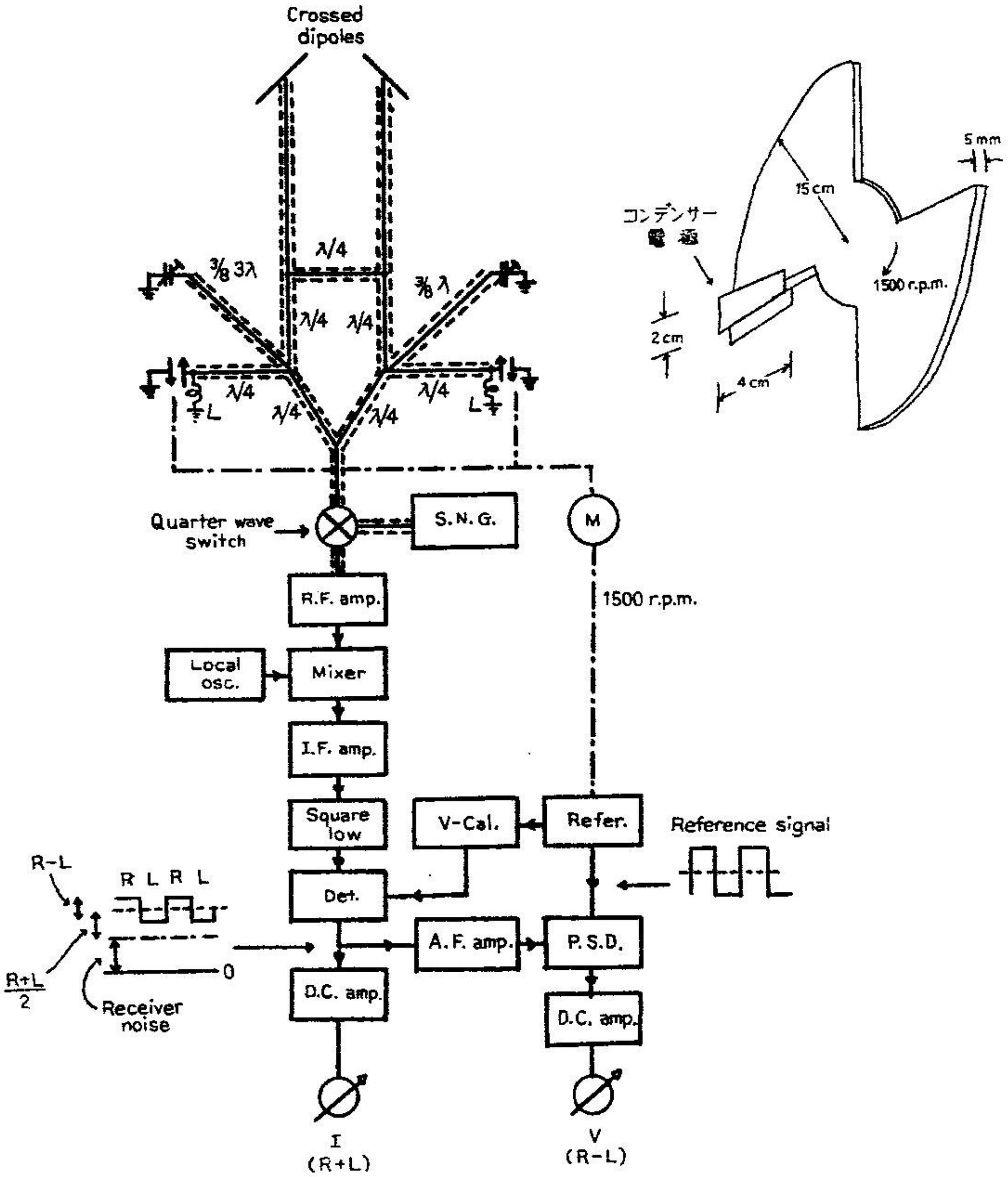


Figure 18: The block diagram of the 300 MHz polarimeter (after Tsuchiya, 1963a).

Figure 19: The 3 GHz parabolic antenna which was used to observe the partial solar eclipse in Tokyo on 14 February 1953 (courtesy: K. Akabane).

Three polarimeters at 17 GHz, 408 MHz and 614 MHz were constructed during 1964 and early 1965 in preparation of the International Quiet Sun Year (IQSY: 1964–1965). Both dipoles for the 408 MHz radiometer and the 614 MHz polarimeter were attached to the 10-m parabolic reflector. Details of the 17 GHz polarimeter are described by Tsuchiya and Nagane as follows (1965). A 0.8-m parabolic reflector with an equatorial mounting was used for the 17 GHz polarimeter. A turnstyle junction deflected the incoming waves into two rectangular waveguides to receive right- and left-handed circularly polarized waves separately. A polarization switch was constituted by a turnstyle junction and a ferrite gyrator driven by 130 Hz square waves. A similar type of switching device was also used for Dicke switching driven by 420 Hz square waves. The VSWR (voltage stand- ing wave ratio) from the input of the polarization switch to the output of the Dicke switch was less than 1.05. The overall insertion loss from the primary feed to the mixer was about 1 dB. The isolation of the polarization switch was more than 29 dB. The noise figure from the mixer to the preamplifier was 14.8 dB. The intermediate frequency was 30 MHz, with a bandwidth of 10 MHz. The overall system was calibrated by a standard circular horn with an absolute gain of 29.7 dB. The daily flux calibrations of solar radiation were done at 00:00, 02:00, 04:00, and 06:00 UT by pointing the antenna beam at the empty sky instead of the Sun to obtain the sky temperature, and next the two input waveguides of the receiver were terminated by the flap-attenuators to obtain the ambient temperature. The 17 GHz polarimeter started routine observations on 22 May 1964.

A 612 MHz multi-phase transit type interferometer was constructed and started routine observations in March 1965. This instrument consisted of two antennas arranged 50 wavelengths apart on an east-west baseline, each of which consisted of a triplicate of 12-element Yagi antennas. The Sun was observed during one hour before and after meridian transit. The total intensity was measured, as well as the output from the interferometer. The absolute flux density from the Sun was calibrated by using both a standard noise source and several discrete radio sources.

3 THE OBSERVATION AND INTERPRETATION OF SOLAR RADIO EMISSION AT THE TAO

3.1 Solar Eclipse Observations

The radio observation of a solar eclipse was an excellent chance to conduct a spatially-resolved investigation of radio sources on the Sun with a simple radio telescope.

The first such observations at the TAO were conducted during the partial solar eclipse of 12 September 1950 from Tokyo and Obihiro in Hokaido (see Figure 2) by T. Hatanaka using two 100 MHz radio telescopes. Unfortunately these observations were never published, and no records of this research project remain.

The partial solar eclipse on 14 February 1953 was observed at the TAO by Akabane using the first 3 GHz transit type parabolic antenna. Figures 19 and 20 show the parabolic antenna and time variation of radio emission observed during the eclipse, respectively. Analysis of this record showed the existence of an enhanced region near the west limb of the Sun which had been associated with a large sunspot one month before, suggesting that some regions of radio enhancement were closely related to sunspots.

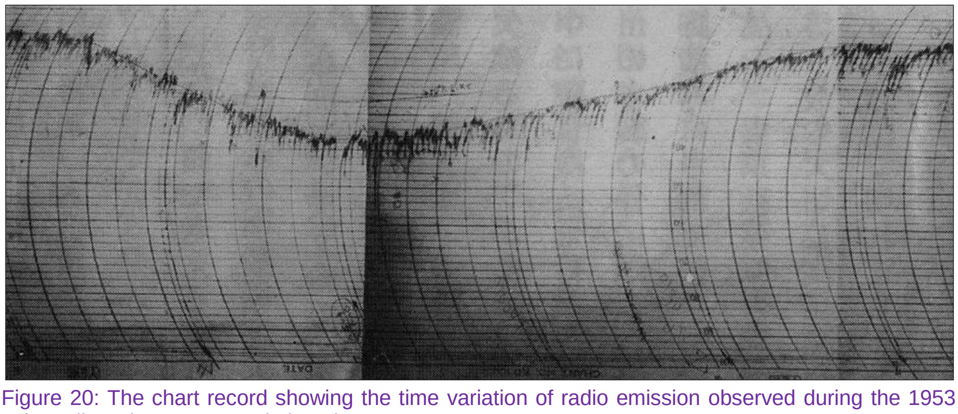


Figure 20: The chart record showing the time variation of radio emission observed during the 1953 solar eclipse (courtesy: K. Akabane).

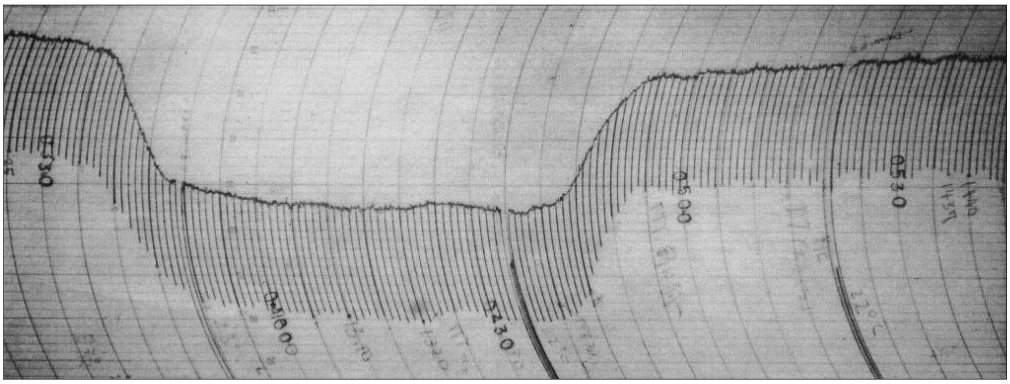


Figure 21: The chart record showing the time variation of radio emission observed during the 1955 solar eclipse (courtesy: K. Akabane).

The partial solar eclipse on 20 June 1955 was observed from three stations, Kagoshima (see Figure 2), Toyokawa and Tokyo at frequencies between 3 and 4 GHz (Hatanaka et al., 1955d; Hatanaka et al., 1955e; Hatanaka, 1957a). At Kagoshima and Toyokawa the Moon covered a large sunspot group in the southern hemisphere and a considerable decrease in flux density was observed (Figure 21), while at Tokyo the flux density decreased only by a few percent when the Moon covered the southern part of this sunspot group. The 4 GHz interferometer at Toyokawa measured the variation in the total flux density of the enhanced region, and its location, size and brightness distribution were deduced from these observations. A comparison between the radio and optical observations revealed that the radio brightness distribution was remarkably similar to the calcium plage around the sunspot group which is shown in Figure 22. Thus, the generation area of the slowly-varying component was clearly identified.

Akabane (1958d) observed the partial solar eclipse of 29 April 1957 from the TAO with the 3 and 9.5 GHz polarimeters. The area near the north pole of the Sun was covered by the Moon during the eclipse but unfortunately no sunspot groups were covered so no useful results were obtained from this eclipse observation.

Subsequently, Akabane (ibid.) observed the partial solar eclipse of 19 April 1958 from the TAO with those two polarimeters. He examined details of the intensity and polarization distributions of the enhanced region which was associated with a bipolar sunspot and proposed that the magnetic field was inclined by about 30° to the east and west from the normal of the enhanced region.

3.2 Type I Bursts

Although in this subsection emphasis is placed on Type I bursts, we will deal with observations of both Type I and III bursts simultaneously if descriptions of both types of bursts are difficult to differentiate from one another in the papers.

As of 1950, the following characteristics of noise storms were known:

(1) the radiation was correlated with the central meridian passage of large sunspots;
(2) the duration was of the order of several hours to one day;
(3) the radiation was circularly polarized, and the sense of the polarization of the storm bursts was the same as the continuum background; and
(4) The bandwidth and the lifetime of a storm burst were about 4 MHz and 1.5 seconds, respectively.

The initial results from the 200 MHz broadside array investigations were given by Hatanaka (1950). He analyzed the relation between the characteristics (or number per hour) of noise storms and the activities of sunspots, and found that burst activity persisted after large and active sunspots had disappeared or become less active.

Hatanaka and Moriyama (1952) systematically analyzed noise storms which were observed with the total flux radio telescopes at 200, 100, and 60 MHz at TAO between January and August, 1951, and they also used data obtained with 81.5 and 98 MHz radio telescopes at the Cavendish Laboratory (Cambridge) and at Potts Hill (Sydney) respectively. They also analyzed data from trial observations of circular polarization with the 60 MHz polarimeter between May and September, 1951. They were able to isolate a number of characteristics of noise storms, such as:

(1) they occurred in a sporadic manner in regions above large and magnetically-active sunspots;

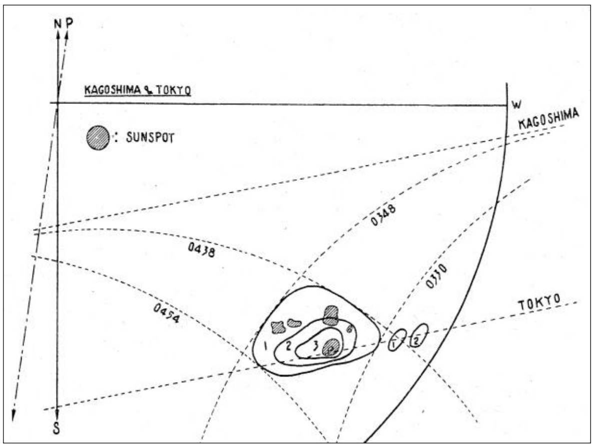


Figure 22: The brightness distribution of the ‘radio spot’ derived from observations of the 20 June 1955 partial solar eclipse superimposed on the optical image (after Hatanaka et al., 1955e).

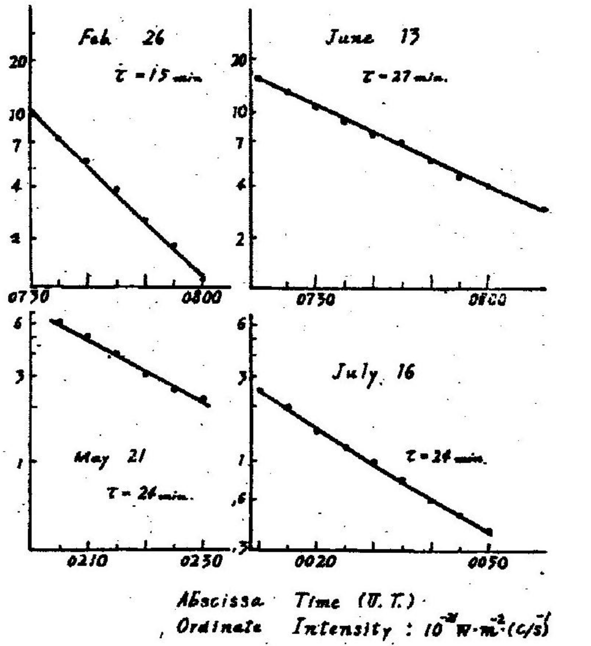


Figure 23: Decay curves of noise storms observed with the total flux radiometer at 60 MHz (after Hatanaka and Moriyama, 1952).

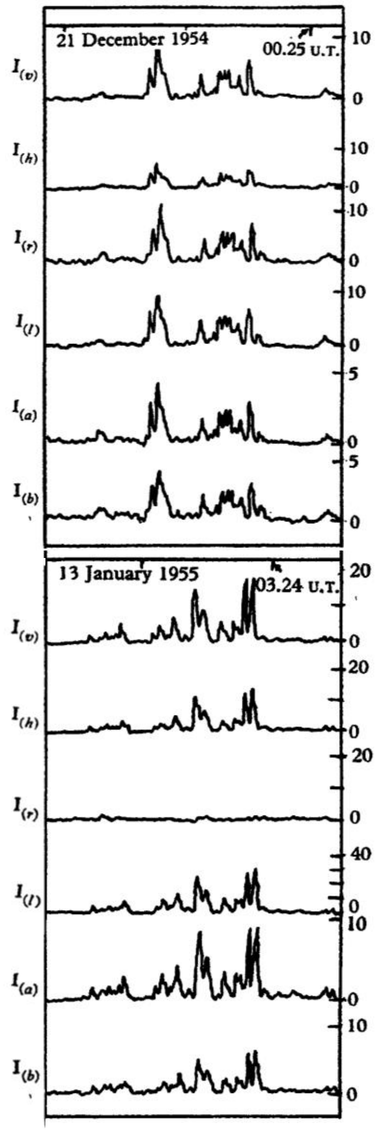


Figure 24: Examples of the records of bursts obtained by the 200 MHz time-sharing polarimeter (after Hatanaka, 1957b).

(2) their maximum occurrence was at the time of the central meridian passage of a sunspot, and it diminished by ~50% two days later;
(3) they were triggered by intense solar flares that accompanied non-polarized outbursts;
(4) they exhibited an exponential decay, with a time constant of about 15 to 30 minutes (Figure 23); and
(5) a right-handed circularly-polarized noise storm was associated with the south pole of a sunspot, and *vice versa.*

After the 200 MHz time-sharing polarimeter was constructed in 1954 the polarization of solar radio bursts was extensively studied at the TAO, with the aim of measuring the Stokes parameters. The initial results were reported as polarization characteristics of Type I bursts observed during active periods in December 1954 and January 1955 (see Hatanaka, Suzuki, and Tsuchiya, 1955b; 1955c; Hatanaka, 1957b). Some examples of these bursts are shown in Figure 24. The main results were:

(1) the radiation is a mixture of two components: one is elliptically polarized and the other is randomly polarized;
(2) the ellipticity varies from nearly 100% (circular) to 10% (nearly linear); and
(3) the degree of polarization is more than 90% on most days, but sometimes drops below 50% and even down to 10%.

Tsuchiya (1963b) carried out a statistical analysis of the degree of circular polarization of noise storms which were observed with the 200 MHz time-sharing polarimeter during 1957 and 1960, with data also contributed by the 200 MHz multiphase interferometer for noise storms observed during 1960. It was revealed that partially-polarized bursts with a degree of polarization of ~50% were most rare, while the enhanced radiation recorded during noise storms had the same polarization characteristics as that of the Type I bursts.

It was known that noise storms were composed of two components: a background continuum, and the storm bursts (Wild, 1951). Takakura (1959a) attempted to explain the background continuum as the superposition of many spikes which had an identical shape, occurred at random and were distributed in amplitude according to a probability density. To compare the theoretical results obtained from this hypothesis with observed properties of noise storms, samples of noise storms were selected from the records obtained between January and August 1955 with the 200 MHz time-sharing polarimeter. If two parameters, i.e. the occurrence frequency of bursts and the distribution of their amplitudes, changed with time, as was likely, almost all noise storms observed were in fairly good agreement with the hypothesis. The above hypothesis was further supported by measuring the post-detection low frequency spectra of noise storms (Takakura, 1959b).

Suzuki (1961) summarized studies on various properties of noise storms at 200 MHz based upon observations made with the time-sharing polarimeter and the multiphase interferometer. He found the following results:

(1) the magnetic field dependence of the sense of the radio polarization was confirmed to be in the sense of the ordinary mode;
(2) noise storms with changing or mixed polarization, including those which did not obey the general rule, were observed in a quite limited region on the Sun, and this region remained active for an exceptionally long period—at least one and a half years;
(3) partially-polarized and non-polarized bursts had much larger source sizes than strongly polarized bursts; and
(4) the bursts in high intensity storms were quite concentrated in position, i.e. towards the center of the solar disk (see Figure 25).

3.3 Type III Bursts

Wild et al. (1959) observed Type III bursts with a swept-frequency interferometer in the frequency range from 40 to 70 MHz and proposed a plasma hypothesis for Type III bursts. Morimoto (1961) compared the Japanese 200 MHz multi-phase interferometer results with Wild's results at lower frequencies. The height of the sources of Type III was found to be 0.4 $R_{\odot}$ above the photosphere. The results of Type III bursts observed at the TAO showed good agreement with the Australian observations made at lower frequencies.

Akabane and Cohen (1961) used the Cornell 200 MHz polarimeter to detect linearly-polarized Type III bursts. Two different sets of bandwidths were used: 10 and 20 KHz during March-June 1959 and 10 and 300 KHz during July-September. They found that many large Type III bursts were weakly linearly polarized (0.05–0.3) in a 10 KHz band and either unpolarized or weakly circularly polarized at 300 KHz. It was inferred from theoretical considerations that the amount of Faraday rotation corresponding to these observational results was ~10^4 radians, which was consistent with the earlier estimation by Hatanaka (1956).

Morimoto (1964) compared the positional data of Type III bursts observed with the CSIRO's 40–70 MHz swept-frequency interferometer with the corresponding flare data to obtain a more accurate height in this frequency range than had been obtained previously. The movement of the source at this frequency range was compared with the movement at 200 MHz observed simultaneously with the TAO multiphase interferometer. The apparent height of the source near 50 MHz was estimated to be 1.07 ± 0.1 $R_{\odot}$ above the photosphere, which gave an electron density for a coronal streamer about three times higher than that found optically. It was also shown that the positional movements of individual sources at the two frequencies within a group were correlated. This suggested that the trajectories of the sources of bursts were approximately parallel and the density variations across the lower and upper parts of the coronal streamer were similar.

Enome (1964) studied the circular polarization characteristics of Type III bursts at 200 MHz with respect to the positions of the sources. A relatively large number of partially-polarized Type III bursts were also found at 200 MHz. The sense of rotation of the partially-polarized Type III bursts, whose locations on the solar disk were near the sources of the noise storms occurring within a few days, was the same as the sense of the associated noise storms.

Takakura and Tlamicha (1964) compared active prominences without flares with radio emission observed with the 200 MHz multiphase interferometer and the 200 MHz time-sharing polarimeter. The number of associations of Type III bursts with optical activity was 8 out of 21. This result may support a statistical significance, considering the fact that the high frequency cutoff for Type III bursts sometimes occurred below 200 MHz and that the radio waves from the extreme limb may not have been observed.

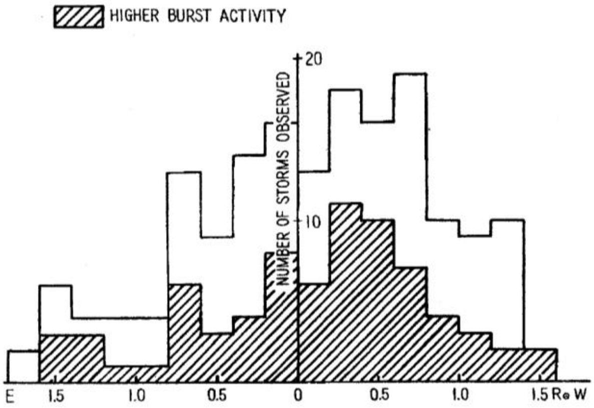


Figure 25: East-west distribution of positions of noise storms observed with the 200 MHz time-sharing polarimeter (after Suzuki, 1961).

Descriptions of Type III bursts contained in the papers by Morimoto and Kai (1961; 1962) and Morimoto (1963) are included in the previous subsection.

Morimoto and Kai (1961; 1962) carried out a statistical investigation of the heights of Type I and Type III bursts at 200 MHz by comparison of their apparent positional variation from the center to the limb of the Sun with the associated optical phenomena. The height of the sources of Type I bursts was ~0.2–0.3 solar radii above the photosphere and that of Type III bursts was slightly higher, when they are observed near the center of the solar disk. The height gradually increased with distance from the center, and for Type I bursts in particular reached 0.6 solar radii at the limb. If it was assumed that the emission originated from the plasma level, the electron density of the Type I source must have been about ten times larger than that of the normal corona. On the other hand, the occurrence distribution of Type I bursts on the solar disk showed a remarkable concentration near the center of the disk, while that of Type III bursts increased for up to 1.0 solar radius from the center and then rapidly decreased.

Morimoto (1963) then estimated the source heights and directivity of Type I and III bursts at 517, 200, 60, 55 and 45 MHz. The heights of Type III bursts at frequencies between 517 and 45 MHz give a distribution of electron densities ~30 times the value of the normal corona, while Type I bursts had a stronger limb darkening than Type III bursts. These observations showed that electron densities above active regions derived from the radio measurements were higher by a factor of 3 than those obtained by Newkirk (1959) from K-corona optical observations, as shown in Figure 26. In order to resolve this discrepancy, he suggested filamentary substructures within Newkirk's model as the radio sources of Type I and III bursts. In addition, he suggested that the filamentary radio sources of Type I bursts lay below a stopping level of extraordinary waves in the streamers so that escaping waves were circularly polarized (ordinary waves), while the sources of Type III bursts were just above the stopping layer so that the escaping waves were weakly polarized or unpolarized.

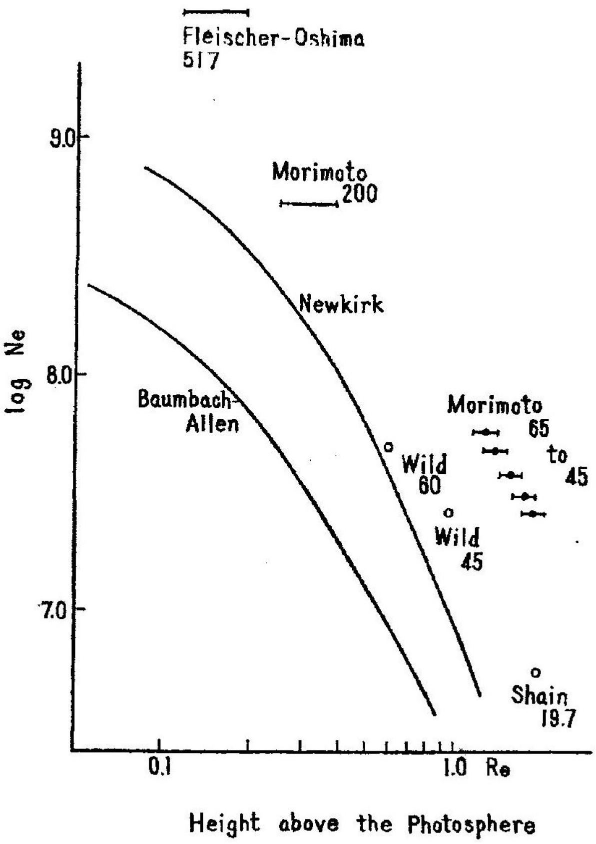


Figure 26: The height of the sources of Type III bursts at frequencies between 517 and 19.7 MHz (after Morimoto, 1963).

Kai (1962) examined the observational features of Type I bursts in detail. The extension of the region in which Type I bursts originated coincided with plages rather than the associated sunspots themselves. The extension of the Type I continuum was the same as the scattering range of individual bursts, which was consistent with the interpretation that the continuum was a superposition of Type I bursts. It was also shown that Type I bursts occurring at the limb of the Sun had a longer duration and were nearly unpolarized. From this Kai concluded that the height at the limb was far above the plasma level so the collision frequency was sufficiently low to give longer duration and both ordinary and extraordinary waves could escape, resulting in unpolarized bursts.

Tsuchiya (1962) observed Type I bursts with the 199–207 MHz narrow band dynamic spectrometer at the TAO during November 1957 and March 1958. He demonstrated that the average bandwidth of Type I bursts around 200 MHz was ~4 MHz, which was the same as at lower frequencies.

3.4 Type IV Bursts

Although emphasis is put on meter-wave Type IV bursts in this subsection, microwave Type IV bursts (long-duration bursts at microwave wavelengths) are also dealt with here. On the other hand, microwave impulsive bursts are described in the next subsection.

Boischot (1957) was the first to recognize the existence of non-storm, flare-related continuum emission at meter wavelengths, and he designated these Type IV emission. Soon afterwards, Takakura (1959c) pointed out that the characteristics and the generation mechanism of this emission were distinctly different at frequencies above and below a certain cross-over frequency between 300 and 600 MHz. He suggested that emission above this cross-over frequency fell into the same category as Type IV and was caused by synchrotron radiation from high-energy electrons. To obtain experimental evidence, the dynamic spectra covering the cross-over frequency were studied by Takakura (1960a) using data from the 300–800 MHz dynamic spectrometer and observations at fixed frequencies of 9.5 GHz and 67 MHz made at the Toyokawa Observatory and the TAO. Based upon the observational results, the distinctive short-lived bursts at frequencies above 1 GHz were called 'microwave bursts', while the long-lived microwave bursts were referred to as 'Type IV bursts'. Takakura and Kai (1961) then examined the dynamic spectra of long duration intense bursts in the frequency range 67 MHz to 9.4 GHz using single-frequency records. They found at least two distinctive groups of bursts, i.e. long-duration bursts at centimeter wavelengths (the 'centimeter-wave Type IV') and Type IV bursts at meter wavelengths (the 'meter-wave Type IV'). These groups are mixed in some frequency ranges where they accompany another group of bursts at decimeter wavelengths (the 'decimeter-wave Type IV'). The Type IV bursts at meter wavelengths were frequently followed after an intermission of 30–60 minutes by similar but longer and weaker radiation (the 'meter-wave post-Type IV'). Takakura (1963a) also analyzed the broad-band spectra of solar bursts using the records obtained during 1958 and 1960 at fixed frequencies between 9.4 GHz and 67

MHz. The histogram of the central frequencies was shown to have three maxima, at 70–100 MHz, 300–500 MHz and above 9 GHz, which corresponded to Type IV_m (Type IV at meter waves), IV_{dm} (Type IV at decimeter waves), and IV_μ (Type IV at microwaves). This tendency is shown in Figure 27. Type IV_μ bursts are almost non-directive while the intensities of Type IV_{dm} and IV_m bursts decrease at about the solar limb by a factor of 0.3 and 0.1, respectively. The center frequency of some Type IV_m bursts drifts from higher to lower at rates of 30–40 MHz per 10 minutes.

When Wild et al. (1959) studied Type IV bursts at frequencies between 40 and 70 MHz they found the position of the source moved from the position of the flare up to 5 solar radii, while the emission at all frequencies was observed at the same position. Morimoto (1961) compared the results obtained by the 200 MHz multi-phase interferometer with Wild's results at lower frequencies and found that at 200 MHz Type IV bursts usually stayed at rest near the flare site, i.e. they showed no ejected motion, which disagreed with the results obtained at lower frequencies. Morimoto (1961) and Morimoto and Kai (1962) found that the height of the sources of Type IV bursts was ~0.2–0.3 solar radii above the photosphere, similar to those of Type I and Type III bursts.

Kai (1965a; 1965c) analyzed the polarization characteristics of eighteen Type IV bursts that were observed between 1957 and 1960 using data from the TAO and the Toyokawa Observatory at frequencies between 200 MHz and 9.4 GHz. The Type IV bursts at 200 MHz were weakly polarized in the initial stage, sometimes changing sense, but after a few tens of minutes they become strongly polarized up to more than 70%. The sense of polarization was the ordinary mode. Type IV bursts observed at the limb were weakly polarized, suggesting some sort of directivity was associated with the polarization. On the other hand centimeter wave Type IV bursts were partially polarized, probably in the extraordinary mode. The degree of polarization was usually 10–30%, and was nearly constant throughout the duration of the burst. The maximum polarization seemed to occur near the frequency of the intensity maximum. In many cases a clear or complex reversal in the sense of polarization was found between 1 and 9.4 GHz. Based upon these polarization observations, Kai (1965b) suggested possible mechanisms applicable to Type IV bursts. The mechanism for microwave Type IV bursts may be synchrotron radiation from inhomogeneous sources which were distributed vertically over the lower corona corresponding to the observing frequencies. The mechanism for Type IV bursts in the decimeter and meter range may be gyro-resonance radiation due to electrons of comparatively lower energies. An alternative possible mechanism is radiation from coherent plasma waves excited by an electron beam, which requires a sufficiently strong magnetic field and comparatively lower energy electrons of density about 10^7 cm^{-3}.

Kai (1963) examined the state of linear polarization of Type IV bursts which were observed with the 200 MHz time-sharing polarimeter between 1957 and 1960. Using completely circularly-polarized bursts (usually Type I bursts) as a calibrator, he estimated that almost all of these bursts had linear components of about 10%.

Kai (1967) analyzed twenty-three microwave Type IV bursts to reveal evolutionary features of microwave Type IV bursts using data observed during 1958 and 1967 at 1, 2, 3.75, and 9.4 GHz at the Toyokawa Observatory and at 17 GHz at the TAO. He found that the turn-over frequencies (f_m) moved progressively towards the lower frequencies, and their decay times (τ) become successively longer. A plot of all available data indicated an approximate relation where $\tau \propto f_m^{-a}$ (where a = 1–2).

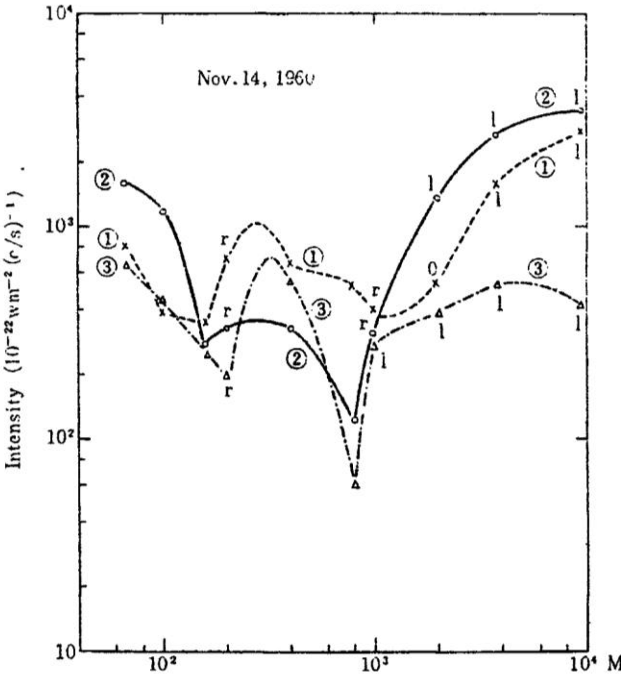


Figure 27: Intensity spectra of Type IV bursts at three times ((1): 03:40, (2) 04:00, (3) 04:20) on 14 November 1960 (after Takakura, 1963a).

3.5 Other Observations

Using the 9.5 GHz polarimeter, Akabane observed intense solar radio bursts which were associated with three large successive solar flares on 3 July 1957 (see Akabane and Hatanaka, 1957; Akabane, 1958b; 1958d). An interesting point was that the state of polarization of the burst corresponding to the third flare changed considerably. It was suggested from comparison with both the associated optical flare and the magnetic field structure that this polarization change was connected with the shift of the activity center of the optical flare. Akabane also summarized the observational results from June 1957 to May 1958 as follows:

(1) the integrated frequency distribution of occurrence for the intensity (I) and for the percentage polarization (r) were proportional to I^{-n} (with n in the range 1.8–1.9) and roughly exp ($-15r^2$), re-

spectively; and
(2) some linear polarization was observed in many bursts (those greater than 100 sfu).

Akabane (1958d) suggested from the analysis of data observed with the 9.5 GHz polarimeter during June 1957 and May 1958 that the S-component had circular polarization ~10% and its sense seemed to change near the central meridian passage of the enhanced region when it was associated with a typical bipolar sunspot. A small amount of linear polarization also was detected in a few cases.

Concerning the emission mechanism of the S-component, two different explanations were proposed. Waldmeier and Müller (1950) suggested that the S-component may have been emitted by free-free transition within a coronal condensation associated with a region of exceptionally high electron density in the solar corona. An alternative explanation by Piddington and Minnett (1951) was that the S-component was due to the gyro-magnetic effect in the sunspot's magnetic field. Kawabata (1960a) conducted a statistical study of the S-component for the period from July 1957 through August 1959 using single frequency observations from Ottawa at 2.8 GHz, the Toyokawa Observatory at 1, 2, 3.75, and 9.4 GHz, and the TAO at 9.5 GHz. The temperature and the optical depths of coronal condensations associated with intense calcium plages were obtained. The temperatures of the coronal condensations were estimated to be 4–6 × 10^6 K. There seemed to be a tendency that the more intense the calcium plage, the higher the electron temperature. By examining the polarized component obtained during the eclipse of 19 April 1958 by Tanaka and Kakinuma (1958), it was found that the polarized component was due to the gyro-magnetic effect in a magnetic field of >1,000 gauss localized to a small area above the sunspot.

It had been pointed out that unusual increases in cosmic-ray emission only occurred in the ascending and descending phases of solar cycles, and avoided the maximum phases. Takakura and Ono (1961; 1962) examined variations in occurrence frequencies of H-alpha flares and microwave outbursts at 9.4 and 3.75 GHz at Toyokawa and 2.8 GHz at Ottawa and found that most intense outbursts showed the same tendency as the cosmic-ray increases, in spite of the fact that importance 3+ flares occurred most frequently at sunspot maximum. From this finding, the authors suggested that the above tendency regarding the unusual increase of cosmic-rays may simply be due to some condition which made it unfavorable for the acceleration of particles at sunspot maximum.

Sudden ionospheric disturbances (SIDs) were believed to be associated with an increase in ionization in the D-region caused by incident solar ionizing radiation. Elwert (1956) suggested that a high temperature region at 10^7 K on the Sun may produce the solar hard X-rays which cause SIDs. On the other hand, Hachenberg and Volland (1959) and Sinno and Hakura (1958) concluded from research on the relationship between SIDs and solar radio outbursts that both the microwave emission and the ionizing radiation responsible for SIDs originated from the same gaseous volume in the solar atmosphere and were generated by a similar emission mechanism. Kawabata (1960b; 1963) then conducted a statistical study of the relation- ship between SIDs and solar microwave emission by using 2.8 GHz Ottawa observations and short wave fade-outs (SWF) published by the C.R.P.L. in Boulder, for the period from January 1957 to July 1959. He also studied the spectrum of post-burst increases using data at several frequencies from 1 to 9.5 GHz obtained at the Toyokawa Observatory and at the TAO. He was able to show that SIDs were closely related to post-burst increases and that these were caused by thermal emission from very hot condensations in the solar corona, with temperatures as high as 10^7–10^8 K. Such condensations emitted sufficient X-rays to cause SIDs.

Takakura (1966) computed the energy distribution of high-energy electrons that emitted gyro-synchrotron radiation responsible for microwave impulsive bursts as a function of time for plausible initial distribution functions. The theoretical decay curves of the radio emission from these electrons were compared with the observed decay curves of the radio bursts to deduce the initial energy distribution. Here, radio data from 1 to 9.4 GHz obtained at the Toyokawa Observatory were used. It was suggested that the most probable initial distribution was the power law $K^{-\gamma}$, with γ of 3–5. On the other hand, X-ray bursts coincident with microwave impulsive bursts were observed by X-ray detectors aboard balloons and rockets. Peterson and Winckler (1959) showed a discrepancy of the order of 10^3–10^4 between the total number of electrons needed to radiate an X-ray burst (200–500 keV) and that required to radiate a coincident microwave burst. Takakura and Kai (1966) then proposed a comprehensive model of microwave bursts and hard X-ray bursts (>20 keV) as follows: (1) The majority of the high-energy electrons are trapped in a localized region and are the source of the hard X-ray bursts, which are invisible at microwave frequencies; while (2) a small fraction, ~10^{-3}–10^{-4}, of the high-energy electrons is trapped in an outer region and contributes to the micro- wave impulsive bursts.

Kawabata (1966b) statistically compared the soft X-ray data obtained mainly by satellite SR-1 and Ariel 1 with the corresponding microwave data obtained at the Toyokawa Observatory, and showed that soft X-ray bursts correlated with microwave long-enduring bursts (precursors, post-burst increases, and gradual rise and fall bursts). In addition, the X-ray burst of 4 September 1960 was associated with a flare which occurred at a sunspot group located about 10° behind the western limb, which suggested that the X-ray source was located in the corona. It was further estimated that the

X-ray source had a temperature of ~6×10^6 K and an electron densiuty of 1.5×10^{49} cm^{-3} at the peak of the emission.

4 THE THEORY OF SOLAR RADIO EMISSION

For frequencies less than 50 MHz Hatanaka (1953) derived a solution for the propagation path of radio waves through the solar atmosphere by elliptic integrals by assuming spherical symmetry of the atmosphere and distribution of the electron density. Then, he tried to apply it to explain the directivity found for solar radio emission such as noise storms.

Van de Hulst (1949) suggested that owing to changes in the electron density within the solar corona, the apparent temperature of the quiet Sun measured at radio frequencies might undergo a periodic change in the course of the sunspot cycle. Hatanaka and Moriyama (1953) calculated the apparent temperature of the quiet Sun with varying values of chromospheric and coronal electron densities to see how these changed with the sunspot cycle. The electron temperature in the chromosphere was assumed to increase exponentially with height until it reached a constant value (10^6 K). The electron density in the corona was presumed to vary by a factor of two during a single sunspot cycle without any change in the form, but in the chromosphere it was assumed to vary in two different ways. The calculated curve fairly well fitted the 5-yr long observations by Covington (1951a; 1951b) at 10.7 cm, but did not fit well the decrease in apparent temperature reported by Christiansen and Hindman (1951) at five frequencies (from 200 MHz to 1 GHz) for the period 1947–1950.

It was known terrestrial magnetic storms and aurorae were related to solar activity. The analysis of these relationships suggested that some agent was emitted from the Sun. Kawabata (1955) assumed that the constituents of such an agent were clouds of completely-ionized hydrogen, and he investigated their motions transverse to magnnetic fields using a simplified model that assumed that collisions between ions and electrons were negligible. The results were applied to the escape of corpuscular streams from the Sun.

Takakura (1956) proposed a possible emission mechanism for polarized bursts and noise storms. If electrons with non-relativistic energy gyrated in groups in magnetic fields above sunspots, extra-ordinary waves of a non-thermal nature were emitted. These waves were reflected or absorbed in the outer region of the corona where the refractive index for the waves became infinite, but on the way up to this layer a part of a wave would be transformed into an ordinary wave if there was a layer where the magnetic field and/or the electron density changed steeply along the path of the wave. Ordinary waves thus generated could propagate through the solar atmosphere and subsequently their effects would be observed at the Earth.

Hatanaka (1956) treated, in general form, the Faraday effect in the Earth's atmosphere on the ellipticity and tilt angle of the polarization ellipse of cosmic radio waves. It was shown that when the path of the radio waves was nearly perpendicular to the direction of the magnetic fields, the ellipticity varied. In the case of the solar atmosphere, the tilt angle was rotated by a very large amount even in the most favorable cases. Therefore, any linearly-polarized radiation emitted from the Sun would be obliterated because of the finite bandwidth of the receiver.

Kawabata (1958) investigated the intensity and the polarization of radio-frequency radiation emitted by an ionized gas in a magnetic field, taking into account the simultaneous interaction of electrons with the surrounding ions. The calculation was made on the assumption that the refractive index of the surrounding medium was unity. It was shown that the Stokes parameters of the radiation emitted by an ionized gas could be obtained from the Fourier transform of the correlation functions between various components of the velocity of an electron.

There seemed to be two kinds of emission, i.e. one with maximum flux between 10 and 100 MHz and the other with a maximum flux at several thousand megahertz. The former emission caused Type II and IV bursts and was probably associated with plasma oscillations, while the latter emission was probably caused by synchrotron radiation of electrons with intermediate energies. Based upon the above consideration, Takakura (1960b) calculated the emissivity, absorption coefficient, polarization and spectrum for synchrotron radiation of electrons in circular orbits with velocities of 0.25−0.90 the speed of light. The spectrum derived from radiation of electrons with electron energy spectra following a power law, as for the example shown in Figure 28, was consistent with the observed average spectra of outbursts at microwave wavelengths. On the other hand, outbursts observed at 1, 2, 3.75 and 9.4 GHz at the Toyokawa Observatory had a circularly-polarized component of 10–100%, where the sense of polarization reversed somewhere between 2 and 3.75 GHz. Takakura (1960b) also showed that this behavior could be expected from synchrotron radiation. Subsequently, Takakura (1960c) calculated the emissivity, absorption coefficient, polarization and spectrum for synchrotron radiation of electrons in helical orbits with velocities of 0.25−0.90 the speed of light. The general tendency was similar to the case in which the orbits of the electrons were circular, but a major difference was a remarkable increase in the radiation at frequencies below the gyro-frequency of ambient thermal electrons.

Uchida (1960; 1962) discussed the exciters of Type II and Type III bursts from the viewpoint of the velocities with which their sources moved in the solar atmosphere. Considering the propagation velocities of several possible types of disturbances in the physical conditions above a sunspot, he concluded that the exciters of Type II bursts were hydromagnetic shock fronts, while those of Type III bursts were the free streaming of charged particles with high velocity. It was also shown that this result was consistent with the observed characteristic features and differences of these two different types of solar radio bursts.

Takakura (1961a; 1962) discussed the acceleration of thermal electrons to relativistic energies due to hydromagnetic waves in order to account for the characteristics of Type IV bursts. The first acceleration could easily arise as a consequence of high velocities of Alfvén waves in the lower corona. In this case, the acceleration was limited

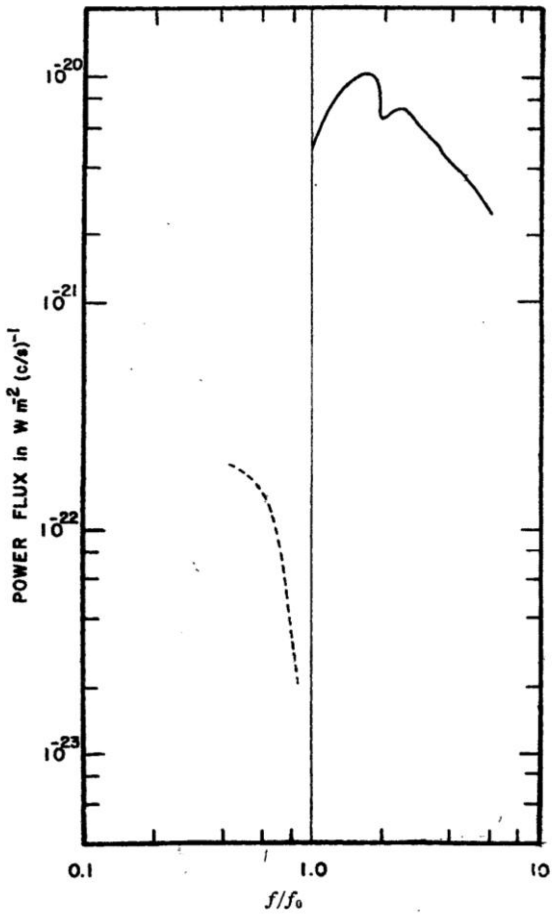


Figure 28: An example of a spectrum calculated under the assumption that the electron spectrum $\propto E^{-1}$, the total number density of high-energy electrons = 1 cm^{-3}, the gyro-frequency (f_0) = 10^3 MHz, the source diameter = 10^5 km and the source depth = 10^5 km. The dashed line shows that self-absorption is strong at frequencies from 0.6 f_0 to 1.0 f_0. (after Takakura, 1960b).

only to the direction parallel to the magnetic field. In order to accelerate the electrons further, up to relativistic energies, redistribution of the velocities of the accelerated electrons may have been caused by collisions of the accelerated electrons with ambient thermal electrons well before their energies were lost by the collisions. The accelerated electrons tended to accumulate in places where the magnetic field was better able to radiate synchrotron radiation. In the case of an intense eruption, a few magnetic bulges would be formed as separate radio sources for meter-wave, decimeter-wave and centimeter-wave Type IV bursts.

Moriyama (1961) derived absorption coefficients for free-free transitions in the radio region from emission coefficients using purely classical lines. In the computation, the Debye shielding length was adopted as the upper limit for the impact parameter. In addition, he criticized the existing chromospheric models based upon the radio data and derived a relation between the local electron temperature and the integral of the density squared over the line of sight from radio data.

Takakura (1961b) discussed limiting the sense of circular polarization of magneto-thermal radiation from two small radio sources above a preceding and a following sunspot as a function of the heliographic longitude of the sunspot, assuming a dipole magnetic field for a bipolar sunspot field and the Baumbach (1938) model for coronal electron densities. The sense of polarization at a fixed frequency was expected to reverse when the sunspot reached a certain heliographic longitude due to the rotation of the Sun. The sense-reversal occurred at western longitudes for emission from the preceding spot and at eastern longitudes for emission from the following spot. The results were compared with solar eclipse observations made on 19 April 1958 of the polarization of the radio waves from a large bipolar sunspot (Akabane, 1958d; Tanaka and Kakinuma, 1958).

Takakura (1963b) proposed a theory of Type I bursts which he suggested were radiated by Rayleigh scattering of coherent plasma waves. In this theory, the coherent plasma waves were excited by a beam of electrons with a group velocity of a few times of the mean thermal speed. The beam electrons perhaps were created by collisions of two wave packets of Alfvén waves propagating in opposite directions to each other.

The coronal magnetic field was hard to estimate from optical observations. Takakura (1964a; 1964b) estimated magnetic field intensity in the solar corona using the radio burst measurements, i.e. heights, motions, intensity spectra and polarization of Type I, II, III and IV bursts in meter waves, assuming their emission mechanisms. From these estimates he derived a magnetic field strength ~10 gauss at heights of 0.2–1.0 solar radii above active sunspot regions. However, it was suggested that the magnetic field must have been very weak, ~10^{-1} gauss or less, at the same height far from the sunspot regions. The magnetic field intensity was also estimated as 270–900 gauss and 18–90 gauss for Type IV$_{\mu}$ and Type IV$_{dm}$, events respecttively.

Kawabata (1964) investigated the gyro-resonance radiation due to electrons having an arbitrary distribution with respect to their energies and pitch angles. He formulated an equation of transfer for the gyro-resonance radiation by taking into account the re-absorption due to the gyro-resonance effect and the Faraday effect assuming that the refractive index of the medium was close to one.

The energy stored in the hot coronal condensations responsible for soft X-ray bursts amounted to 10^{31} erg. The ejection of plasma clouds which produced terrestrial magnetic storms also required energy of the order of 10^{32} erg. A possible source to generate such large energies was the energy of a sunspot magnetic field. Based upon this consideration, Kawabata (1966a) proposed a mechanism for the acceleration of the plasma clouds that produce the geomagnetic storms. If turbulences with velocity ~30 km/s were generated near an X-type magnetic neutral point in the chromosphere, a magnetically-isolated cloud would be ejected into the upper solar atmosphere. The ejected cloud then would produce a collapse of the coronal condensation which was responsible for soft X-ray bursts and microwave impulsive bursts. The cloud then escaped from the Sun and produced a geomagnetic storm. A collision-free shock ahead of the cloud was responsible for Type IV bursts. A series of scenarios is shown in Figure 29.

Takakura (1966; 1967) also wrote two review papers for *Space Science Reviews* and *Solar Physics*.

5 CONCLUDING REMARKS

After a fruitful period of solar research at Mitaka, the TAO shifted its observation site for solar radio astronomy to Nobeyama, which was located 150 km north-west of Tokyo and was free of city noise. In 1969 a new 160 MHz compound interferometer was constructed there consisting of an east-west array with a resolution of 2′ and a north-south array with spatial resolution of 4′ (Takakura et al., 1967). After a preparation period, a 17 GHz one-dimensional solar interferometer with a multi-correlator system was constructed in 1978 (Nakajima et al., 1980). In 1990, the solar radio groups at Nobeyama and Toyokawa Observatory were combined into a new group, and the 17 GHz Nobeyama Radioheliograph was constructed in 1992 based upon the technical and scientific backgrounds of both groups (Nakajima et al. 1994). In 1995, it was upgraded to a dual-frequency system operating at 17 and 34 GHz, with spatial resolutions of 14″ and 7″ respectively.

6 NOTES

1 This is the third in a series of papers reporting the results of an international collaborative project conducted under the auspices of the International Astronomical Union's Working Group on Historic Radio Astronomy to overview the early development of Japanese radio astronomy. As such, it follows an introductory paper (Ishiguro et al., 2012) and a paper detailing—for the first time—Koichi Shimoda's attempt to observe the 9 May 1948 partial solar eclipse

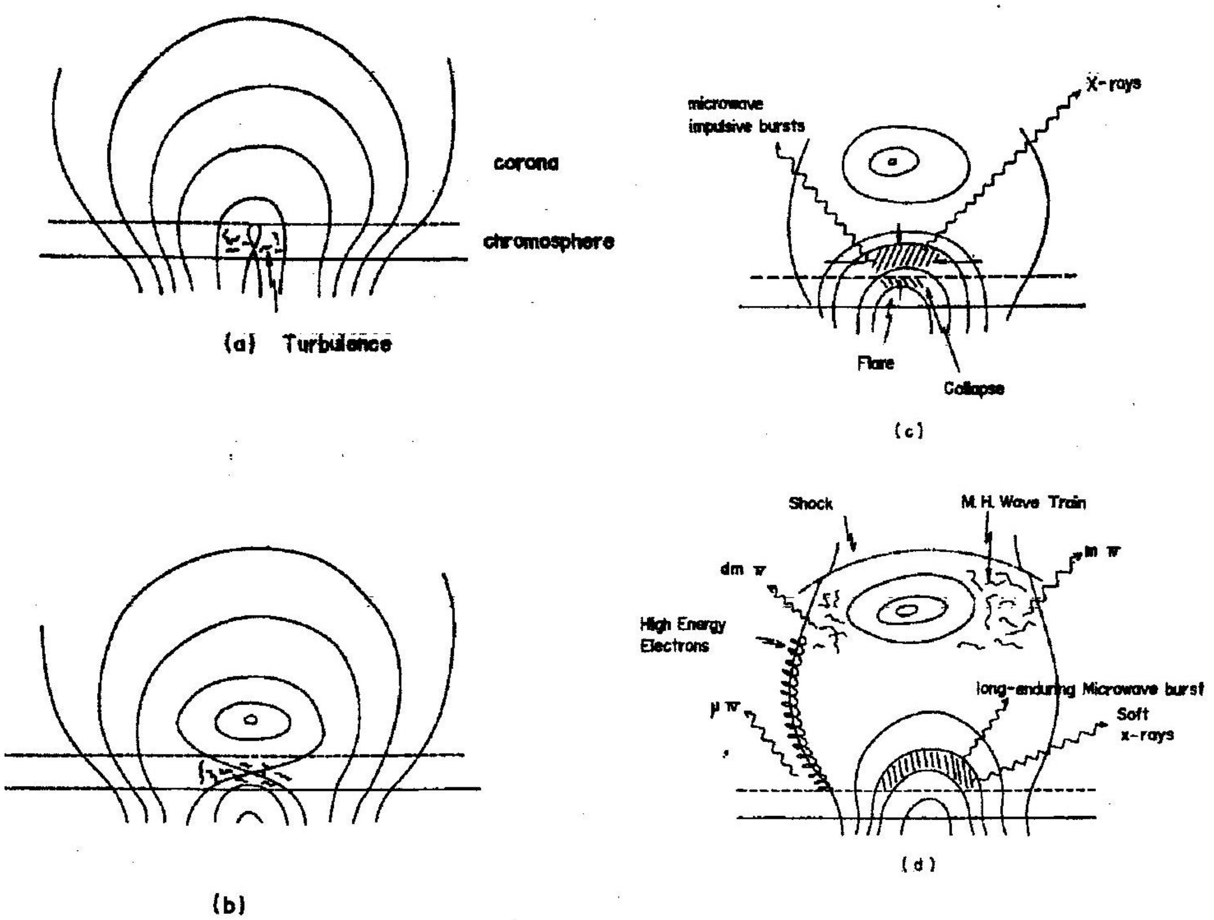


Figure 29: Various scenarios involving solar flares derived to explain the emission of associated radio emission. (a) Generation of turbulence near a neutral point. (b) Ejection of a magnetically-isolated cloud into the corona. (c) The collapse of a coronal condensation which triggers flares. (d) Escape of the cloud and generation of a geomagnetic storm (after Kawabata, 1966).

(Shimoda et al., 2013). This present paper outlines the research in early radio astronomy conducted at the Tokyo Astronomical Observatory (TAO) under the direction of Professor Takeo Hatanaka, and it is particularly appropriate that it should be published in 2014, exactly one hundred years after his birth. Accordingly we would like to dedicate this paper to the memory of Professor Hatanaka, a leading pioneer of Japanese radio astronomy.

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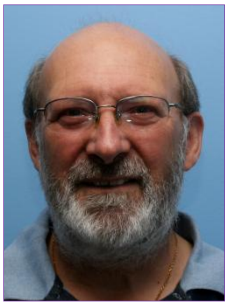
Dr Hiroshi Nakajima learned experimental physics at the Graduate School of Nagoya University during 1965 and 1970, and began his career in solar radio astronomy in 1970 at the Nobeyama Solar Radio Observatory of TAO. Since then, he has technically led the construction of various solar radio telescopes such as the 17, 35 and 80 GHz solar patrol radio telescopes, the 17 GHz one-dimensional solar interferometer with a multi-correlator system, and the Nobeyama Radioheliograph at 17 and 34 GHz. He also assisted in the design of the Hard X-Ray Telescope on the Yohkoh Satellite. Upon comparing radio observations with corresponding hard x-ray and gamma-ray ones he found various new observational results relating to high energy solar phenomena. For the past ten years he has given technical advice to the solar radio astronomy group at the National Astronomical Observatory of China about the construction of the Chinese Spectrum Radioheliograph.

Dr Masato Ishiguro is a Professor Emeritus of the National Astronomical Observatory of Japan (NAOJ). He started his research in radio astronomy at Nagoya University in 1970 where he investigated radio interferometry techniques. In 1980, he moved to the Tokyo Astronomical Observatory of the University of Tokyo to join the project to construct large millimeter-wave telescopes at the Nobeyama Radio Observatory (NRO) where he was in charge of constructing the Nobeyama Millimeter Array. He was the Director of the NRO from 1990 to 1996 and contributed to the open use of the telescopes. While doing research at the NRO, he worked on a plan for a large array at millimeter and submillimeter wavelengths. Since 1998, he had been leading the Japanese involvement in the international project to construct the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. He was a Professor at the NAOJ from 1988 until he retired in 2009. He is now the Japanese representative on the Committee of the IAU Working Group on Historic Radio Astronomy.



Professor Wayne Orchiston is a Senior Researcher at the National Astronomical Research Institute of Thailand in Chiang Mai. In his earlier years Wayne worked at the CSIRO's Division of Radiophysics in Sydney and later at its successor, the Australia Telescope National Facility. He has published extensively on the history of radio astronomy in Australia, France and New Zealand, and he and Masato Ishiguro lead the IAU Project on the History of Early Japanese Radio Astronomy. Wayne was the founding Chairman of the IAU's Working Group on Historic Radio Astronomy, and he currently serves as its Secretary. He has supervised five Ph.D. theses on the history of radio astronomy. In 2013 he was honoured when minor planet 48471 Orchiston was named after him.

Dr Kenji Akabane is a Professor Emeritus of the University of Tokyo. He started solar radio observations at a microwave frequency at the Tokyo Astronomical Observatory (TAO) of the University of Tokyo in 1952. He stayed in the United States from 1957 to 1960, studying at Cornell University and the University of Michigan. After coming back from the US, he showed a great interest in the field of cosmic radio astronomy and led a project to construct the 6-m millimeter wave radio telescope on the campus of the TAO, which was completed in 1970. After that he was motivated to construct the largest millimeter wave radio telescope in the world, and was appointed as the founding Director of the Nobeyama Radio Observatory in 1982. He was a Professor at the National Astronomical Observatory of Japan from 1970 until he retired in 1987. He then worked at the University of Toyama from 1987 to 1992, and then was the President of Matsusho Junior College for seven years, from 1992.

The late Professor Shinzo Enome died on 24 March 2011 at the age of 72. He began his career in solar radio astronomy in 1966 at the Research Institute of Atmospherics, Nagoya University (Toyokawa), and in 1988 moved to the National Astronomical Observatory of Japan (NAOJ) to participate in the construction of the Nobeyama Radioheliograph. He played a very important role in this project by unifying the solar radio astronomy groups from Toyokawa and Nobeyama into a single research group. As the Director of the Nobeyama Solar Radio Observatory, he led the construction of the radioheliograph and succeeded in completing the construction in two years. In 1999 Enome-san retired from the NAOJ, and was awarded an Emeritus Professorship. From the start, he was an active member of the IAU Early Japanese Radio Astronomy team and it is therefore fitting that he should be a posthumous co-author of this paper.

Dr Masa Hayashi is Director General of the National Astronomical Observatory of Japan (NAOJ). He trained in radio astronomy at the Nobeyama Radio Observatory of NAOJ and became an Assistant Professor at the University of Tokyo in 1987. He moved to the Subaru Project at NAOJ in 1994, became a Professor of NAOJ in 1998, and served as Director of the Subaru Telescope from 2006 to 2010. He then was a Professor of Astronomy at Tokyo University from 2010 to 2012, before accepting his current position.

Professor Norio Kaifu has a D.Sc. from Tokyo University, and specializes in radio astronomy, infrared astronomy and star formation. He was one of the founders of the Nobeyama Radio Observatory, led the construction of the Nobeyama 45-m mm-wave radio telescope, and found many exotic organic molecules in dark clouds. Then he was involved in the construction of the 8-m aperture Subaru Telescope on Mauna Kea as Director, before becoming Director General of the National Astronomical Observatory of Japan in 2000. As Director General he led NAOJ to be one of the three major international partners in the ALMA Project. Since his retirement as NAOJ Director, he has served the Science Council of Japan as President of the Natural Science & Engineering Division, and also was a Professor of the Open University of Japan until 2012. Currently he is President of the International Astronomical Union. In addition to 150 papers in astronomy he has published some 30 books in Japanese, both for students and for general readers. Well-known books among these are: *From Galaxy to the Universe* (Shin-Nihon-Shinsho, 1972), *Cosmic Radio Astronomy* (co-authored with K. Akahane and H. Tabara, Kyoritsu Shuppan, 1986 and 2012), *Poetries of the Universe* (Chukou Shinsho,1999), *101 Books to Understand the World* (Iwanami Shoten, 2011), etc. Besides several honors in science, Norio Kaifu was awarded the Mainichi Book-Review Award in 2011, and was honored when minor planet 6412 Kaifu was named after him.

Dr Tsuko Nakamura was until very recently a Professor at the Teikyo-Heisei University in Tokyo, where he taught Information Sciences since 2008. Prior to that, he worked at the National Astronomical Observatory of Japan for many years. His research interests lie in observational statistics of very small asteroids and in the history of Japanese astronomy, and he has published about forty papers in this latter field. His books include *Five Thousand Years of Cosmic Visions* (2011, in Japanese, co-authored by S. Okamura), *Mapping the Oriental Sky*, *Proceedings of the ICOA-7 Conference* (2011, co-edited by W. Orchiston, M. Sôma, and R. Strom) and *Highlighting the History of Astronomy in the Asia-Pacific Region*, *Proceedings of the ICOA-6 Conference* (2011, co-edited by W. Orchiston, and R. Strom). Tsuko is now Vice-chairman of the IAU Working Group on Historical Instruments.

The late Dr Atsushi Tsuchiya died in August 2011 at the age of 80. He began his career in solar radio astronomy in 1953 at the Tokyo Astronomical Observatory, where he specialized in low frequency observations of burst activity. In 1971 he left the radio astronomy group and transferred to the Observatory's lunar laser ranging program where he remained until his retirement in 1989. He then worked for the Japan Land-survey Association until his death. In wrote two books on land-survey applications of the GPS, and these were published in 1995 and 2008. Despite his more recent research interests, from the start Atsushi was an active member of the IAU Early Japanese Radio Astronomy team, and he contributed material for this paper prior to his death. It is therefore only fitting that he should be a posthumous co-author of this paper. The photograph of him included here was taken at the TAO when he was a graduate student.

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ANCIENT ASTRONOMICAL CULTURE IN UKRAINE. 1: FINDS RELATING TO THE PALEOLITHIC ERA

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Abstract: In this paper we describe some archaeological finds in the territory of modern Ukraine which are thought to provide evidence of the ancient astronomical culture of our ancestors. These finds date to Upper and Middle Paleolithic times (i.e. 100,000-12,000 BCE).

Among the finds unearthed at the Gontsy and Kiev-Kirillovskaya archaeological sites are mammoth tusk fragments which feature engraved patterns that have been interpreted as tables of lunar phase observations. More remarkable are two mammoth ivory bracelets from the site of Mezin which contain elaborate engraved ornamentation that also has been connected with a lunar calendar. In this paper we also mention astronomical finds at Paleolithic sites on the Crimean peninsula, including the famous solar petroglyph at Chokcurcha-1 and a possible 'star map' engraved on a mammoth shoulder bone that was found at Chokurcha-2.

After briefly discussing the problems associated with trying to assign astronomical meaning to these types of archaeological finds, we conclude that a complicated lunar mythology was indeed developed in Paleolithic times.

Keywords: archaeoastronomy; Paleolithic astronomy; Ukraine; ancient lunar-solar calendars

1 INTRODUCTION

During the past 140 years or so a number of remarkable artifacts made from mammoth bones and tusks that reveal the long history of astronomy in Ukraine have been recovered from Paleolithic archaeological sites such as Gontsy, Mezin and Kiev-Kirillovskaya.

Most speculative are fragments of mammoth tusks with engraved patterns on them that have been assigned astronomical meaning. However, it is difficult given our contemporary outlook to try to correctly interpret the astronomical knowledge and beliefs of ancient peoples. Nevertheless, during the 1960s American, Russian and Ukrainian researchers first attempted to establish an interrelation between lunar cycles and systematic grooves or pits on various Eurasian Paleolithic finds (see Abramova, 1962; Frolov, 1965; Marshack, 1964; 1970; Okladnikov, 1967; Rybakov, 1962; Shovkoplyas, 1965).

In two research papers, and a book titled *The Roots of Civilization*, the American archaeologist Alexander Marshack (1918–2004) initiated a 'revolution' in prehistoric archaeology concerning 'lunar notations' on European Upper Paleolithic remains (see Marshack, 1964; 1970; 1972). He was the first to direct attention to the works of Édouard Lartet (1801–1871), the famous French archaeologist and geologist. Back in the nineteenth century, Lartet argued that the geometrical 'patterns' formed by notches, dots and other regular symbols on portable artifacts may have been used by primitive people to register time, especially between periodic natural processes. After studying numerous stones, bones and other finds, Marshack concluded that such patterns possibly were calendar records based on lunar cycles.

Although his conclusions subsequently were not universally accepted by archaeologists and astronomers (e.g. see Elkins, 1996; Robinson, 1992), at the time Marshack's ideas were developed by others, including the well-known Hungarian geologist László Vértes (1914–1968; see Vértes, 1965) and the Russian historian, B.A. Frolov (1939–2005). In 1965 Frolov independently made a detailed study of patterns on nearly two hundred items from Eurasian Paleolithic sites and concluded that elements of the ornaments were characterized mostly by groups of 5, 7, 10, and 14 lines. He put forward the hypothesis that the 'rhythm 7' and 'magic sevens' depicting the allocation of time originated in Paleolithic times (for details see Frolov, 1974; 1992; 2000).

2 ASTRONOMY, AND ARCHAEOLOGICAL FINDS FROM THE PALEOLITHIC ERA

There is abundant evidence that the Paleolithic inhabitants belonged to the genus *Homo sapiens*, and the primitive art of these people is seen on many of the objects that have been excavated at archaeological sites in Europe, including the territory of modern Ukraine (see, for example, Chernysh, 1979; Efimenko, 1953; Frolov, 1971; Okladnikov, 1967; Shovkoplyas, 1965; and Zosimovich, 1992). The more we analyze the diversity of the Paleolithic archaeological finds the more we are convinced that the evidence points to astronomical observations and calendars used in daily life that were part of a 'Paleolithic pre-scientific knowledge base'. However, most of these conclusions have been published by archaeologists, while Ukrainian astronomers by and large have not been involved in these discussions—with the notable exceptions of the isolated studies by Zosimovich (1992), Pavlenko et al. (2006) and Vavilova and

Artemenko (2010). We therefore decided to fill this gap by collecting data on remarkable finds unearthed in Ukraine which appear to give an indication of the astronomical knowledge of our ancient ancestors.

Ukraine is blessed with an abundance of Paleolithic sites. Although mammoth bone huts and other structures and artifacts made primarily from mammoth bones and tusks are known from ancient settlements throughout Eurasia, they are mainly concentrated in the north-western tributaries of the Dnipro River basin and in the Crimea, making Ukraine an ideal area in which to study Paleolithic society. The well-known settlements of Dobranichivka, Gontsy, Kiev-Kirillovskaya, Mezhirich, Mezin, Semenivka and others (see Figure 1) have been dated by ^{14}C isotope analysis to between 27,000 and 12,000 BCE (for details, see Iakovleva, 2005).

2.1 Mammoth Tusk Fragments With Engraved Patterns

2.1.1 The Fragment from Gontsy

The first Paleolithic settlement found in eastern Europe was discovered by G.S. Kyriakov in 1871 on the banks of the Uday River near the village of Gontsy in the Poltava region of Ukraine. In 1873 this site was excavated by F.L. Kaminsky, a teacher and amateur archaeologist. In 1914-1915 the first professional excavations were carried out under the supervision of the well-known Ukrainian archaeologist and historian V.M. Scherbakivski (1876–1957), who was Head of the Archaeological Department at the Poltava Museum from 1910 to 1922. Further excavations followed in 1935, by I.F. Levitski and A.I. Brusov, and between 1977 and 1981 by V.I. Sergin. From 1993 up to the present day extensive excavations have been carried out by a joint Ukrainian-French team led by L.A. Iakovleva (Institute of Archaeology, National Academy of Science of Ukraine) and F. Djindjian (University of Paris). As a result, six mammoth bone dwellings within an area of some 40 × 80 meters have been identified at the Gontsy settlement. Bone and ivory ornaments and red ochre also have been recovered, and specialized working areas for stone, bone and ivory have been identified. This site was occupied at least twice during the Late Upper Paleolithic period, between 14,110 and 14,620 BP at the beginning of the climatic change that marked the end the last Ice Age (Iakovleva and Djindjian, 2005).

Among the unique finds unearthed in the earliest excavations (see Abramova, 1962) is a well-preserved mammoth's tusk fragment covered by a finely-engraved pattern (Figure 2). Subsequently, this pattern was interpreted as representing lunar phase observations. This mammoth tusk fragment no longer exists, and all we have is a sketch and a description made by V.M. Scherbakivski. Our recent conversations with officials at the Poltava Museum confirm that the 'traditional' explanation—that the mammoth tusk fragment was lost in a fire following a WWII bomb attack—is open to question. More likely, it was destroyed earlier, during the Civil War of 1918-1920, or else was taken abroad for safekeeping when V.M. Scherbakivski emigrated to Prague, the Czech Republic, in 1922.

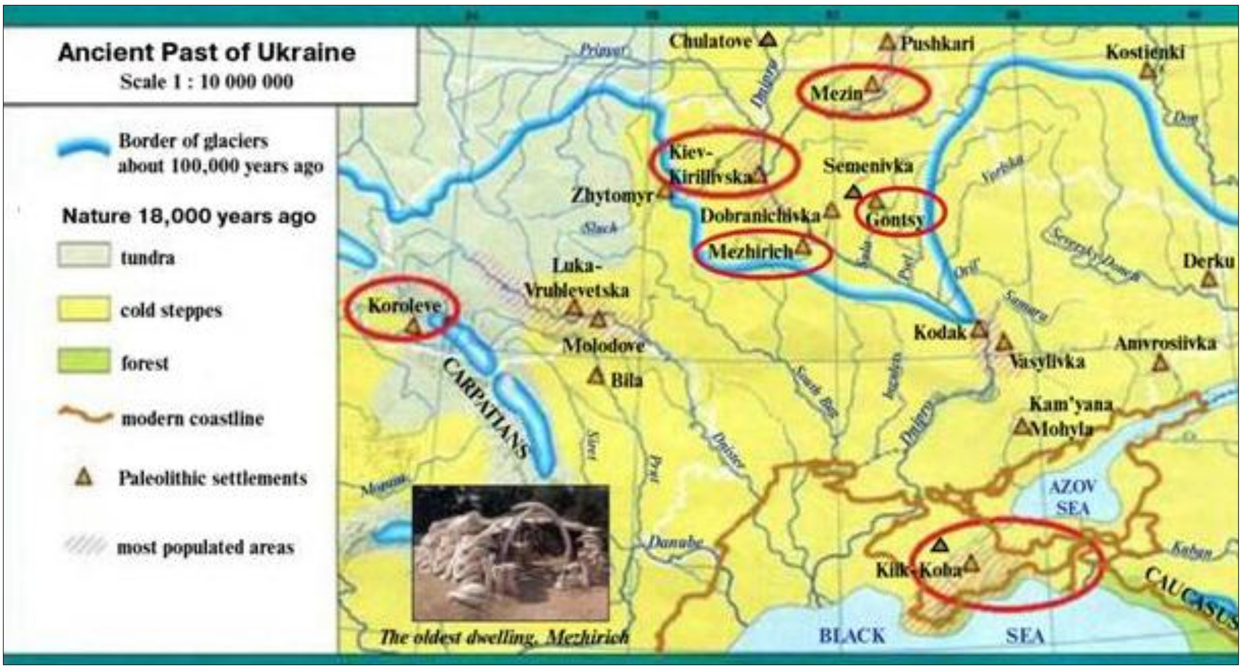

Figure 1: A map showing Paleolithic settlements in the territory of Ukraine, including Dobranichivka, Gontsy, Kiev-Kirillovskaya, Kiik-Koba, Kodak, Mezhirich, Mezin, Molodove and Semenivka (prepared by the authors).

Referring to Figure 2 (lower image) we can see that in the centre of this tusk fragment there is a thin curved line, from which on both sides alternating lines of different length depart at right angles, first a long one and then several very short ones, followed again by another long one and several very short ones, etc., totaling 32 long and 78 short lines (Abramova, 1962). The thoroughness and the depth of the incisions as well as the uniformity of the spacing between the very short notches suggest that the pattern on this mammoth tusk was used to reflect important recurring events. The well-known Russian archaeologist P.I. Boriskovsky (1911–1991), one of the first researchers of this tusk fragment, noted in 1957 that this decorative pattern had a certain logic. Later it was interpreted as a table of lunar cycle observations, where the thin deep line represents the time axis, while the short perpendicular strokes mark the phases of the Moon (Zosimovich, 1992). An interpretation is as follows: Full Moon is marked by a double stroke, while First and Last Quarters and also New Moon are marked by long lines. As for the positions of strokes: one stroke pointing outwards represents the first lunar month; two strokes pointing outwards indicate the second lunar month; the image of the third lunar month is damaged; and four strokes pointing outwards mark the fourth lunar month.

2.1.2 The Fragment from Kiev-Kirillovskaya

Another example of a mammoth tusk with a similar inscribed pattern was unearthed at the Kiev-Kirillovskaya site in Kyiv by the famous Russian-Ukrainian archaeologist of Czech origin, Vikentiy Khvoyko (1850–1914), and is described in Khvoyko (1903). This site dates to 15,000 BCE.

In 1893 during the excavation of a 21-m deep cultural layer Khvoyko uncovered a well-preserved collection of artifacts made from mammoth bones, tusks and molars. These items once belonged to at least 50 individuals of different ages. The 30-cm long mammoth tusk fragment with engraved markings is very similar to the aforementioned Gontsy mammoth tusk fragment (see Figures 2 and 3). This also looks to have been used as some sort of astronomical calendar.

So these two Ukrainian examples and similar fragments discovered at other Eurasian sites suggest that Paleolithic man had a knowledge of astronomy and not only marked the changing phases of the Moon but also kept a count of time.

2.2 Engraved Bracelets

The remains of another Upper Paleolithic settlement on the bank of the Desna River near Mezin village in the Chernihiv region (see Figure 1), were found accidentally in 1908, when a hole

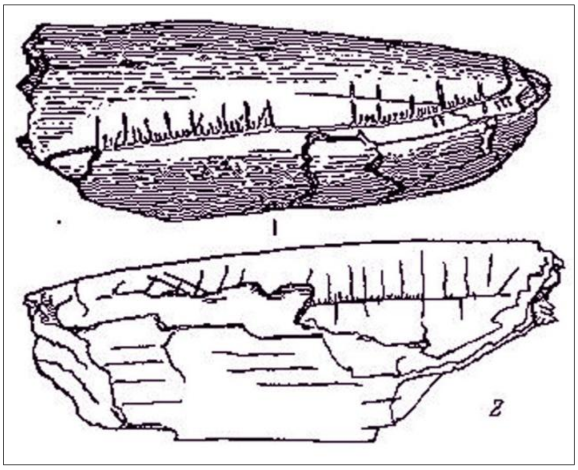

Figure 2: Sketches of the engraved patterns on the mammoth tusk fragments from the Kiev-Kirillovskaya (1, upper) and Gontsy (2, lower) (after Abramova, 1962: Table XXXIX).

was being dug for a cellar. This news immediately was reported at the XIV Archaeological Meeting in Chernihiv in August 1908, but it was not until 1930 that the first excavation of this site took place. Further excavations followed in 1932, 1954-1956 and more recently, making the Mezin settlement (Figure 4) one of the most studied Paleolithic sites in Ukraine.

Among the unique finds from this site were mammoth ivory phallic figurines and birds as well as bones painted with red ochre; a female statuette with a carved double pubic triangle and engraved chevrons; a mammoth ivory needle with an eye engraved with chevrons (e.g. see Shovkoplyas, 1965). This style of decoration is now referred to as ‘Mezin art’.

Figure 3: A general photograph (upper) and close-up of the right-hand end (lower) of the engraved mammoth tusk fragment from Kiev-Kirillovskaya (courtesy: National Museum of History of Ukraine, Kyiv; the photographs were provided by the authors).

Figure 4: An artist's reconstruction of the Paleolithic Mezin settlement on the banks of the Desna River (courtesy: V.V. Tarnovsky Chernihiv Historical Museum, Chernihiv, Ukraine; cf. the "Mezin scene" in Jelinek, 1975).

Among the early finds was a 20,000-yr old ornamented bracelet engraved out of mammoth ivory, and a second bracelet was found in 1956. Both have a magnificent design which can be found to this day on the embroidery of Ukrainian costumes. This pattern predates and is similar to the famous Greek 'meander' pattern. These two bracelets have been described by Okladnikov (1967: 102-103; our English translation) as

> ... authentic masterpieces of the bone-carvers' art, causing surprise due to the fact that they were made with stone instruments, without access to a lathe, drills or chisels … Bone material for these ornaments had an exceptional aesthetic value … The aesthetic character of these decorations cannot be denied in cases where they had some magical significance. Neither magic, including the magic of numbers, nor the cult of the ancestors automatically had a direct relation to the rhythmical alternation and the symmetrical arrangement of the ornamentation.

The patterns on the bracelets have been interpreted as depicting lunar calendars based exactly on the period of 10 lunar months or 280 days (for details see Abramova, 1962: Table XXXIV; Frolov, 1977; Pidoplichko, 1998; and Vavilova and Artemenko, 2010). Because of its historical importance the Mezin wide bracelet was selected to feature on a new coin, and this was issued by the Bank of Ukraine on 17 February 2006 (see Figure 5).

Figure 5: The coin with an image of the Mezin wide bracelet that was issued by the National Bank of Ukraine in 2006.

2.2.1 The Mezin Wide Bracelet

The first of these bracelets (Figure 6) was unearthed in 1912, and has the form

> … of a wide and thin bent plate, the external surface of which is covered by the complicated geometrical decorative meander and fir-tree pattern. At the ends of the bangle are three large openings for lacing. The width of the bone plate is 5.3 cm. (Abramova, 1962: 35, cf. Table XXXIV; our English translation).

The pattern on this bracelet was described in detail by Frolov (1977), and he proposed that it may represent a rare example of an ancient lunar-solar calendar. Upon analyzing the decorative pattern (see Figure 7), one finds that

> … two reiterating meander groups are divided twice by zones of zigzags. Each of the zigzags consists of 7 lines. We can clearly identify 5 different patterns: A, C, and E in the centre and at the edges of the meander zone; and B and D zones. (Frolov, 1971: 98; our English translation).

This ornamentation of parallel strokes separated in the areas of the zigzags, consists in total of 564 lines (20 lunar months). It is interesting that the number of lines in the central area and in the zigzags is equal to 366, which almost corresponds to one solar year (Zosimovich, 1992: 14). Of course, it could be a simple coincidence, but the conclusion also can be drawn that the pattern on this bracelet represents an ancient lunar-solar calendar based exactly on the period of 10 lunar months, or 280 days.

2.2.2 The Mezin Composite Bracelet

The second Mezin bracelet, discovered in 1956, is also a remarkable find. As Figure 8 shows, it is composing of five joined mammoth tusk rings (length ~19 cm, width ~1 cm) edged with ornamentation. The external surfaces of the bracelet are covered with a fretwork geometrical pattern in which rows of fir trees are directed to opposite sides and form a clear meander pattern (see Abramova, 1962; 1995; Shovkoplyas, 1965: 104-105).

A pattern is formed as a result of the junctions of the recurring groups of parallel strokes, which are directed at an angle to the edge of the bracelet. Frolov (1977) has interpreted this meander pattern as a primitive calendar (Figure 9) with fertility and crop symbols. His interpretation is as follows. Most groups consist of 14 strokes, although there are groups with 13 and 15 strokes. The directions of the strokes in two adjacent groups differ by 90°. Each part of the bracelet with 27-29 strokes can be interpreted as a calendar of the lunar month. It is possible that the 90° change of direction of the strokes may reflect a lunar disc that is increasing during the first part of the month and decreasing in the second part of the month:

> Groups of 14(±1) strokes, which change their direction periodically exactly after this number, could correspond to the same visibility occurrence, in this case with the increasing lunar disc before Full Moon, and with the decreasing lunar disc before the New Moon during the 28-29 days of the lunar month. Obeying this rhythm, two lunar months are 'written' at the edges of plates. As a result all of the days in 10 lunar months could be 'written' on all 5 plates of the bracelet. (Frolov, 1974: 63-64; our English translation).

It is important to emphasize that the base of these possible paleo-astronomical calendars (10 lunar months, or 280 days) coincides with the mean period of pregnancy for women. Many scientists consider that such a period relating to the Moon could have been chosen by prehistoric people as the *obvious* time-measurement unit for long-term observational events. Incidentally, upon studying in detail the ornamentation on both Mezin bracelets, Shovkoplyas (1965) noted that they had specific female attributes. We should note that although other bracelets made from mammoth tusks have been found at Paleolithic sites in Belgium, France and Russia, the Mezin bracelets have no analogues when it comes to their ornamentation.

Figure 6: The Mezin wide bracelet on display at the National Museum of History of Ukraine in Kyiv (the photograph was provided by the authors).

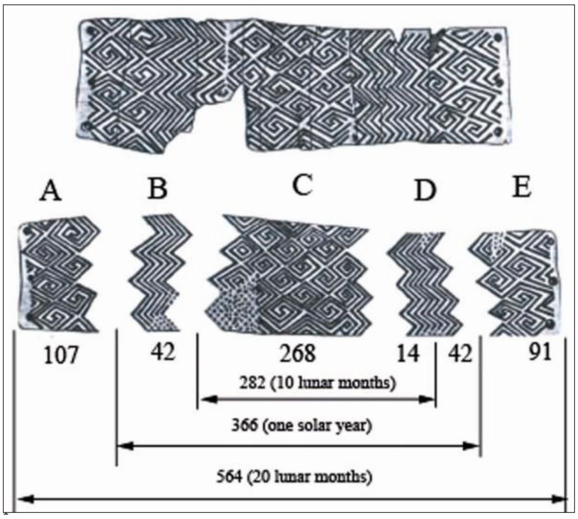

Figure 7: An explanation of the ornamentation on the Mezin wide bracelet as a possible ancient lunar-solar calendar (after Frolov, 1974).

Figure 8: The Mezin composite bracelet is part of the collection of the Institute of Archaeology of the National Academy of Science of Ukraine displayed in the National Science Museum of Natural History in Kyiv (photograph courtesy E. Pichkur).

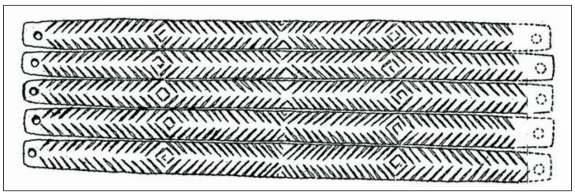

Figure 9: An explanation of the ornamentation on the Mezin composite bracelet as a possible ancient lunar calendar (after Frolov, 1974).

In 1896, Shturcite wrote that history knows of no peoples who cannot define time duration using the Sun and the Moon. But originally they recorded only large intervals, such as a year (the period of a complete 'cycle' of the Sun) or the orbital period of the Moon (which was denoted by its new reappearance and a specific name).

The fixing of such an important number—14—in the form of cuts, nicks, etc. could occur long before the emergence of abstract ideas about it. Frolov (1974: 120-121; our English translation) notes:

> The tradition of this "separation" of the monthly lunar cycle onto 2 "vectors" of equal duration and opposite direction is reflected in the ornamentation on the 5 plates of the Mezin composite bracelet. This slender, streamlined pattern with groups of 14 strokes can probably be traced back genetically to the simplest cuts, pits and other marks, the number of which was equal to the number of days in one or two lunar months (see examples from the settlements at Avdeev, Kostenky-1, Malta, Dolni Vestonice, Pshedmosti, etc.). Similar examples in Aurignacian to Magdalenian collections from Western Europe were analyzed in depth by A. Marshack, in Hungary by L. Vrertes, in Spain by M. Grande …

So, the transformation from the crude engravings on mammoth tusks to the sophisticated ornamentation on the Mezin bracelets or from 28-dashes-days to 7-ornament elements-days, are two sides of the overall process of learning about the world by artistic and rudimentary mathematical and astronomical means.

3 THE FINDS FROM THE CRIMEAN PENINSULA

The Crimean Peninsula is blessed with an abundance of Paleolithic sites, including Ak-Kaya, Shaitan-Coba, Staro-selie and Volchy (Wolf) Grotto, where Neanderthal families lived between 100,000 and 40,000 BCE. Since their discovery during the first half of the twentieth century these sites have been well described in the archaeological literature (e.g. see Boriskovsky, 1957), but here we will only focus on the two caves at Chokurcha.

The Chokurcha-1 karst cave (Figure 10) is on the banks of the Small Salgir River in the Simferopol district and was named after the village of Chokurcha. Chokurcha-1 dates between 40,000 and 45,000 BCE and as such is the most ancient settlement in Europe with highly aesthetic and scientific examples of ancient art (Efimenko, 1953). The first excavations began there in 1927 by the Soviet geologist P.I. Dvoychenko and a local amateur archaeologist, S.I. Zabnin, who revealed skeletons of Neanderthals, remains associated with their everyday lives (including hunting implements), as well as the bones of ancient animals, some of which are now extinct. Between 1927 and 1929 the well-known Crimean archaeologist N.L. Ernst (1889–1956) studied in detail about 500 finds recovered from the site, including Mousterian microliths, and in 1940-1941 B.I. Tatarinov studied the famous petroglyphs on the walls of the cave, including a 0.5-m image of the Sun with rays, which he interpreted as an object of worship. Unfortunately, during WWII the cave was not pro-

Figure 10: The Chokurcha-1 cave is now a Ukrainian heritage site.

tected, and some of these finds were almost completely destroyed. Today surviving fragments are on display in museums in Simferopol, Odessa and Kyiv. In 2009 this cave was restored, and it is now part of Ukraine's national heritage.

In 1974 a second local cave site, Chokurcha-2, was discovered by A.A. Stolbunov, a teacher who studied local lore, and in 1979 it was professionally described by the well-known Russian archaeologist O.N. Bader (1903–1979). In this second cave a unique collection of miniature images of 'men-birds', 'men-bears' and 'men-mammoths' was found. Among the finds, which are thought to date to about 11,000 BCE, was a mammoth shoulder bone with numerous engraved point marks. In 1979 the astronomer V.M. Chernov studied this object using for comparison the well-known star maps prepared by the famous Russian astronomer Aleksandr A. Mikhailov (1888–1983). After applying corrections for the epoch and other parameters, he concluded that this was a Paleolithic map of heaven—possibly the oldest one known—and that it contains 102 stars from 17 constellations in the Northern and the Southern sky (Figure 11). The boundaries of the Southern sky region shown on this map were $\alpha = 12^h–21^h$, and to $\delta = -40°$ (see V. Mitrokhin, http://www.proza.ru/2006/12/21-214, and Sushko, 1981). Of course, this explanation is speculative and requires additional tests.

Unfortunately, the Chokurcha-2 site was destroyed in the 1970s despite the best efforts of local scientists and respected researchers such as O.N. Bader, L.V. Firsov, A. Marshack, A.P. Okladnikov and A.L. Yanshin, who wrote letters to various governmental institutions in Moscow, Kyiv and Simferopol drawing attention to the archaeological importance of this site. Most of the excavated artifacts were lost, and a full radiocarbon analysis of the site was never carried out.

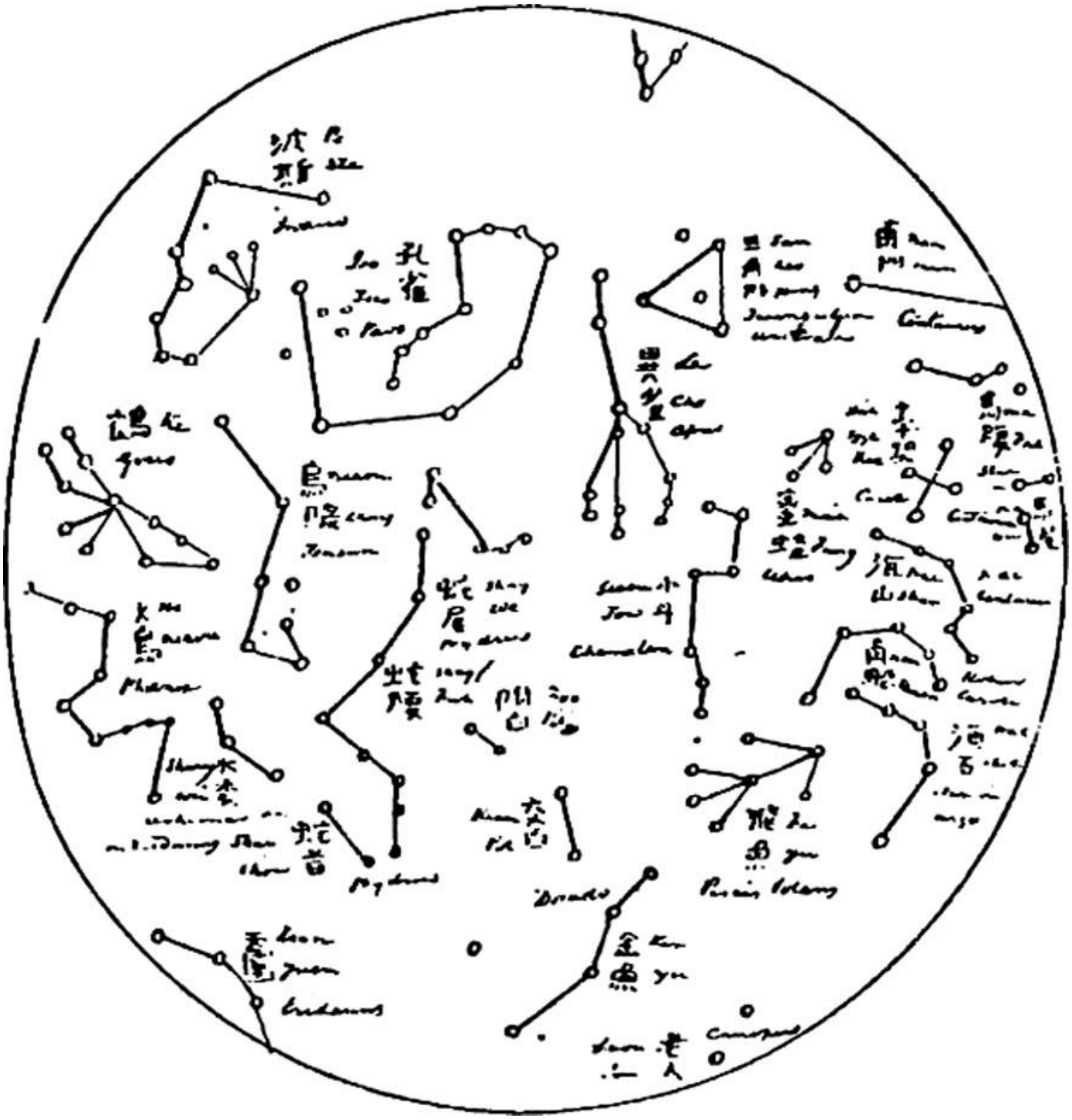

Figure 11: The possible map of the heavens, which was reconstructed by Chernov (1979) after analyzing the engraved point marks (shown here as small circles) on a mammoth shoulder bone that was found at the Chokurcha-2 archaeological site.

4 CONCLUDING REMARKS

In this paper we have described some remarkable finds from Paleolithic sites in Ukraine which may be related to ancient astronomical calendars. Of course, these finds raise many questions, which need to be discussed.

First, we should note that the geometrical ornamentation on these finds, which reaches a maximal complexity with the Mezin bracelets, and in particular the wide bracelet, is not casual. The decoration on these bracelets is so intricate that its preparation required elaborate input, skill, time and mastery in comparison with other artifacts unearthed at these sites. We believe these bracelets reflected valuable elements of ancient knowledge about rhythms of the cosmos and may also indicate that Paleolithic people recognized the 7-day interval between successsive lunar phases. We conclude that a complicated lunar mythology originated in, and was utilized during, Paleolithic times.

This conclusion will not be complete without a brief description of conditions of life of our ancestors in those times. We can do this by using the Mezhirich settlement as an example, but before doing so it is as well to remind ourselves about the marked variations in climate that occurred at this time:

> The weather of Ice Age Europe was harsh. The Older Dryas period (14,000-13,700 BC) was a variable cold, dry period of Europe offered an alternation of steppe and tundra environments depending on the permafrost line and the latitude. The Older Dryas period was preceded by the Boiling (14,650-14,000 BC) and followed by the Allerod period (12,000-11,000 BC) during which temperatures in the northern Atlantic region rose from glacial to almost present day level. (Childe, 2009).

The Mezhirich settlement was discovered in 1965 when a farmer began excavating a cellar, and almost two meters below ground level he struck the massive lower jaw of a mammoth with his spade. Further dwellings were uncovered at the Mezhirich site, and these are now believed to be amongst the oldest-known houses in the world; they date to 15,000 BCE. For each house, the roof supports were made up of about three-dozen curved mammoth tusks, some of which were found in their sockets in the skulls during the excavations (see Figure 12). In the late Ice Age mammoth bones served as a viable alternative to wood, stone and clay. They were used for the framework and foundation of these houses, when wood was scarce and there were no available caves.

Similar dwellings have been found at Mezin and other sites, but those discovered at Mezhirich were very well preserved. It has been estimated that the total number of bones incorporated in the structure of a single dwelling must have been derived from a minimum of 95 mammoths. Anal-

Figure 12: One of oldest dwellings discovered at the Mezhirich settlement has been reconstructed by I.G. Pidoplichko and is now on display in the National Science Museum of Natural History in Kyiv.

ysis of the remains in one of the houses identified

> … a variety of activity that occurred: stone tool manufacture and repair; use of red and yellow ochre pigment; use of bone needles in sewing; skinning of fox and weasel, leaving the complete skeleton intact; cooking of large and small mammal; use of bones as fuel in the fires; some possible use of berries and seeds. The food remains include mammoth, rhinoceros, horse, bison, hare and birds. (Pidoplichko, 1976: 195).

Among the most interesting finds were: the earliest map in the world, inscribed on a mammoth tusk (see Figure 13), which has been interpreted to show a river with dwellings along the banks; one of the earliest-known musical instruments, which were made of decorated mammoth bones, with a mammoth skull used as a kind of drum-like instrument (Abramova, 1962); an ivory female figurine, which was engraved with a series of straight lines which may have been meant to depict a triangular vulva (perhaps re-engraved a few times), and other straight lines which may represent a simple stick figure with a head and arms. Debates about why the figurine was made and how it was used (if re-engraved it could indicate multiple uses) are continuing. The description of these hand-made items, together with the suggestion of lunar calendars, hypothetically impart cognitive and numbering abilities to our Stone Age ancestors and help dispel the popular perception of Ice Age cave-folk as grunting brutes with little or no intelligence (see Flavin, 2008).

We plan to follow this introductory paper with a second paper documenting later evidence of prehistoric astronomy in Ukraine. It will deal with the *Tripolye Culture*, the stone steles, and an ancient astronomical observatory which has been discovered in Ukraine in recent decades.

5 ACKNOWLEDGEMENTS

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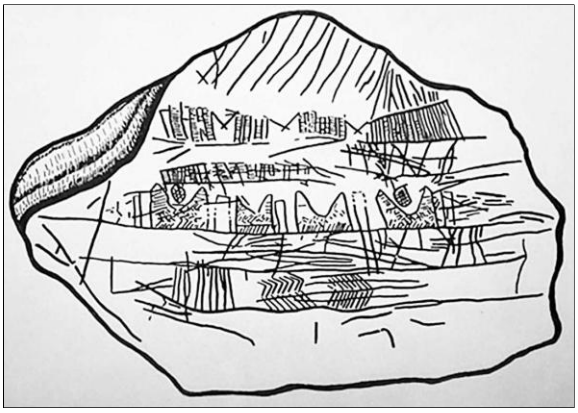

Figure 13: The inscribed mammoth tusk from Mezhirich supposedly containing the earliest-known map in the world (after: http://donsmaps.com/mammothcamp.htm).

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THE BEGINNINGS OF MODERN ASTRONOMY AT THE UNIVERSITY OF ST ANDREWS

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Abstract: Although the University of St Andrews is much older, teaching of and research in modern astronomy began there little more than sixty years ago. Their inception was strongly associated with one man, Erwin Finlay-Freundlich. Some account is given here of his work in St Andrews and the influence he had on younger generations.[1]

Keywords: modern astronomy, University of St. Andrews, Erwin Finlay-Freundlich.

1 BACKGROUND

The University of St Andrews, Scotland's oldest and the third oldest in the English-speaking world, has recently celebrated the six-hundredth anniversary of its foundation. As in other medieval universities, astronomy figured in the curriculum as one of the subjects in the *quadrivium*. In 1563, John Napier, Baron Napier of Merchiston (1550–1617), the inventor of logarithms, matriculated as a student there at the age of 13. He apparently decided to continue his education elsewhere as there is no record of his having graduated from the University.

About a century later, James Gregory (Figure 1), the inventor of the Gregorian telescope, was appointed the first occupant of the Regius Chair of Mathematics in 1668. He had a temporary observatory and laid out a meridian line (Figure 2) in a building that still stands and is in regular use by the University (see Amson, 2008). He planned a separate observatory some distance away from that building and was authorized by the University to purchase instruments for it, but he decided to move to the newer University of Edinburgh. Apparently he found the other professors in St Andrews too conservative in their thinking, and although his planned observatory was built, possibly after he left in 1674, it did not last long.

Astronomy languished in St Andrews until the nineteenth century when Sir David Brewster (Figure 3; Morrison-Low, 2004) was for a long time Principal of the University. Regular undergraduate courses in modern astronomy did not begin, however, until well after Brewster's time.

One of Gregory's successors in the Regius Chair of Mathematics was Sir Peter Redford Scott-Lang (1850–1926) who long cherished the idea of reviving teaching and research in astronomy in the University. His dream was realized after his death by his bequest, transmitted by his daughter, that endowed a Lectureship in Astronomy, to be named after John Napier. The University thus was in a position to look for someone to occupy this post shortly before the outbreak of WWII.

Figure 1: James Gregory, 1638–1675 (after: molecular. magnet.fsu.edu/optics/timeline/people/gregory.html).

2 ERWIN FINLAY-FREUNDLICH

The man eventually chosen to become the first Napier Lecturer (and later Professor) was Erwin F. Freundlich (Figure 4). His name will be familiar to all those who have studied the history of the acceptance of Einstein's theory of relativity because he was among the first astronomers to realize the potential for testing that theory by astronomical observations. Indeed, Freundlich attempted to measure the deflection of light rays passing near the Sun even before Einstein pub-

Figure 2: Gregory shown at work in what was then the University's library, which he used as a temporary observatory. The wooden meridian line that he set into the floor is clearly visible (after: st-andrews.ac. uk/divinity/rt/kjl/).

Figure 3: Sir David Brewster, 1781–1868 (courtesy: en.wikipedia.org).

Figure 4: Erwin Finlay-Freundlich, 1885–1964 (courtesy: kuriositas.com).

Figure 5: Professor Felix Klein, 1848–1925 (courtesy: thefamous people.com).

Figure 6: The Einstein Tower at the Potsdam Astrophysical Observatory (courtesy: en.wikipedia.org).

lished the final version of general relativity. In a preliminary theory, Einstein was predicting only half the value for the deflection that he gave in his final version. Freundlich organized an expedition to the Crimea in the summer of 1914 to observe a total solar eclipse, but his party, all Germans, arrived in Russia just before the outbreak of WWI and was promptly interned as a group of enemy aliens as soon as hostilities opened. Fortunately the party was soon repatriated in exchange for some Russian officers who had been taken prisoners of war.

In his biography of Einstein, Hoffmann (1972: 133) suggests that the failure of this expedition was fortunate in another way. If Freundlich had found a value for the deflection similar to that found five years later by Eddington, it would not have seemed a confirmation of Einstein's theory, the subsequent modification of which, to agree with observations, might have looked like an *ad hoc* adjustment rather than a brilliant prediction.

Although this episode in Freundlich's career is well documented and is mentioned in nearly every biography of Einstein that has been published (e.g. see Crelinstein, 2006), I find that little is known of the rest of his work in astronomy and especially of the time after he left Germany in 1933. I published a few reminiscences of the man on the occasion of the centenary of his birth (Batten, 1985) and there is an excellent account of his early work by Hentschel (1997), which I reviewed in this *Journal* (Batten, 1999). An account from a rather different angle was given by my late friend and fellow St Andrean, Eric Forbes (1972). Now, fifty years after Freundlich's death, seems a good time to look once again at his work and significance.

Freundlich was born in Biebrich am Rhein, Germany, on 29 May 1885. From 1905 to 1910 he studied at the University of Gőttingen (with one term at the University of Leipzig). Although he apparently took at least one course from Karl Schwarzschild, he did not then have a great interest in astronomy. His principal teacher was Felix Klein (a fact of which he was quite proud), and he regarded himself as a pure mathematician. Klein (Figure 5), however, recommended him for a position at the Royal Observatory in Berlin, then under the direction of Hermann Struve.[2] According to Hentschel (1994), Freundlich was exceptional among German astronomers in being interested in the then new techniques and problems of astrophysics, and virtually alone in seeing the possibility of testing relativity theory using astronomical observations.

This latter interest of Freundlich's led to a period of collaboration with Einstein, of which Freundlich was also proud. The relationship cooled after a few years, but not until after Freundlich had raised funds to build the Einstein Tower in Potsdam (Figure 6) as an observatory dedicated to testing the theory of relativity, in particular the predicted gravitational redshift of light from the Sun. Naturally, he became the Director of this Observatory and would probably have ended his days there but for the rise of Hitler. Freundlich had a Jewish grandmother and had married a Jewish wife. Moreover, he openly expressed his contempt for the Nazis and, understandably, left Germany soon after Hitler came to power, but not before he had led three other eclipse expeditions. The last of these, to Sumatra in 1929, was successful and indicated a deflecttion of light *greater* than Einstein's prediction. In 1933, however, he was invited to the University of Istanbul, to found an astronomy department there, build an observatory and write a textbook that could be translated into Turkish. While doing these things, he also taught, his best-known student there being Paris (Pariz) Pişmiş (Figure 7), who later emigrated to Mexico.

Having completed the tasks he agreed to do, Freundlich moved again, in 1937, this time to the German University in Prague. I have often puzzled over this move: surely by 1937 it was already clear what was likely to happen in Czechoslovakia. Perhaps Freundlich was homesick for Germanic culture, which he could find in the Czech capital, and placed more reliance than was prudent on the Franco-British guarantees to that small country. Inevitably, he had to move again, but not before he had taught Zdeněk Kopal (Figure 8), who although at Charles University attended Freundlich's lectures.

It was at this time that the University of St Andrews was looking for its first Napier Lecturer. According to several obituary notices, Sir Arthur Eddington played a role in bringing Freundlich to Britain. No doubt the latter's interest in testing relativity theory helped to bring him to Eddington's attention and it is entirely in accord with Eddington's manner that he should quietly help the victims of Nazi persecution. Some years ago, at a meeting in Cambridge to mark the sixtieth anniversary of Eddington's death, Hermann Bondi testified how Eddington had helped him to come from Vienna to Cambridge. There were other factors that perhaps helped. Freundlich's mother, born Ellen Finlayson, was a Scot, while his brother, Herbert, was a well-known physical chemist and probably knew the then Principal of St Andrews, Sir James Colquhoun Irvine, who had earlier been Professor of Chemistry at the University.

Whatever the relative importance of these various factors, Freundlich came to Britain and was installed in St Andrews shortly before the outbreak of WWII. He adopted British citizenship and the name Finlay-Freundlich, derived from his original surname and his mother's maiden name. Usually in St Andrews, however, he was addressed simply as Professor Freundlich (the Napier Lectureship became a Chair in 1951).

Figure 7 (left): Dr Paris Pişmiş (1911–1999), one of Freundlich's early students (courtesy: www.aras.am/FamousAstronomers/pishmish.html).

Figure 8 (right): Professor Zdeněk Kopal (1914–1993), another one of Freundlich's early students (courtesy: img.radio.cz).

3 MODERN ASTRONOMY AT ST ANDREWS

As Gregory had been before him, Freundlich was commissioned by the University to build an observatory, a task that he undertook for the third time in his life. A small building was completed in 1940 which still stands, although now much modified. In the early 1950s, I attended almost all my astronomy lectures there. Any large instrument, however, had to wait for the end of the War. During that conflict, much of Freundlich's time and energy was dedicated to teaching astro-navigation to the aircrew at the nearby RAF base of Leuchars, and he even penned a book on the topic (Figure 9). I have often wondered what the young RAF officers made of someone with a heavy German accent (he never lost it) teaching them how to navigate safely during their attacks on the Luftwaffe and Germany. An added irony

Figure 9: Cover of the 1945 first edition of Freundlich's book (courtesy: ebay.co.uk).

Figure 10: Robert Waland (left) and Professor Freundlich in the Optical Shop at St. Andrews in 1947, examining an 18.75-in mirror (courtesy: Dumfries Museum and Camera Obscura).

is that, at the same time, a young technician, who would one day become the President of the International Astronomical Union, was at the same RAF base testing early forms of radar which would eventually render astro-navigation obsolete (see Hanbury Brown, 1991: 48-50).

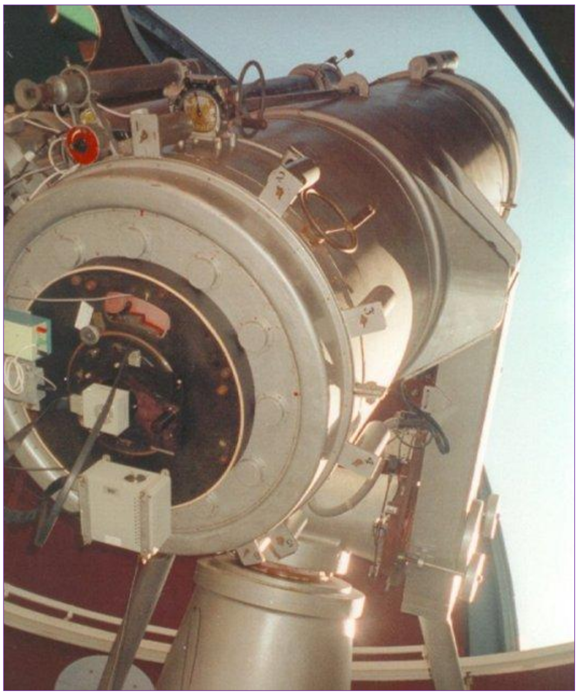

Figure 11: The 0.9-m James Gregory Telescope (courtesy: st-andrews.ac.uk).

The end of the war enabled Freundlich to turn his attention, for the third time in his life, to building a new observatory. He decided to attempt the construction of a Schmidt-Cassegrain telescope. Although this design is now familiar to us in the form of Celestrons and similar telescopes, it was an untried design in the 1940s—and, even now, you cannot easily buy a Celestron of 0.5-m or even 1-m aperture, which is precisely what Freundlich decided to build. For the theoretical design, he relied heavily on the advice and calculations of E.H. Linfoot (1905–1982; Fellgett, 1984) in Cambridge. For the practical realization of the project, he relied on the skill of R.L. Waland (Figure 10), a local amateur telescope maker whom Freundlich 'discovered' while giving popular lectures in and around St Andrews. Freundlich was so impressed by the quality of Waland's work that he hired him as the chief technician for the project. The 0.5-m pilot model was built first, and it had not long been in operation when I arrived at St Andrews in the fall of 1951. It proved useful and the decision was made to go ahead with the full-size model. Unfortunately, this took longer to build than had been hoped, and it was not completed until about the time of Freundlich's retirement (Figure 11). This fact, coupled with disagreements between Freundlich and his successor, D.N.W. Stibbs, and Waland's consequent resignation, meant that the full-size model never realized its full potential.

Research was not Freundlich's only concern, however; he also instituted an honours undergraduate programme in astronomy. It is of interest that, at that time, three of the four universities then established in Scotland were offering an undergraduate programme in astronomy, while no university in England did so. In those days, the University was much smaller and less well-known than it is today. The total number of students in the early 1950s was about 2,000, of whom 500 or so were in University College, Dundee, then a part of the University of St Andrews. Astronomy classes were correspondingly small. Typically, the first-year course attracted 20 to 25 students. The senior years were often taught all together. In my final year, I *was* the class, and received no formal instruction at all.

I emphasize these facts because from this small pool of students some five or six emerged over the years who had successful careers in astronomy. Leonard Searle (1930–2010; Figure 12) went from St Andrews to Princeton for his doctorate, and spent most of his career at Mount Wilson Observatory, becoming Director in 1989. William Nicholson spent his working life in the Nautical Almanac Office. Eric Forbes (1933–1984; Meadows, 1985), my exact contemporary, after some detours, became a well-known historian of astronomy, based at the University of Edinburgh. I myself went to Manchester for my doctorate (Figure 13; see, also, the biodata entry photograph at the end of this paper), and spent most of my career at the Dominion Astrophysical Observatory in Canada. Thorstein Saemundsson went to London for his doctorate and returned to Iceland for a career in geophysics. In addition to these undergraduates, Alan Jarrett (Figure 14; Glass and Koorts, 2007) was a graduate student and later became Director of the Boyden Observatory in Bloemfontein, South Africa.

Freundlich continued in research, still concerned with the astronomical evidence for general relativity. Remember that the laboratory tests of the theory that are now possible, to say nothing of the observations of pulsars, were simply unknown in the 1940s and early 1950s. I have already mentioned that Freundlich's results from the Sumatra eclipse expedition seemed to show a deflection greater than predicted by general relativity. This fact sowed the first seeds of doubt in his mind about that theory and he ended his life quite skeptical about it. He published a theory of photon-photon interaction (Freundlich, 1954) to account for the cosmological redshifts. It was a variation of tired-light theory that never won wide acceptance and is now almost forgotten. Also in 1954, despite having suffered a heart attack the year before, Freundlich led yet another eclipse expedition, this time to Sweden. Once again, he was foiled by clouds. Ironically, I saw the eclipse from the climatically less-favoured west

Figure 12: Leonard Searle (courtesy: en.wikipedia.or).

Figure 13: Erwin Freundlich flanked by two generations of his students: Zdeněk Kopal (left) and the writer. This photograph was taken in Manchester by T.W. Olle, in 1957 (Batten Collection).

coast of Sweden—while he was on an island in the Baltic Sea. He was well aware of the difficulties of getting a conclusive result from this type of observation, but had he found a similar result in Sweden to the one he obtained earlier in Sumatra, his doubts about general relativity would certainly have increased.

Freundlich finally retired from St Andrews in 1959 and returned to his native Germany, indeed to Wiesbaden close to his place of birth, where he was made an honorary professor by the

Figure 14: Alan Jarrett, 1925–2007 (right) and Gordon Malcolm at the Boyden Observatory (after Glass and Koorts, 2007).

University of Mainz. He died on 24 July 1964. About a month later, the International Astronomical Union met in Hamburg. It had been my intention to visit him on my way home from that meeting and he had already agreed to receive me. It is one of my regrets that his death prevented that final meeting with him.

4 RETROSPECTIVE

As I look back on Freundlich's career, I am struck by the fact that his own research, important as it seemed at the time, has proved ephemeral, but his influence on the younger generations has lasted. His early work on stellar statistics, which I have not discussed, is quite superseded, even though, as Kopal (1986: 95-99) tells us, he came close to discovering galactic rotation. Both his attempts to verify, and his later doubts about, general relativity are likewise now seen as largely irrelevant. His period as Director of the Einstein Tower, however, was one of interaction with several colleagues (Crelinstein, 2006,) and in all three of the universities in which he taught he left a legacy of students who went on to their own careers in astronomy. His tenure was short, both in Istanbul and Prague, but in each city he taught at least one outstanding student. I know from conversations with each of them that they found him an inspiring teacher. He had a much longer tenure in St Andrews but, as I have stressed, a small pool of talent on which to draw. That he produced so many students in two generations testifies to his ability to inspire younger people, and his chief influence seems to have been in his teaching rather than his research.

Under his successor, the Astronomy Department in St Andrews was greatly strengthened and has continued to flourish since Stibbs' retirement even though it is now a part of the School of Astronomy and Physics. Stibbs deserves much credit for the flourishing of astronomy in the University of St Andrews, but he did not start from scratch. Although he and Freundlich had a poor personal relationship (as I heard from each of them) they would, I hope, agree that they each made an important contribution to the present happy state of affairs.

5 NOTES

1. This is an expanded version of a talk given during the National Astronomy Meeting of the Royal Astronomical Society in St Andrews in 2013.
2. Freundlich's relationship with Struve was a rather troubled one and it is slightly ironic that I, in later life, should have chosen to write about the Struve family (see Batten, 1988.)

6 ACKNOWLEDGEMENTS

I am grateful to Dumfries Museum and Camera Obscura for permission to publish Figure 10.

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TWENTY-FIVE YEARS OF HELIOSEISMOLOGY RESEARCH IN UZBEKISTAN

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Abstract: The Ulugh Beg Astronomical Institute was involved in the IRIS helioseismology project from the mid-1980s through to the end of the project in 2001. This project aimed to study the deep interior of the Sun using Doppler spectral line shift measurements integrated over the whole solar disk. In order to obtain long, continuous observational data showing periodicity a network of six stations more or less regularly distributed around the globe and equipped with identical spectrophotometers was deployed. One of these instruments was installed on Mt Kumbel in Uzbekistan in 1988. In addition, from 1996 to 2002 the Ulugh Beg Astronomical Institute was involved in observations for the TON project, which was aimed at carrying out helioseismic studies of the subsurface structure of the Sun and its dynamics.

The participation of the Ulugh Beg Astronomical Institute in both projects was crucial not only for obtaining long-term observational data, but also for the scientific analyses of the observational data and the preparation of the resulting research papers. Many scientific results came out of these two projects, but more importantly, many graduate students used these projects to obtain their Ph.D.s.

Keywords: helioseismology, Uzbekistan, Ulugh Beg Astronomical Institute, IRIS, TON, Kumbel Observatory

1 INTRODUCTION

After the discovery of the solar five-minute oscilparisonlations in the early 1960s (Leighton et al., 1962), it took about a decade before there was a clear understanding that this surface phenomenon was merely the visible part of the seismic waves that emanated from the interior of the Sun (Ulrich, 1970). In the early 1970s helioseismology began to develop as an efficient method of probing the interior structure and dynamics of the Sun.

In fact, these seismic waves are, physically speaking, acoustic waves that are excited by the turbulent noise of the boiling nature of the solar surface. The frequencies of these waves are not, of course, in the range of those of our usual music, but the comparison of the helioseismic methods with listening to music is quite relevant. The solar frequencies are about 100,000 times slower than the typical musical frequencies. As there are nearly 100,000 seconds in one day, this comparison explains why a few hundred seconds of 'musical listening' require a few hundred days of continuous measurement of the solar oscillations. Then, the scientific benefit for solar physics is similar to the 'musical benefit' of carefully listening to music (the music itself, instruments, their perfect or imperfect tuning, interpretations, etc.). But instead of a knowledge of musical culture, helioseismologists just need some physical and mathematical skills. Then they can access the distribution of certain physical parameters (density, temperature, chemical composition, local motions such as rotation or convection, etc.) throughout the spherical volume of the Sun.

The acoustic noise at the solar surface excites the resonance of many eigenfrequencies. These resonances are trapped in a volume defined by acoustic reflection near the surface (acoustic waves cannot move out) and an internal acoustic refraction that eventually forces the waves that are moving downwards to return towards the solar surface. These eigenmodes can be as different as the global resonance of the total volume of the sphere on the one hand, and the resonance of just a thin layer under the surface of the photosphere on the other hand. But some of them can also be very similar, with a small frequency difference that is mainly due to a small difference in the depth of the resonant volume. In this case, their frequency difference becomes a nearly direct measurement of the value of the sound speed at their deepest penetration, so that a 'nearly direct' measurement of the sound speed from the solar surface to the solar core can be determined if many of these frequencies can indeed be obtained from observations. Mathematically speaking, it means an inversion of the differential measurements.

Fortunately, nearly 10 million resonant modes of oscillation are observable at the solar surface. The response of the solar surface to the superposition of all seismic waves resembles motions at the surface of an ocean. The detection of these modes is a really challenging task, since the velocity amplitude of a typical acoustic mode (p-mode) is of the order of 1 cm/sec, with an associated intensity variation of about 10^{-7}. Such minute oscillations can be detected by measuring either the Doppler shifts of a spectral line or the intensity of the optical radiation.

The main task of observational helioseismology is the determination of the individual p-mode frequencies and their other parameters. The measurements must be made continuously over a long period of time in order to determine oscillation frequencies with the extremely high precision necessary to make useful inferences about the solar interior. As we have seen, these useful inferences are coming from the small differences of neighboring resonant modes. These observational time series should be as uninterrupted as possible because gaps in the data produce spurious peaks (sidelobes) in the oscillation power spectrum, which hinder subsequent analyses.

The first attempt to obtain uninterrupted observations was made by a University of Nice team at the Geographical South Pole during the southern summer of 1979/1980 (Grec et al., 1980; 1983). As a result of six days of nearly continuous observations it was possible for the first time to resolve individual peaks in the solar oscillation power spectrum. For this pioneering work Eric Fossat, Gerard Grec and Martin Pomerantz were awarded a Gold Medal by the Royal Academy of Belgium. Shortly afterwards it was realized that the atmospheric conditions at the South Pole would not allow continuous observations for longer than about one week. However, in order to resolve the multiple structure of an individual peak, uninterrupted observations for as long as a few months were required.

This fact explains why all observing programs developed in the 1980s aimed at obtaining continuous observations over periods of months, and even years, in order also to track the variations that occurred in all helioseismic parameters in the course of the solar cycle. Three main ideas were considered in order to obtain continuous observations for longer than the typical 8-12 hour daily run possible at any mid-latitude single site. The first was to go to the Antarctic, where—as previously mentioned—during summer uninterrupted observations were possible for as long as one week. Another option was to detect solar oscillations from space, where a suitable instrument located on a spacecraft with a totally sunlit orbit could provide uninterrupted observations over a period as long as the lifetime of the spacecraft. The third idea was to deploy a network of observing sites around the globe, that were suitably located at complementary longitudes and latitudes.

In 1982 IAU Commission 12 voted for the following resolution: "… recognizing the extreme importance of the observation of solar seismology … [and] strongly supporting international cooperation in establishing a worldwide network of observing stations." The team from the Laboratoire d'Astrophysique at the University of Nice presented a project named IRIS (International Research on the Interior of the Sun) to the French astronomical agency (INSU) in 1983 and it was funded from 1984. Thus the IRIS network project was launched, along with the GONG project in the USA (Harvey et al., 1996). As the core instrument of the IRIS project, a sodium cell spectrophotometer providing full-disk Doppler shift measurements of the sodium D1 line was suggested (Grec et al., 1991). The plan was to install these instruments at six complementary sites around the globe.

The first IRIS network spectrophotometer was installed in 1988, on a remote mountaintop site at Kumbel in Uzbekistan (Figure 1). Further IRIS stations were then deployed at the rate of one per year until 1994 when the sixth spectrophotometer was installed at Culgoora, Australia. Meanwhile, the first data were acquired in July 1989 (when Kumbel was the only network station), but were immediately complemented by a summer campaign using a prototype magneto-optical filter instrument that was designed by A. Cacciani and operated at the Jet Propulsion Laboratory in California (Cacciani and Fofi, 1978). Thus, the first day of IRIS data acquisition already marked the beginning of a two-site network program.

The headquarters of the IRIS project were established at the University of Nice in France, and Figure 2 shows the worldwide geographical distribution of IRIS stations.

Here it is necessary to mention that observations made with the IRIS instrument were spatially unresolved, combining light from the entire visible surface of the Sun (i.e. observing the Sun as a star), which limited the detectability to only those modes of oscillation whose wavelengths were comparable to the diameter of the Sun and hence could penetrate down to the solar core. P-modes registered with spatial resolution provided information on the sub-surface structure of the Sun (see paragraphs on the TON project in Section 4 below). Figure 3 shows examples of low degree p-modes (top row) and high degree p-modes (bottom row) accessible by imaged helioseismology.

Figure 1: A panoramic view of the Kumbel IRIS station established in Uzbekstan in 1988 (photograph: Sh. Ergamberdiev).

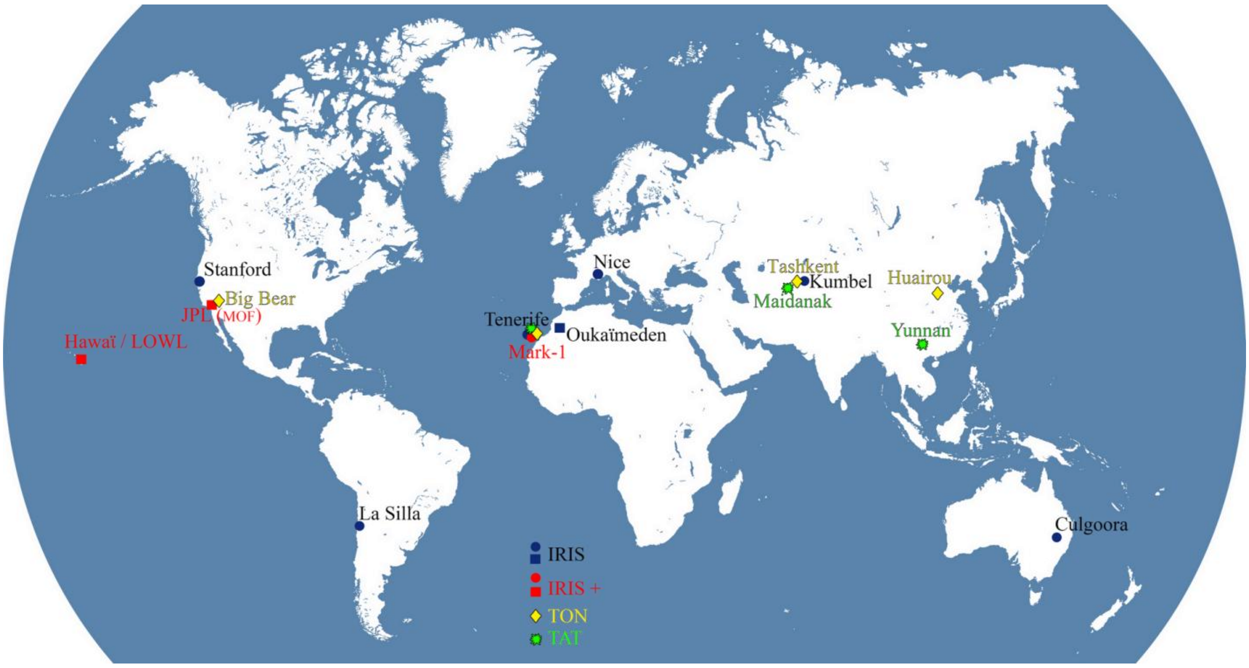

Figure 2: The worldwide IRIS and TON networks. Those shown by red squares are stations of the other full-disk helioseismology projects whose data were merged with the IRIS data. See the text for details. The stations of the TAT (Taiwan Automated Telescope) asteroseismological project are also shown.

Reviews of the first eleven years of the IRIS project were presented in Fossat et al. (2002) and Fossat (2013). This present paper mainly focuses on the participation of the Uzbekistan team in the IRIS project (which ended in 2001).

2 THE IRIS STATION AT KUMBEL MOUNTAIN

Within the distribution of the northern hemisphere sites selected for the worldwide IRIS network, one instrument had to be installed some-

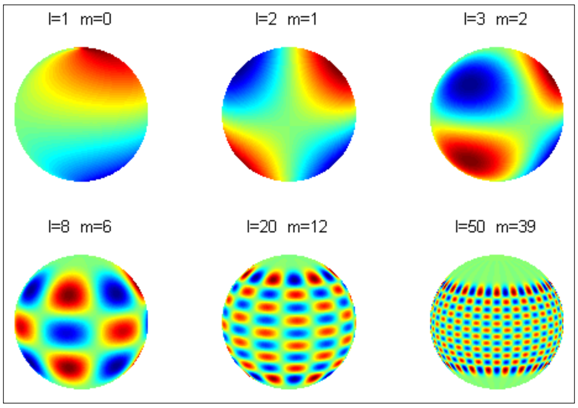

Figure 3: Examples of low degree p-modes (top row) and high degree p-modes (bottom row) accessed by imaging helioseismology.

where in Central Asia. On the basis of an analysis of meteorological data and after visual inspection of several pre-selected sites, it was finally decided to install an instrument on top of Kumbel mountain, 75 km northeast of downtown Tashkent and at an altitude of 2300 m above mean sea level (Baijumanov et al., 1991a; 1991b).

Since Kumbel was an isolated remote mountain, in contrast to other intended stations in the network, it was necessary to build not only a shelter for the spectrophotometer but also living facilities for observers. All this construction work was done during the summer of 1988 and 'first light' at Kumbel was recorded in August 1988. A personalised story of this fantastic astronomical adventure is recounted in Appendix I. Figure 1 shows the Kumbel station and Figure 4 the IRIS instrument that was installed at this station.

During its eleven years of operation (one full solar cycle) the Kumbel station alone provided the IRIS data bank with more than 40% of the total observational data. However the contribution of the Kumbel team to the success of the IRIS project was not limited to only providing data as the Uzbek astronomers also actively participated in all subsequent stages of the work, such as data analyses and the writing up of the resulting research papers.


Figure 4: A close-up showing the spectrophotometer at the Kumbel IRIS station (photograph: Sh. Ergamberdiev).

Here we have to mention that before scientific analyses of the observational data began, there was a long process of selection, characterization and calibration in m/s of the velocity signal due to the solar oscillations. The first version of a software package which took into account Doppler shifts caused by all known astronomical motions contributing to the line-of-sight velocity between the instrument and the solar surface was developed in Tashkent (Ehgamberdiev et al., 1991a). It also took into account the apparent residual velocity generated by the non-uniform integration of the solar rotation in the Earth's stratified atmosphere (Ehgamberdiev and Khamitov, 1991). During the Second IRIS workshop, Shuhrat Ehgamberdiev was elected Chairman of the raw data calibration software team, and other members were Eric Fossat (Nice), Bernard Gelly (Nice), Shukur Kholikov (Tashkent), Pere Palle (Tenerife) and Luis Sanchez (Tenerife). The main duty of the team was to produce a complete software package which would select and calibrate the data, in order to obtain for each day and each site a velocity-versus-time signal. Data obtained at each IRIS station had to be subjected to this procedure before it was possible to merge them into a resulting single data string.

Figure 5 illustrates two daily data records obtained at the Kumbel and Oukaïmeden stations on 27 July 1989 after applying the calibration subroutine. The high coincidence of the records (see, for example, the small-scale variations around 9.8 h UT) obtained at these two sites, which were separated by about five hours in longitude, demonstrates first of all the high sensitivity of the IRIS spectrophotometer to detect such tiny solar oscillations, and secondly the efficiency of the calibration software.

Figure 6 shows an average of about 100 daily solar oscillation power spectra and the level of so-called solar noise (solid line) caused by motions in the solar atmosphere (granulation, supergranulation, etc.) estimated by J. Harvey (1985). This power spectrum appears to be photon noise-limited in the high frequency range and solar noise-limited at low frequencies. For a long time the low frequency noise level estimated by J. Harvey was regarded as not being accessible by ground-based observations. Figure 5 first of all shows that the level of that noise should be recalculated as it was over-estimated. On the other hand it demonstrates the ability of the IRIS instrumentation and data analysis to detect solar oscillations.

3 SCIENTIFIC RESULTS

3.1 Single Site Data Analysis

Usually an 'IRIS day' began at Kumbel where observations were started around 1h UT. During

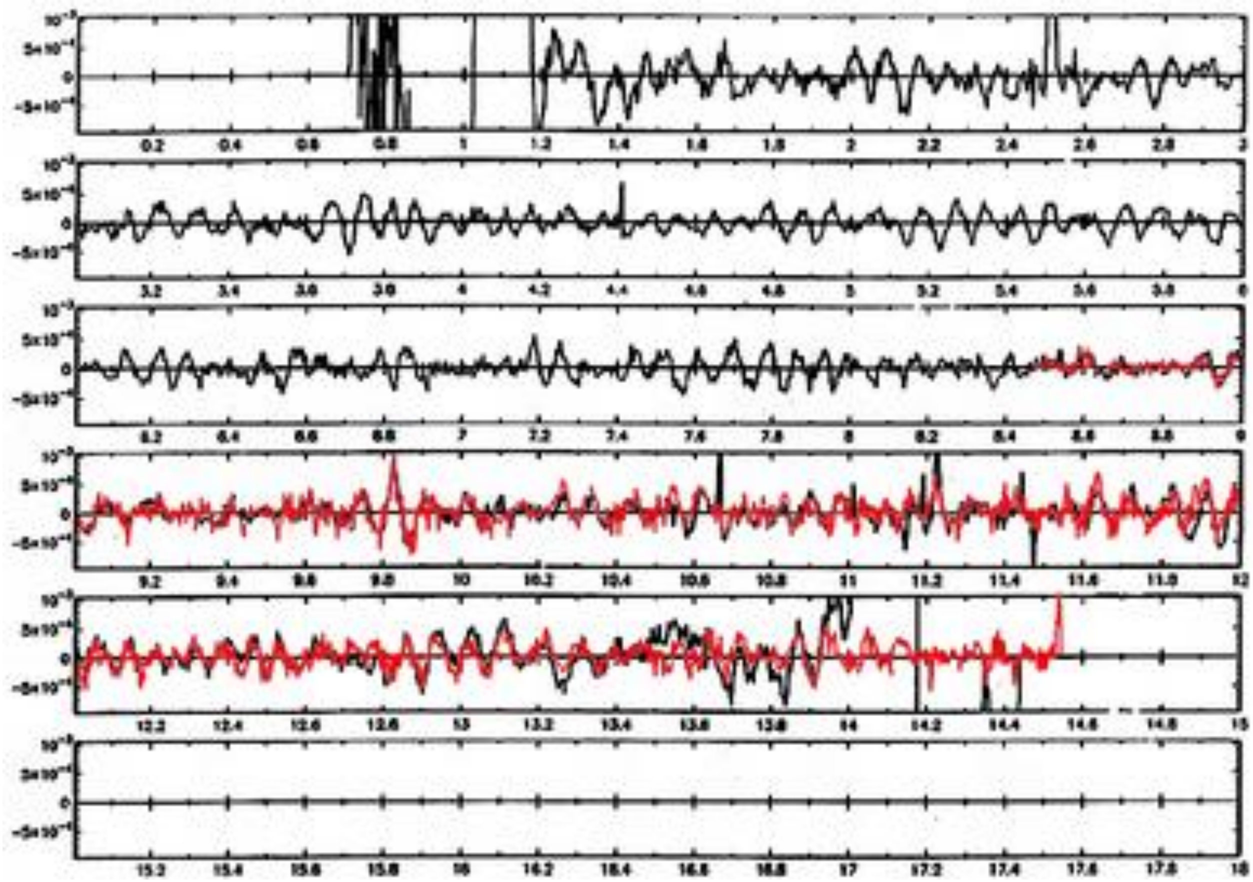

Figure 5: Two merged records showing 7.5 hours of solar oscillations obtained on 27 July 1989 at the Kumbel (black line) and Oukaïmeden (red line) stations.

the first two years of operation of the Kumbel spectrophotometer, which began in July 1989, many high-quality daily data were collected. However, it was not possible to compile a long-duration data-set because at that time the IRIS network was not yet completely deployed (in particular, La Silla and Stanford were not fully operational). Another reason was the absence at that time of an appropriate data-merging procedure, which was only developed later (see Fossat, 1992). In such a situation, our curiosity to learn something about the physics of the p-modes could only be satisfied through the analysis of data from a single site.

At a single site, one day of observations typically lasted 10-11 hours and thus provided a daily power spectrum with a frequency resolution ~25-30 µHz. This was not enough to resolve individual peaks, but it was enough to show the discrete nature of the power spectra. Peaks in the daily power spectra implied four or six unresolved individual p-modes.

Despite a less-than-optimistic view of this approach adopted by some theorists, two important scientific results were extracted from the low-resolution daily power spectra.

For the study of the statistical properties of p-modes, 99 days of data obtained solely at the Kumbel station were used. Comparisons of the different daily power spectra showed that the peaks had quite high amplitude fluctuations with time. However, by itself this was not an indication of a temporal amplitude modulation of p-modes. Upon making certain assumptions about the partial amplitude interdependence and individual p-mode phase independence, the amplitude modulation rate was estimated to be about 25% (Ehgamberdiev et al., 1992). This result appeared to be inconsistent with the more-or-less generally-accepted theory of the interaction between the oscillations and stochastic turbulent

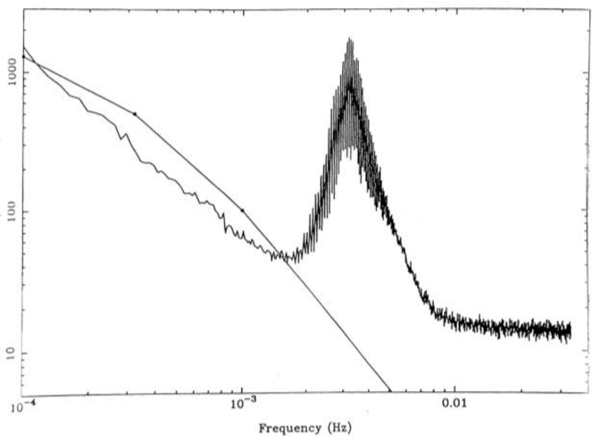

Figure 6: The average of about one hundred daily solar oscillation power spectra and the level of noise (solid line) caused by motions in the solar atmosphere (supergranulation etc.) (after: Ehgamberdiev et al., 1990: 21).

convection. Meanwhile, theories on the physical mechanism invoked for the p-mode excitation had to satisfy this new constraint, and explain the p-mode energies, their frequency range and line-widths. Theorists from Liege University in Belgium carried out research on the interpretation of this interesting observational result (see Gabriel and Lazrek, 1994).

Another result obtained through an analysis of data from a single site related to the measurement of the acoustic cut-off frequency. Solar acoustic p-modes exist because acoustic waves can be trapped inside cavities in the interior of the Sun, where they are reflected back and forth between lower and upper boundaries of the cavity. Near the solar surface, the reflection occurs due to rapid changes in density and sound speed. Reflection takes place only for waves with frequencies less than a critical one, commonly called the ‘acoustic cut-off frequency’. Acoustic waves with frequencies higher than this cut-off frequency can propagate through the solar atmosphere.

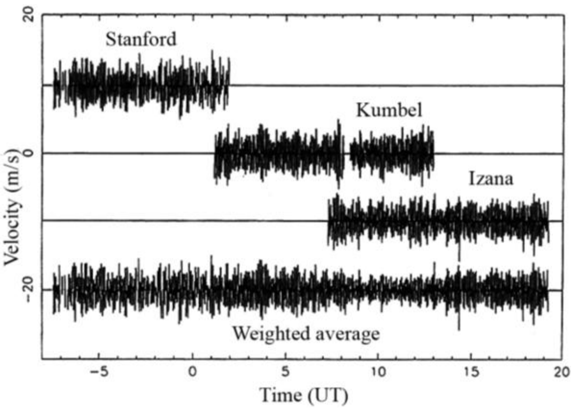

Figure 7: An example of a very successful day when three stations provided 100 percent coverage of data, along with their weighted average.

The average power spectrum of observations made at the IRIS stations of Kumbel, Izana, La Silla and Oukaïmeden was used for this analysis. The value of 5.55 ± 0.1 mHz was obtained for the acoustic cut-off frequency using these observational data, but this appeared to be higher than any of the theoretical predictions. A surprisingly-precise measurement of the acoustic cut-off frequency of the solar atmosphere proved that helioseismology was not necessarily limited to the deep interior.

Using data from the IRIS network obtained between 1989 and 1996 (inclusive) we attempted to see if there were any changes in the values of the acoustic cut-off frequency of the solar low-*l* p-modes in the course of the solar cycle. Upon applying three different methods of analysis we found that the cut-off frequency was variable, changing from 5.77 ± 0.02 mHz at sunspot maximum to 5.37 ± 0.04 at sunspot minimum (Serebryanskiy et al.,1998).

The good quality of the IRIS data at high frequencies above this cut-off made it possible to provide solar physicists with an answer to an old question about the heating of the chromosphere. The acoustic power density that exists between the cut-off frequency and the frequency after which it becomes flat (photon noise) can be used to estimate the acoustic energy flux that dissipates in the chromosphere. The estimated value of that energy (~10^7 erg/cm^2/s) appeared to be just enough to compensate for the energy losses in the chromosphere (Athay, 1970).

3.2 The Sun as an Instrument that Produces ‘Repetitive Music’

In an ideal case all helioseismology projects aim at obtaining the best temporal coverage of data as close as possible to 24 hours a day and 365 days a year. This is mainly in order to avoid the presence of ‘sidelobes’ in the Fourier spectra. These sidelobes, or artificial secondary peaks, interfere with other peaks that are real, and thus make accurate p-mode parameter measurements difficult. However, the ultimate goal of 100 percent duty cycle (percentage of filling with data) is hardly ever achieved by any of the observing programs, so the analyst is always faced with the presence of gaps in the time series subjected to Fourier analysis.

Figure 7 shows a successful day when three stations provide 100 percent coverage data, and their weighted average. However, such a situation was not often achieved. In fact, the network duty cycle reached better than 60% only in the northern summers, but was down to much less than 50% during the winters due to bias in the geographical locations of the IRIS stations (four in the northern hemisphere and just two in the southern hemisphere), and also due to the large longitude gap represented by the Pacific Ocean.

Facing this situation, it was decided to develop cooperation between the IRIS team and scientific groups operating other helioseismology instruments. Data from several summer seasons of the JPL’s Magneto-Optical Filter project (Cacciani et al., 1988), the Mark-1 potassium data from the Tenerife site of the BiSON network (Elsworth et al., 1988) and the integrated signal from the LOWL images obtained at Mauna Loa in Hawaii (Tomczyk et al., 1995) were merged with the IRIS signal to produce a time series we called IRIS^{++}. As a result, the duty cycle of the IRIS data was strikingly improved, but it was capable of further improvement. After testing different deconvolution algorithms, an interesting method of partial gap-filling was developed. It should be noted here that the standard mathematical deconvolution technique completely ignored the specific properties of the signal. However, taking into account what we knew about the signal itself helped us to approach the problem from another perspective and try to predict with a high level of confidence the signal which was not observed (Fossat et al.,1999).

To take advantage of what we knew about solar oscillations at the time, we turned our attention to the IRIS autocorrelation function. We filtered the signal in the p-mode frequency range from 1.5 to 5 mHz and saw that after about four hours the signal had a very high level of coherence (>70%). Just like musical songs, this suggested that the solar oscillations were almost periodic, i.e. repetitive in time, with a quasi-periodicity of a little more than four hours (Fossat et al.,1999). This fact is demonstrated in Figure 8, where a solar oscillation signal is cut into three parts, each 4.1 hours apart, and these are shown one below the other. The marked similarity of the signals does not require any additional comment.

With this specific feature of the solar oscillation it became obvious that simply replacing a gap by the signal collected four hours earlier or four hours later provided a gap-filling method with a confidence level of >70%.

This idea was extremely simple. Doing it in practice also was very simple, and it was demonstrated that p-mode helioseismology was not so demanding of the duty cycle. In the most extremely-favorable situation, we could imagine a data set with just a 33% duty cycle, containing four hours of data followed by an eight hour gap, and so on. After this 'repetitive music' gap-filling, it was hardly possible to distinguish a Fourier peak from the original one.

Surprisingly, what started as a pure mathematical problem finally acquired a physical meaning. We realized that what we were seeing in the autocorrelation was evidence of the returning acoustic waves after they had travelled all the way down to the other side of the Sun through the center, and back to the visible surface! This took about one hour along any one radius, and thus four hours for the complete return trip.

3.3 Frequency Determination from IRIS Network and IRIS^{++} Data

The seismic exploitation of helioseismological data requires extremely accurate measurements of the acoustic mode frequencies. With a line-width ~1 μHz, a large number of p-mode frequencies can be estimated with an uncertainty of half their line-widths, i.e. about 10^{-4} in relative terms. Although such accuracy looks impressive, it appears insufficient when facing the demand of theoretical seismic inversions, which require relative accuracies of about 10^{-5} in order to improve the existing solar models. At such a high level of demand, the task becomes harder.

A first attempt at p-mode frequency estimation from the IRIS data obtained during four summer seasons (1989-1992) was made by Gelly et al. (1997). Beside IRIS data, the anaysis included the magneto-optical filter measurements of Cacciani et al. (1988) and the data of the BiSON network's potassium instrument in Tenerife (Elsworth et al., 1988). Even with these additional data sets, the duty cycle did not exceed 50%.

The next attempt to estimate the precise frequencies was made by Serebryanskiy et al. (2001) using 7.5 years of IRIS data, from 1989 to the end of 1996. This work included not only the p-mode frequencies, but also their variation during the solar cycle, their line-widths and their profile asymmetries. However, the relatively low duty cycle (still less than 50%) again limited the accuracy of the results.

After exploiting the 'repetitive music' gap-filling method, an extended list of IRIS p-mode frequencies and rotational splitting was published by Fossat et al (2002). In that same year a list of frequencies and splitting from nearly 2,000 days of GOLF data was published by Gelly et al (2002). Two lists of GOLF frequencies, from low activity and high activity, could be averaged and compared to the IRIS frequencies averaged over the complete solar cycle. The mean difference across the entire frequency range was almost zero (just a few nHz).

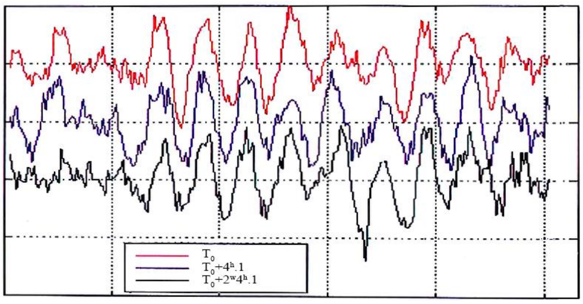

Figure 8: The solar oscillation signal cut in three parts 4,1 hours apart and shown one under another. The horizontal time span displayed here is one hour.

This precise low degree p-modes frequency determination and the subsequent modeling of the internal structure of the core was an important contribution to the resolution of one of the most important task of solar physics: the solar neutrino puzzle.

The Sun is a natural nuclear fusion reactor. A proton-proton chain reaction converts four protons into helium nuclei, neutrinos, positrons and energy. The excess energy is released as gamma rays, as kinetic energy of the particles and as neutrinos—which travel from the Sun's core to the Earth without any appreciable absorption by the Sun's outer layers. The measurement of the solar neutrino flux is extremely difficult since neutrinos essentially do not interact with anything, but the derived values were between one third and one half of the values that were predicted by modelling the solar interior. This discrepancy, which lasted from the mid-1960s to about 2002, came to be known as the 'solar neutrino problem'.

Early attempts to explain this discrepancy proposed that the temperature and pressure in the interior of the Sun could be substantially different from what was computed using solar models. However, these solutions became more and more untenable as advances in helioseismology made it possible to measure the interior temperatures of the Sun right through to the solar center, with an incredibly high precision of better than 10^{-3}. Helioseismology and the 'cold' solar core definitely proved to be inconsistent.

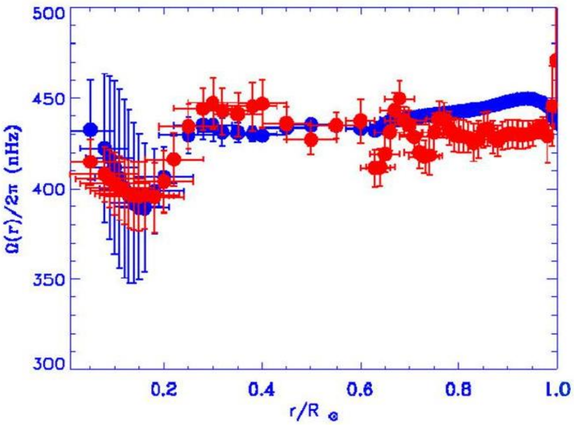

Figure 9: This plot shows the equatorial profile of the solar rotation using p-modes frequency splitting measurements from IRIS and MDI data on board the SOHO spacecraft. Comparison of profiles obtained using low and intermediate modes (blue) and a one obtained using only low-degree (red) modes (*l* =1-4) shows that the rotation profile along the whole solar radius can be obtained with only the low degree p-modes (after: P.M. Di Mauro, pers. comm., 2002).

The discrepancy has since been resolved by new understanding of the physics of neutrinos. Essentially, as neutrinos have mass, they can oscillate and change from one type to another. However, the detector developed by Raymond Davis Jr. was sensitive to only one type, so instead of detecting all solar neutrinos it only one recorded a fraction of them, between one third and one half.

For their pioneering work on the resolution of the solar neutrino problem Davis and Masatoshi Koshiba shared the 2002 Nobel Prize in Physics.

3.4 Solar Core Rotation

The Sun does not rotate as a solid body. The latitudinal differential rotation, easily visible at its surface, has been demonstrated by helioseismology to persist down to the base of the convection zone, at a depth of $0.71R_{\odot}$. The rotation of the solar core could be much faster, if the loss of angular momentum by the solar wind during the 4.5 billion-year life of the Sun on the Main Sequence had not been efficiently coupled to the very deep and dense layers. The rotation of the upper internal layers down to the base of the convection zone had been determined with amazing precision by imaging helioseismology (Libbrecht, 1988). The deeper layers of the Sun remained inaccessible until the two main ground-based networks for full disk (i.e. unresolved) helioseismology, IRIS and BiSON, were able to accumulate enough observations to provide access to the measurement of the low degree p-modes splitting influenced by the rotation of the solar core. From 1993, the IRIS group attempted to measure this value (Loudagh et al., 1993; Fossat et al., 1995), and in 1996 they published the result of their most reliable analyses based on three time series, each a little longer than four months, obtained during the northern summers of 1990, 1991 and 1992 (Lazrek et al., 1996). The unexpectedly low value of the rotational splitting implied a solar core rotation rate that was no faster than the envelope, and possibly was even slower. This result was confirmed by the BiSON group (Elsworth et al., 1995), and later by the 11-year IRIS data bank, as well as by the comparison between IRIS and GOLF measurements (Fossat et al, 2002), that helped to reduce the error bar by one more step.

Figure 9 shows the solar core rotation obtained by Di Mauro et al. (1998) using our IRIS splitting values together with MDI data. It is extremely interesting to note that most of the rotation along the total solar radius can be obtained with only the low degree (*l* = 1-4) p-modes. This opens up exciting perspectives for asteroseismology!

Measurements of the rotation of the solar core are related to the classical question about the interpretation of Mercury's orbital precession. This problem was first addressed in the 1800s. Due to various effects, such as tiny perturbations caused by other planets, the observed precession of Mercury's orbit is about 532 arc-seconds per century. A significant part of this value was explained in terms of Newtonian gravitational theory, but the residual 43 arcsec per century that could not be explained in this way was the subject of long discussion until Einstein (1915) demonstrated that his General Theory of Relativity predicted precisely that amount.

If the solar core would rotate about ten times faster than its envelope (as all stellar evolution theories predict), then the Sun should have the shape of a flattened spheroid. In this case it cannot be assumed that its gravitational field would exactly suit the inverse square law. As soon as the Sun is not an ideal spherical body, then Einstein's theory can explain only a fraction of the residual effect. The IRIS measurements proved that the solar core does not rotate faster than its envelope (i.e. it has a period of about one month). Due to this unprecedented result, obtained through the IRIS project, deviations in the Sun's gravitation field from the inverse square law can be ignored.

3.5 Variation of Helioseismic Parameters During the Solar Cycle

The long duration of the observations obtained through the IRIS project allowed an analysis of variations in the solar p-mode frequencies and other parameters in the course of the solar cycle. Such analyses played a crucial role in our understanding of the physics behind the variations that occur during the solar cycle as manifested, for example, by changes in sunspots and the switching of the magnetic poles about every eleven years. The mode frequency turned out to be the most sensitive parameter.

Analyses of IRIS++ frequencies of low-degree solar p-modes confirmed the overall trend of the p-mode frequencies from the minimum to the maximum of solar activity. The frequencies remained almost unchanged below 2 mHz, then in the range 2.0–3.7 mHz the frequencies increased with increasing solar activity. Above 3.7 mHz, the frequency shift dropped to zero, and became negative for frequencies higher that 4.5 mHz (Salabert et al., 2004; see Figure 10). It also was interesting to investigate shorter periodicities in the frequency shift and the detailed correlation of the shift with various solar cycle indices such as the sunspot number and the 10.7cm radio flux. Upon analyzing separately the even and odd degree modes it was found that even modes reacted later than the odd modes, which seemed more closely correlated with solar activity short-time fluctuations. This was interpreted as a consequence of the geometry of the modes.

The mode amplitude and line-width also showed a dependence on solar activity. It was found that the mode amplitude anti-correlated with the solar cycle while the line-widths correlated with changing solar activity. It also was found that the overall change in the amplitudes was approximately −26%, and for the line-width was typically +11%. Regarding the velocity power, this was anti-correlated with solar activity, showing a variation of about −11%, but a correlation was found between the solar activity cycle and the energy supply rate.

The resulting line-width obtained with IRIS++ data seemed to confirm what Houdek et al. (2001) had suggested, namely that the damping rate for the modes in the range of 2.4-3.0 mHz increased when the horizontal size of solar granules decreased from solar minimum to solar maximum (Muller, 1988) but their vertical size remained constant. Using these two parameters the velocity power of the modes as well as the energy supplied to them were estimated and it was found that the velocity power changed by –11%, while the rate of energy supply remained constant with solar activity.

3.6 Mode Profile Asymmetry

Another interesting problem we addressed within the IRIS project was the mode profile asymmetry observed in power spectra of solar p-modes. It was found that p-mode profiles were not pure Lorentzian, but displayed an excess of power at lower or higher frequencies in part depending on the observational techniques used to analyze the solar oscillations. It was realized that asymmetry resulted from a combination of two effects: localization of the source of the p-mode oscillation and the visibility of the source itself (the so-called 'correlated noise'). To extract the asymmetry parameters from the IRIS power spectra we fitted the p-mode profiles using the formalism of Nigam and Kosovichev (1998). Our results qualitatively agreed with the results of the BiSON project (Chaplin et al., 1999), and more details can be found in Serebryanskiy et al., 2001.

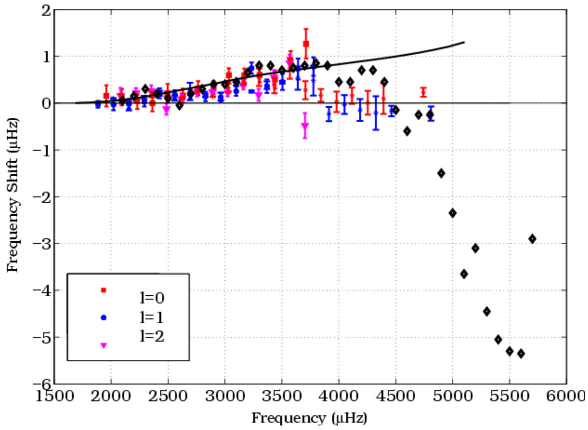

Figure 10: The IRIS frequency shifts in the frequency range from 1.8 mHz to the acoustic cut-off frequency. Using different methods it was possible to confirm the overall trends of the p-mode frequencies from solar minimum to solar maximum. However, the values and signs of these trends are different for different modes (after Salabert et al., 2004: 1138). See the text for details.

4 THE TAIWAN OSCILLATION NETWORK PROJECT

The Taiwan Oscillation Network (or TON) is a ground-based network set up to measure ionized calcium K-line intensity oscillations in order to study the internal structure of the Sun (Chou et al., 1995). The TON project was funded by the Taiwanese National Research Council from the summer of 1991, with the headquarters located in the Physics Department at the National Tsing Hua University (NTHU) in Hsinchu, Taiwan, where the telescope systems were designed, built and tested. The first TON network telescope was installed at the Teide Observatory, Tenerife, Canary Islands (Spain) in August 1993. The second one was installed at the Huairou Solar Observing Station near Beijing in January 1994, and the third telescope system was installed at the Big Bear Solar Observatory, California, in June 1994. The locations of these and other TON stations are shown in Figure 1.

The TON was designed to obtain information on high-degree solar p-mode oscillations, along with intermediate-degree modes. The TON network used 3.5-inch Maksutov-type telescopes to observe K-line full-disk solar images with 16-bit 1080 × 1080 water-cooled CCDs. The diameter of the Sun was set at 1000 pixels. The measured amplitude of intensity oscillations was about 2.5%. The TON instruments provided data on the solar p-modes with a spherical harmonic degree, *l,* as high as 1000.

4.l Local Helioseismology at the UBAI: An Historical Retrospective

Initially Uzbekistan was not going to be part of the TON collaboration, but Shuhrat Ehgamberdiev persuaded Dean-Yi Chou that Uzbekistan could play a significant role, so in 1996 a TON instrument was installed in Tashkent on UBAI land (Figure 11). It is necessary to mention here that, unlike the IRIS instrument, the TON experiment was not sensitive to the atmospheric transparency gradient, and required good seeing for high-resolution imaging. It was well known that the atmosphere in Tashkent was very calm in the hottest season, with maximum clear day-time. To avoid the influence of ground turbulence which aggravated image quality the TON instrument was placed on top of a 6-m high pillar. As a result, it was easy to achieve a resolution of 2 arc-seconds and access modes with *l* up to 1000.

Following the deployment of the TON telescope in Tashkent the UBAI was the most active member of the TON team. As in the case of building the IRIS station, all work on the installation of the TON instrumentation was done by Taiwanese and Uzbek teams, without involving any professional builders. The Tashkent instrument provided the TON network with daily observations from 1996 until 2002. Besides carrying out observations, the UBAI team also actively participated in the scientific analyses. In 1998 Shukur Kholikov, who at the time was a senior researcher at UBAI, was invited to NTHU to work with the local helioseismology team using TON data. His work foreshadowed the success that would occur in the next few years after Alexander Serebryanskiy and later Oleg Ladenkov joined NTHU to continue research on local helioseismology using TON and SOHO/MDI data (Scherrer et al., 1995). Their efforts resulted in a series of papers on new methods and results in helioseismology, including the study of the lifetime of the high-degree solar acoustic modes, meridional circulations and a search for evidence of magnetic fields at the base of the solar convection zone.

4.2 The Main Scientific Results Obtained Through the TON Project

The most important scientific result obtained using helioseismology and TON experimental data was the first estimation of sunspot depth. The story of this discovery is very interesting.

After the successful installation of a TON instrument in Tashkent Dean-Yi Chou went to Hawaii to attend a meeting on helioseismology. There he met Barry Labonte who told him about an interesting method of submarine detection, announced in *Nature* (Buckingham et al., 1992). Two different well-known methods of submarine detection used ‘active’ and ‘passive’ techniques. The active method consisted of illuminating an underwater object with a pulse of sound, and its presence was inferred from the echo it produced. The passive approach involved simply listening for the sound that the object itself emitted. The method suggested by Buckingham relied on using the scattering of acoustic noise by an object. The ocean is filled with incoherent noise which has many natural sources. An object drowned in such an ambient acoustic field modifies this field by scattering acoustic energy in all directions. This scattered radiation can be focused into an image using some kind of acoustic lens (say an acoustic reflector or refractor). After appropriate signal processing, an image of the object can be displayed on the computer monitor.

This breakthrough idea was used by Dean-Yi Chou and co-workers in a helioseismological study of changing acoustic noise background by a sunspot. The method was called acoustic imaging (Chang et al., 1997; Chen et al., 1998; Chou et al., 1999; Chou, 2000), since it allowed a check to be made layer by layer of the presence of a sunspot at different depths. Figure 12 demonstrates how contrast of a sunspot, which absorbs the acoustic energy, changes with depth. One can see that traces of the sunspot are disappearing at a depth of about 40,000 km. For the first time scientists were able to peer through the solar atmosphere down to deep inside the solar interior in order to investigate the formation of active regions.

From our everyday experience we knew that an image of the object illuminated by scattered daylight could be formed by an optical lens. The solar acoustic waves, which were continuously generated and dissipated stochastically by turbulent convection, played the same role as ambient light. However, unlike an experiment in the

Figure 11: View of the TON instrument installed in Tashkent in 1996 (left) and its platform (photograph: Sh. Ehgamberdiev).

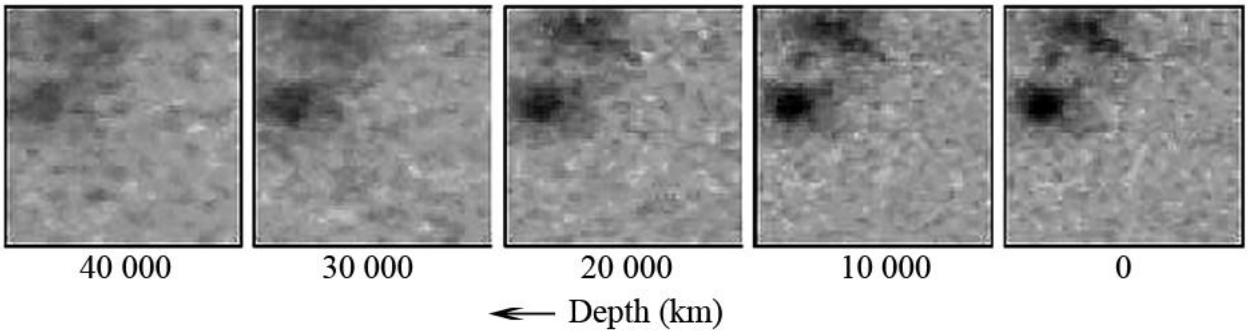

Figure 12: This shows a direct acoustic image at the surface of the Sun (far right) and acoustic images reconstructed at various depths for the active area NOAO 7993. One can see that the suppression of acoustic intensity increases with depth. At 40,000 km below the surface the signature of the sunspot almost disappears (after Chang et al., 1997: 826).

ocean, in the case of the Sun it was impossible to use a parabolic reflecting dish. For ambient acoustic imaging of the Sun 'a computational acoustic lens' was used. It had to be taken into account that different p-modes had different paths and arrived at the surface at different times and at different distances from the target points. On the basis of the relationship between travel time and the distance traveled by the acoustic waves, the intensity of the acoustic signal at the target point was coherently detected.

A similar method was developed by Lindsey and Braun (1997) but this was a solely mathematical approach, while the work of the TON team included the mathematical method and the application of the method to observational data. Especially, they proposed to use time-distance curves, which were the key to the method to be realized.

4.2.1 Life-time of the High-degree Solar p-modes

The excitation and damping mechanism for acoustic solar oscillations (p-modes) is conventionally analyzed by measuring p-mode profiles in power spectra of solar acoustic oscillations. The lifetimes of the high-*l* solar p-modes are difficult to measure with the conventional method due to the broad width of these mode profiles in power spectra and mode blending. The TON team was the first to use the time-distance technique to measure the lifetime of the wave packets formed by the high-*l* p-modes (Burtseva et al., 2007; Burtseva et al., 2009; Chou et al., 2001; Chou and Ladenkov, 2007). This method allowed the measurement of the lifetime of the central mode of the wave packet as a function of frequency.

4.2.2 Meridional Circulation in the Solar Convection Zone

Instead of the old 'pot-on-the-stove' model of vertical convection of the Sun, horizontal jet streams were found in the top layer of the convective zone. Small ones were found around each pole, and larger ones that extended to the equator were called 'meridional circulation' or 'meridional flows'.

Meridional circulation in the solar convection zone plays a crucial role in flux transport dynamo theories. For example, the time-scale of the solar activity cycle depends on the structure and magnitude of the meridional circulation.

Using the TON data obtained between 1994 and 2003 the TON team found that an additional divergent meridional flow component existed and its change with time correlated with the magnetic fields of the 11-year cycle. This divergent flow extended down to 0.8 $R_{\odot}$ but peaked at a depth of 0.9 $R_{\odot}$, and its amplitude correlated with the sunspot number (Chou and Dai, 2001; Chou and Ladenkov, 2005). This phenomenon was confirmed by other authors (Beck et al., 2002) and by our recent results (Serebryanskiy et al., 2011). Our recent study using GONG++ and SOHO/MDI data shows the meridional flow speed increasing with depth, although the absolute flow speed may have suffered from systematic effects. This research was carried out as a close collaboration between the UBAI, the Astrophysical Laboratory of the NTHU, the National Solar Observatory (NSO) at Tucson, Arizona) and New Mexico State University (NMSU) at Las Cruces, New Mexico, USA).

4.2.3 Searching for Magnetic Fields near the Base of the Solar Convection Zone

It is generally believed that solar magnetic fields are generated near the base of the convection zone. The detection of variations in the physical

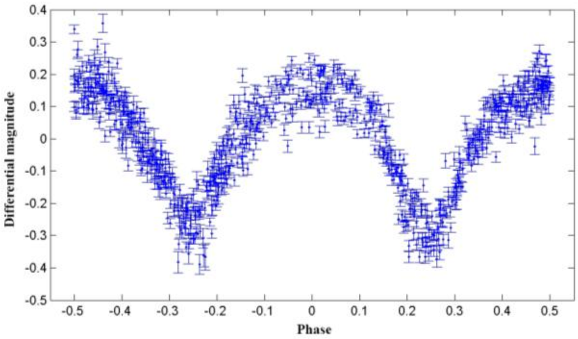

Figure 13: A light curve of the variable star GSC 02007-00761, which was found to be a close binary system rather than a δ Scuti variable (after: Ehgamberdiev et al., 2008: 358).

parameters of the solar-cycle near the base of the convection zone could indicate the existence of magnetic fields there. The time-distance technique can be used to measure solar-cycle variations in the travel time around the Sun of particular wave packets formed by p-modes to indicate the presence of magnetic fields near the base of the convection zone (Chou and Serebryanskiy, 2002; Chou et al., 2003). Another means of probing the solar interior is to use the solar-cycle variations of p-mode frequencies, normalized by mode mass, as a function of phase speed. Using this method, the TON team was able to infer magnetic field strengths of between 1.7×10^5 G and 2.9×10^5 G near the base of the convection zone (Chou and Serebryanskiy, 2005; Serebryanskiy and Chou, 2005). These results were cited as among the most interesting results in astrophysics in 2005 and 2006 (see Trimble et al., 2006; Trimble et al., 2007). Recently, this result also was confirmed by Baldner and Basu (2009).

5 ASTEROSEISMOLOGY

Having both a rich heritage in variable star research (Grankin, 1999; Grankin et al., 2007; Mel'nikov and Grankin, 2005; Shevchenko et al., 1993) and solid experience in helioseismology, it was natural that the UBAI team should turn its vision towards asteroseismology, which represents the most efficient method to study stellar interiors in detail. Asteroseismology also uses the observed pulsation spectrum to determine the current structural properties of a given star, from which we may deduce its evolutionary history. Indeed, the theory of stellar evolution need no longer depend solely on theory and measurements made on one unique star, our Sun, now that several classes of known pulsating stars can be studied using this seismic technique.

Currently, δ Scuti stars are among the most promising candidates for asteroseismological analysis. These stars are more massive or more evolved than the Sun. Their structure is drastically different, with only a thin convective layer near the surface and two different regions deep inside where nuclear hydrogen-burning occurs. They also exhibit a wide variety of pulsation behavior, with enough amplitude to be detected by ground-based observations. They can then provide relatively easy access to seismic parameters, and nicely complement solar studies. An important feature of these stars for us is their relatively bright magnitude and high amplitude variability. The consequence is that they do not necessarily require a space mission, and we can use several small-aperture telescopes located at different longitudes, just as we did with the IRIS network.

In 2006 we began to establish a network of six educational observatories located at Uzbekistan universities. All were equipped with small telescopes. We found that the observation of δ Scuti stars also was an ideal means for teaching students some of the basics of scientific research, and it also was a good way of obtaining real scientific data at a relatively low cost.

Figure 13 shows a result of this observing campaign. Using the 20-inch Grubb-Parsons telescope installed at the Educational Observatory of the Samarkand State University, in 2006 we and students from the University were able to obtain a light curve of the variable star GSC 02007-00761, which was thought to be a δ Scuti star. However, the analysis of this light curve allowed us to confirm that this star was not a δ Scuti variable, but in fact was a close binary system. We determined the main parameters of this double system and precisely measured its period: 0.2709 days. We also obtained the temperature, radius and mass of each component of this system. More details can be found in Ehgamberdiev et al. (2008).

In order to carry out long-term international observations of δ Scuti stars and perform asteroseismic analyses of their light-curves Taiwanese astronomers established the TAT (Taiwan Automated Telescope) network (Chou et al., 2006). In 2007 a TAT was installed at Maidanak Observatory in Uzbekistan, and this is shown in Figure 14. Maidanak Observatory is located in the southern part of Uzbekistan, at an altitude of 2,700 m above mean sea level (Ehgamberdiev et al., 2000).

The TAT network has proved to be quite efficient in finding new δ Scuti stars. In 2008 HD 163032 was discovered to be a δ Scuti star, and after four years of observations we were able to precisely determine the mode parameters and their variation with time (Fernández, et al., 2013). We also determined these same parameters for another already-known δ Scuti star, V830 Her (ibid.; see Figure 15).

Later we turned our TAT towards one of the targets of the Kepler space mission: NGC6811. Our main program was to conduct light-curve analyses of known variable stars, and to make follow-up observations for Kepler. At the time we wrote this paper we had obtained light curves of stars in the field of NGC6811 and discovered several new δ Scuti candidates, but were awaiting the arrival of Kepler observations.

6 CONCLUDING REMARKS

IRIS was a network for full-disc helioseismology, with six observing stations distributed around the Earth. This project was initiated by Eric Fossat and Gerard Grec from the University of Nice after almost fifteen years experience in researching solar oscillations. They realised that a spectrophotometer which detected Doppler shifts of the sodium D1 line integrated over the whole visible disk of the Sun would allow astronomers to investigate the deep interior of the Sun.

The IRIS network has provided astronomers with the longest time series of full-disk helioseismological data. Freely available on the CDS data base, the eleven years of data for 1989–2000 cover a complete solar cycle, from the maximum of Cycle 22 to the maximum of Cycle 23.

The most crucial achievement on the way to the success of the IRIS project was the scientific involvement of local teams, and the commitment of an IRIS community of enthusiastic and qualified astronomers from different countries.

From 1988, the IRIS group organized thirteen annual workshops, in France, Uzbekistan, Morocco, Spain, England, Italy and the U.S.; provided observations for twelve Ph.D. theses; and successsfully produced data and results despite a very modest level of financial support (between 1% and 10% of the support enjoyed by the other

Figure 14: The Taiwan Automated Telescope at Maidanak Observatory (photograph: A. Serebryanskiy).

networks). The spirit of real co-operation was a key to this success, and the local teams, often at remote sites, were fully included in the scientific exploitation of the data bank. Five specific 'cooperant' (alternative military service) positions were awarded to the IRIS program, four in Uzbekistan and one in Australia, and University of Nice post-doctoral fellowships were awarded to many of our colleagues.

Many former Uzbek members of the IRIS and TON projects are still working in various fields of astronomy. For example, Shukur Kholikov is an Associate Scientist of the GONG helioseismology project (at the National Solar Observatory in Tucson, Arizona); Olga Burtseva is an Assistant Scientist working for the National Solar Observatory's Integrated Synoptic Program; Alexander Serebryanskiy is now the Head of the Variable Stars and Asteroseismology Department at the UBAI; and Sabit Ilyasov, who has passed his his second dissertation (Doctor Nauk) is now a Vice-director of the UBAI.

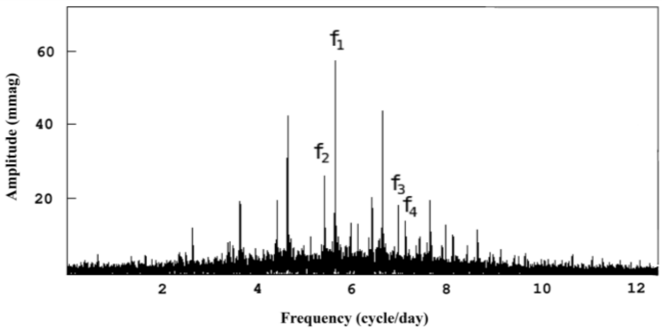

Figure 15: An example of the amplitude spectrum of the δ Scuti star V830 Her based on data obtained by the TAT network during 2008-2011 (after Fernández et al., 2013: 36).

7 NOTES

1. The TAT uses a 9-cm Maksutov-type telescope with f = 25, manufactured by Questar. The CCD camera is Apogee Alta U6 16-bit 1024 × 1024, and the CCD chip is a Kodak KAF-1101E, with a scale of 2.18 arcsecs per pixel, which gives a field of view of 0.62 × 0.62 square degrees.
2. The IRIS scientific committee prepared a text of the Acknowledgments that should accompany each paper written using IRIS data. However, this text was prepared at the beginning of the IRIS project and was never upgraded. As a result, a number of colleagues who joined the community later and made crucial contributions to the success of the project are not mentioned in these Acknowledgments. So, we present an updated version of the Acknowledgments below.

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As for the participation of the UBAI team in the TON and TAT projects, this would not have been possible without the very friendly attitude and support of Professor Dean-Yi Chou, with whom the UBAI has had a very fruitful collaboration in helioseismology since the mid-1990s. He also provided his personal support to UBAI team members who visited the NHTU as postdocs and visiting scientists. The UBAI would also like to express its gratitude to Dean-Yi Chou for his continuous support in various ways of the asteroseismology research carried out with the TAT at Maidanak Observatory.

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observer at the Kumbel station of the IRIS project.

Later, in 1996, he joined the TON project as an observer and data reduction scientist. In 2000 he defended his Ph.D. thesis, which was devoted to a study of the Sun using global helioseismology observations obtained through the IRIS network. Since 2000 his scientific interest has also included local helioseismology. He was a postdoc at the National Tsing Hua University in Tai-wan where he worked with Dean-Yi Chou studying the solar interior using TON and SOHO/MDI data. He was a postdoc in 2004-2005 at the National Solar Observatory in the USA where he worked with the GONG team and studied the solar interior using GONG and SOHO/MDI data. Since 2001 he has been the author or coauthor of more than 25 publications.

APPENDIX 1: A HISTORY OF KUMBEL STATION OF THE IRIS NETWORK

by Shuhrat Ehgamberdiev

Within the distribution of the northern hemisphere sites selected for the worldwide IRIS network, one instrument had to be installed somewhere in Central Asia. In the 1980s this area was referred to as the south of the Soviet Union. Immediately after receiving funding from INSU—the French Institute for the Studies of the Universe—in 1984, Eric Fossat and Gerard Grec from the University of Nice headed to the unknown, for them, "... country of the Soviets ...", aiming to find a site where they could install an IRIS instrument.

They arrived at ASTROSOVET (the Astronomical Council), an organization based in Moscow that coordinated academic research in the field of astronomy for the whole of the USSR. Staff at ASTROSOVET strongly advised Fossat and Grec to go to the Crimean Astrophysical Observatory, which at that time was the center of Soviet helioseismology. In fact, its Director, the well-known astrophysicist, Academician Andrei Severny, a few years earlier had announced the sensational discovery of the 160-minute oscillation of the Sun, which he interpreted as reflecting a gravitational mode of the Sun. However, these 160-minute oscillations have not been substantiated either by the IRIS data or by any other contemporary solar observations, and the historical signal is now considered to occur during the redistribution of power from the diurnal cycle as a result of the observation window and atmospheric extinction. Today little attention is paid to this topic, but in the 1980s it was widely discussed at all conferences on helioseismology Meanwhile, the identification of gravity modes remains one of the key challenges of helioseismology.

It was no surprise that it was left to Severny to decide on where in the USSR the French telescope should be installed, and he proposed to have it in the Crimea. However, the astroclimate of Crimea did not differ markedly from that of Nice, which did not suit the French astronomers. The high humidity and frequent clouds along the sunny shores of the Crimean Peninsula made it quite unsuitable for whole-disc observations of solar oscillations, which are highly sensitive to the transparency of the atmosphere.

The next time Eric Fossat and his colleague Jean-Francois Manigault arrived in the USSR they contacted another famous Soviet scientist, Academician George Zatsepin, who ran the Baksan Neutrino Observatory of the Institute of Nuclear Research (INR) of the Soviet Academy of Sciences, located in the Caucasus. Zatsepin helped organizing a trip to Uzbekistan for the French scientists, accompanied by his collaborator, Elena Gavryuseva, and they arrived in Tashkent in the fall of 1985.

This was when I first met Fossat and Manigault. Fall is a great season in Uzbekistan, not only because this time of year we have the world's sweetest melons and grapes, but also due to the huge number of clear sunny days. These factors combined to make quite an impression on the French visitors, and soon after an agreement was signed between the University of Nice, the INR and the Astronomical Institute of the Academy of Sciences of Uzbekistan. Although we were real partners with the INR, at that time the Astronomical Institute was not allowed to sign any agreement with a foreign institute by itself, without control from a Moscow institution.

From that time, Uzbek scientists began to be actively involved in helioseismology. The first important decision was to choose a location for the IRIS spectrophotometer. During the visit of the French scientists, the plan was to install the instrument on the premises of the Astronomical Institute in Tashkent, but studies revealed that the dusty skies there during the summer months, when a maximum number of clear days occur, would not allow the acquisition of high-quality data. The solution was to find a site in the mountains where the density of atmospheric dust was much lower, and the natural choice was the mountainous area of Chimghana one hour drive from Tashkent.

As result of many helicopter flights around the Chimgan area, Mt Kumbel, which was located on a spur of the Big Chimgan summit, captured our attention. It was an isolated mountain top that at the same time provided enough space to accommodate an IRIS station. When we climbed 2,300-m high Mt Kumbel on foot we found that a funicular ski trail had been built there, but the road to the top had not been paved and apparently there were no plans to develop it further. Nevertheless, this serious obstacle did not stop us, as we already were so 'infected' by the idea of having an IRIS station on Mt Kumbel. Pure enthusiasm, multiplied by a lack of experience, proved to be quite a powerful incentive for us. In other words, we were not aware of the enormity of the work and the challenges that we were about to face. In November 1987 Eric Fossat and Gerard Grec visited Mt Kumbel and the seeing impressed them. Our choice was highly approved.

Success in any venture largely depends upon many random circumstances, as well as an element of luck. In order to accommodate our staff of researchers on M. Kimbel we had to buy special caravans, but in a controlled economy it would be almost impossible to make such purchases immediately. These caravans generally were provided, on demand, to construction companies, not to academic institutions, and their requests were made years in advance. Of course the Astronomical Institute could order two of these caravans, but there was a waiting time of many years and our caravans were required urgently.

Oddly, pure chance made it happen for us. I learned from my wife that there was a family of a very influential government official among our neighbors, whose daughter would walk her toddler around the neighborhood along with my wife and our baby daughter. That man was a senior manager of a leading construction company in Uzbekistan. As my wife knew his daughter quite well, the two women arranged for me to meet him. By chance, two construction companies had recently 'terminated' their previous orders, so we could get two caravans to be delivered to our Institute within a couple of weeks.

However, now we had to work out how to transfer one of the caravans to the top of the Mt Kumbel given that there were no roads near the mountain that we could use. Once again, luck was on our side. We had a Civil Defense officer at our Institute, as was required at that time for every state organization. These individuals typically were hired from a pool of military retirees, and their duties included training personnel on how to use personal safety equipment and how to behave in the event of a nuclear attack. Our Civil Defense officer was a former pilot, a wonderful man, and I had a very good working relationship with him. As soon as I informed him of our 'problem', he made a great suggestion. He was residing in a part of Tashkent called Aviagorodok, which translates as a 'Town of Aviators' because it was built especially for aviation engineers and their families. He knew that the latest Soviet military helicopter was the MI-26, which was used during combat operations in Afghanistan, and he told me that there were a few of these helicopters in Uzbekistan and one of these "... could easily transport your caravan to the top of Mt Kumbel." But the "easily" part turned out to be not so easy at first because all I had to do was get the Chief Commander of the Division that was in charge of the MI-26 to agree to do me a 'small favor'. Through the wife of our Civil Defense officer, who happened to work there, we managed to make contact with the Chief Commander (which was not easy as the Division belonged to the KGB Border Forces). I learned that the Chief Commander was a general, and I wrote him a formal letter requesting his help.

I knew that the Director of our Astronomical Institute at that time would not be willing to sign such a letter, so I drafted the letter on behalf of the President of the Academy of Sciences of Uzbekistan. When I went to get his signature and handed the letter to one of his assistants she looked at me with suspicion and asked: "Does your Director know about this?" to which I replied "yes". But since the addressee of the letter was quite out of the ordinary, she decided to make sure and call my Director. Fortunately, he was not in his office, and since there were no cellphones in those days the fate of this matter was decided.

Armed with the letter signed by the President of the Uzbekistan Academy of Sciences, I went straight to the Chief Commander. Frankly, I was quite overwhelmed by pure excitement: after all, I was a mere junior researcher at a relatively small academic institution, and here I was trying to convince a Soviet Air Force General to take a chance and help me. What if I could not make this happen? That would spell the end of the entire project.

As soon as I arrived at the building where I was supposed to meet the Chief Commander, I informed the Duty Officer that I was there at the request of the President of the Academy of Sciences. Soon another officer appeared who accompanied me to a reception area where I was asked to wait. Finally, I met the Chief Commander, and found myself in a very spacious office. Ironically, I really cannot recall exactly how I started the conversation, but I do remember the most important words that I used, whilst applying my powers of persuasion at that time, were the following, "If we, the scientists, cannot meet the needs of the French scientists and thus disgrace ourselves, then at least, you, the Soviet Army, should show them how powerful you are." The Chief Commander burst out laughing, and I knew right then that I had managed to get my point across. He called one of his officers and told him: "Here is a young man who has persuaded us to show our strength to the French. Help him." Then he added: "We must get his caravan up the mountain."

We went into a room where many military pilots sat and were discussing details of air battles over Kandahar and Mazar-i-Sharif in Afghanistan. The colonel who was in charge of my case took out a detailed military map and asked me to show him exactly where Mt Kumbel was. Then we agreed that we would go on a 'reconnaisance mission' the next day so that he could familiarize himself with precisely where the caravan should be delivered.

When we finally brought the caravan to the designated pick-up point, an MI-26 helicopter was waiting for us. In the course of looking for a place that would be suitable for our IRIS station I had flown frequently on MI-8 helicopters so was quite familiar with them, but when I saw the MI-26 it absolutely astounded me. It picked up our 15-ton caravan as if it was a box of matches and raised it high in the air. While I was in the Chief Commander's office I overheard pilots discussing details of their upcoming flight, and they warned me that in the event of strong winds and turbulence, for safety reasons they would have to jetison the caravan. But luckily the weather was perfect that day. When the MI-26 helicopter flew to the top of Mt Kumbel a huge cloud of dust appeared so everything underneath was completely invisible. I remember asking the pilots for details about the conditions on the ground, because within a radius of 70 meters from the rotor the MI-26 was similar to a hurricane. They finally landed the caravan, but it was 50 meters away from the intended site. Then the helicopter flew away, and we waved, expressing our deepest gratitude to the pilots and people who helped us make this happen. Subsequently, we utilized methods similar to those used in building the Egyptian pyramids in order to get the caravan precisely to the location we had selected.

Although there is a lot of controversy now about the Soviet era, ordinary people back then were much more honest and decent than these days. Many of the quite difficult matters we faced during the construction process were resolved easily, thanks mainly to the support and genuine attitudes of local people. What can one say about the fact that we managed to fly in a military helicopter totally free of charge in order to complete our mission? Or that colleagues from the Hydro-meteorological Center took us along on their flights? Or, finally, that the pilots who were flying us around to so many different places, knowing that we were looking for a site for the observatory, not only made many additional flights, but also would land at some unusual and quite difficult places and then come back to pick us up when we were ready to return home. I can only imagine how much these 'excursions' would cost if this were to happen today. And I am not even talking about transferring a caravan to the top of Mt Kumbel.

We all were driven by enormous enthusiasm, and over a period of three months in the summer of 1988 we completed construction of the IRIS station. Although just a handful of staff, we managed to raise and carry several hundred tons of construction materials, each time manually loading and unloading the MI-8 helicopter that we used. We carried out all of the construction ourselves without any assistance from professional construction workers, and our colleagues from France turned out to be not only excellent scientists but also quite skilled construction workers.

Finally, in August 1988 the spectrophotometer was operational and we received our first signal. I remember as if it were yesterday the impact this work made on all of us. Observing the signal registered on a chart-recorder, we were able to see all the components of the radial velocity be-tween the Sun and the telescope. At dawn the IRIS instrument registered the speed at which the Kumbel station and the Earth moved towards the Sun while in the evening the station would move away from the Sun. Day after day, this speed curve shifted as a whole, thus showing how the radial velocity component of the Earth's orbit changes during our orbit round the Sun. Altogether, all of the components of the radial velocity that should exist were seen through the IRIS instrument, and along this smooth curve one could see tiny ripples. These were the oscillations of the solar surface—the primary objective of our entire adventure.

THE ASTRONOMY OF TWO INDIAN TRIBES: THE BANJARAS AND THE KOLAMS

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Abstract: We report field studies of the astronomical beliefs of two Indian tribes – the Banjaras and the Kolams. The Banjaras are an ancient tribe connected with the gypsies of Europe while the Kolams have been foragers until recently. They share their landscape with each other and also with the Gonds whose astronomy was reported previously (Vahia and Halkare, 2013). The primary profession of the Banjaras was trade, based on the large-scale movement of goods over long distances, but their services were taken over by the railways about one hundred years ago. Since then the Banjaras have begun the long journey to a sedentary lifestyle. Meanwhile, the Kolams were foragers until about fifty years ago when the Government of India began to help them lead a settled life.

Here, we compare their astronomical beliefs of the Banjaras and the Kolams, which indicate the strong sense of identity that each community possesses. Our study also highlights their perspective about the sky and its relation to their daily lives. We show that apart from the absolute importance of the data on human perception of the sky, the data also reveal subtle aspects of interactions between physically co-located but otherwise isolated communities as well as their own lifestyles. We also show that there is a strong relationship between profession and perspective of the sky.

Keywords: Indian ethnoastronomy, the Banjaras, the Kolams

1 INTRODUCTION

India is one of the most complex regions in terms of co-habitation of a wide varieties of tribal societies that include the entire spectrum, from lifestyles akin to early hunter-gatherers to the most modern aspects of human civilisation. Many of these cultures are broadly classified as tribal, and they have remained intellectually isolated in an endogenous environment in spite of connections with all the trappings of modern civilisation. For example, they sell their goods at modern Indian markets and use other trappings of modern life, such as mobile phones very comfortably, but culturally and in daily life, they consciously keep themselves isolated from other communities and from urban people, and they try to preserve as many aspects of their ancient lifestyles as they can against the onslaught of modernity. For an excellent review of tribes of India see Fürer-Haimendorf (1982).

One might naively expect that since the sky is common to everyone and many of these Indian communities share a similar landmass and present-day lifestyle as settled farmers, their astronomical beliefs would be largely similar. However, in an earlier study (Vahia and Halkare, 2013) we showed how this assumption is wrong when we described the astronomical beliefs of the largest of the ancient Indian tribes, the Gonds. In the present study, we extend this survey to two more tribes of India—the Banjaras and the Kolams—who share the same landmass with the Gonds but have quite different histories when it comes to the amount of time that they have lived settled lives. The Gonds have been living in settled communities for centuries, while the Banjaras only began a settled existence about a hundred years ago and the Kolams only in recent memory. In Figures 1 and 2 we show the geographical distribution of the two communities.

In this paper we first discuss the histories of the two communities. Then we report on their astronomical systems before comparing these with each other and with Gond astronomy. However, there are some specific terms for astronomical constellations and asterisms that are unique to India, and which we will refer to. In

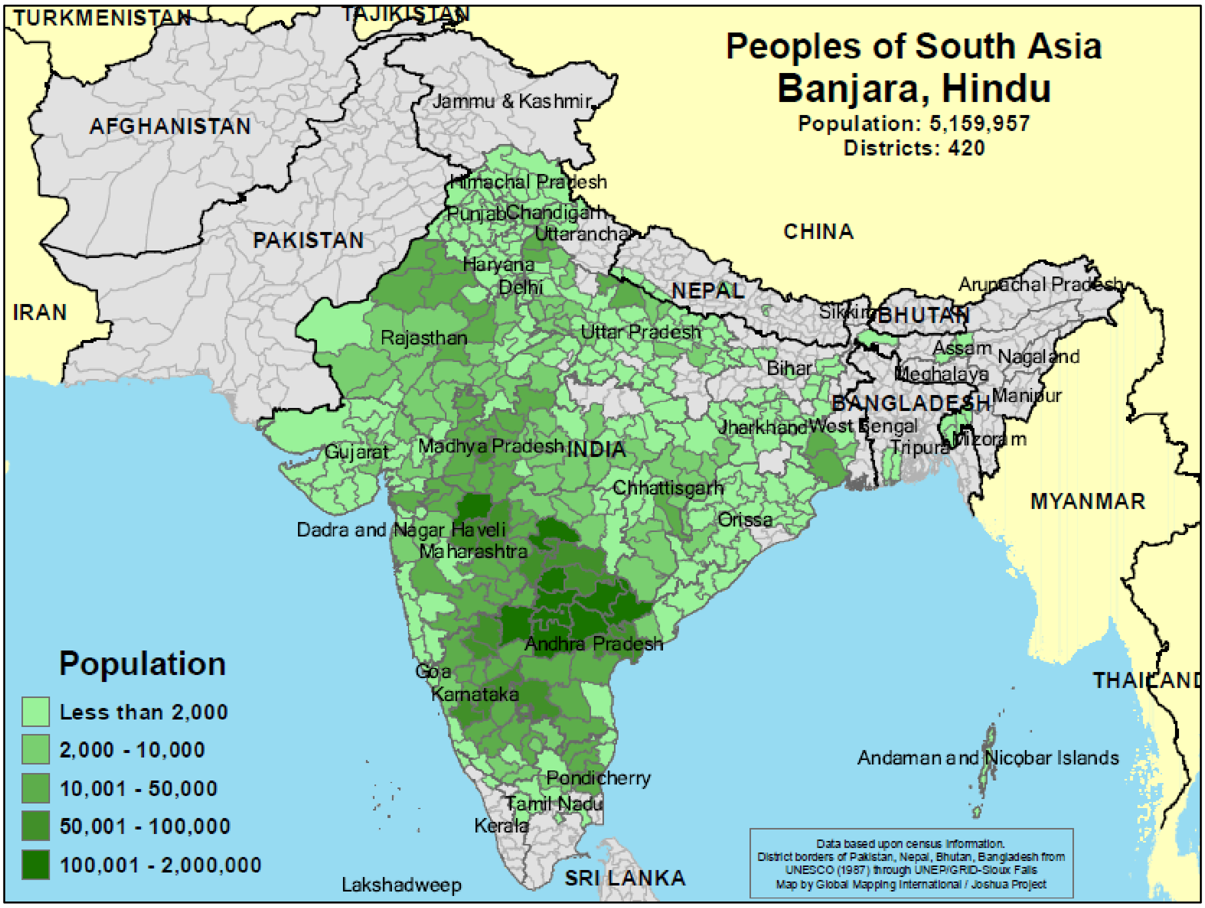

Figure 1: Geographical distribution of the Banjaras (courtesy: http://www.joshuaproject.net/).

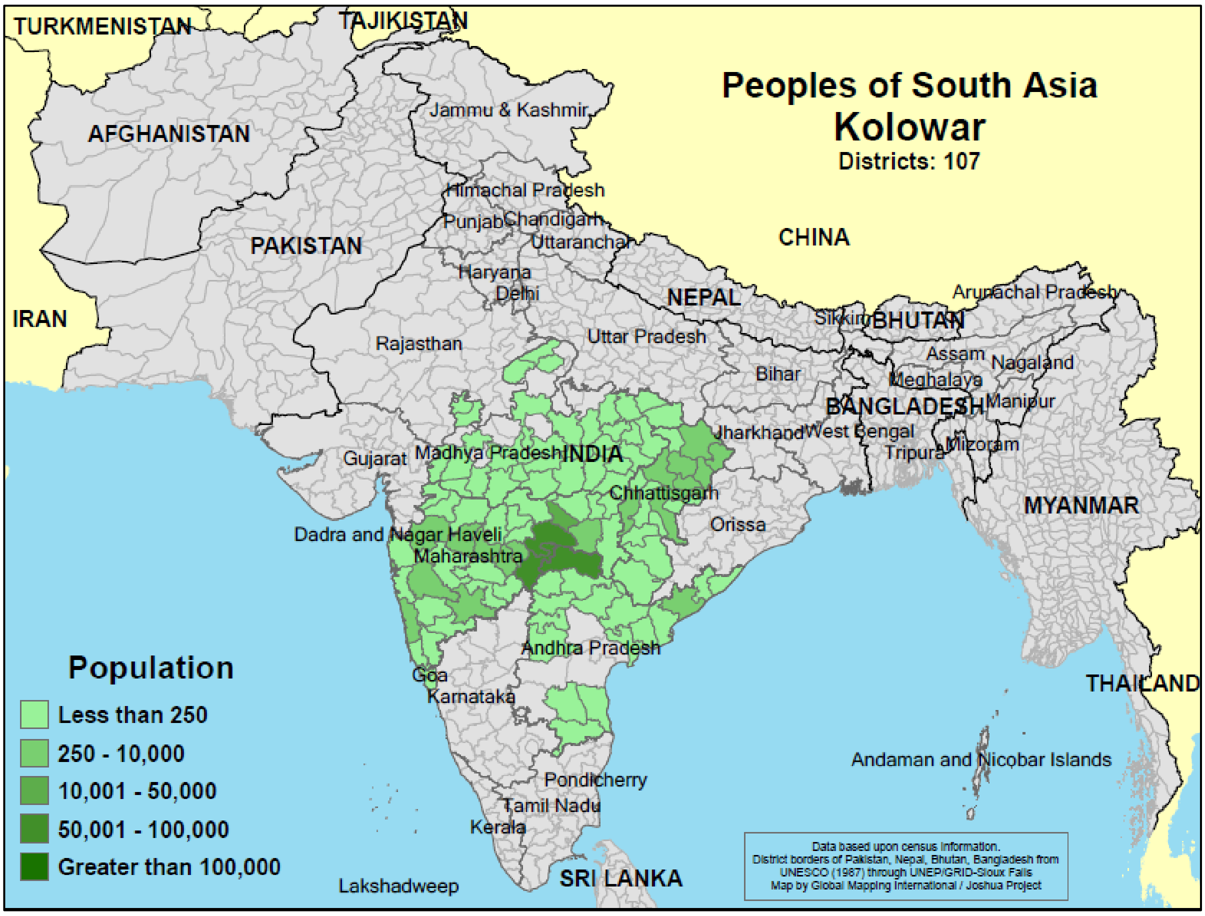

Figure 2: Geographical distribution of the Kolams (= Kolowars) (courtesy: http://www.joshuaproject.net/).

particular, the seven most prominent stars in Ursa Major (sometimes referred to as the Big Dipper) that look like a spoon are called *Saptarshi* (*sapta* is seven, and *rishi* are saints). In the interest of readability, we have listed our records of individual villages in the Appendices and only presented our main observations in the body of the paper.

2 THE BANJARAS

The Banjaras are one of the largest tribal groups in India with a population of more than 5 million, and are found in large parts of the country (see Figure 1). Traditionally they were connected with travelling caravans and the transportation of goods, and they traded over vast stretches of the Indian subcontinent. They have a variety of names, such as Lambaras, Lambadas, which are subgroups within the larger Banjara population. The group we visited refer to themselves as Gor manus (people), and is one of the many subgroups of the Banjaras. The word Banjara has several possible origins. The most likely of these are: from 'Ban', which means 'forest' (people who go into the forest), or from 'Baniya', which means 'trader' in the modern Hindi language (see e.g. Deogaonkar and Deogaonkar, 1992: 10).

There are two prevailing systems of beliefs amongst them: one group claims its roots from the (defeated) Rajputs of Rajasthan from the period of Prithviraj Chauhan (~1,200 AD), and the other group claims not to be Rajputs at all but instead to belong to a tribe whose roots go back to the Harappan period (~2,000 BC). The latter are snake worshippers, and they say that this distinguishes them from the Sun- or Moon-worshipping Rajputs. Since snake-like ornaments are known amongst Harappan dolls, they use this connection to insist that originally they were traders from the Harappan period. This is a potentially important link, since genetically they have an affinity to the gypsies of Europe (Mastana and Papiha, 1992) and the Harappans are known to have traded with West Asia. There are also claims that the Banjaras are descendants of Luv, the elder son of the legendary Lord Rama of Ramayan. For a summary of their lifestyle, see Deogaonkar and Deogaonkar (1992), and Vanjara et al. (2012). However, both groups agree that from ancient times, their primary profession was to move and trade goods throughout India.

In view of their profession, the Banjaras were not settled and were migrants across the vast Indian sub-continent, and until the arrival of the railways they were the sole transporters of goods across the country and beyond. They moved in large groups of up to several hundred people, with herds of cows and bullocks loaded with goods. They made very little use of horses, and traded bullocks for a very wide variety of goods, from gold to salt. They stayed only for a few days at any one place, except during the monsoon seasons when they preferred to stay at the same place for several weeks. Some Banjaras believe that their ancient currency was metal. One of their important items of trade was salt, which was obtained from coastal areas and then was traded in the hinterland. This has left such a strong mark on them that even today, deep in the hinterland, some 500 km from the nearest sea coast, they still recall trading in salt.

The Banjaras only settled in permanent residences about one hundred years ago. They call their villages '*Tanda*', a reminder that technically they are large moving groups that have set up a temporary residence. However, they do not seem to have used astronomy for navigation and used forward patrols and route markings to find their way about.

With their extensive experience in commerce, it is not surprising that politically the Banjaras are one of the most advanced of the tribes of India (Deogaonkar and Deogaonkar, 1992: 9). Over the last sixty years, at least one Chief Minister of the State of Maharashtra was a Banjara, and several Ministers in the State of Maharashtra, in neighbouring states, and in the national Governments of India have been Banjaras. They have also adapted to using the internet and other technology to maintain and propagate their identity, and they have a strong presence on the web (see e.g. www.banjaratimes.com/index2.html).

The Banjaras have seven primary goddesses, with their own mode of travel. They are.

1) *Tulaja* or *Shitala* (the Goddess of Smallpox) (who uses a tiger)
2) *Maryama* (a lion)
3) *Mataral* (an elephant)
4) *Kankali* (a buffalo or bull)
5) *Hanglaj* (a horse)
6) *Chimar* or *Chimad* (a horse)
7) *Shyamki* (carried on a palanquin by humans).

Apart from these, they have two great saints: *Sevalal Maharaj* (the common greeting is "Jai Seva- Be Seva", meaning serve people, or Hail Sevalal Maharaj) and *Jetalal Maharaj*. They largely follow only those Hindu festivals that are related to farming and their specific lifestyle, but even these have been modified so that now they have their own unique style.

The names of the month used by the Banjaras derive from modern Indian languages. Their main festivals are *Diwali*[1] and *Holi*. On *Diwali*, they worship the goddess of wealth—a very modern concept. However, the Banjaras celebrate it differently: on the morning of *Diwali* they have a feast for the ancestors. They also built up mounds of cow dung and plant wheat on the day after *Diwali*. In July, in a festival called *Pola*, cows are decorated and worshipped, a concept that has its roots in rural agrarian culture. *Holi* is a spring festival celebrated in late March, and it is followed by the marriage season, from *Chaita* (around April) to *Ashad* (June)—before the monsoon season. During the New Moon of *Akhadi* (July), a goat is sacrificed in anticipation of a good monsoon. When young girls come of age, there is the festival of *teej* in August/ September when they sow wheat seeds (as a symbol of the goddess of fertility) in a bowl for eight days. The family then celebrates the ninth day when the goddess is merged with the soil. After this, the next festival begins on the eighth day of *Ashwin* (October) during the *Navratra* festival (a festival of nine nights, celebrated at the end of the farming season) when, again by local tradition, a goat is sacrificed. The last day of *Navaratra*, called *Dasera*, is in October (on the tenth day after the New Moon), and it is also celebrated with fanfare. Most of this information was given to us by the Bajaras we interviewed, but Deogaonkar and Deogaonkar (1992: 40-44) also discuss the festivals of the Banjara, though in a somewhat sketchy manner. It is probably no coincidence that the dates and times of Hindu festivals coincide with those of the Banjaras since the festivals of both communities arise essentially from farming-related rituals marking the sowing and harvesting seasons and other periods. The exact dates of the celebrations coincide with the Full or New Moon closest to the change of the seasons and may have been adjusted a little each year.

2.1 Genetic Data on the Banjaras

Genetic data on the Banjaras are sparse, possibly because their group identity is difficult to define. Studies such as the one carried out by Sachdev (2012) have focused on the Banjaras of the Rajasthan region, where they conventionally are believed to have originated. Mastana and Papiha (1992) have compared the genes of the Banjara sub-tribe called Lambana with the gypsies of Central and Western Europe. Their results suggest that gypsy populations of Eastern Europe still have great affinity with Indian nomadic groups, and the genetic differentiation in these populations may primarily be due to isolation, high rates of migration of subgroups towards Europe and genetic drift. The Western gypsies are more homogeneous as a local population, which may have resulted from a high degree of admixture.

In a recent study, Moorjani et al. (2013) compared the Roma population with various South Asian groups. They estimate that the Roma harbour about 80% West Eurasian ancestry—derived from a combination of European and South Asian sources—and that the date of the admixture of South Asian and European ancestry was about 850 years before the present. They provide evidence for Eastern Europe being a major source of European ancestry, and North-West India being a major source of the South Asian ancestry in the Roma. By computing allele sharing as a measure of linkage disequilibrium, they estimate that the migration of the Roma out of the Indian subcontinent was accompanied by a severe ‘Founder Effect’, which appears to have been followed by a major demographic expansion after their arrival in Europe. A Founder Event is when a very small group separates from a parent group carrying some vagaries in their genetic signal which then persist in the new community even though these provide no specific survival benefit. This may include facial features, body size, etc. (see e.g. Stone and Lurquin, 2010: 113).

2.2 Banjara Astronomy and Meteorology

The list of Banjara villages visited by us and their individual memory of astronomy and other information provided by them is given in Appendix 1, while the results are summarised in Table 1 below. Village 5 is not included in this Table since at that village we met a historian who supplied us with many details of the Banjaras but no insight into their astronomical knowledge and beliefs.

The most commonly-known astronomical objects amongst the Banjaras are the stars in Orion (which they see as a deer), and the Pleiades asterism, which they proudly proclaim to be a piece of jewellery that is worn on the forehead and that typically has many little metallic balls (generally of silver) strung together to appear like a bunch of grapes. They know of an evening star and morning star—no particular star, just the one that tells them that the day or the night has just begun. They have many indicators to predict the intensity of the monsoon, the two most favoured being the glow around the Moon, and the activities of the crow: if it builds its nest high up in a tree in late May strong rains are unlikely but if it builds a well-protected nest in the lower branches then the rains are expected to be heavy. The direction from which the rains will come is opposite to the direction in which the nest is made in relation to the tree trunk.

The Banjaras are aware of comets as stars with tails, and they think of them as bad omens. Meteors also are considered bad omens. *Saptarshi* (the Big Dipper) is divided into the four stars of the polygon that form the death bed (*Jamkhat*), with a procession of three people following the bed. Upon dying, Banjaras walk along the Milky Way (the path of the dead) to reach the heavens. They do not seem to have stories

Table 1: The astronomical knowledge and beliefs of the Banjaras.

	Knowledge or Belief	Banjara Village					
		1	2	3	4	6	7
1	The Sun: *Dan* or *Dado*	x					x
2	The Moon: *Chanda* – similar to the Sanskrit name	x	x	x	x		x
3	The lunar maria: a tree or an old lady weaving cotton under a banyan tree	x		x			x
4	Eclipses are recognised	x					x
5	A meteor: *Tara tutgo* (a broken or falling star; usually a bad omen)	x	x	x	x		x
6	A comet: *Seshar Tara* (a smoking star or star with a tail; a good or bad omen)	x	x	x	x		x
7	The Milky Way: *Mardaar wat* (the path of the dead or the path of animals)	x		x	x		x
8	The Bigger Dipper: *Jamakhat* or *Yamakhat* (the cot of the dead)	x	x	x	x	x	x
9	Canis Major: *Medi* – connected with processing the harvest	x					
10	The Pleiades: *Shirser Jhumko* or *Jhumko tara* (jewelry worn on the forehead)	x			x	x	x
11	Orion: *Halni*, *Halini* or *Harini* (a deer)	x	x	x	x	x	x
12	Taurus: *Kamedi* (a dove), close to *Halni*				x		
13	The morning star: *Porya Tara*	x	x	x	x	x	x
14	The evening star: *Subtara* (a good omen)	x		x	x	x	
15	The Pole Star is identified	x	x	x			
16	A gnomon was used to determine time					x	
17	An intercalary month (*Dhonda Mahina*) synchronises solar and lunar calendars	x					
18	Names exist for the four cardinal directions		x				
19	The monsoon is predicted by the size of the glow around the Moon	x	x	x	x		
20	The monsoon is predicted by the direction of lightning		x	x	x		
21	The monsoon is predicted by the location of crows' nests		x		x		x
22	The monsoon is predicted by the sighting of Taurus in the east	x			x		
23	The monsoon is predicted by the direction of clouds		x				
24	A bad monsoon is predicted if ants are coming out of the ground with their eggs				x		
25	A bad monsoon is predicted if it hails				x		
26	A rainbow indicates the end of the current rains				x		

about the afterlife, and the worship of ancestors is more in the sense of gratitude than out of any expectation (unlike the belief in main-stream Hinduism).

3 THE KOLAMS

The Kolams (also known as the Kolowars) are a relatively small tribal group. They are found largely in south central India (Figure 2), and their total population at around 400,000 is less than one tenth that of the Banjaras. Until as recently as the 1940s and 1950s they typically practiced slash and burn farming, and they would beat the earth by hand using a wooden stick to soften it rather than use a plough. They largely relied on foraging for their survival. For an extensive review of the Kolams see Deogaonkar and Baxi (2003). They were, therefore, renowned for their familiarity with the jungle and skill in divination and the propitiation of local gods. This reputation has led many Gond communities to entrust the cult of certain local divinities, and particularly those of the gods holding sway over forests and hills, to the priests of nearby Kolam settlements. It is because of this sacerdotal function of the Kolams that the Gonds refer to this entire tribe as 'Pujaris' or priests (Fürer-Haimendorf, 1982: 13). The Kolams refer to their habitations as *Pods*. Fürer-Haimendorf (ibid.) further notes that till the 1940s Kolams (and a closely-related group, the Naikpods) practised slash-and-burn cultivation using hoes and digging sticks. Currently, under the policy of the Government of India to preserve forest areas and clear them of human habitation, only small numbers of Kolams live in hill settlements. Now, most of them are found in villages on the plains, where they work as tenant farmers or agricultural labourers. Some of them own the land they cultivate. They are scattered over a large area. Kolams and Naikpods originally had languages which closely resembled each other but have been diluted by the onslaught of modernity.

Where Gonds and Kolams lived in close proximity, the Gonds usually settled at the foot of the higher ridges and cultivated the valleys, plateaux, and gentle slopes, while the Kolams built their hamlets on ridge tops and cultivated the steep hillsides. The crops sown and reaped consisted mainly of small millets, sorghum, maize, and certain vegetables such as beans, taro, and marrows. This provided a family with sustenance only for about seven to eight months the year, and during the remaining months wild fruits, herbs and roots formed the mainstay of their diet (Fürer-Haimendorf, 1982: 85).

The Kolams have five primary Gods (*Ayak*): *Bhimayak, Jangobai, Nadadi Amma* (village goddess)*, Vaanadeya* (forest god) and *Sandun* (Sun) who is also called *Suryak* (Sun).

The Kolams divide the year into twelve months (conventional months are lunar with an intercalary month every three years). The corresponding modern calendar months, listed below, are approximate since the Kolam calendar is lunar in nature, starting with Full Moon, as used by the Kolams.

- *Bhavai – Devkaran* – May
- *Bud bhavai Nela* – June

- *Aakhadi Nela* – July
- *Pora* – August
- *Petala* – September
- *Divala* – October
- *Konka divala* – November
- *Sati Nela* – December
- *Pusi Nela* – January
- *Bhimrasi* – February
- *Duradi* – March
- *Saita* – April

Their counting system is decimal, with names similar to the Dravidian numerals with numbers 1 to 10 given as *Okkad, Indi, Mundi, Nale, Eda, Aar, Ed, Enmdi, Tomdi* and *Padi*. They have no special name for zero.

3.1 Genetic Data on the Kolams

Rao et al. (1992) have reported a study of several Gond tribes and Kolams from Maharashtra, along with other data such as the level of endogamy etc. On the basis of these data, they show that Kolams have historically lived in isolated groups with a high level of endogamy (31%) but have genetic similarity to Raj Gonds (see also, Majumder and Mukherjee, 1993). This is expected due to the fact that they have historically served as priests to the Gonds (Fürer-Haimendorf, 1982: 13). However, Sachdeva et al. (2004) reporting on the Kolams of Andhra Pradesh show that the genetic distance between the two is relatively large. This seems to suggest that the contact between the two tribes is sensitive to the region of interaction. After studying. the Kolams of Andhra Pradesh, Sirajuddin et al. (1994) concluded that they seem to have remained isolated even to the present day with very little new gene inflow into the population.

3.2 Kolam Astronomy

The list of Kolam villages visited by us is given in Appendix 1, along with their astronomical and other knowledge. Salient features of their astronomical beliefs are given in Table 2

The most commonly-known asterism among the Kolams is the Pleiades which they see as a collection of one large and several small birds. To them, *Saptarshi* is a cot which three stars (a Kolam, a Gond and a *Pradhan* – chieftain) are trying to steal.

They also have a fairly detailed myth about solar eclipses. A total solar eclipse is considered to be a good omen. A partial solar eclipse where the part of the Sun towards the zenith is covered, is a bad omen for humans, but if the part of the Sun towards the horizon is covered it is inauspicious for animals. The underlying idea is that the tax-collecting gods have come to collect their due and if they can get their complete share (totality) they are satisfied; otherwise they make up the deficit by making animals or humans pay. Two villages also discussed lunar eclipses as having different shades, the lighter shade (red) arises when Moon is being run over by a caterpillar while the darker shade (black) suggests that a frog is eating up the Moon.

Another detailed and commonly-held story is that of an asterism called *Samdur*, which we identify as the Great Square of Pegasus. The reason for this is that apart from the direction pointed out by them, *Samdur* means both the sea (badly pronounced) and an object where all points are equidistant. Pegasus rises in the east soon after midnight in June. While showing the asterism the Kolams also consistently pointed to the east. We therefore searched for an asterism that could meet this description. Pegasus fits this description well. It is a great lake that provides water for the land. This constellation was studied in detail, and five different animals come to drink and feed there. They are a frog, buffalo, deer, horse and peacock (and, on occasions, a pig). These animals all predict up-coming rain: the peacock and deer produce average rain while all of the other animals suggest a good monsoon. Of the other animals, an especially clear sighting of the frog is very auspicious. We show this in Figure 3, where we have positioned each animal based on our understanding of the patterns that best fit that specific animal. As it turns out, the two animals that are further east of Pegasus indicate a bad monsoon and the asterisms that are to the northeast of Pegasus indicate a good monsoon. An alternative explanation is that *Samdur* refers to Centaurus, which is seen in the south in June. In this case, the fit for the different animals is shown in Figure 4.

Another unique story is that of Cygnus where they identify three pots placed on top of each other. They know of Scorpius as a snake and probably include some stars above the conventional Scorpius in this.

In Crux—the only southern constellation they recognise—they can see the *Mahua* tree just as the Gonds do. They see Taurus as a bird with two eggs. They know only the inner stars of Orion as the belt of a hunter, and the region around the Orion Nebula as a sword which may be a weak memory of the original Hindu myth which sees all of Orion as a deer and the three stars of the belt as an arrow. On the Moon, they can see an old lady sitting under a tree and spinning cotton.

An interesting aspect of the 270 solar eclipses that the Kolams could have seen between AD 1000 and 2000 is that only one was annular (on 30 December 1758) and one was total (on 22 January 1898) as per the Eclipse Predictions of Fred Espenak and Chris O'Byrne (NASA's GSFC: (http://eclipse.gsfc.nasa.gov/eclipse.html). It is probably because of this that the Kolams place so much emphasis on partial eclipses.

Table 2: The astronomical knowledge and beliefs of the Kolams.[2]

	Knowledge and Belief	Kolam Village									
		1	2	3	4	5	6	7	8	9	10
1	Solar eclipses: They consider these are payments of dues by the Sun – a partial eclipse means partial payment and the rest has to be paid by either humans (if the eclipsed section is in the top half of the Sun) or animals (if the eclipses section is in the bottom half of the Sun)		x	x	x	x	x	x	x	x	x
2	Lunar eclipses: light red colour if a caterpillar or scorpion is eating the Moon and dark red if a frog is eating it						x		x	x	x
3	A comet: *Sipur suka* (a star with a tail; a bad omen)		x	x			x		x	x	x
4	A meteor: *Suka erengten* (a broken star, falling star or a star with a tail; stellar excreta; a bad omen)		x	x	x						x
5	The Milky Way: *Margam*, *Panadi*, *Bhori Sanko* or *Jev* (an animal path)	x	x	x	x	x				x	x
6	The Big Dipper (four stars in a quadrangle): *Mandater* (a cot)	x	x	x	x	x	x	x		x	x
7	The Big Dipper (the three trailing stars): a Kolam, a Gond and Pardhan (chief), starting from the cot	x	x	x	x	x	x	x		x	x
8	Crux: *Irukmara* or *Ipamaka* (a *Mahua* tree whose flowers are fermented to produce alcohol); α Centauri is *Murta* (an old lady) and β Centauri is *Kadma* (a young lady), both there to collect flowers.		x	x	x	x	x		x	x	x
9	Cygnus: *Kavadi Kunde* or *Kavedi Koda* (a tower of three pots)	x		x	x	x		x	x		
10	*Danedare Pila*, a spiral-shaped asterism: probably the tail of Scorpius			x						x	
11	Great Square of Pegasus: *Samdur* (a sea from which rain water comes)		x		x	x	x	x	x	x	x
12	Stars around Pegasus: the following animal asterisms are seen around Pegasus: a peacock, buffalo, frog, deer and horse, and sometimes also a pig; their relative brightness decides the intensity of up-coming rain		x			x	x	x	x	x	x
13	Leo: *Murda* (a dead body – this is a Gond myth)		x							x	
14	Orion: *Tipan* or *Trivpate* (an instrument used to sow seeds)	x	x	x	x	x	x	x		x	x
15	The Pleiades: *Kovela Kor* (one large and several small birds)	x	x	x	x	x	x	x	x	x	x
16	The Pleiades: *Sappa* (an instrument used to process the harvest)	x									
17	Scorpius: *Borenagu* or Nago (a snake), or *Nagun* (a cobra)			x	x	x	x	x	x	x	
18	Scorpius: *Tuntor* or *Tootera* (a scorpion)	x	x							x	x
17	Taurus*: Bhori, a* bird (Aldebaran) with two eggs	x		x			x	x		x	
19	The morning star: *Vegud suka* (star of the morning)	x		x	x	x	x	x	x	x	x
20	The evening star: *Jevan suka* (a star of dinner time)	x		x	x	x	x	x	x	x	x
21	Sirius: *Met* (a pole to which a bull is tied and moves in a circle on the ground (*Kalave*) to separate the rice from the husk)	x	x	x		x					
22	Names exist for the four cardinal directions	x									x
23	The monsoon is predicted by the size of the glow around the Moon					x					x
24	A rainbow: Ayak or Aikawa (indicates the end of the current rains)				x		x			x	x

4 CONCLUDING REMARKS: A COMPARATIVE STUDY

Here we provide a comparative discussion of the astronomical beliefs of three different Indian tribes in relation to their evolving survival needs and inter-tribal influences. The three tribes in question are the Gonds (see Vahia and Halkare, 2013), along with the Banjaras and the Kolams, whose astronomy is reported here. It should be kept in mind that we have studied the three tribes in regions where they are spatially co-located, but all three tribes in general have a much wider geographical distribution. Table 3 provides an overview of the three communities.

In general, most of the astronomical observations made by these communities fall into two groups. The first set refers to the period just before the monsoon and the asterisms noted are connected with the expectation of monsoonal rain (March to May), while the other set of observations were made immediately after the monsoon (i.e. September to December).

Amongst the three tribes, the Gonds are the most settled and probably the most ancient tribe, with a continuing history, farming traditions and settlement dating back three thousand years or more. Against this, the Banjaras are more recent settlers. While they trace their origin to *Prithviraj Chauhan* (12th century AD), they are probably a much older group whose profession was that of migrants and traders (see e.g. Deogaonkar and Deogaonkar, 1992: 12). They share common traits with the gypsies of Europe. Some of them insist that the Banjaras date back to the Harappan period when they were the traders who took goods from the Harappan Civilisation all the way to West Asia and beyond, as well as within the Indian subcontinent. They were forced to settle down when their main profession as transporters and traders was threatened with the arrival

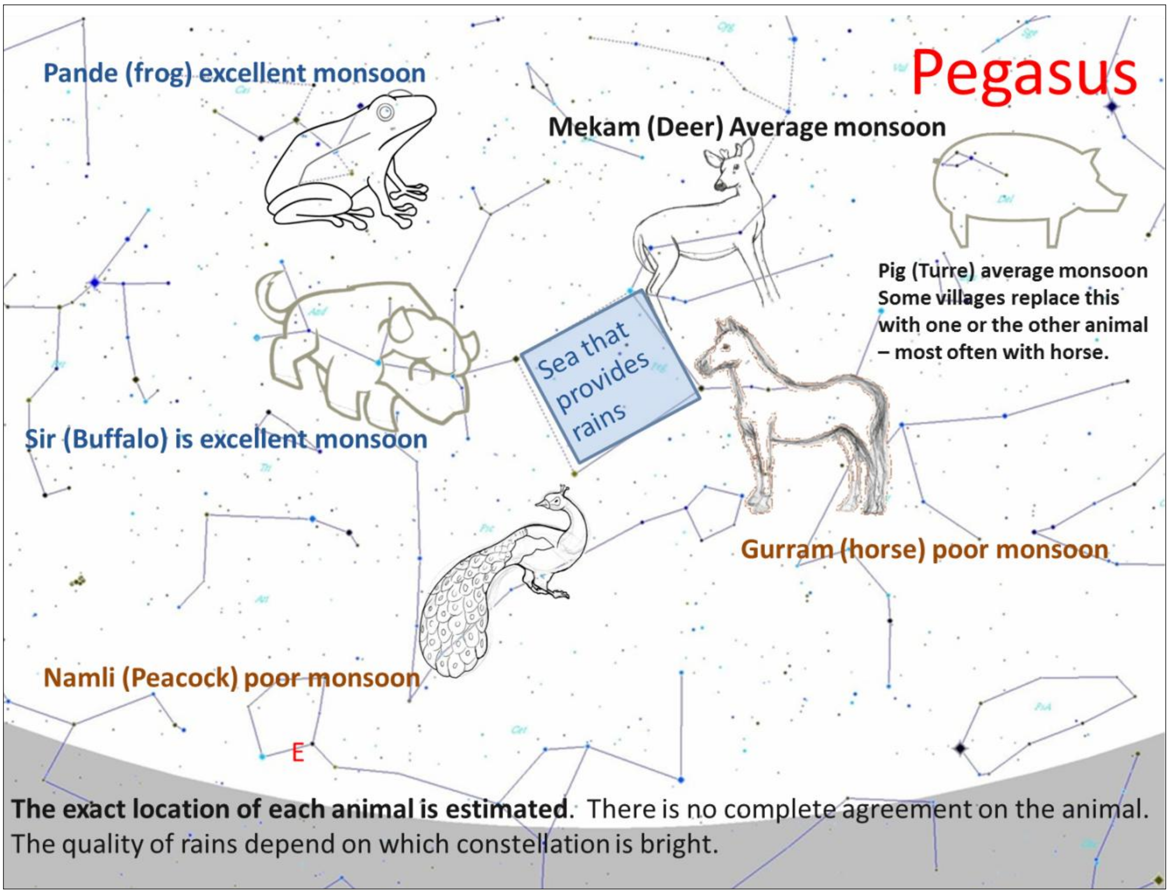

Figure 3: *Samdur* as Pegasus, the great sea that provides the rains, and the five or six associated animals.

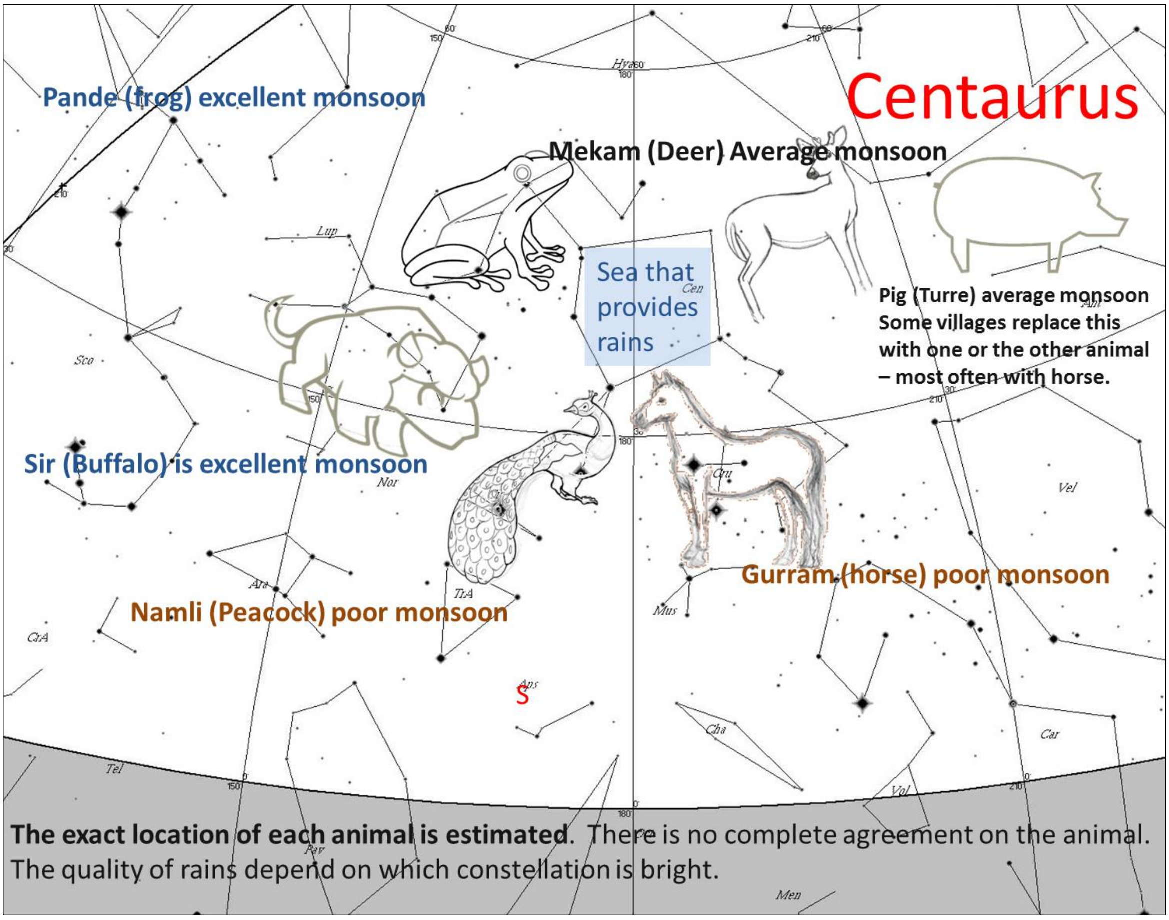

Figure 4: The alternative explanation, that *Samdur* may represent Centaurus,

of railways in India more than one hundred and sixty years ago. However, having been hardened by millennia of travel, they proved to be a robust community which quickly and aggressively took to settled life across the sub-continent. Since then, Banjaras have held many important administrative and political posts in India. The Kolams, the smallest of the traditional tribes considered here, essentially survived as foragers with only the simplest form of farming. It is only in the last few decades that the Indian Government's aggressive attempts to settle them have made them adopt various trappings of citizens of a modern state. In the course of our research, we met some elders who had been foragers as youngsters and have now settled down on the land given to them by the Government.

An interesting feature of these tribes is their strong sense of identity, aggressive desire to live in isolation from other nearby communities, and as far as possible not interact in any way. This has allowed the three communities to retain their traditional genes, languages and cultural traditions even though modern education has produced severe stress on all of these aspects. As we shall see below, their strong sense of tribal identity has allowed each group to create its own astronomical myths and stories. The complexity of their astronomical ideas and beliefs is directly related to the period during which they have lived a settled lifestyle.

Their astronomical knowledge, especially the number of markers they use to predict the monsoon, suggests that native astronomy is a continuing tradition. They continue to rely on their beliefs and predictions that are continuously evaluated and modified (or more markers are added) to improve their predictions. Another pattern that emerges is that just like seasons, their association of the sky with philosophical ideas is also related to the period that they have spent in a settled existence. These particular wanderers, it would seem, have little interest in philosophy and astronomy. For example, even though the Banjaras were travellers and movers of goods, they did not use astronomy for travel, and relied entirely on local knowledge and markers left behind to guide them.

Table 3: A comparison of the social aspect of the three Indian tribes studied by us.

Property	Banjara	Kolam	Gond
Population size	A large ethnic group spread over all of India. Population more than 5 million.	A very small primitive tribe. Population less than 0.5 million.	The largest ethnic group. Population about 10 million.
Geographical spread	All India	Central India	Central India
Language spoken	Austro Asiatic – a mix of Rajasthani and Gujarati with a sprinkling of local adaptation (Deogaonkar and Deogaonkar, 1992: 57). Language code: ISO 639-3 lmn	Dravidian, with some primary forms of Telugu and Kannada language (Deogaonkar and Baxi, 2003: 38). Language code: ISO 639-3 kfb	South Central Dravidian. Language code: ISO 639-2 gon ISO 639-3 gon – inclusive code Individual codes: ggo – Southern Gondi gno – Northern Gondi (From Wikipedia)
Original profession	Trading and transportation	Foraging, hunting	Farming
Current profession	Farming	Farming	Farming
Gods	One primary goddess + seven other goddesses.	One primary goddess, four *Deva* + natural forces. *Maruti* temples were also seen. There are separate village *devis* (goddesses).	Nine gods + *Lingo*, *Jingo*. Temples contain iron tools and weapons.
Approach to nature	Indifferent; they rely on terrestrial signals to predict the upcoming monsoon.	Sensitive to all aspects of nature, particularly in foraging.	Very reverential and sensitive.
Astronomy	Simplest astronomy that barely goes beyond the beliefs of others except for finding jewelry in the sky. Surprisingly, they do not use astronomy for travel.	Extensive, if a somewhat generalised visualisation of the sky in the sense that they do not seem to record changes in the sky over the year, and they recall the sky only during the immediate pre-monsoon period when it is well observed.	Fairly extensive. Regarding farming, they have a myth that Ursa Major was not allowed to sleep, suggesting that they remember it being circumpolar. From precession calculations it can be shown that this happened more than 3,000 years ago. Stories of all aspects of life are found in the sky.
Predictive astronomy	Not very sensitive.	Pegasus delivers water.	Extensive and used even today.
Treatment of dead	Buried the dead and then they were forgotten. Ancestors were worshipped as a group twice a year.	Buried the dead but remembered them regularly every year and on important occasions. Graves marked by stones.	Buried and remembered as a group. Graves marked by stones.
Stories of origin	Firmly remember a relation to the Rajputs. Others claim a an Harappan ancestry.	Cannot recall much. Worked as priests for the Gonds in AD 1200.	Stories go back to 1000 BC.
Festivals	Farming and related festivals.	Farming and related festivals.	Farming and related festivals.

In Table 4 below, we list the observations reported in more than just one village. The list is in decreasing order of frequency of report, but we ignore minor local fluctuations which are faithfully reported in the Appendices. The principle differences and similarities that appear are as follows:

1) Orion and Taurus are seen collectively as a farming scene by the Gonds while imagination is more nebulous amongst the other tribes. To the Gonds, Orion is the plough, Taurus is a bird trying to eat the seeds, and the Pleiades is a bunch of stones thrown to chase it away. The eastern end of Orion and Canis Major complete this scenario, with other farming-related activities. The Kolams recognise the three stars in the Belt of Orion as farming equipment, and see Taurus as a bird with two eggs. In addition, they vaguely recall that in the Big Dipper there is a facility with other farming activity. In marked contrast, the Banjaras barely notice Orion and Taurus.
2) The Pleiades asterism is seen as a piece of jewellery by the Banjaras, a group of birds by the Kolams and a bunch of stones thrown at Taurus by the Gonds.
3) All three tribes rely on the glow around the Moon prior to the monsoon season to predict the intensity of the upcoming rains.
4) A comet is a star with a tail for the Banjaras, while the Gonds see it as a broom of the Gods. The Kolams also mention the broom and tail but are not very specific about its effect upon humans.
5) The Kolams have a deep-seated vision of the great lake in Pegasus and the set of animals coming there to drink, which they use to predict the monsoon. The two other tribes ignore Pegasus, although the same Kolam word '*Samdur*' is used by the Gonds to identify Auriga.
6) Similarly, to the Kolams Cygnus is a set of three pots stacked one on top of the other —an idea that is completely alien to the other two tribes.
7) Only the Banjaras could identify the Pole Star.
8) The Banjaras ignore Scorpius, while the Kolams and the Gonds see this constellation as a snake or a scorpion.
9) The most interesting differences occur in the perception of eclipses. Both the Banjaras and the Gonds ignore eclipses while the Kolams have elaborate stories to explain solar and lunar eclipses.
10) The Banjaras use the crow's nesting habits at the end of May to predict the onset of the monsoon.
11) Both the Gonds and the Kolams know of Crux as the *Mahua* tree, while the Banjaras ignore it.
12) The Banjaras think that the Milky Way is the path dead humans follow, while for the Kolams and the Gonds it is an animal path.
13) In the case of S*aptarshi* (the Big Dipper), the Banjaras consider it to be a cot of the dead while the Kolams have a vague idea of some attempts to steal it. The Gonds are very clear that the legs of the cot are made of precious metals and therefore are worth stealing.
14) One interesting, but surprisingly rare story supplied by just one Kolam village is that Ursa Major is a container with water, which is emptied during the monsoon. The failure of this imagery to gain popular acceptance may be because Ursa Major appears as a spoon facing downwards for a much shorter period than the length of the monsoon season. The monsoon comes to this region in mid to late June. The front two stars of *Saptarshi* (the most prominent stars of Ursa Major) are aligned to Orion. Hence when Orion rises, the container is vertical to the horizon and when Orion is in the western horizon, the container seems to empty itself, a scene that would be witnessed in the sky at sunset in June.
15) Leo as a procession of death is only known to the Gonds. Meanwhile, Crux, Cygnus and Pegasus are only known to the Kolams.
16) All three tribes have the idea that dinner should start when the first star is seen and that the day should begin when the morning star is seen.

In Table 5 we list the differences between the three tribes for the same astronomical entity. As can be seen from the table, even spatially-overlapping communities tend to have dramatically-differing knowledge of and interest in astronomy.

Most of the observations of the sky were made from March till July, close to the monsoon season. These tribes seemed to assume that the sky was the same at other times of the year or they do not bother to look at the sky except in the post-summer period when they needed to start worrying about the rain and sowing their crops. This indifference towards the sky is also interesting in the sense that even though it must have been visually striking, these tribes did not seem to have been impressed by it as a matter of curiosity. For example, they do not seem to have kept track of the movement of the rising (or setting) point of the Sun on the horizon in the course of the year, which contrasts markedly with southern India where megalithic solar observatories abound (see Menon et al., 2012).

Also, traditionally the Kolams were foragers, and they seem to have a lot more to say about the sky in a nebulous manner. The long tradition

Table 4: Comparison of astronomical and meteorological perspectives of the tribe tribes. The entries in red print indicate the unique features of that tribe. The entries are listed by the frequency of their appearance in the different villages. Only information from two or more villages is listed here.s

Banjara	Kolam	Gonds
Orion: *Halni*, *Halini* or *Harini* (a deer)	The Pleiades: *Kovela Kor* (one large and several small birds)	Orion: *Naagardai* (a plough); the belt of Orion: *Tipan*
The Big Dipper: *Jamakhat* (the cot of the dead)	The Big Dipper (four stars in a quadrangle): *Mandater* (a cot)	The Big Dipper (four stars in a quadrangle): *Sedona* (old lady's) *Katul* (cot)
The morning star: *Porya Tara*	The Big Dipper (the three trailing stars): a Kolam, a Gond and a Pardhan (chief), starting from the cot	The Big Dipper (the three trailing stars): three thieves trying to steal the cot, the legs of which were made of gold, silver and copper
The evening star: *Subtara* (a good omen)	Orion: *Tipan* or *Trivpate* (an instrument used to sow seeds)	The morning star: *Pahat Sukum*
A comet: *Seshar Tara* (a smoking star or star with a tail; can be either a good or a bad omen)	The morning star: *Vegud suka*	The evening star: *Jevan Sukum*
A meteor: *Tara tutgo* (a broken or falling star; usually a bad omen)	The evening star: *Jevan suka*	Comets: *Jhadani*, *Bhimal Saat*, *Kayshar*, *Jhadu*, *Bahari* (a weapon of the gods; a good omen)
The Moon: *Chanda* – similar to the Sanskrit name	Solar eclipses: They consider these are payments of dues by the Sun – a partial eclipse means partial payment and the rest has to be paid either by humans or by animals	The Milky Way: *Dhor Sari*, *Rasta*, *Sagur*, *Murana Marg*, *Pandhan*, *Sadak* (the great path of animal migration)
The Milky Way: *Mardaar wat* (the path of the dead or the path of animals)	Great Square of Pegasus: *Samdur* (a sea from which rain water comes)	The Sun: *Lingo*, *Purbaal*, *Bera*, *Vera*, *Din*, *Suryal*
The monsoon is predicted by the size of the glow around the Moon	Crux: *Irukmara* or *Ipamaka* (is a *Mahua* tree)	The Moon: *Jango*, *Chandal, Nalend* or *Nalen*
Pleiades: *Shirser Jhumko or Jhumko tara* (jewelry worn on the forehead)	Stars around Pegasus: the following animal asterisms are seen: a peacock, buffalo, frog, deer and horse, and sometimes also a pig; their relative brightness decides the intensity of up-coming rain during the monsoon season	The Pleiades: *Mogari*, *Mongari*, *Kutpari*, *Thengari*, *Mundari* (stones thrown at birds)
The Pole Star is identified	The Milky Way: *Margam*, *Panadi*, *Bhori Sanko* or *Jev* (an animal path)	Meteors: *Ulka*, *Sukir Pelkta*, *Tara Urungta* (generally these are considered to be stellar excreta, or occasionally souls that are falling from their holy places in the sky)
The monsoon is predicted by the direction of lightning	Scorpius: *Borenagu* or Nago (a snake), or *Nagun* (a cobra)	Canis Major: *Purad* or *Hola*
The monsoon is predicted by the location of crows' nests	Cygnus: *Kavadi Kunde* or *Kavedi Koda* (a collection of three pots stacked one on top of the other)	The monsoon is predicted by the size of the glow around the Moon
The lunar maria: a tree, or an old lady weaving cotton under a banyan tree	A comet: *Sipur suka* (a star with a tail; a bad omen)	Auriga: *Samdar* (this indicates the nature of the up-coming monsoon)
The monsoon is predicted by the sighting of Taurus in the east	Taurus: *Bhori* (a bird, Aldebaran, with two eggs)	Scorpius: *Michu* (responsible for producing the dead body, *Murda*, which is seen in Leo)
The Sun: *Dan* or *Dado*	Scorpius: *Tuntor* or *Tootera* (a scorpion)	Sirius region: *Topli* (the basket of seeds used when sowing the fields)
Eclipses are recognised	Sirius: *Met* (a pole to which a bull is tied and moves in a circle on the ground (*Kalave*) separating the rice from the husk)	Taurus: *Medi* (part of a large farming scene also involving Canis Major, Lepus and Orion)
	A meteor: *Suka erengten* (a broken star, falling star or a star with a tail; stellar excreta; a bad omen)	
	A rainbow: Ayak or Aikawa (indicates the end of the current rains)	
	Lunar eclipses: light red colour if a caterpillar or scorpion is eating the Moon and dark red if a frog is eating it	
	Danedare Pila, a spiral-shaped asterism: probably the tail of Scorpius	
	Names exist for the four cardinal directions	
	Leo: *Murda* (a dead body –a Gond myth)	
	The monsoon is predicted by the size of the glow around the Moon	

of farming amongst the Gonds is equally evident in their beliefs of all aspects of astronomy and religion. The general indifference of the Banjaras to the sky (except for the Pleiades being seen as a rich piece of jewellery) is also apparent as a result of our survey. Clearly, the relationship of man to the sky is a reflection of his relationship to the land.

Table 5: Differences in the perspectives of the three different tribes for the same astronomical object.

Object	BANJARA	Kolam	Gonds
Orion	*Halni*	*Tivpate*	*Tipan*
Ursa Major	*Saptarshi*: *Jamakhat* (the cot of death)	*Saptarshi*: *Mandater* (cot)	*Saptarshi*: old lady's cot
Morning Star	*Porya Tara*	*Vegud suka*	*Pahat Sukum*
Evening Star	*Subtara* (star of good omen)	*Jevan suka*	*Jevan Sukum*
Ursa Minor		The three following stars are three people, a Kolam, a Gond and Pardhan (chief)	The three following stars are three thieves
Comets	*Seshar Tara* (a smoking star or star with a tail; a good or bad omen)	*Sipur suka* (a star with a tail; a bad omen)	*Jhadani*, *Bhimal Saat*, *Kayshar*, *Jhadu*, *Bahari* (a weapon of the gods; a good omen)
Pleiades	*Shirser Jhumko* or *Jhumko tara* (jewelry worn on the forehead)	*Kovela Kor* (one large and several small birds)	*Mogari*, *Kutpari*, *Thengari*, *Mundari* (stones thrown at birds)
The Milky Way	*Mardaar wat* (the path of the dead or the path of animals)	*Margam*, *Panadi*, *Bhori Sanko* or *Jev* (an animal path)	*Dhor Sari*, *Rasta*, *Sagur*, *Murana Marg*, *Pandhan*, *Sadak* (the great path of animal migration)
Meteors	*Tara tutgo* (broken or falling stars; usually a bad omen)	*Suka erengten* (a broken star, falling star or a star with a tail; stellar excreta; a bad omen)	*Ulka*, *Sukir Pelkta*, *Tara Urungta* (generally considered to be stellar excreta)
Taurus region	*Kamedi* (the dove; if seen in the east will bring rain)	*Bhoria* (a bird, Aldebaran, with two eggs)	*Medi* (part of a large farming scene also involving Canis Major, Lepus and Orion)
Crux	No mention	*Irukmara* or *Ipamaka* (a *Mahua* tree)	A *Mahua* tree.
Scorpius	No mention	*Borenagu* or Nago (a snake), or *Nagun* (a cobra); or *Tuntor* or *Tootera* (a scorpion)	*Michu* (responsible for producing the dead body, *Murda*, seen in Leo)
Cygnus	No mention	Cygnus = *Kavadi Kunde*, three pots stacked on top of each other.	No mention
Pegasus	*Samdur* (nearby animals predict the monsoon)	*Samdur* (nearby animals predict the monsoon)	No mention
Solar eclipses	Recognised but not explained	Indicates that payments are due to the Sun by humans or animals	No mention

5 NOTES

1. In some regions of India occupied by Banjaras this ceremony is spelled and pronounced *Divali*.
2. Where alternative spellings of the same word are presented in Appendix 1, only the first version of the word, as it appears in the Appendix, is listed in this Table.

6 ACKNOWLEDGEMENT

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APPENDIX 1: DETAILS OF THE VILLAGES VISITED DURING THE SURVEY

A1.1 Banjara Villages Visited

Over a one week period we visited a total of 18 villages, 7 Banjara and 11 Kolam. The route taken by us is given in Figure A1.

A1.1.1 Dapora Village

Location 20° 12.27′ N, 78° 47.73′ E (225 meters above mean sea level).
Post: Dapora, Taluka Manora, District Washim. On the Karanja (Lad) – Manora Road, 16 km from Karanja.
Population: 8,000
Date of Visit: 2 May 2013.
Persons Met:
Devananda Ratansing Rathod (M72)
Puranasingh Mersing Rathod (M75)
Shankar Janusing Rathod (M55)
Astronomical and Other Beliefs:
Orion is *Harini* (a deer).
Jamakhat (*Yamakhat*) – The first four stars of the Big Dipper form the cot used by *Yama*, the God of Death to ferry the dead. The remaining three stars form the funerary procession.
Spots on Moon appear to be an old lady sitting under a banyan tree spinning cotton yarn.
They consider the glow around the Moon important for predicting the monsoon.
Porya Tara: a morning star.
Subtara: evening star (star of good omen).
They know that there is a Pole Star.
Milky Way: *Mardaar wat*, the path of the dead where the person carried by *Jamkhat* eventually travels (presumably to heaven).
Taurus when seen in the east brings rain.
The Sun in called *Dan* (Din means day).
The Moon is called *Chanda* (similar to the Sanskrit name for the Moon).
Solar and lunar calendars are synchronised by using an intercalary month (*Dhonda Mahina*).
In Canis Major they can see the *Medi*, a pole where the bullock is tied for crushing the harvest to extract the grain.
They know that solar eclipses occur.
A comet is called a smoking star and is a good omen.
They know a meteor as *Tara tutgo*, a broken star.
They know the Pleiades as *Jhumko tara*, a decorative forehead element.
They sang a song saying "As the morning star rises, we begin loading grain … (on the back of a bull)."

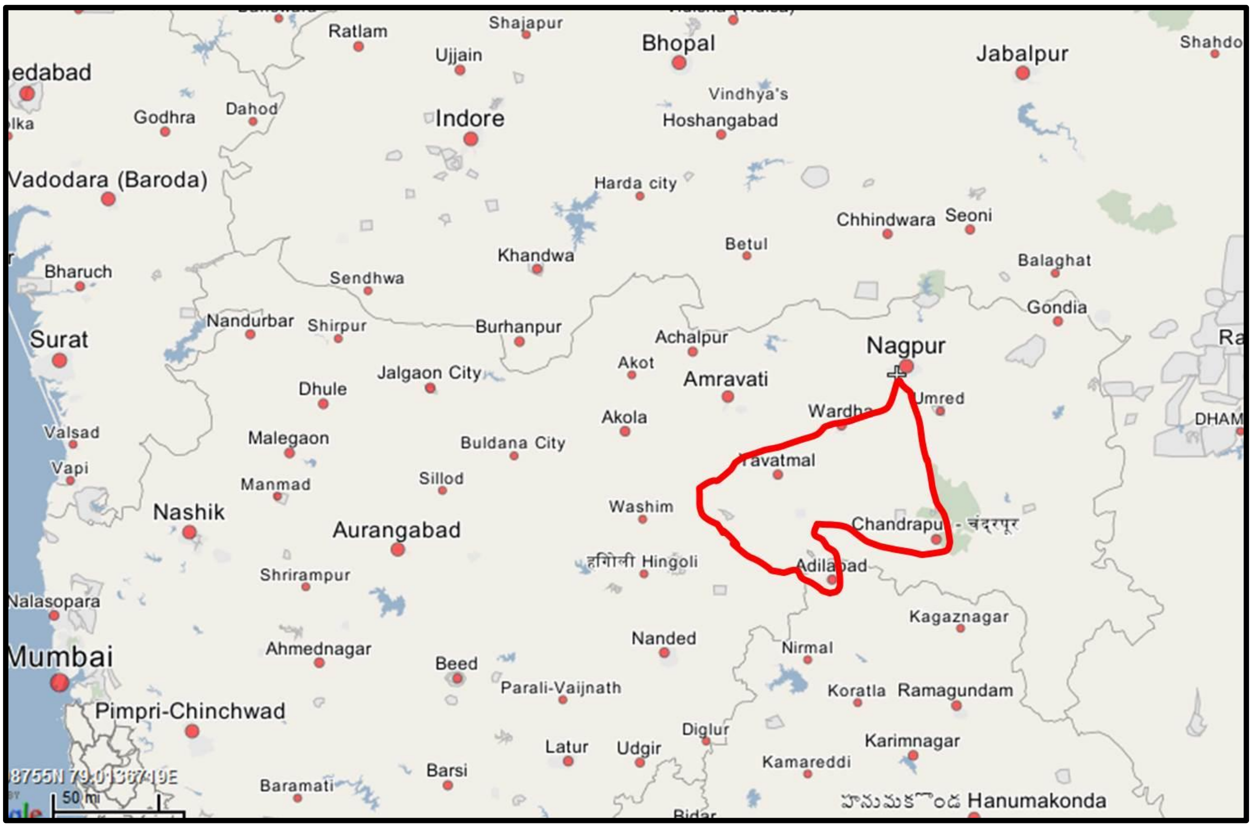

Figure A1: The route taken in the course of surveying Banjara and Kolam astronomy.

A1.1.2 Phulumari Village

Location: 20° 5.759′ N, 77° 33.619′ E (415 meters above mean sea level).

Post: Phulumari, Taluka Manora, District Washim. On the Manora – Ratanwadi – Fulumari Road, 18 km from Manora. It also is approachable from Digras Pusad, Manora and Washim. It is surrounded by a hilly forest area. The place is a pilgrimage centre for Banjaras in association with Sewala Maharaj and a Garasha Temple of a Bull (*Nandi*).

Population: around 10,000. Claimed to be one of the biggest *Tanda* (Banjara villages) in India.

Date of Visit: 2 and 3 May 2013

Persons Met (brackets indicate subclan and age):

Hirasing Nandu Rahod (Khola) (M80)
Parasram Rama Rathod (Ransot) (M62)
Bansi Shankar Rathod (Bhojawat) (M64)
Babusing Bhola Rathod (Khetawat) (older than M55)
Bhavurao Ganpat Chavan (Mood) (Sarpanch – village head) (M50)
Pralhad Narsing Rathod (Khetawat) (M68)

Astronomical and Other Beliefs:

Porya Tara is the Morning Star visible at 4 am (they have a song to celebrate the rise of this star that encourages them to begin their day). This indicates the last quarter of the night.

Moonlight is called *Chandani* (a canonical word in Sanskrit and Marathi).

The Pleiades are called *Shirser Jhumko* (an ornament for the forehead).

Orion is *Halani*. Harvesting starts when Orion appears in the sky in the east and is completed before it begins to set at sunrise.

The Big Dipper: *Jamkhat*, the bed of God *Yama* (god of death).

The Moon as a forecaster of the monsoon – if there is an extended glow around the Moon then there will be good rains, but if it is restricted, the rains will be poor.

Directional stars *Dhruv* (the Pole Star) shows north, *Vani tara* is a star at the zenith, and *Porya* (the morning star) shows east. North: *Dongari*; northeast: *Dharau* (and also *Ishan* in modern languages); east: *Suryatal* (*literally* the Sun's direction—the place from which the Sun (Surya) rises); southeast: *Agneya* (similar to *Agni* in modern languages); south: *Dakshin*, as in modern languages; as is *Pashim*: west.

If it is cloudy to the east or there is a red glow at sunrise, it will rain heavily.

If there is lightning in the southeast, rain is expected sometime between three hours and three days.

If there is lightning in the northeast, there will be good rain.

If a crow builds his nest at the top of a tree in May, less rain is expected, but if it makes it's nest lower good rains are expected from a direction such that the trunk of the tree will protect the nest.

The Banjara remember having seen a comet (a star with a smoke) in 1965, most probably Comet Ikeya–Seki (C/1965 S1). It was seen for a fortnight until sunrise. In general a comet brings draught unless it comes from the north or the southeast, when it is a good omen. They also remember having seen a comet (a star with a tail) in March 1972 (the *Phalgun* month).

A meteor is a broken star. A meteor that is seen to originate from the zenith and move to the east is a bad omen.

If a male fox (*Salya*) barks at night it is a good omen, but if a female fox (*Sali*) barks it is a bad omen.

They listed the seven important goddesses (and the animal they use for travelling).

The dead are buried with the head to the west or the north.

A1.1.3 Katarwadi Village

Location: 19° 56.52′ N, 77° 39.13′ E (348 meters above mean sea level).

Post: Kasola, Taluka Mahagaon, District Yavatmal. Twelve kilometres from Pusad, (a subdivisional headquarter) off the Pusad – Mahur Road.

Date of Visit: 3 May 2013.

Persons Met:

L.D. Rathod (M58)
Ajay Rathod (M40)
Baburao Maharaj Khamalwadi (about M60)
Baliram Maharaj Kalulalnagar Bori (about M60)
Mohan Aade Manoharnagar Bori (about M60)
Savairam Aade Maharaj Katarvadi (about M60)
Pandurang Teja Rathod (about M65)
Janusing Motiram Pawar Moli (ex Head) (about M50)
Sajanibai Pandurang Rathod (F70)

Astronomical and Other Beliefs:

The Morning Star: *Porya tara*.

Orion is *Halani*. It is seen in the east and faces east-west and rises at 7 pm.

Saptarshi is *Jamkhat* which keeps turning from east to west.

The Pole Star is *Dhruv tara* (as in modern languages)

The Milky Way is *Pandi*, the path of animals.

The orientation of the Milky Way is north-south.

In the Moon they can see a Banyan tree along with an old lady (*yadi*) spinning cotton yarn.

Lightning in the north means rain.

They know the relation between the glow around the Moon and the monsoon.

The Evening Star is *Shubham* (an auspicious star).

They have seen a comet but do not know what it is.
A meteor brings death.

A1.1.4 Kasola Village

Location: 19° 54.80′ N, 77° 39.7′ E (342 meters above mean sea level).
Post: Kasola, Taluka Mahagaon, District Yavatmal. Called *Sevalal Tanda*, it has about 900 houses and 3,755 cows. The main occupation used to be transport but is now farming.
Date of Visit: 3 May 2013.
Persons Met:
Birbal Munna Chauhan (M88)
Devlal Rodba Jadhav (M65)
Haribhau Phulasingh Rathod (M70)
Astronomical and Other Beliefs:
The Morning Star is *Pora* (*Porya*) *tara* .
The Evening Star is *Sukachi Chandi* (Venus?), a glow that brings happiness. It is useful for telling time.
Orion is *Halni*
They know *Jamkhat*. They think that if is sinks the world will end (this is a partially borrowed idea from the Gonds).
The Milky Way is the path of the dead (*mardarwat*).
The Pleiades are remembered is the *Shirser Jhumko.*
They know Taurus as *Kamedi* (the dove) which is close to *Halni* (Orion).
They know that the Moon has dots, and a lunar halo indicates rain in slightly differently ways: if the glow is broken (*tala)* then the rains will be better, but if it is complete (*khala*) there will be little rain.
Comets: *seshar tara*, and are auspicious.
A meteor is a broken star and is a bad omen.
They know about the crow's nest in May and its relation to the seasons.
They know that lightning in the east brings rains in anywhere from 3 hours to 3 days.
If there is a hailstorm in summer, the monsoon will be bad.
If ants come out with eggs then the rain will be poor.
They know that a rainbow (*Indra-dhanush* from modern languages) means the end of the current spell of rains.
They have heard of twelve zodiacal signs but have no idea what they are.
If a male fox (*Salya*) barks (*kolbhuki*) at night it is a good omen, but if a female fox (*Sali*) barks it is a bad omen.

A1.1.5 Chinchkhed Village

Location 19° 52.25′ N, 78° 10.334′ E (270 meters above mean sea level).
Chinkhed Post: Chinchkhid Taluka Kinwat District: Nanded. On the Pusad – Mahur – Kinwat Road, 20 km from Mahur.
Date of Visit: 4 May 2013.
Persons Met:
Bhimaniputra Mohan Naik (M66) [The author of several books and papers on the origin of the Banjaras.]
Astronomical and Other Beliefs:
The Banjaras are the Pani tribe of Vedic literature and are snake worshipers. They are not Rajputs.
Their main profession is transportation and trade—mainly in salt, cows, food grains and occasionally metals.
Have often have been hounded as thieves.
Their main identifier is the horned head gear.
They worship *Shivaling* (the amorphous symbol of *Shiva*).
The history of the Banjaras goes back to the Harappans. The Rajputs converted to the Banjaras *en mass* after the defeat of Rana Pratap against the fellow Rajputs in 1597 and reprisals were feared. Being providers of the Muslim army the Banjaras were exempt from persecution.
They became farmers after the arrival of the railways made them redundant.

A1.1.6 Palaitanda Village

Location 19° 37.776′ N, 78° 43.2′ E (305 meters above mean sea level).
Post Toyaguda, Mandal Bela, Block and District Adilabad. On the Adilabad – Satnala – Jamini – Palaitanda Road, about 26 km from Adilabad.
Date of Visit: 6 May 2013.
Persons Met:
Chavan Dashrath (M65)
Chavan Baliram (M70)
Chavan Jogram (M60)
Chavan Prakash (M50)
Chavan Gunibai (F80)
Chavan Hamalibai (F90)
Rathod Shakuntala (F70)
Astronomical and Other Beliefs:
Orion is *Halni*
The Morning Star is *Porya tara.*
They know that by using the Evening Star that rises in the east, one can determine the passage of time during the night.
They know how to use a gnomon to determine the time of the day.
They know that the Evening Star demands a sacrifice of a wheat bread (a *chapatti*)
They know *Saptarshi* as *Jamkhat.*
They know the Pleiades as *Jhumko.*

A1.1.7 Nagrala Village

Location 19° 39.372′ N, 79° 6.604′ E (485 meters above mean sea level).
Post: Jiwti, Taluka Jiwti, District Chandrapur. On the Chandrapus – Rajura – Gadchandur – Bailampur – Nanakpathar – Nagarala Road,

16 km from Gadchandur and 70 km from Chandrapur.
Date of Visit: 8 May 2013.
Persons Met:
Seva Amru Chauhan (M70)
Vinayak Chandar Rathod (M46)
Ramji Sakharam Rathod (M45)
Motiram Todba Rathod (M65)
Janabai Sakharam Jadhav (F60)
Tayabai Chandar Rathod (F70)
Malabai Motiram Rathod (F60)
Sahebrao Sakharam Jadhav (M32)
Astronomical and Other Beliefs:
A comet is a star with a tail and it brings a famine.
The Big Dipper: (*Saptarshi*) *Jamkhat.*
Orion is *Halni.*
The Milky Way is the way to heaven.
The Morning Star: *Porya Tara.*
The Sun is *Dado* (not related to any Indian language), and the Moon is *Chanda* (similar to the modern Indian word) and they can see a tree on it.
They know that eclipses occur but don't know why but they know that they should make donations at that time (a very Hindu concept).
The Pleiades are *Jhumko*.
Meteors are stars that come down by magic and are not good.
They know the story of the crow and its nest.

A1.2 Kolam Villages Visited

A1.2.1 Dubaguda Village

Location: 19^{o} 36.27′ N, 78^{o} 45.086′ E (331 meters above mean sea level).
Post: Sayeedpur, Mandal Bela, District Adilabad, State Andhra Pradesh. Along the Satnala – Jamini – Sayeedpur – Dubaguda Road, 35 km from Adilabad.
The village is on the River Deyalamadg and is isolated from the main road by the River. There are about 80 houses. The population is about 500, 25 of whom are educated to 10th Standard (age 15 or so); there are 5 graduates. There is a primary school in the village.
Date of Visit: 5 May 2013.
People Met:
Bapurao Tekam (M55)
Lasama Tekam (M70)
Maharu Tekam (M44)
Lakuu Kodapa (M55)
Lakshmibai Aatram (F52)
Aaibai Tekam (F55)
Bhimbai Kodapa (F47)
Astronomical and Other Beliefs:
Followers of four gods by number–4th to 7$^{th.}$ (carried from old contact with the Gonds who have nine gods, number 1st to 9th; the Kolams were once priests of the Gonds).
The counting system (for >3) is largely taken from Telugu.
Directions are north: *Telganam*; south: *Kalam*; east: *Potkuranai*; west: *Potpodnavai.* East is also called *Suryatu* (the sunrise direction).
They know of the Pleiades as *Kovela Kor*, a constellation with one large and several small birds. The Pleiades also are known as *Sappa*, an instrument that is used to beat the grain in order to separate the husk.
Big Dipper (*Saptarshi*): *Mandater*, meaning a cot. The three following stars are three people, a Kolam, a Gond and a *Pardhan* (chief).
They know Orion as *Tivpate*, an agricultural instrument used to sow the seeds.
The Morning Star is *Vegud suka* and the Evening Star is *Jevan suka.*
The Milky Way is *Margam,* a path.
Taurus is *Bhori*, a bird (Aldebaran) with two eggs.
Scorpius is *Tuntor* (a scorpion).
Canis Major is *Mete*, the central pole around which a bull is tied and made to go around as it separates husk from grain. The ground is known as *Kalave.*
They also see a group of three stars one on top of the other called *Kavadi Kunde* (Cygnus), representing three earthen-ware pots put on top of each other and seen in the northeast after sunset in May-June.

A1.2.2 Janguguda Village

Location: 19^{o} 37.79′ N 78^{o} 44.0′ E (318 meters above mean sea level).
Post: Saidpur, Mandal Bela, Block Adilabad, District Adilabad, State Andhra Pradesh. 30 km from Adilabad on the Adilabad – Satnala – Jamini – Palaitanda – Janguguda Road.
Date of Visit: 5 May 2013.
People Met:
Sidam Surya (M60)
Madavi Bapurao (M60)
Sidam Bhimrao (M45)
Madavi Kaniram (M28)
Devbai Attram (F40)
Jango Attram (M40)
Astronomical and Other Beliefs:
The Big Dipper (*Saptarshi*) rises in the east in May. It is assumed to be a container with four edges whose opening is towards the zenith when it rises. In early June, at sunset it is close to zenith and 'upside down'. This is when it pours out the rains. The remaining three stars are on their way to drink the water.
They know *Saptarshi* as *Mandter*, where the four main stars are a cot that is being sought by three people.
The great square of Pegasus: *Samdur* (four stars), identified by the mention that it has four stars that appear near the zenith at sunrise in early May. If it appears bright the rains will be good.
Five different animals appear near *Samdur*

(Pegasus). They are: *Namli* (a peacock), *Barre* (a buffalo), *Pande* (a frog), *Mekam* (a deer) and *Gurram* (a horse). The rain in a particular year depends on which animal is the most conspicuous in the sky at that time.

We suggest that the stars in the northeast in Pegasus is the deer; Cassiopeia is the peacock; Aquila is the horse; Cygnus is the buffalo; and Pisces is the frog.

The Pleiades is *Kovela Kor* (one large bird with lots of little birds). If it is sharp in the sky in June then the crop will be good.

Orion is *Tipan*, a set of three stars.

Sirius in Canis Major is *Mete*, the central pole around which a bull is tied and made to go around as it separates husk from grain. The ground is known as *Kalave. Adhara* in Canis Major is *Tiva Pate*, a three-legged stool on which one stands to drop the harvest onto the ground to separate husk from crop in the wind.

They know of the *Mahua* tree (*Ipamaka*) that is seen in October in the southern sky. This was identified as Crux by the Gonds.

They know of comets as *Sipursuka* (stars with tails). They consider them bad omens.

They refer to a meteor as *Suka erengten* (a broken star).

Scorpius is *Tuntoor* (a scorpion).

They refer to the Milky Way as *Panadi* or *Margam*, which means path. They know the Milky Way goes from northeast to southwest.

Leo is *Murda* (dead body) with mourners (*Ladvya*); this is almost a direct, but imperfect, memory of the Gond myth.

They know of eclipses. A total solar eclipse is good but a partial eclipse of the top of the Sun is bad for humans while a partial eclipse of the lower part of the Sun is bad for animals. The belief is that some tax collector has come to collect the taxes and if the Sun is fully engulfed the debt has been paid up in full, otherwise humans or animals have to pay the balance.

A1.2.3 Jamini (Duttaguda) Village

Location: 19°39.105′ N, 78° 41.992′ E (302 meters above mean sea level).

Village Jamini (Dattaguda), Post Toyaguda, Mandal Jainad, Block and District Adilabad, State Andhra Pradesh. On the Adilabad – Satnala – Jamini – Dattagud Road, 25 km from Adilabad.

Date of Visit: 5 May 2013.

Persons Met:

Mohan Pendur (Village Head) (M42)
Bapurao Kodapa (M42)
Mesram Shankar (M53)

Astronomical and Other Beliefs

The Big Dipper is *Mandter*.

The Pleiades is *Kovela Kor* (one big and lots of small birds).

The Morning Star is *Vegud Suka.*

The Evening Star is *Jevan* (dinner) *suka* (star).

They know *Irukmara* as the tree of *Mahua* in Crux. They know the neighbouring small stars as flowers of *Mahua* (*Irup pokke)*. One bright star (α Centauri) in the region is called *Murta* (an old lady) and β Centauri is *Kadma* (a young lady). They are there to collect the flowers.

They know a constellation called *Kawadi Kunde* (Cygnus) which looks like three pots on top of each other. This constellation rises in the northeast in May-June early in the evening.

They know an asterism called *Dandare Pila* which is an anticlockwise spiral that rises in October-November in the northeast. If it is bright and clear, it is good omen, but if it is hazy this is a bad omen. This may be the tail of Scorpius.

They know of the Milky Way as ‘The Path’, or the animal path.

They know of Taurus as a bird with eggs.

They also know Scorpius as *Borenagu* (a snake), which is seen at sunrise in *Pusa maas* (January).

They identify Sirius in Canis Major that rises January (*Pusa maas*) as *Mete*, the central pole around which a bull is tied and made to go around as it separates husk from grain. The ground is known as *Kalave. Adhara* in Canis Major is *Tiva Pate*, a three-legged stool on which one stands to drop the harvest into the ground to separate the husk from the crop in the wind.

Orion: *TIpun*.

They know of meteors and *Suka Yerangtin* (a falling star), and recall that it once fell on a tree and burning it down.

A comet is *Sipur suka* (a star with a tail), and is considered a bad omen.

They know the solar eclipse story.

A1.2.4 Laxmipur Village

Location: 19° 41.809′ N, 78° 21.049′ E (345 meters above mean sea level).

Post: Kuchalapur, governed from Kochlapur, Mandal Talamadgu, Taluka and District Adilabad. On the Mahur – Adilabad Road, 25 km before Adilabad. The first village in Andhra Pradesh on the road from Mahur.

The village has 48 houses and a population of about 200.

Date of Visit: 6 May 2013.

Persons Met:

Kadopa Bhimrao (M45)
Kumra Bhimrao (M55)
Tekam Kappu (M60)
Aatram Tukaram (M45)
Tekam Laxmibai (F70)
Tekam Bhimbai (F65)

Astronomical and Other Beliefs:

The Morning Star is *Vegud Suka.*

The Evening Star is *Jevan Suka* (dinner star).
The Pleiades is *Kovla Kore.*
The Big Dipper is *Mandetar*, a cot being pursued by the people, Kolvar, Gond and Patadi.
The Milky Way is *Panadi*.
Pegasus is *Samdur*.
They are clear about Orion, including its entire structure, not just the belt.
Scorpio is *Nagun* (the cobra), that rises at 4 am.
Cygnus is *Kavdi Kunde.*
They know of Crux as the *Mahua* tree.
They think of meteors as stellar excreta.
Their month goes from New Moon to New Moon.
They do not know the arrangement around Sirius.
They know a rainbow as *Ayak*, which will end the rain.
They know the complete story of solar eclipses.

A1.2.5 Sonapur Village

Location: 19^{o} 41.486′ N, 78^{o} 21.905′ E (336 meters above mean sea level).
Village Sonapur, Post Kuchalapur, Mandal Talamadgu, Block and District Adilabad. On the Adilabad – Sunkadi – Lingin – Sonapur Road, about 20 km from Adilabad.
Date of Visit: 6 May 2013.
People Met:
Tekam Letanna (M60)
Tekam Rambai (MF60)
Tekam Muttubai (M55)
Aatram Aiyu (M55)
Madavi Supari (M35)
Astronomical and Other Beliefs:
The Morning Star is *Vegud Sukum*.
The Evening Star is *Jevan Sukum*.
Pegasus is *Samdur*, including five animals around it: *Namli* (a peacock), which is not good; *Barre* (a buffallo), which is excellent; *Pande* (a frog), which brings good rains; *Mekam* (a deer), which brings average rains and *Gurram* (a horse) which brings average rains.
They know of the cot in the Big Dipper (*Saptarshi*), with a Kolam, a Gond and a Patadi in pursuit of it.
The Milky Way is *Bhori Sanko*, an animal path.
Cygnus is *Kavedi koda*.
Scorpius is *Borenag* (the cobra), which rises in the northeast, south of the zenith seen in *Pusa Maas* (February).
They know the story of eclipses and identify three different types depending upon whether the upper, lower or middle part of the Sun is covered. The first is bad for humans, the second is bad for animals, and the third is good for humans and animals.
They know about the glow around the Moon: when the aura is small the rains are far but if the glow is large the rains are nearby.
The Pleiades is *Kovela Kore*.
Orion is *Tipan*.
The region around Sirius is known as *Met*.
They know of Crux as *Ipamak*, the *Mahua* tree.

A1.2.6 Landgi Pod Village

Location: 19^{o} 52.522′ N, 78^{o} 39.753′ E (273 meters above mean sea level).
Post: Matharjun, Taluka Zarijamni, District Yeotmal, State of Maharashtra. On the Bori – Mandavi – Piwardol – Gavara – Landgi Pod Road, about 10 km from Bori and 2 km from Matharjun.
Date of Visit: 7 May 2013.
Persons Met:
Bajirao Punjaram Madavi (M60)
Laxman Punjaram Madavi (M55)
Kishore Bhovanu Mesram (M21)
Mahadev Punjaram Madavi (M65)
Astronomical and Other Knowledge:
The Morning Star is *Vegun suka.*
The Evening Star is *Jevean Suka.*
The Pleiades is *Kovala Kor.*
The Belt of Orion is *Kavadi Kunde.*
The cot of the Big Dipper is being stolen by three thieves who are following it (this story is taken from the Gonds).
Orion is known as *Tipan.*
They know the region around Orion as a farming scene with *Medi, Kalave* and *Tandel/ Aidal* (a bull).
The great square of Pegasus is *Samdur*, that rises at 3-4 am. They know that if the pig (*Ture*) is close to *Samdur*, it will be a bad monsoon; if it is *Mekam* (*Rohi*) or the deer (*Gorya*) it will be average; if it is the buffalo (*Sir*) it will be an excellent monsoon; if it is *Pande* (*Beduk*, the frog) it will be a good monsoon.
They know that monsoon arrives in the month of *Budbhavai* (June).
They know Crux as *Irukmara* (*Ipemak*), that is the tree of *Mahua*. Their story of Crux is slightly different, with Alpha and Beta Centauri called *Oedda* (man) and *Pilla* (woman), instead of old and young lady, respectively.
Scorpius is *Nagpan* (the cobra).
A comet is *Sipharsukka* (a star with a tail).
They know the story of solar eclipses, but in reverse: if the bottom of the Sun is covered it is a bad omen for humans, but if the upper half is covered it is bad for animals.
They know of Taurus as the constellation of one bird with two small eggs (*Bhori*).
About lunar eclipses, the eclipse is dark if a frog (*Beduk*) attacks the Moon and pale if a caterpillar (*Gongpatad*) is eating the Moon.
A rainbow is the *Bhimayak's* bow.

A1.2.7 Chinchpod Village

Location: 19^{o} 54.589′ N, 78^{o} 40.432′ E (283 meters above mean sea level).

Post: Matharjun, Tahsil Zarijamni, District Yeotmal. On the Pkandarkawa – Shibla – Matharjun Roa,. 28 km from Pandharkawada.
Date of Visit: 7 May 2013.
Persons Met:
Anandrao Tekam (M55)
Layanibai Tekam (F80)
Astronomical and Other Beliefs:
The Evening Star is *Jevan Suka.*
The Morning Star is *Vegud Suka.*
The Pleiades is *Kovela Kore.*
Cygnus is *Kawadi Kundel.*
They know of the cot in the Big Dipper (*Ter*) and the thieves (*Dongal*).
Pegasus is *Samdur*. *Namli*: more rain; Peacock: less rain; *Mekam*, *Rohi*: more rain; *Ture*, *dukkar* (the pig): a good monsoon is expected; *Gorya* (the deer): less than normal rain; *Pande*, *Beduk* (the frog): an excellent monsoon is expected.
They know of Taurus is a bird with eggs.
They know of Scorpius as a cobra (*Bornagu* or *Nagpan*).
Orion is *Tipan.*
They know the story of solar eclipses.
Burials are east-west, with the head facing the west.

A1.2.8 Bhimnala Village

Location: 19° 55.603′ N, 78° 40.162′ E (269 meters above mean see level).
Post: Matharjun, Taluka Zarijamni, District Yeotmal Stat Maharashtra. On the Shibla – Rajni – Shiratoki – Bhimnala Road, 6 km from Shibla.
Date of Visit: 7 May 2013.
Persons Met:
Bhima Tukaram Aatram (M65)
Sonu Letu Tekam (M35)
Lalu Surya Tekam (M60)
Dilip Bhima Tekam (M22)
Sudhakar Aayya Aatram (M24)
Astronomical and Other Beliefs:
The Pleiades is *Kovela Kora*, a group of birds.
Cygnus is *Kuvadi Kunde.*
They know the Morning Star as *Pele suka.* However, the star for waking up is *Veka Potur* (the son of the morning).
The Evening Star is *Jevan Suka.*
They know *Samdur*, including the relation between the intensity of rains and the animals (*Guram*, the horse) etc.
They know Crux as the *Mahua* tree (*Irupmak*).
They know Scorpio as a cobra.
A comet as a broom star.
They know about solar eclipses.
For lunar eclipses, they suggest that if the Moon is being eaten by a scorpion it will be red but if a frog is eating it, it will be black.

A1.2.9 Raipur (Khadki) Village

Location: 19° 39.904′ N, 79° 5.957′ E (508 meters above mean sea level).
Post: Jiwati, Taluka Jiwati District Chandrapur. On the Chandrapur – Rajura – Ghadchandur – Bailampur – Nanakpathar – Nagrala Road, 3 km from Nagrala.
Date of Visit: 8 May 2013.
Persons Met:
Soma Rama Sidam (M60)
Jhadu Boju Kodape (M50)
Jaitu Bhima Sidam (M42)
Maru Jangu Kodape (M45)
Ayyo Tukaram Sidam (M35)
Astronomical and Other Knowledge:
Farming is by tilling the land, by hammering to break the ground, and then sowing.
They know of *Samdur* and the animals that approach it decide on the rain: *Turre*, *Dukkar* (the pig) good rain; *Mokam* (the deer), *Gurram* and *Tumali*: average rain; *Barre*, *mais* (the bullock): lots of rain.
Saptarshi is a cot, *ava ter,* which is being pursued by three thieves, *Dongal* a Kolam, a Gond and a Patadi.
The Morning Star is *Vegur Suka.*
The Evening Star is *Jevan Suka.*
The Pleiades is *Kovela Kor.*
Unlike other villages, they state that *Kavde Kunde* is the belt of Orion and *Tipan* is the sword of Orion (in other villages *Kavde Kunde* is Cygnus).
They have heard of Leo (as described by the Gonds).
Scorpius is *Tootera* (a scorpion), but it also is referred to as a snake (*nago*).
They know of a counter-clockwise spiral of stars that also looks like a snake about 10° east of Scorpius.
The Milky Way is the path of animals.
They know stories of solar and lunar eclipses.
They also know Taurus as a bird with two eggs.
Crux is *Ipemak.*
They know *Tiva*, *Miti*, *Kovela* and *Konda* around Canis Major. These are various tools associated with farming and are described in detail by the Gonds.
They know a comet as *Sipur Suka* (a star with a tail), and consider it a bad omen.
A rainbow is *Aikawa*.
Burials are oriented east-west, with the head to the east. The burial site is away from the village. A commemorative community site as per the god is created in the village and is worshipped as a common site for all ancestors on important occasions.

A1.2.10 Kakban Village

Location: 19° 38.743′ N, 79° 7.038′ E (487 meters above mean sea level).
Post: Jiwati, Taluka Jiwati, District Chandrapur about 70 Kolam houses with very few Gonds

and Banjaras.
Date of Visit: 8 May 2013.
Persons Met:
Nanaju Maru Madavi (M43)
Bhima Raju Aatram (M40)
Raju Mutta Aatram (M50)
Bhujangrao Marotrao Kotnake (M50)
Netu Naru Sidam (M50)
Maru Jangu Kodape (M40)
Astronomical and Other Knowledge:
They know of *Samdur,* with *Namali* bringing less rain, *Turre* and *Barre* bringing moderate rain, *Gurram* bringing less of rain and *Pande* bringing good rain.
The Pleiades: is *Kovela Kor*, with the little bright star at the base called *Kovela Komdi*. At maximum it rises 70^{o} above the horizon.
The belt of Orion is *Kavadi Kunde*, and the sword is *Tipun*.
Saptarshi is a golden cot that is being pursued by a Kolam, a Gond and a Patadi, in that order.
Crux is the *Mahua* tree, with the bright star near it an old lady and the dimmer star a young girl.
The Evening Star is *Jevan Suka.*
The Morning Star is *Vegud Suka.*
A meteor is *Suka Erangtu*, and is a bad omen.
They know Canis Major as *Medhi*, *Khala*, and *Banati*, *Tlva pate*. These are images from the Gonds, who view the entire region as a farming scene.
A comet is *Sipur Suka*, and is a bad omen.
Scorpius is *Tuntoora*, the scorpion.
The Milky Way is *Jeev* (a path, the path of life).
They know the complete story of solar eclipses.
They know the story of lunar eclipses. If the frog is attacking the Moon the eclipse will be dark red, and if it is being eaten by a caterpillar the eclipse will be lighter.
A rainbow is *Ayyakawa*, which belongs to the grandparents (the grandfather, *Ayyak*, towards the violet and the grandmother, *awa*, towards the red).
Cardinal directions are: *Kaland* (north), *Potkurina* (east), *Telagnaam* (south) and *Potpadna* (west).
Burials are oriented east-west with the head to the east. They worship the ancestors. A memorial pillar if made from stone is called *Gunda* and if made of wood is called *Mundem*.
A month is from New Moon to New Moon, and one month is added every three years.
They know of the glow around the Moon and the rains.

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THE 1761 DISCOVERY OF VENUS' ATMOSPHERE: LOMONOSOV AND OTHERS

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Abstract: Russian polymath Mikhail Vasil'evich Lomonosov claimed to have discovered the atmosphere of Venus during the planet's transit over the Sun's disc in 1761. Although several other astronomers observed similar effects during the 1761 and 1769 transits, Lomonosov's claim for priority is the strongest as he was the first to publish a comprehensive scientific report, and the first to offer a detailed explanation of the aureole around Venus at ingress and egress, which was caused by refraction of the sunlight through Venus' atmosphere. His observations, moreover, were successfully reconstructed experimentally using antique telescopes during the 2012 transit. In this paper we review details of Lomonosov's observations (which usually are poorly covered by commentators and often misunderstood); compare other reports of the eighteenth century transit observations, and summarize their findings in a comprehensive table; and address recent calls to reconsider Lomonosov's priority. After reviewing the available documentation we conclude that everything we learned before, during and after the twenty-first century transits only supports further the widely-accepted attribution of the discovery of Venus' atmosphere to Lomonosov.

Keywords: Lomonosov, atmosphere of Venus, transits of Venus, experimental replication

1 INTRODUCTION

Venus was the first extraterrestrial body (other than the Sun) that was proven to have a detectable atmosphere. The discovery was made by the Russian polymath Mikhail Vasil'evich Lomonosov (1711–1765; Menshutkin, 1952; Shiltsev, 2012a; 2012c), who observed the 1761 transit of Venus from St. Petersburg, detecting a luminous arc around Venus at egress, which led him to realize that it was caused by refraction of the sunlight through the planet's atmosphere. Lomonosov promptly reported his results at length, in Russian and in German, in two different scientific papers (Lomonosov, 1761a; 1761b), concluding that

> … the planet Venus is surrounded by a significant airy atmosphere similar to (if not even greater than) that which surrounds our terrestrial globe. (Lomonosov, 1761a; here and in the remainder of this paper, the English translations are after Shiltsev 2012b, unless otherwise stated).

Since the late nineteenth century, Lomonosov's priority has been widely accepted (e.g., see Bond, 2007: 46; Lomb, 2011: 190-191 Lur-Saluces, 1933: 297; Lyubimov, 1855: 30; Maor, 2000: 90; Marov and Grinspoon, 1998: 16; Maslikov, 2007; Moore, 1961: 84-87; Perevozchikov, 1865; Schilling, 2011: 42; Sharonov, 1952a; Shirley and Fairbridge, 1997: 393; Smith, 1912; Tchenakal, 1961; Wulf, 2012: 75-77). However, Pasachoff and Sheehan (2012a) recently expressed skepticism about this discovery in this journal, questioning whether Lomonosov could have detected Venus' atmosphere with his telescope, and calling for a re-examination of the circumstances of the discovery.

In this paper we describe Lomonosov's findings and compare them with similar observations of the eighteenth-century transits; review the discussions on the discovery of the atmosphere during the nineteenth and twentieth centuries; critically study the arguments presented by Pasachoff and Sheehan (2012a); and discuss the results of the successful experimental reconstruction of Lomonosov's discovery during the 2012 transit of Venus.

2 LOMONOSOV'S OBSERVATIONS DURING THE 1761 TRANSIT OF VENUS

Lomonosov observed the transit of Venus on 26 May (old style; 6 June, new style), 1761, from his estate in St. Petersburg (modern address: Bolshaya Morskaya, 61) at latitude 59° 55′ 50″ N and longitude 30° 17′ 59″ E (Chenakal, 1957a). He used "… a 4½ ft. long telescope with two glasses … [and a] … not-so-heavily smoked glass …" as a weak solar filter (Lomonosov, 1761a: 7). The reason for the filter was that he

> … intended to observe the beginning and the end of the phenomena only and then to use the power of the eye, and give [his] eyes a respite for the rest of the transit. (Lomonosov, ibid.).

His original telescope was destroyed during WWII, a victim of the heavy bombardment that leveled Pulkovo Observatory and the suburbs of St. Petersburg. For a long time there was uncertainty regarding the type of telescope Lomonosov used, as evidenced by the commentary in the standard edition of Lomonosov's works (Vavilov and Kravets, 1950-1983). Although some hints were given by Melnikov (1977) back in the 1970s, only recently has research uncovered a pre-WWII publication (Nemiro, 1939) in which a witness describes several notable antique telescopes in the Pulkovo museum collection, which was established more than fifty years prior to that date:

> … the most numerous group of tools are the instruments ordered to observe the transit of Venus across the solar disk in 1761 and 1769. This group includes achromatic telescopes by Dollond, the reflectors by Short of the Gregorian design with lens-heliometers, and quadrants by Sisson. One of these Dollond refractors was used by famous Lomonosov to make the biggest discovery – he discovered the existence of an atmosphere of Venus during its passage through the disk of the Sun in 1761. (Koukarine et al., 2012; our English translation).

The full list of old astronomical instruments in the collection of the Pulkovo Observatory compiled in the late nineteenth century includes two Dollond achromats of 4½ feet length dating to Lomonosov's time, one with an objective of 2.1 inches aperture and another with a 2¾-inch objective (Struve, 1886).

In 1761, the achromatic refractors just recently invented by the renowned English optician John Dollond (1706–1761) most distinctively differed from the old, non-achromatic refractors by having the second lens ('glass') in the objective, hence the reference to "two glasses" in Lomonosov's description. Given that Lomonosov's transit drawings (see Figure 1) are reversed, one can conclude that his telescope was a 4.5-foot reversed image astronomical refractor, with a two-lens achromatic objective made by John Dollond (Petrunin, 2012).

Pasachoff and Sheehan's (2012a: 5) reference to Lomonosov's refractor as "non-achromatic" is therefore incorrect. Furthermore, Lomonosov's Dollond achromat was a much more serious scientific instrument than one recent translator's careless rendering as "… a sort of spy-glass …" would suggest (Marov, 2005: 213). The outstanding quality of the eighteenth-century Dollond achromats was specifically noted by observers of the 2012 transit of Venus who used antique telescopes (e.g., see Kukarin et al., 2013). Some of the Dollond telescopes similar to the one used by Lomonosov have been analyzed using modern optical techniques and have demonstrated excellent performance (e.g., see Petrunin, 2012). ZYGO-type interferometeric measurements of the 4.5-ft Dollond achromat employed for the replication of Lomonosov's discovery gave the following results (with reference to the diffraction-limited optical parameters in parenthesis): peak-to-peak wave front error of 1/3.9 wavelength (1/4 or less); rms error of the wave front of 1/21 waves (1/14 or less); and a Strehl ratio of 0.916 (0.8 or more). Consequently, Koukarine et al. (2012) concluded: "… the optics of this telescope made almost two and half centuries ago are of very good quality even by today's standards."

During his observation of the 1761 transit of Venus Lomonosov reported three different types of phenomena:

1) phenomenon *PI* = a 'blister' or 'bulge' which lasted for a few minutes after the 3rd contact (this is illustrated in Lomonosov's Figures 3, 4 and 5, and at point A in Figure 1—see our Figure 1). Lomonosov's Figures 3-5 indicate that the 'blister'-'bulge' at 3rd contact (which we will henceforth refer to as an 'arc') started to grow from the beginning of egress (egress phase 0), when Venus was fully on the Sun's disc, all the way to an egress phase of about 0.1 (where 1/10th of Venus' diameter was external to the solar photosphere). Therefore, it lasted for a few minutes before it disappeared.
2) phenomenon *PII* = the 'blurriness' of the solar limb at the time of 1st contact (illustrated in Lomonosov's Figure 1 at point *B*), and a similar 'blurriness' at 4th contact.
3) phenomenon *PIII* = a "hair-thin bright radiance" close to 2nd contact, which lasted about a second (this was not illustrated).

It ought to be noted that Lomonosov concluded the existence of an atmosphere of Venus on the basis of only two out of the three different phenomena observed by him, namely *PI* and *PII* above, leaving the "hair-thin bright radiance" near the 2nd contact (*PIII*) out of the argument.

The *Chronicles of the Life and Work of M.V. Lomonosov* (Chenakal, et al., 1961), which present all the known documented facts of his life, indicate that Lomonosov commenced the writing of his observational report the day after the transit. He submitted his 17-page long paper, written in Russian and titled "The appearance of Venus on the Sun, observed at the St. Petersburg Imperial Academy of Sciences on May 26, 1761" (Lomonosov, 1761a) for publication on 4 July 1761 (o.s.), and 250 copies were published by the St. Petersburg Imperial Academy of Sciences on 17 July 1761 (according to the records of the Russian National Library)—and they were fully distributed within a few months (Tyulichev, 1988). It is of interest to note that pages 10-16 of the published report are devoted to a defense of the heliocentric hypothesis and a discussion of the possibility of life on Venus in light of the discovery of its atmosphere—a subject of wide scientific interest at the time (e.g., see de Fontenelle, 1686). A German translation of the Russian paper (Lomonosov, 1761b) was made shortly after (presumably by Lomonosov himself), and 250 copies were printed in August 1761, destined for wide distribution abroad (Sharonov, 1952b; Tyulichev, 1988). The Russian and German texts are essentially identical, differing by only eight insignificant words and phrases (Chenakal and Sharonov, 1955). Four English translations of the nucleus of Lomonosov's Russian paper (Lomonosov, 1761a: 7-9) have been published to date. Meadows (1966) is the closest to the original, and has just a few insignificant omissions. Marov (2005) contains a number of errors and deviations from the original text, although none of these alters the major content and conclusions of the original; however, Marov's version does provide a useful discussion of the historical background of the 1761 observations made at St. Petersburg, as well as references to known drafts and preparatory documents that led to Lomonsov's published report. The recent paper by Pasachoff and Sheehan (2012a) offers a relatively good translation, with few deviations from the original text, but unfortunately the commentary is marked by several important misconceptions and misinterpretations (see Section 5 below). The most recent, complete and heavily-annotated translation by the present author (Shiltsev, 2012b) is, I believe, the closest 'word-for-word' rendering, and is free from the deficiencies of the three preceding translations.

Lomonosov's transit paper was included in all the major editions of his *Complete Works* issued by the St. Petersburg and the USSR-Russian Academy of Sciences, e.g., in those published in 1803, 1891-1948, 1950-1983 and 2011. The most complete one (Vavilov and Kravets, 1950-1983) also contains five related notes, letters and drafts and extended editorial commentaries. The transit paper itself, particularly its scientific (physics) content and historical importance have been discussed in great detail in several publications by practicing astronomers and historians of science (see the following sections).

In his own words (cf. Shiltsev, 2012b):

> … Collegiate Councilor and Professor Lomonosov kept an alert watch mostly for physical observations at his place, using a 4½ ft.-long telescope with two glasses. The tube had attached a lightly-smoked glass, for he intended to observe the beginning and the end of the phenomenon only and then to use the power of the eye, and give [his] eyes a respite for the rest of the transit.
>
> Having waited for Venus to appear on the Sun for about forty minutes beyond the time prescribed in the ephemerides, [he] finally saw that the Sun's edge at the expected entry became indistinct and somewhat effaced, although before [it] had been very clear and equable everywhere (see B, *Fig. 1*); however, not seeing any blackening and thinking that his tired eyes were the cause of this blurring, [he] left the eyepiece. After a few seconds, [he] took a glance through the eye-piece and saw that in the place where the Sun's edge had previously appeared somewhat blurred, there was indeed a black mark or segment, which was very small, but no doubt due to the encroaching Venus. Then [he] watched attentively for the entry of the other (trailing) edge of Venus, which seemed to have not yet arrived, and a small segment remained beyond the Sun. However, suddenly there appeared between the entering trailing edge of Venus and the solar edge, a hair-thin bright radiance separating them, so that the time from the first to the second was no more than one second.
>
> During Venus' egress from the Sun, when its front edge was beginning to approach the solar edge, and was (just as the naked eye can see) about a tenth of the diameter of Venus, a blister [pimple] appeared at the edge of the Sun (see A, *Fig. 1*), which became more pronounced as Venus was moving closer to a complete exit (see *Fig. 3* and *Fig. 4*). LS is the edge of the Sun, mm is the Sun bulging in front of Venus. Soon the blister disappeared, and Venus suddenly appeared with no edge

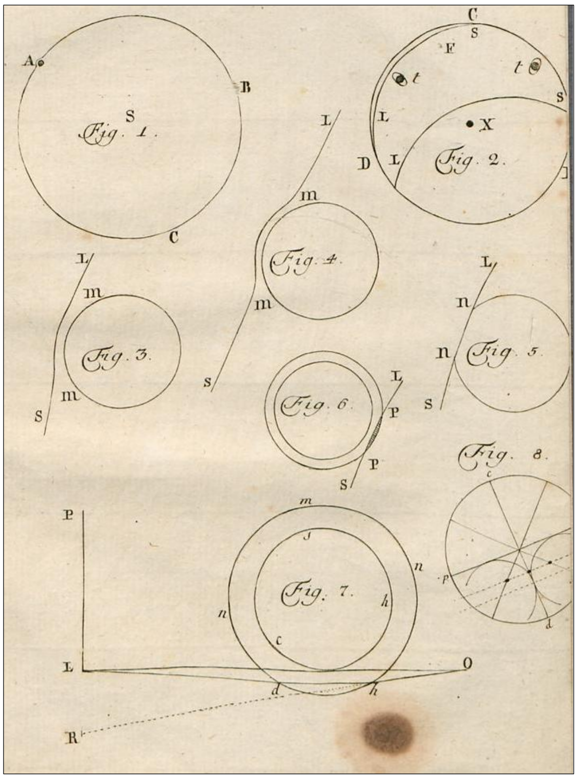


Figure 1: Lomonosov's drawings of the sequence of phenomena during the phases of ingress and egress of the 1761 transit of Venus (after Lomonosov, 1761a: 17).

> (see *Fig. 5*); nn is a segment, though very small, but distinct.
>
> Complete extinction or the last trace of the trailing edge of Venus on the Sun at its very emergence followed after a small break and was characterized by a blurring of the solar edge.
>
> While this was happening, it clearly appeared that as soon as Venus moved away from the axis of the tube and approached the edge of the field of view, a fringe of colors would appear due to the refraction of rays of light, and its [Venus'] edges seemed smeared the further [it] was from the axis X (*Fig. 2*). Therefore, during the entire observation the tube was permanently directed in such a way that Venus

was always in its center, where its [Venus'] edges appeared crisply clear without any colors.

From these observations, Mr. Councilor Lomonosov concludes that the planet Venus is surrounded by a significant atmosphere of air similar to (if not even greater than) that which surrounds our terrestrial globe. This is because, in the first place, the loss of clearness in the [previously] tidy solar edge B just before the entry of Venus on the solar surface indicates, as it seems, the approach of the Venusian atmosphere onto the edge of the Sun. The clarification of this is evident in *Fig. 6*; LS is the edge of the Sun, PP is a portion of Venus' atmosphere. At the time of Venus' egress, the contact of its front edge produced the bulge. This demonstrates nothing but the refraction of solar rays in the atmosphere of Venus. LP is the end of the diameter of the visible solar surface (*Fig. 7*); *sch* is the body of Venus; *mnn* is its atmosphere; LO is the [light] ray propagating from the very edge of the Sun to the observer's eye tangential to the body of Venus in the case of the absence of an atmosphere. But when the atmosphere is present, then the ray from the very edge of the Sun L*d* is refracted towards the perpendicular at *d* and reaches *h*, thus, being perpendicularly refracted, it arrives at the observer's eye at O. It is known from optics that the eye sees along the incident line; thus, the very edge of the Sun L, due to refraction, has to be seen in R, along the straight line OR, that is beyond the actual solar edge L, and therefore the excess of the distance LR should project the blister on the solar edge in front of the leading edge of Venus during its egress.

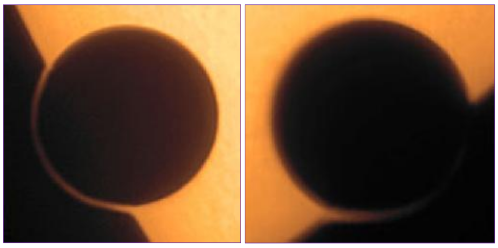


Figure 2: Photographs of the ingress (left) and egress (right) of Venus taken by Lorenzo Comolli at Tradate, Italy on 8 June, 2004 (after Comolli, 2004).

Fig. 8 (in Figure 1) illustrates the method used by A.D. Krasilnikov and N.G. Kurganov at the St. Petersburg Academy Observatory (Chenakal, 1957b) to measure the minimal distance from Venus to the center of Sun and the diameter of Venus.

Lomonosov's *Complete Works* also contain "*Preparatory Notes for the "Appearance of Venus on the Sun…*"" which add a little to the description of phenomenon *PIII*:

… then suddenly there appeared between the entering trailing edge of Venus and the solar edge, *a hair-thin bright part of the Sun*, so that the time from the first to the second was no more than one second. (Vavilov and Kravets, 1950-1983(4):389-390; my English translation).

As we will see in the following sections, observations of atmospheric effects similar to Lomonosov's were reported by many astronomers during the transits of the eighteenth, nineteenth and twenty-first centuries. For example, Figure 2 shows photographs taken in Italy with a modern 20-cm Schmidt-Cassegrain telescope and a digital camera during the 2004 transit (Comolli, 2004). Characteristic features of the luminous arc (*PI*) similar to what was drawn in Lomonosov's *Fig. 4* are clearly seen—the arc is thinner and fainter in the middle, and wider and brighter at the ends approaching the Sun's limb. The dimmer part of the arc may not appear well marked, and can assume the form of a 'whisker' (an incomplete arc), as in Figure 2 (right). Recent discussion about the formation of the arc and mod-eling of its appearance (see García-Muñoz and Mills, 2012) is fully consistent with all of these observations. Replication of Lomonosov's discovery with antique refractors during the 2012 transit resulted in similar observations (see Section 6 for details).

Most commentators on Lomonosov's report agree that he correctly and fully described the physical mechanism of refraction underlying his observations, and that he came to the right conclusion: that Venus possesses a dense atmosphere. It fully follows the basics of the theory of refraction which he had earlier studied because of its implications for the accuracy of maritime navigation, e.g., "… the rate of refraction corresponds to the transparent matter, i.e. air, thus the amount of matter that a ray propagates is the rate of refraction." (Lomonosov, 1759).[1] Only in the mid-1960s did the farsightedness of his assumption that Venus' atmosphere can be even more dense than that of the Earth become clear, when Venus' atmosphere was revealed to be nearly two orders of magnitude thicker than our terrestrial atmosphere (Marov and Grinspoon, 1998).

We also should note how precise, accurate and descriptive Lomonosov's drawings are (see Figure 1). For example, the diameters of the Sun and Venus in his *Fig. 4* differ by a factor of about 32, which is very close to the actual value. As we will see below, not many other observers achieved such accuracy with their drawings.

3 OTHER EIGHTEENTH CENTURY ACCOUNTS OF A VENUSIAN ATMOSPHERE

About two dozen observers of the 1761 transit reported phenomena which were caused by Venus' atmosphere or perceived to be caused by it. Besides the *PI, PII* and *PIII* phenomena observed by Lomonosov (that is, the arc or bulge of light over the part of Venus off the Sun during ingress/egress; the 'blurriness' of the solar limb at the points of external contact; and the "hair-thin bright radiance" close to the points of internal contact), there were observations of a ring (light or dark) around Venus when it was fully on the disc of Sun, which we will classify as phenomenon *PIV*. What follows is a brief overview of the 1761 reports, with the details of their reports of the atmospheric effects. In particular, all known drawings of the *PI* phenomenon are reproduced below. Many more observers in 1769 saw similar effects, but this discussion is limited only to descriptions of those relevant to the discussion in Section 5.

3.1 Observations of a Complete or Partial Arc Around that Part of Venus Which was off the Sun's Disc (*PI*)

A very clear description of the luminous arc around Venus off the Sun's disc during ingress and egress was given by the noted Swedish scientist, Torbern Bergman (1735–1784), who observed the transit from the University of Uppsala. His account, dated 25 August, was read in London at the 19 November 1761 meeting of the Royal Society and was published in the *Philosophical Transactions* … (Bergman, 1761-1762):

> We believe that we saw Venus surrounded by an atmosphere for the following reasons. Namely, before the completion of the ingress, when about a quarter of the diameter of Venus was still beyond the limb of the Sun, the whole of Venus was visible, because the part protruding was surrounded by a feeble light, as shown in Fig. 1 [see Figure 3 here] … This was observed much more clearly at the egress; for, initially, the part projecting beyond the limb of the Sun was surrounded by a similar, but brighter light. The part *a* (Fig. 2) which was furthest from the Sun became weaker in proportion to the egress of Venus until a stage was reached when only horn-shaped segments could be seen (Figure 3). I continued to observe the light unbroken, however, until the egress of the central point of Venus. (after Meadows, 1966: 120).

Bergman observed with a 21-ft long non-achromatic refractor, but did not specify the filter used. His description of the arc in general matches that of Lomonosov. He noted that in the later phase of egress, the arc had broken into two horn-shaped segments. His drawings show some deficiencies though (see Fig. 3). First of all, the arc is presented equally thick around Venus' circumference, as well as the horns. Secondly, the points of the arc and horns in contact with the Sun's edge are shown as very distinct sharp angles that cannot represent physical reality. Thirdly, the ratio of the diameters of Venus and the Sun as drawn is about 1:10, which is far from the actual ratio of about 1:32. This indicates that the drawing may have been designed to illustrate qualitative points rather than quantitative conclusions. It is also to be noted that Bergman observed the notorious 'black drop effect' (Schaefer, 2001) shown in his Figs. 4-6. He suggested that it originated from strong refraction of sunlight in Venus' atmosphere (which it has no relationship to), and he mistakenly shows the wrong curvature of the Sun's limb in his Fig. 5. Despite all these deficiencies, there is little doubt that Bergman refers to a true luminous aureole caused by refraction in the atmosphere of Venus, even though he offered no explanation for the phenomenon depicted in his Figs. 1-3.[2]

In the same volume of the *Philosophical Transactions* another Swede, Pehr W. Wargentin (1717–1783), the Director of Stockholm Observatory and Secretary of the Royal Swedish Academy of Sciences, reported his observations

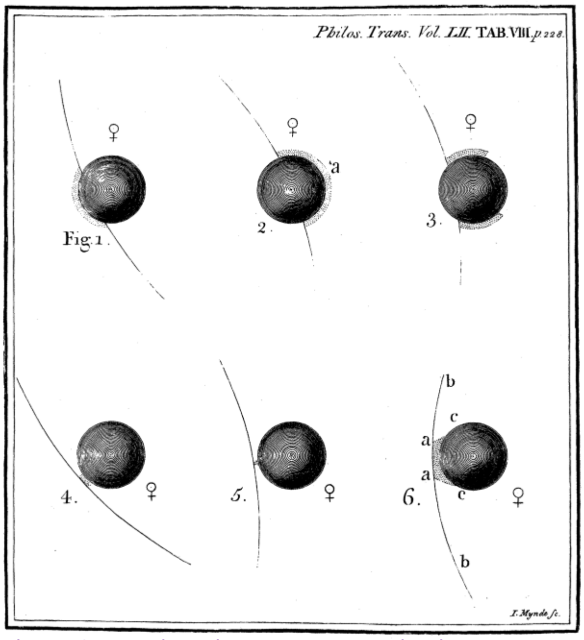


Figure 3: Drawings by T. Bergman showing Venus at ingress and egress (after Bergman, 1761-1762: 223).

(Wargentin, 1761-1762: 212-213), and made the following short remarks and cautious conclusion:

> It is worth noting that the limb of Venus, which then had emerged, was conspicuous even outside the Sun, as a kind of weak light occurred [over Venus' limb] and lasted during the entire emersion. Whether such a sight of the edge of Venus is due to the bending of the rays of the Sun, or to refraction in the atmosphere of Venus – is for others to decide. (my English translation).

Wargentin's drawing (Figure 4) presents the aforementioned phenomenon in a somewhat improbable way (is the lower part of Venus dark or is it illuminated?), and with Venus' size completely out of proportion to that of the Sun. Another, earlier, drawing by Wargentin (see Strömer et al., 1761) is presented as *fig.13* in our Figure

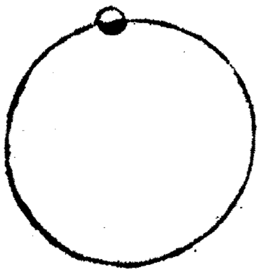


Figure 4: Drawing by P.W. Wargentin (after Wargentin, 1761-1762: 213); see, also, his *fig.13* in Figure 5 below.

5 (see the discussion below) and better illustrates what he actually saw.

From the observatory founded by Anders Celsius in Uppsala, Sweden, astronomer Professor Mårten Strömer (1707–1770) observed the 1761 transit of Venus with a 20-ft non-achromatic refractor. Strömer was assisted by Torben Bergman (see above) and Frederick Mallet (1728–1797), the Professor of Mathematics at the University, who used an 18-in long reflector. Both Strömer and Mallet also saw the arc at ingress and egress and included corresponding drawings in their initial report (see Figure 5 below). This report (Strömer, et al., 1761) is not dated but could be placed in the third quarter of 1761 at the earliest.

Mallet described *fig. 6* in Figure 5 as follows:

> Once Venus was three-quarters of the way onto the Sun, it was noted by all observers that a weak glow or streak surrounded the remaining fourth, to show Venus entirely round (Fig. 6). H. Mallet also saw through the telescope that the Sun extended small fine horns to surround Venus; to begin with he believed these to stem from a small defect in the telescope, as always tends to happen with objects that are close to the horizon or otherwise are covered by thin clouds or fog, but when Venus moved further onto the Sun, the deviations from the Sun's circular figure, which the horns formed, were seen even more clearly. (Strömer et al., 1761: 146; English translation by Dr Andreas Jansson).

Meanwhile, here is Strömer's description of *fig.10*:

> … at 9, 28,0 Venus' edge seemed to him to touch that of the Sun: and when this moment had been written down, and the Sun's edge was again observed at 9, 28,7 it was more open than he had expected (Fig. 10). The Sun's horns *a, b* seemed quite blunt, and one should judge from this that Venus was still entirely inside the Sun's disc – although the Sun's edge was dark or covered. The outer tangent of the Sun's and Venus' edges became uncertain by a ... shaking of the tube, causing the lens to move, so that it is uncertain if the correct focus was found. Venus appeared then no longer connected to the Sun at 9. 46m.15 s. These observations were comparable to those of the others present. (Strömer et al., 1761: 150; English translation by Dr Andreas Jansson).

Subsequently, Strömer et al. (1761: 151) reported that:

> While Venus was exiting the Sun, at first the exiting portion seemed surrounded by a narrow and faint glow: then it did not extend further than a portion of Venus, as the exiting portion increased. Different observers saw the extent of the glow to be of different magnitudes. Before Venus had half exited, which according to H. Stromer appeared to happen at 9. 35 m. 11 sec, the Sun's horns appeared to extend and surround Venus in a similar manner as during the entry: the tips of the Sun's horns always seemed too blunt against Venus' small disc, and when she was about to detach from the Sun, H. Mallet thought that she stuck to the Sun too much against her round shape, but at the end he became aware that Venus' round edge changed into an angular figure (Fig. 12), which to begin with was blunt, but then became pointed. (English translation by Dr Andreas Jansson).

Although Mallet and Strömer did not initially draw the conclusion that the observed phenomena had an atmospheric origin, later Mallet (1766) supported Wargentin's version of such an explanation. Their drawings *6–12* in Figure 5 feature correct proportions, but are somewhat schematic, as shown by the uniform thickness of the arc, and the sharp joining of the arc to the Sun's disc (as also seen in Bergman's drawings, above).

The prominent French astronomer Abbe Jean Chappe d'Auteroche (1722–1769) observed the transit from Tobolsk in the Asian part of Russia

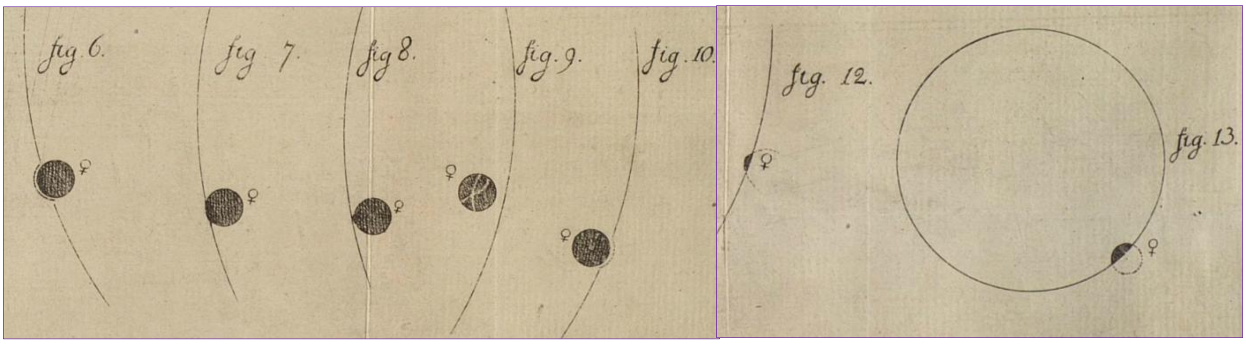


Figure 5: The 1761 transit observations from Upsala, Sweden (after Strömer, et al, 1761: 167).

with a 19-ft non-achromatic refractor. His results were delivered orally to the St. Petersburg Academy of Sciences on 11 January 1762 and published by the Academy shortly thereafter (see Chappe d'Auteroche, 1762). A copy of his report was published in 1763 by the French Royal Academy of Sciences (Chappe d'Auteroche, 1763), and both papers have essentially the same set of illustrations (shown here in Figure 6). During ingress (*Fig. 1* in this Figure) Chappe d'Auteroche (1762: 14) reported:

> …I could see the part of the disc of Venus that had not yet entered [the Sun], and a small ring-shaped atmosphere around this disc … (my English translation).

Similarly, at egress (*Fig. 2* in Figure 6)

> … one can see that part of the disc of Venus which is already out, and a crescent-shaped ring, of which the convex part is turned towards the inferior edge of Venus. (Chappe, d'Auteroche 1762: 15; my English translation).

In Figure 6, Chappe d'Auteroche's *Figs. 3* and *4* show the illuminated crescent structure of Venus at various moments during the transit.

As we have seen, Chappe d'Auteroche claimed to have seen at ingress and egress "… a small ring-shaped atmosphere …" on that part of the disc of Venus that was off the Sun. This luminous arc was described as a very broad crescent roughly a quarter of Venus' radius, but it changed its dimensions and orientation as Venus traversed the Sun. This phenomenon does not match any other observations made during the 1761 transit, or later transits for that matter. In his 1763 report Chappe d'Auteroche attempts to explain the crescent as being part of Venus side-illuminated by the Sun (which stemmed from the argument that the Sun's angular size was significantly larger than that of Venus). However, it is easy to understand, from purely geometrical considerations, that such an illumination cannot be projected on the part of Venus which was outside the Sun's disc. Sharonov (1960: 36) also argues that even while the planet was on the Sun, the zone that would be side-illuminated should seem much thinner and darker than shown in Chappe d'Auteroche's drawings.

Given these improbable observations and explanations, one must question the relatively high degree of credibility attributed to Chappe d'Auteroche's observations in several reviews (e.g., see Meadows, 1966; Link, 1959; 1969; Pasachoff and Sheehan, 2012a). We should note that Chappe d'Auteroche's contemporaries viewed his observations quite differently. For example, a prominent member of the French Royal Academy of Sciences, Baron Frederick Melchior de Grimm (1723–1807), wrote to the encyclopedist Denis Diderot about Chappe d'Auteroche's results:

> … the work has but just appeared, and it is already so decried, that no person of sense will place the least confidence in it. The Academy of Sciences itself hesitates whether it ought in any way to rely upon the astronomical observations which the Abbe has sent from Siberia. Many of our Academicians say that there is good reason to doubt both the accuracy of the observations, and the truth of the report. They are very much led to suspect, on comparing this report with the observations of other astronomers upon different parts of the globe, that the Abbe did not in fact see the transit at all, that the Sun was veiled by clouds during the whole time that it took place, but that not being willing to lose entirely the fruits of his journey, he sat himself down in his room to calculate the probable beginning, progress, and end of the event, and presented these calculations as the result of his observations. This suspicion is probably based upon something that may have stupidly or ignorantly been said by one or other among the companions of our astronomical adventurer. They may perhaps have said, that the Sun did not appear at all that day at Tobolsk; the Abbe himself speaks of his anxiety at this most important moment of his journey, upon seeing the clouds which covered the horizon at sunrise, but then he dwells no less upon his travels when the Sun had dispersed these clouds; he speaks of all this, however, in the perfect tone of a libertine scholar. (Grimm et al., 1850: 378; my English translation).

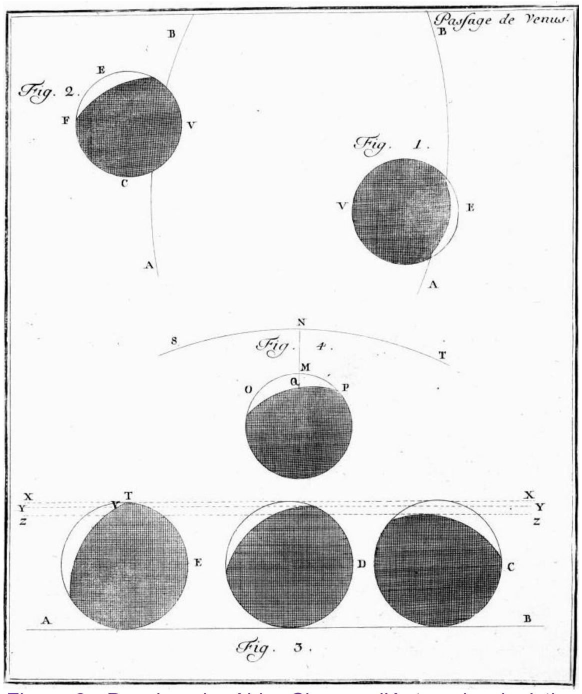


Figure 6: Drawings by Abbe Chappe d'Auteroche depicting the ingress and the egress during the 1761 transit of Venus (after Chappe d'Auteroche, 1762: 23).

We do not know all the arguments used against Chappe d'Auteroche then, but one can suppose that such suspicion could partly be due to his changing the contact times from publication to publication (for example, there is a 7-second difference between Chappe d'Auteroche (1761-1762) and Chappe d'Auteroche (1768)).

Chappe d'Auteroche's skills and experience as a practising astronomer also were questioned in the report of a local Tobolsk authority on how unprofessionally Chappe d'Auteroche handled his 19-ft telescope (see d'Encausse, 2003: 327-329).

Several other observers of the 1761 transit of Venus reported seeing the arc, but they did not provide any drawings. The German Georg Christoph Silberschlag (1731–1790) observed the transit from the 'Kloster Berge' Monastery and published a short emotional note one week later in the popular weekly newspaper *Magdeburgische Privileg Zeitung*:

> It has to be mentioned that when Venus was touching the Sun's inner border, the solar border expanded into a region parallel to Venus' circumference. Experts will ascribe this phenomenon definitively to the action of Venus' atmosphere, in which strong refraction of light must take place. Interesting circumstance! The existence of Venus' atmosphere, which could be claimed to exist only by analogy thus far, is now confirmed by the observation. Venus is certainly a planetary body just like the Earth, especially since high mountains were already observed by Cassini. We add: one could object to the claim that Venus has an atmosphere by pointing out that every solid body will bend light that passes in close proximity, even in a vacuum. However, the refraction was too strong. And as one could see very clearly the transit of Venus over the Sun from the 5th to almost the 7th hour one could also recognize a fringe around the very rotund Venus, which probably cannot be explained by any other reason than the existence of an atmosphere. (Silberschlag, 1761; English translation by Dr Wolfram Fischer).

Eight years later, this report appeared in essentially the same form in a scientific publication (see Kordenbusch, 1769: 55-56). One has to note that besides the arc at egress, which is generally conceded to be an atmosphere-induced phenomenon (*PI*), for several hours Silberschlag also observed a ring around Venus as it transited the Sun's disc (*PIV*), a phenomenon that was not associated with Venus' atmosphere (see the discussion below).

Reverend William Hirst (d. 1774), the Chaplain on one of His Majesty's (i.e., George III's) Ships in the East Indies used a 2-ft reflector to observe the 1761 transit from Madras, India, on behalf of the Royal Society of London (Kapoor, 2013). After the event Hirst wrote to the President of the Society announcing that during the transit he had seen an atmosphere around Venus:

> The morning proved favourable to the utmost of their wishes, which the more increased their impatience. At length, as Mr Hirst was stedfastly looking at the under limb of the Sun, towards the south, where he expected the planet would enter, he plainly perceived a kind of penumbra, or dusky shade … Mr. Hirst is apprehensive, that to be able to discern an atmosphere about a planet at so great distance as Venus, may be regarded as chimerical; yet affirms, that such nebulosity was seen by them, without presuming to assign the cause. They lost sight of this phenomenon as the planet entered the disk, nor could Mr. Hirst perceive it after the egress. (Hirst, 1761: 397-398).

By the time the 1769 transit occurred Hirst was back in England and he carried out successful observations, but what is interesting is that in his report he also refers to his 1761 observation of an atmosphere around Venus:

> … when I took the observation of the transit of Venus at Madras, in the year 1761, I saw *a kind of penumbra or dusky shade, which preceded the first external contact two or three seconds of time, and was so remarkable, that I was thereby assured the contact was approaching, which happened accordingly* ... (Hirst, 1769: 231; his italics).

The distinguished Russian scientist and University of St. Petersburg Professor, Stepan Rumovsky (1734–1812) observed the transit from Selenginsk (east of Lake Baikal) with a 15-ft non-achromatic refractor and briefly commented (in just one sentence) that at egress "… the leading edge of Venus seemed to be surrounded by a circle of light." (Rumovsky, 1762; my English translation).

There is a short note by Lomonosov (in Vavilov and Kravets, 1950-1983(X): 577) that another noted Russian astronomer, Academician Nikita Ivanovich Popov (1720–1782), also saw Venus' atmosphere when he observed the transit from Irkutsk, but no details were found in Popov's recently-discovered logbooks and unpublished reports (see Kuznetsova, 2009).

The well-known French astronomer, Pierre Charles Le Monnier (1715–1799), observed the transit from the Chateau de Saint-Hubert at Perray-in-Yvelines (near Paris) in the presence of the King. He used an 18-ft non-achromatic refractor. In his report on the transit, Le Monnier (1763) mentions that:

> ... the Sun was always perfectly clear, and often too bright as the glass has been very lightly smoked, and there was no glimpse of an atmosphere around Venus, not even during the final moments of the transit, when the Sun was most fiery … [At egress] however, I saw for a minute or two the entire disk of Venus, although it was already partly out of the Sun, but I was not certain as to the duration of this appearance … (my English translation).

It is notable that Le Monnier (a) expected that the atmosphere of Venus would appear while the planet was on the Sun, yet he did not see any aureole or penumbra; and (b) was the only astronomer known, besides Lomonosov, who specifically mentioned using a lightly-smoked glass (i.e. a weak solar filter).

3.2 Observations of an 'Atmosphere' During the External Contacts (*PII*)

Currently, there is still no complete agreement on whether the disturbance of the solar limb during the external contacts is an indication of Venus' atmosphere. Given how short the moment is, it is not surprising that very few observers reported it.

The Russian scientist Joseph Adam Braun (1712–1768) from the St. Petersburg Imperial Academy of Sciences observed the blurriness with an 8-ft non-achromatic refractor but doubted its relation to Venus' atmosphere, perhaps in response to the claims by his fellow St. Petersburg Academician, Lomonosov:

> As far as the beginning is concerned, what I particularly noticed as the disc of Venus began to lose its rotundity, when Venus began to enter [the Sun], it did not appear as in progress, perfectly black and round, but was rather dark, irregular, and rough, perhaps the cause was the vapors in the atmosphere, yet I hesitate to attribute this irregularity to the atmosphere of Venus. (Hell, 1762: 92-94; my English translation).

3.3 A Circular 'Atmospheric' Ring Around Venus While it was on the Sun (*PIV*)

The most popular category of the 1761 reports in which the word "atmosphere" occurs—and more than a dozen by my count—related to observations of 'rings' around Venus while it was fully on the disc of the Sun. The large number of such reports is presumably related to widespread expectations of how the planet's atmosphere would manifest itself (see the discussion on Le Monnier above), and the fact that Venus spent many hours transiting the Sun (contrary to the relatively short ingress and egress periods of less than 20 minutes), and to the fact that in the eighteenth and nineteenth centuries such aureoles were observed during transits of Mercury (which has no atmosphere), as Sharonov (1960) has noted.

The phenomenon is not predicated by current models of refraction in Venus' atmosphere (Garcia-Muñoz and Mills, 2012), and should most probably be attributed to imperfections of the optical instruments rather than being related to atmospheric effects (see Meadows, 1966). The illusive nature of the *PIV* phenomenon can be concluded from the great variety of observational results: the aureole looked like a bright ring to some (e.g. Dunn, 1761-1762); a dark penumbra to others (e.g. Ferner, 1761-1762); a pale red ring (e.g. Maraldi, 1763); a very broad cloud-like aureole up to one-quarter of Venus' diameter (e.g. Rohl, 1762); or a thin aureole only 1/400 of the planet's diameter (e.g. Dunn, 1761-1762). Among others who noticed an 'atmospheric ring' around Venus during the transit were Desmares and de Mairan (see d'Auteroeche, 1763: 365), Fouchy (1763), Hellant (1761) and Planman (1768).

The Professor of Astronomy at Greifswald University in Germany, Lambert Heinrich Röhl (1724–1790), observed the transit from near Greifswald with a 16.5-ft non-achromatic refractor and noted the full spectrum of luminous phenomena: a penumbra-type ring around Venus while the planert was on the solar disc (*PIV*); the formation of a 'hump' on the solar limb at 3rd contact (*PI*); and a disturbance of the solar limb at the end of the egress (*PII*) (Röhl, 1762). Some of these are shown in Figure 7, below, where *Fig. II* explains the phenomena at external contact; and *Fig. III* shows the formation of the 'hump' at 3rd contact. *Fig. IV* illustrates the effects seen at egress. Röhl concluded:

> But what immediately emerged from the observations was an amazing depth of knowledge about the atmosphere of Venus, which is one quarter the diameter of the planet and therefore is significantly bigger in comparison to the Earth's atmosphere of several miles; also a slight refraction of rays reveals the atmosphere of Venus. Horizontal refraction on Venus exceeds ten seconds. All this seems to agree very well with nature. Of course, one may conclude by analogy, that the action of the atmosphere exposed to the nearby solar rays is greater and that refraction of light diminishes with ascending height. (Röhl, 1762: 12; my English translation).

The physics of the refraction leading to the observed effects is shown in good detail in Figure 7, but the abnormal thickness of the presumed atmosphere of about one quarter the diameter of Venus most probably indicates serious optical imperfections in the telescope. In a subsequent publication Röhl (1768) discusses the 1761 results in more detail, and he reviews the many other aureole observations that he was aware of.

3.4 Observations of the 'Atmosphere' During the 1769 Transit of Venus

The last transit of Venus in the eighteenth century took place eight years later, on 3 June 1769. The 1761 indications of a Venusian atmosphere, although not widespread, did not go unnoticed, and several reviews on the subject were published (e.g. see Chappe d'Auteroche,

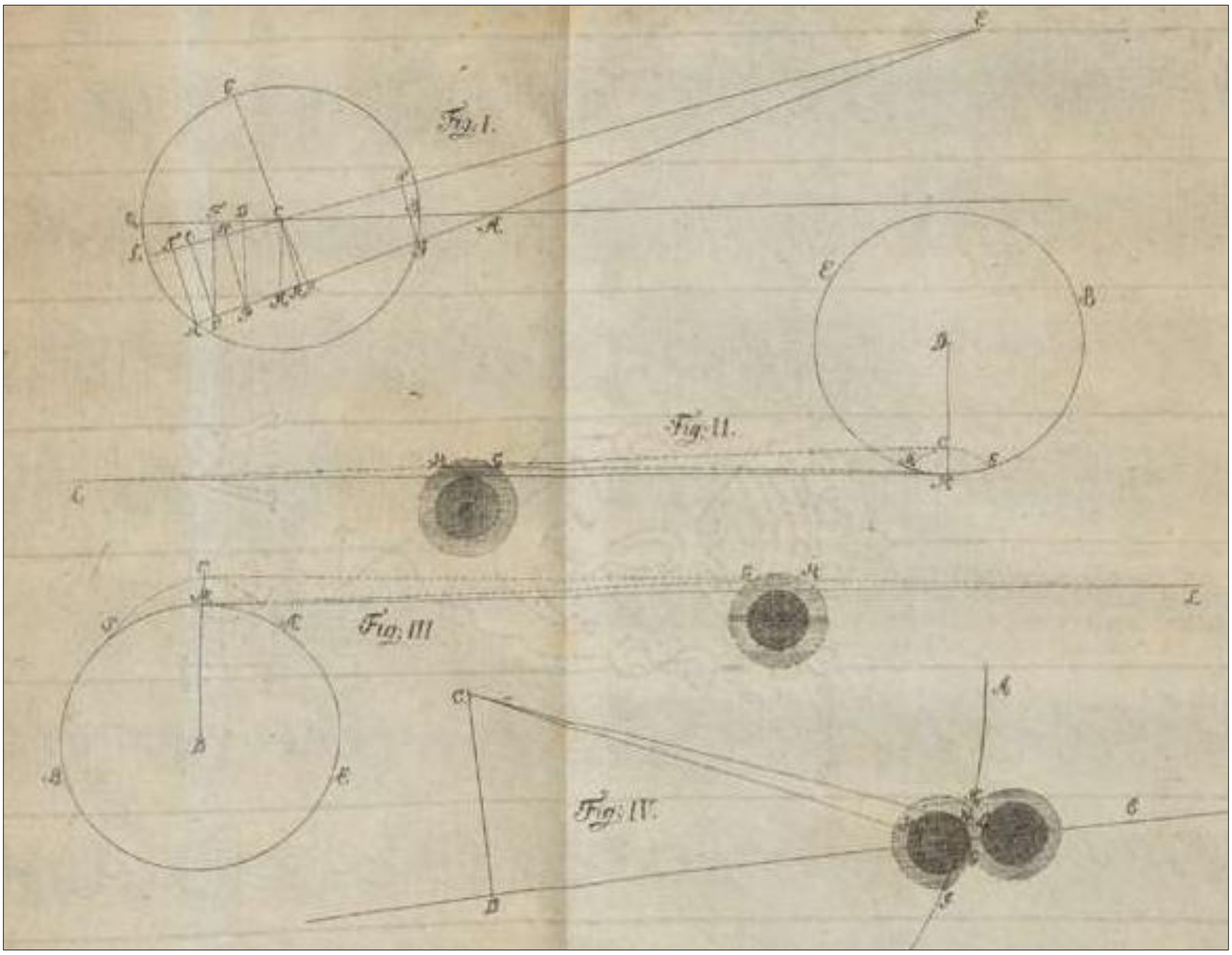


Figure 7: Evidence of an atmosphere around Venus, as observed by Lambert Heinrich Röhl (after Röhl, 1762: 13).

1763; Röhl, 1768). The phenomenon was deemed worthy of further exploration, and was discussed by Rumovsky (1771: 41-56) and Maskelyne (1768) in preparation for the 1769 transit. Stepan Rumovsky's instructions written and accepted in 1767-1768 essentially summarized Lomonosov's experience with observing the atmosphere and called for observers to adopt relaxed positions for the body and to make observations with well-rested eyes. British Astronomer Royal Nevil Maskelyne (1732–1811) paid serious attention to the procedures for the fabrication of smoked-glass filters for use in 1769. As a result, many more observations of phenomena *PI–PIV* were reported after the transit. Below only a few of the results are presented, which will be relevant to the discussion in Section 5.

The renowned American self-taught astronomer, David Rittenhouse (1732–1796), observed the transit at Norriton, near Philadelphia, with a 36-ft focal length 3-inch aperture non-achromatic refractor, and saw outward-looking pyramids of light around the planet after it advanced about one third of its diameter onto the Sun (see Figure 8). This unusual structure broadened and spread completely around the circumference of Venus that was off the Sun after the middle of the ingress and got brighter as the second (internal) contact approached. Rittenhouse provided the following detailed description:

> When the Planet had advanced about one third of its diameter on the Sun, as I was steadily viewing its progress, my sight was suddenly attracted by a beam of light, which broke through on that side of Venus yet off the Sun. Its figure was that of a broad-based pyramid; situated at about 40 or 45 degrees on the limb of Venus, from a line passing through her center and the Sun's, and to the left hand of that line as seen through my telescope, which inverted. See TAB.XV. fig.1 - About the same time, the Sun's light began to spread round Venus on each side, from the points where their limbs intersected each other, as is likewise represented in fig.1. As Venus advanced, the point of the pyramid still grew lower, and its circular base wider, until it met the light which crept round from the points of intersection of the two limbs; so that when half the Planet appeared on the Sun, the other half was entirely surrounded by a semicircular light, best defined on the side next to the body of Venus, which constantly grew brighter, till the time of the internal contact. See fig.2. Imagination cannot form any thing more beautifully serene and quiet, than was the air during the whole time; nor did I ever see the

> Sun's limb more perfectly defined, or more free from any tremulous motion; to which his great altitude undoubtedly contributed much. When the internal contact (as it is called) drew nigh foresaw that it would be difficult to fix the time with any certainty, on account of great breadth and brightness of the light which surrounded that part of Venus, yet off the Sun. After some consideration, I resolved to judge as well as I could of the co-incidence of the limbs; and accordingly gave the signal for the internal contact at 2h28'45" by the clock, and immediately began to count seconds, which any one, accustomed to it, may do, for a minute or two, very near the truth. In this manner, I counted no less than 1'32" before the effects of the atmosphere of Venus on the Sun's limb wholly disappeared, leaving that part of the limb as well defined as the rest. (Smith et al., 1769: 310-312).

Rittenhouse did not offer any explanation for these observations. The outward-looking ray-like fractured-light aureole (a bunch of wide rays of light) as Rittenhouse described is not how refracted light is supposed to be shaped, and essentially has not been seen in an identical form by any other observer over the past six transits. Still there might be grounds for some scholars to qualify Rittenhouse's observations as the *PI* phenomenon accompanied by some optical illusions (e.g. see Pasachoff and Sheehan, 2012a). Rittenhouse's drawings are of high quality and in correct proportion, so the height of the 'light pyramids' can be estimated to be 4″-11″.

One of Rittenhouse's collaborator was John Lukens (1720?–1789), the Surveyor-General of Pennsylvania and Delaware, and he noticed "… a large tremulous shadow …" at the point of the 1st (external) contact (phenomenon *PII*), and very briefly described "…a border of light encompassing the part of her (Venus) that was yet off the Sun …" (phenomenon *PI*). Another collaborator, Dr William Smith (1727–1803) the Provost of the College (later University) of Pennsylvania, also reported seeing phenomenon *PII* at the external contact, and *PIII* similar to that observed by Lomonosov prior to internal contact:

> … as to the internal contact, the thread of light, coming round from both sides of the Sun's limb, did not close instantaneously, but with an uncertainty of several seconds, the points of the threads darting into each other, and parting again, in a quivering manner, several times before they finally adhered. (Smith et al., 1769: 315).

He also analyzed a tremulous motion at the point of the external contact (*PII*) as follows:

> … as for the first disturbance made on the Sun's limb, it may be worth considering, whether it was really from interposition of the limb of Venus or of her atmosphere? The former, one could not easily imagine it to be, unless her limb and body were more uneven than they appeared to be seen on the Sun. An atmosphere it might more probably seem to be, not only from the faintness of the colour, but the undulatory motion, which might arise from the growing density of the atmosphere, as it pushes forward on the Sun, varying the refraction of the rays. If such an atmosphere be allowed, then it probably gives the same tremulous motion, at the internal contact, to the thread of light creeping round Venus; and prevents its closing quietly till the atmosphere (or at least its densest part) be wholly on the Sun; and consequently the true coincidence of the limbs be past. For though the atmosphere of Venus can not be seen on the Sun, yet part which is surrounding, or just entering on the Sun's limb, having, as it were, a darker ground behind it, may be visible. But these are only little conjectures submitted to others; though if they have any foundation, it would make some difference in the time estimated between the contacts. (Smith et al., 1769: 316-317).

The Royal Observatory's Charles Green (1735–1771) and career Naval officer Lieutenant James Cook (1728–1779) were the two official astronomers on the expedition organised

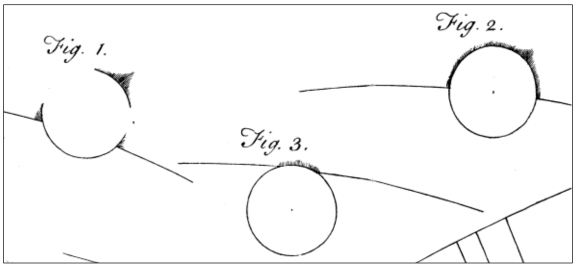
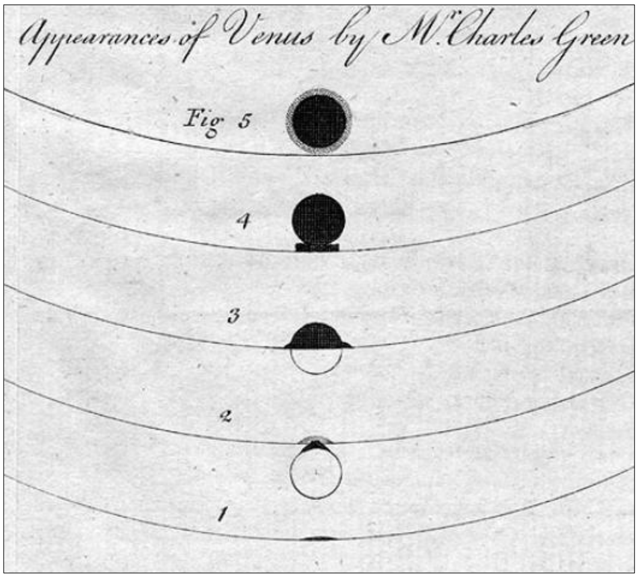


Figure 8: David Rittenhouse's 1769 drawings of the ingress (after Smith et al., 1769: plate XV 311).

by the Royal Society (of London) to observe the 1769 transit from "King George's Island in the South Sea" (Tahiti), but they were assisted by a number of other officers and supernumeraries from *H.M.S. Endeavour* located at three different observing sites on or just off the coasts of Tahiti and Morea (for details see Orchiston, 2005). Green later died at sea on the passage home from Batavia (now Jakarta) and all the astronomical observations apparently were prepared for publication by Cook with assistance from Nevil Maskelyne (the Astronomer Royal). Even though eleven different individuals successfully observed the transit, for some unexplained reason observations made by only three of them (Cook, Green and one of Joseph Banks' retinue, the botanist Daniel Solander) were included in the paper that was published in the *Philosophical Transactions of the Royal Society*. In this paper Green and Cook (1771) reported seeing a pale waterish penumbra of a thickness about 1/8th of Venus' semidiameter around the planet while it was on the Sun (*PIV*), and possibly phenomenon *PII* (disturbance of the solar limb



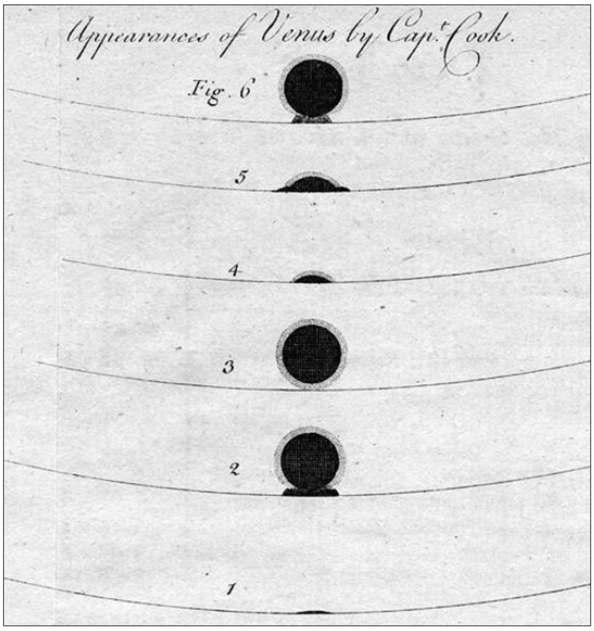


Figure 9: Drawings of the 1769 transit of Venus as observed from Tahiti by Green (left) and Cook (right) (after Green and Cook, 1771: 410).

at external contact) during the ingress—see Green's Figure 4 in our Figure 9 above.

Maskelyne (1769: 357-359, 363) also observed the transit from the Royal Observatory at Greenwich, and he clearly saw the arc (*PI*) but did not see the aureole (*PIV*):

> It had been thought by some, that Venus' circumference might probably be seen in part at least, before she entered at all upon the Sun, by means of the illumination of her atmosphere by the Sun; I therefore looked diligently for such an appearance, but could see no such thing.
>
> I was also attentive to see if any penumbra or dusky shade preceded Venus' first impression on the Sun at external contact, such a phenomenon having been observed by the Rev. Mr. Hirst, F.R.S. at the former transit of Venus, in 1761, which he observed with much care and diligence at Madras, in East-Indies; but could not discern the least appearance of that kind … When Venus was a little more than half immerged into the Sun's disc, I saw her whole circumference completed, by means of a vivid, but narrow and ill-defined border of light, which illuminated that part of her circumference which was off the Sun, and would otherwise have been invisible. This I might probably, have seen sooner, if I had attended to it ...
>
> An ingenious gentleman of my acquaintance having desired me to examine if there was any protuberance of the Sun's circumference about the point of the internal contact, as he supposed such an appearance ought to arise from the refraction of the Sun's rays through Venus' atmosphere, if she had one; I carefully looked out for such a circumstance, but could see no such thing; neither could I see any ring of light around Venus, a little after she was got wholly within the Sun: but, I confess, I did not re-examine this latter point afterwards, when she was further advanced upon the Sun, at which time other persons at the observatory saw such an appearance … How far the ring of light, which I saw round that part of Venus' circumference which was off the Sun, during the immersion, may deserve to be considered as an indication of an atmosphere about Venus, I shall not at present inquire; but I think it very probable, that the protuberance, which disturbed Venus' circular figure at the internal contact, was owing to the enlargement of the diameter of the Sun, and the contraction of that of Venus, produced by the irregular refraction of the rays of light through our atmosphere, and the consequent undulation of the limbs of the two planets.

Notably, Maskelyne is quite cautious in attributing the arc to Venus' atmosphere, while he implied that the black protuberance at and after the internal contact (phenomenon *PV*)—now referred to as the 'black drop effect' (see Schaefer, 2001)—is due to turbulence in the Earth's atmosphere.

Maskelyne had invited a group of experienced observers to view the transit with him, and they produced a wide variety of descripttions, with some seeing and some not seeing the *PI, PII* and *PIV* phenomena (Meadows, 1966). One of them, the Reverend William Hirst (who observed the 1761 transit from Madras in India) also observed "… a violent coruscation, ebullition, or agitation of the upper edge of the Sun …" five or six seconds before 1st contact (see Figure 10), very much like Lomonosov's phenomenon *PII.* What made Hirst (1769) believe that the effect was not an optical deception, but perhaps was due to Venus' atmosphere, was that the remaining parts of the Sun's limb, at and beyond points *a* and *b*, remained perfectly quiescent.

3.5 Summary of the Observations of the Atmospheric Effects in 1761

Four different types of aureole phenomena were observed during the 1761 transit. More than a dozen observers reported seeing either a bright or pale penumbra around the disc of Venus while the planet was on the Sun's disc (*PIV*), a phenomenon that cannot be attributed to the atmosphere. Very few saw light radiances at the very time of internal contact, (*PIII*), a phenomenon that could in principle be caused by Venus' atmosphere, but much more convincingly was attributed to telescope imperfections or optical illusions. Similarly, the appearance of tremulous motion on the edge of the Sun prior to the point of external contact (phenomenon *PII*) could hardly be accepted as an indication of the planet's atmosphere with any high degree of certainty. Contrary to phenomena *PIV*, *PIII* and *PII*, the observation of the arc of light outlining the part of Venus' disc off the Sun during ingress or egress (*PI*) assumes "… seeing an arc of light at the place where there should be nothing (black background) if the atmosphere is absent …", and, therefore, can be considered as a true manifestation of Venus' atmosphere, as it is now understood and modeled from the first principles of physics (see Garcia-Muños and Mills, 2012). Slight variations in the observed features of the phenomenon (full arc or partial arc, 'whiskers', different degrees of brightness) could be attributed to differences in the instruments and methods used, namely the type of telescope, the aperture of the objective lenses, the attenuation of the solar filters, etc. Finally, the 'black drop effect' (phenomenon *PV*) was reported by many eighteenth century observers and was already understood to be an artificial, purely optical, nuisance that bore no relation to Venus' atmosphere.

Table 1 summarizes all reports known to the author of sightings of the arc (phenomenon *PI*) during the 1761 transit, and three 1769 observations relevant to the discussion in Section 5 below. The table contains information about the instruments and methods used (telescope types: 'A' = achromatic refractor, 'N' = non-achromatic refractor, 'R' = reflector, with the length in feet; the aperture of the objective and the type of solar filter; thickness of the observed luminous arc off the Sun's disc where illustrations are provided, which serves as an indicator of the quality of the instrument and, of course, of the seeing at the time of the observation); date of publication (the first communication which in most cases reflects the time of the report's submission and the time of publication of the original scientific report); quality of the report and of the atmosphere question (length of the report and length of the atmosphere discussion, number of Illustrations, depicted ratio of Venus-to-Sun diameters as an indication of the quality of illustrations), depth of the physics reasoning for a presumed atmosphere of Venus (whether refraction in Venus' atmosphere is mentioned, and whether a detailed explanation of refraction-induced phenomena has been offered).

Let us see how different observers fare using these criteria.

Quality of the Instruments and the Methods: seemingly all the observers except Green had instruments sufficient for the arc observation. Nevertheless, assuming approximately similar objective lens diameters (~2"–3"), the equivalent chromatic and spherical aberrations occur in achromatic refractors, which are about 16 times shorter than non-achromatic refractors (Maksutov, 1979). In 1761, the achromats were a relative novelty: according to Newcomb (1891), out of 97 reports of the 1761 transit, a majority (47) used non-achromats, 25 employed reflectors, and only 3 had achromatic refracting telescopes which had recently been made available by Dollond (the remaining 22 optical systems were not identified). Therefore, one might expect that Lomonosov's 4½-ft long achromat was capable of outperforming all the listed non-achromats of between 12 and 36-ft focal length. The fact that the thickness of the arc observed by Lomonsov (about 3.7″) is the smallest among the various reports supports this conclusion. Also, only Lomonosov and Le Monnier specifically mentioned using weak solar filters—the method critically helpful to assure observation of the arc, as shown in the 2012 replication experiment (Koukarine, et al., 2012). So, overall, one can consider Lomonosov to have had an advantage in the quality of his instruments and methods.

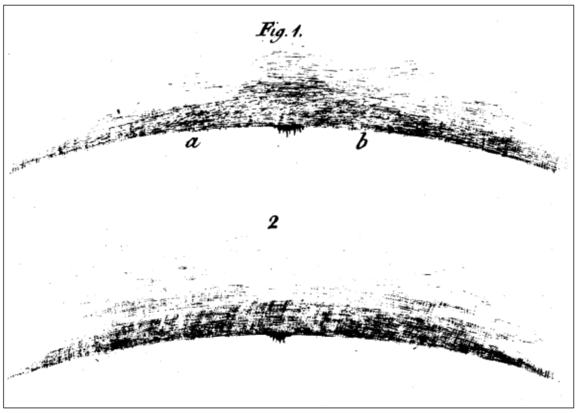


Figure 10: Phenomena recorded by William Hirst preceding the 1st (external) contact during the 1769 transit of Venus (after Hirst, 1769: 229).

Time of Publication: although we list the dates of the first recorded communications on the subject, they probably are not that relevant due to the diversity of media used (private communications, reports, newspaper notes). Seemingly all the listed observers immediately appreciated any unusual effects they observed and communicated them one way or another. (As an exaggeration,

Table I: Summary of 1761 and 1769 transit of Venus observations reporting a luminous arc off the Sun at ingress and/or egress.

	1761										1769 (some)		
	Lomonosov	Bergman	Wargentin	Chappe D'Auteroche	Mallet	Strömer	Silberschlag	Hirst	Rumovsky	Le Monnier	Green	Rittenhouse	Maskelyne
Telescope	A, 4½	N, 21	N, 19	N, 19	R, 1½	N, 20	N,12/ 24	R, 2	N, 15	N, 18	R, 2	N, 36	R, 2
Aperture	2.1″ - 2¾″ (?)	No data	1.75″	2″	No data	No data	No data	No data	No data	No data	No data	3″	No data
Filter	Weakly smoked glass	Green & weak red glass	Smo-ked glass	No data	Green glass	Red glass	No data	No data	No data	Lightly smoked glass	No data	Deeply smoked glass	Smok-ed glass?
Arc thick-ness	~3.7″	~5.7″	--	off/on Venus 5-7.5″	4-5″	5-6″	--	--	--	--	no arc, 8″ penum-bra	Pyra-mid 4″-11″	--
1st commun-ication	June 07	Aug. 28	June 09	Aug. 24	--	--	June 13	July 01	Apr. 26, 1762	June 10	Apr 13, 1770?	July 18	--
1st scientific. publication	July 15	Nov. 19	Nov. 12	Jan. 11 1762	Q3 1761	Q3 1761	1769	Apr. 22 1762	July 08, 1762	1763	Nov. 21 1771	1769	June 15 1769
Report Length (pp.)	17	5	6	22	8	8	2	3	28.	5	25.	14	12
Information on the arc	3 pp.	½ p.	4 lines	½ p.	9 lines	12 lines	½ p.	8 lines	11 lines	9 lines	1 p.	~1 p.	2 pp.
Illustrations	8	6	1	4	1	1	None	None	None	None	5	4	None
Venus/Sun diameter	1:32	1:10	1:9	1:7	1:30	1:30	--	--	--	--	1:31	1:32	--
Refraction explained	Yes	No	No	No	No	No	No	No	No	No	No	No	No
Reconstruc-tion	2012	--	--	--	--	--	--	--	--	--	--	--	--

one could claim that the first who saw the arc was Stepan Rumovsky as his station was the furthest eastward). Following the generally-accepted rules regarding priority in science, which consider only the time of the publication of the first scientific report, it seems clear that Lomonosov was the first to formally publish a paper with observational data of the aureole interpreted as evidence for Venus' atmosphere. This should be sufficient to establish his priority of discovery.

Comprehensiveness and the Quality of the Scientific Report: Although the total length of Lomonosov's 1761 report is second only to Rumovsky's (17 vs 28 pages), it is much more important to consider how detailed is the discussion of Venus' atmosphere, as that alone shows appreciation of the importance of the observation by the observer. Seemingly, the arc was considered as a nuisance by Hirst, Le Monnier, Rumovsky and Wargentin, as they only allocated several lines of text to a description of the phenomenon. Bergman, Chappe d'Auteroche, and Silberschlag were a little more expansive as they not only dedicated about half a page to the effect, but the first two also illustrated their observations with one or more drawings. Still, in that regard, Lomonosov's report is an absolute leader: not only did he elaborate at length on the effects due to Venus' atmosphere, but he also provided eight drawings to better explain his observations and reasoning. Moreover, his drawings are of amazing accuracy as indicated by the correct ratio of the diameters of Venus to the Sun, so one can use them with conviction for scientific data processing (as Sharonov did in 1952). The drawings by Bergman, d'Auteroche and Wargentin are given mostly for illustrative purposes, and show the observed phenomena out of proportion. Note that the drawings of the 1769 transit by Rittenhouse and Green are of high quality and trustworthy, too, and the 1769 report by Maskelyne contains an equally-detailed description of the phenomena. One can presume that such an attention to detail in 1769 was due to awareness by the astronomers of the potential appearance of Venus' atmosphere, an advantage which neither Lomonosov nor any of the other 1761 observers enjoyed.

Depth of Physics Reasoning for the Atmosphere of Venus: Among the 1761 observers of the arc, only Lomonosov, Silberschlag and Wargentin concluded that the arc is caused by refraction of sunlight through the atmosphere of Venus, the last-mentioned with some caution, and the first two astronomers in a much more assured way. Lomonosov's advantage in this category is unquestioned, as he is the only one to give a correct physical explanation of refracttion, with illustrations and detail matching that shown in modern optics textbooks.

Replication of the Observation: Finally, it has to be taken into account that only Lomonosov's observation was successfully replicated during the transit of 2012, and a thin arc of light on that part of Venus off the Sun's disc during the ingress (*PI*) was successfully detected with original eighteenth-century Dollond achromatic refractors similar to that deployed by Lomonosov, and with his experimental techniques carefully emulated (e.g., lightly-smoked glass filters, and periodic rest for the eyes to maintain sensitivity; see Koukarine et al., 2012).

Therefore, the detailed analysis of all optical effects observed during the 1761 transit of Venus shows that only 9 astronomers (with two possible additional ones, Chappe d'Auteroche and Popov, still classed as doubtful) actually saw the aureole caused by refraction of sunlight in the atmosphere of Venus during ingress or egress. Of all of them, Lomonosov should be credited with priority for the discovery because he:

(1) expeditiously and formally published his scientific results;
(2) was one of the few to understand the effect and was the only one to offer an in-depth physics explanation of the aureole due to refraction in the atmosphere of Venus; and
(3) displayed comprehensiveness and quality in his scientific reporting, for his description of critically-important methods (e.g. the use of a very weak solar filter with an achromatic telescope) allowed replication of his discovery more than two and a half centuries later.

Note that the first two arguments listed above were laid out long ago by Perevozshikov (1865), Sharonov (1952b; 1960) and Chenakal and Sharonov (1955).

4 FURTHER DEVELOPMENTS DURING THE EIGHTEENTH, NINETEENTH AND TWENTIETH CENTURIES

The present version of the situation was far from being commonly accepted in the eighteenth and nineteenth centuries. The main reasons for the doubt were: (a) the subtleness of the *PI* effect, which required special conditions and adequate instruments and methods of observation to guarantee its detection; and (b), the relative irreproducibility of the observations due to the infrequency of transits of Venus.

4.1 The Discussion of Venus' Atmosphere Between the 1769 and Nineteenth Century Transits

Most astronomers were not prepared to accept the observations of luminous phenomena reported during the eighteenth century transits as definite proof of an atmosphere around Venus.

They were deterred by the fact that these observations were far from common (only about a dozen out of hundreds of observations) and by the discrepancies between different reports (not one, but four different phenomena: *PI-PIV*). At that time there also was no theory to explain refraction in Venus' atmosphere and predict what effects should be observable. As a result, most late eighteenth century and early nineteenth century astronomy textbooks either ignored the luminous effects seen during the transits (e.g. see Bailly, 1785: 109; Fergusson, 1785: 498) or else explained them as optical illusions (see Dunn, 1774: 32). The Lowndean Professor of Astronomy at Cambridge University, Roger Long (1680–1770) was one of the very few to support the presence of an atmosphere around Venus as a result of the transit observations, and he considered reports such as those by Chappe d'Auteroche, Dunn and Hirst as a proof (with some doubts about Chappe d'Auteroche's crescents), even though their evidence was not in accord with the understanding of the physics of such phenomena that prevailed at this time (see Long, 1774: 580).

In his *Astronomie*, France's foremost astronomer, Jérôme Lalande (1732–1807) was noncommittal on the issue. He did not see any ring of light around Venus when he observed the 1761 transit, but he was aware of the observations by Chappe d'Auteroche, Fouchy, Le Monnier and Wargentin "… that would lead one to prejudge the atmospheres of the planets of the system, if the ring could not be explained by purely optical reasons …" (Lalande, 1792: 561), an obvious reference to phenomenon *IV* which indeed is purely an optical illusion. Lalande's doubts were well known to and cited by Johann Hieronymous Schröter (1745–1816), Germany's leading observational astronomer, who offered somewhat less disputable evidence of a Venusian atmosphere during observations of the extension of the cusps of Venus by some 4.5° (see Schröter, 1792). However, Schröter's paper also reported obserations of an atmosphere around the Moon (which is non-existent) and gigantic mountains on Venus which extended above its ca. 67-mile high atmosphere (which again was wrong). Meanwhile, England's foremost observational astronomer, William Herschel (1738–1822) strongly criticized Schröter's numerical estimates, but he did agreed with his qualitative conclusion that it was the atmosphere of Venus which caused the extensions of the cusps (Herschel, 1793). One could not say that such an observation had convinced everybody, possibly because both observers made a number of very debatable claims in the course of their careers. We have already mentioned the excessively-high mountains on Venus supposedly seen by Schröter, while Herschel firmly believed that the Sun had a luminous atmosphere and solid habitable ground below, which sometimes was seen by looking down through sunspots (Kawaler and Veverka, 1981). The doubts and confusion over the issue of a Venusian atmosphere were quite obvious to others,[3] and it is telling that John Herschel (1792–1871), William's son, used neither the transit observations of the luminous arcs/rings nor his father's and Schröter's reports on the extension of the cusps when he wrote about Venus in his popular textbook, *Outlines of Astronomy* (Herschel, 1849). Instead he merely inferred the existence of an atmosphere from the lack of permanent surface details—a qualitative argument that was easy to prove and by that time had been known already for about a century.

4.2 The Atmosphere of Venus During the Nineteenth Century Transits

Better instruments and methods of observation in the nineteenth century allowed many more astronomers to observe the arc of light (*PI*) at in-

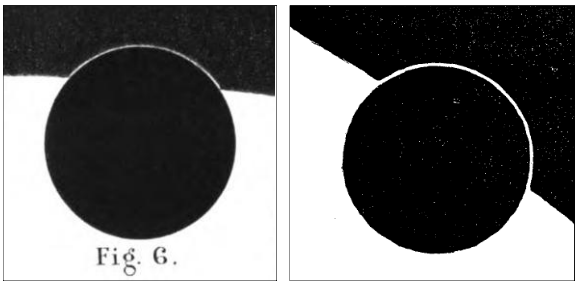


Figure 11: On the left is H.C. Russell's drawing of the arc of light around Venus during the egress phase of the 1874 transit (after Russell, 1883: Figure 6), and on the right is C.L. Prince's drawing of "…the planet's atmosphere shortly before internal contact …" during the 1882 transit (after Prince, 1883).

gress and/or egress during the 1874 and 1882 transits.[4] The appearance of the atmosphere at ingress or egress was not a surprise anymore, and many observers studied the phenomenon in detail. In Australia, Sydney Observatory Director, Henry Chamberlain Russell (1836–1907) observed the 1874 transit with a 12½ ft refractor of 11.5 inches aperture (reduced to 5 inches for the visual observations) and a magnification of 100× (Russell, 1883). He experimented with filters of different strengths and colors, and had no difficulty observing the arc (see Figure 11).

Many of Russell's New South Wales colleagues left quite detailed descriptions and drawings of the phenomena observed at ingress and egress (for details see Orchiston, 2004), and most of these were published by Russell (1883) in his report of observations by professional and amateur astronomers and Government and University of Sydney scientists associated with Sydney Observatory's 1874 transit program. It is interesting that many of the drawings included in this report are exactly like, or very close, to what Lomonosov and others saw during the eighteenth century transits. For example, drawings similar to Lomonosov's *PI* (the arc, full or partial) were provided by A.W. Belfield (Figures 1 and 3 in Plate IV), Captain Arthur Onslow (Figures 14 and 15 in Plate II), Archibald J. Park (Figures 5 and 6 in Plate IV), Russell (Figures 6 and 7 in Plate II) and L. Abington Vessey (Figures 3, 4, 5, 11 and 12 in Plate III). Robert Ellery (1827–1908), the Director of Melbourne Observatory, also published drawings reminiscent of *PI* (see Ellery, 1883: Figures 1, 2 and 14 in Plate I), as also did Australia's foremost nineteenth century astronomer, John Tebbutt (1834–1916; see Orchiston, 2002) who observed the transit from his privately-maintained Windsor Observatory near Sydney (see Tebbutt, 1883: Figures 8, 9 and 13 in Plate IV). However, in most of these drawings the thickness of the arc is significantly smaller than that observed during the eighteenth century transits, which is a clear sign that the astronomers were using larger aperture telescopes. Still there were some contradictory observations. For example, the experienced New South Wales amateur astronomer William J. Macdonnell (1842–1910) observed an arc as thick as the one shown in Bergman's 1761 drawings, but with some subtle ray-like structure which is reminiscent perhaps of the rays reported by Rittenhouse in 1769 (see Russell, 1883: Figure 7 in Plate IV). Meanwhile, during the very early moments of the egress, Sydney University's Professor Archibald Liversidge (1846–1927) saw the part of Venus that already was off the Sun's disc fully illuminated (see Russell, 1883: Figures 16 and 17 in Plate II), a phenomenon that probably is similar to Lomonosov's *PIII*. Some observers reported seeing a broadening of the luminous arc in Venus' polar regions, often in the form of a small, broad-based inward-pointed pyramid.

Many more similar reports were published after the transit of Venus on 6 December 1882 (e.g. see Eastman, 1883; Langley, 1883; Prince, 1883), and an attempt to develop further the theory of refraction of solar rays in the atmosphere of Venus during the transit was published by Johns Hopkins University's Professor Charles Sheldon Hastings (1848–1932) in 1883. It is noteworthy that Otto Wilhelm von Struve (1819–1905), the Director of Pulkovo Observatory in St. Petersburg, attempted to observe the 1874 transit with old Dollond telescopes that previously were used by Russian expeditions during the eighteenth century transits (see Abalakin et al., 2009).

4.3 Twentieth Century Discussions, and the 2004 Transit

There were no transits in the twentieth century, so most of the discussions on the subject of the atmosphere aureole were based on reports from previous transits. At the same time, knowledge about the atmosphere of Venus expanded immensely due to new methods of research. Spectroscopy, radio astronomy and space probes uncovered many mysteries of Venus' CO_2-dominated atmosphere, and scientists were able to learn a lot more in the second half of the twentieth century than in the previous 350 years of telescopic observations (see Marov and Greenspoon, 1998). The circumstances surrounding the discovery of the atmosphere in 1761 were discussed by several researchers, including O. Struve, V. Sharonov, F. Link and A.J. Meadows. None of these astronomers saw the phenomenon themselves, and often they based their interpretations of the eighteenth century reports on their own understanding of the various effects in the planet's atmosphere. Many were not aware of the details of Lomonosov's paper as it had not been properly translated into English. Nevertheless, in general we can see a growing appreciation of Lomonosov's discovery, and his observation of the arc during the transit (phenomenon *PI*) was eventually named the 'Lomonosov Effect' (Sharonov, 1952a) or 'Lomonosov's Phenomenon' (Sharonov, 1952b; cf. Link, 1969) and, later, 'Lomonosov's arc' (Tanga, et al, 2011; 2012).

Otto Struve (1897–1963), a US astronomer and grandson of Otto Wilhelm Struve (Director of Pulkovo Observatory in St. Petersburg at the end of the ninerteenth century), in 1954 published a very sympathetic article about Lomonosov in *Sky and Telescope* magazine where many astronomical achievements and inventions of the Russian were described (Struve, 1954). As for the discovery of Venus' atmosphere, the article presented a mixed bag of correct and incorrect statements and guesses. First of all, it claimed that

> … for unknown reasons the article by Lomonosov was not published during his lifetime and it has remained unknown to most historians of science … it was printed in Vol. V of Lomonosov's collected works, edited by M.I. Sukhomlinov in 1891-1902.

In fact, Lomonosov's paper *was* published during his lifetime and was widely disseminated, and it was reprinted many times (see the discussion in Section 2). Moreover, the German translation of the paper was available in the USA (e.g. at Cornell University library), and was known to American scientists long before Struve wrote his paper (e.g. see Smith, 1912). Secondly, Struve wrote:

> The question still remains whether the blister on the edge of the Sun, seen by Lomonosov, actually represented sunlight passing through Venus' atmosphere that was either refracted in that atmosphere or underwent considerable scattering by small particles …

Then Struve questioned Sharonov's (1952a) analysis which attributed the arc ('blister') to refraction, and stated

> … of course, it is now known that when Venus is several degrees from the Sun its atmosphere can be observed as a faint, narrow luminous ring around the planet. This faint luminosity was not observable in the telescopes of Lomonosov's day. However, when Venus is entering or leaving the Sun at transit, the ring is more conspicuous. David Rittenhouse saw it at the 1769 transit … but this phenomenon is not bright enough to account for Lomonosov's observation.

Here we see that Struve mistakenly tended to believe that the arc was due to scattering. Nor was he aware that Rittenhouse saw rather bright light as well, and that in 1761 a dozen other astronomers (before Rittenhouse) observed the arc. Finally, Struve put forward as a more convincing argument for phenomenon *PII*,[5] which we now consider less convincing then seeing the arc, concluding:

> … it is more difficult to dispose of his [Lomonosov's] observations of the haziness at the edge of the Sun when the planet was just outside the limb … Lomonosov's intuition has since been proven sound, that Venus has an atmosphere and is physically similar to the earth.

Contrary to his Yerkes Observatory colleague, Gerard P. Kuiper (1905–1973), who thought that what Lomonosov observed was the 'black drop effect' (Menshutkin, 1952: 148), Struve correctly pointed out that Lomonosov did not report seeing that phenomenon (*PV*). Struve's reservations concerning Lomonosov's discovery were caused by his own interpretation of the effects of Venus' atmosphere that he thought should be observed during the transit—but these were not completely correct according to modern knowledge.

Vsevolod Sharonov (1901–1964), a prominent Soviet astronomer and Director of the Leningrad University Observatory, published a series of papers on Lomonosov's arc. In Sharonov (1952a) which he based on Lomonosov (1761a), he computed the horizontal refraction, ω, in the corresponding layer of Venus' atmosphere, the "… transparent gaseous layer above the cloud-like aerosol layer which hides the surface of Venus …", to be less than 22″. That conclusion comes from his optical analysis of the formation of the arc as a refracted image of sunlight and the fact that in most cases reported by Lomonosov and other transit observers the arc formation at ingress starts with horns or whiskers near the Sun's limb and spreads over the rest of Venus' disc that is then off the Sun (with the order reversed at egress)—see the left-hand diagram in Figure 12. Asymmetry and/or irregularities in the light distribution over the arc could be explained by different conditions of the gases in the corresponding regions of the atmosphere or by differences in the altitude of the upper boundary of the cloud cover. In such cases, the larger horizontal refraction angle (ω > 22″) results in the Sun's image first appearing at the point on the limb of the planet which is diametrically opposite to the limb of the Sun, and then spreading along the limb and encircling the planet with a luminous fringe (see the right-hand diagram in Figure 12).

Sharonov (1958: 302) explains:

At ω <16″ the cone of rays refracted in the atmosphere of Venus is divergent; at 22″ >ω> 16″ the cone converges and its apex is beyond the Sun. In both instances the luminous rim is formed according to the conditions of the first case … [see the left-hand diagram Figure 12, below]. At ω = 22″ the annular fringe appears instantaneously, and at ω > 22″ the focus is located nearer than the Sun, which corresponds to the second case of the formation of the luminous rim … [see the right-hand diagram in Figure 12, above]. The published data concerning the Lomonosov phenomenon observed during the transits of 1761, 1769, 1874 and 1882, show that the fringe appeared to form either instantaneously or gradually with "whiskers" growing from the solar limb (first case). Hence, the horizontal refraction in the atmospheric layer adjacent to the nontransparent layer of the cloudlike aerosol of Venus never exceeds 22″ … Thus we reach the conclusion that the horizontal refraction in the transparent part of the atmosphere of Venus ranges between 15 and 20″ under ordinary conditions; sometimes the horizontal refraction increases inordinately, which can be explained either by specific physical conditions of the gas in the corresponding regions of the atmosphere (temperature, pressure, composition), or by differences in the altitude of the upper boundary of the cloud cover. The second explanation is more plausible.

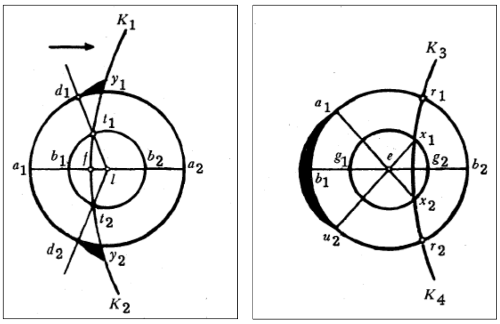


Figure 12: Sharonov's analysis of the angle of horizontal refraction, *ω*, where K_1K_2 and K_3K_4 indicate the solar limb. The diagrams show the formation of Lomonosov's arc as projected on the celestrial sphere. The left-hand and right-hand diagrams relate to *ω* = 22″ and *ω* > 22″ respectively (after Sharonov, 1958: 300).

Sharonov (1952b; 1955; 1960) also performed a detailed analysis of the circumstances of Lomonosov's discovery (in particular, his leading role in organizing the Russian transit observations in 1761, altercations with another St. Petersburg Academician, F.U.T. Epinus, and the exact dates of his 1761 publications), and he made a detailed comparison of many eighteenth century transit reports of aureoles, by Russian (Lomonosov and Rumovsky), Swedish (Bergman, Mallet, Melander, Planman, Stromer and Wargentin), French (Chappe d'Auteroche, deMason, Fouchy and Le Monnier), English (Dunn) and American (Rittenhouse) astronomers. He pointed out the distinct difference between Lomonosov's phenomenon *PI* (the arc) and optical illusions (*PIV* and *PV*), but was undecided on *PIII* (the hair-thin irradiance close to internal contact) which he thought could possibly be incorrectly described, or could be real (as similar radiance was seen by others in 1874 and 1882). Sharonov agreed with D.M. Perevozshikov (1865) on Lomonosov's priority in the discovery on the basis of timely publication, completeness of the report and an understanding and correct explanation of the formation of the arc by refraction. Sharonov also was a key comentator on the subject in Lomonosov's *Complete Works* (Chenakal and Sharonov, 1955).

The Czech astronomer and founder and editor of *The Bulletin of The Astronomical Institute of Czechoslovakia*, Frantisek Link (1906–1984), independently analyzed old observations of the arc made during the transits of 1761 (all those listed in our Table 1 except Silberschlag, Hirst and Mallet), 1769 (a total of eight), 1874 (35) and 1882 (32). Link developed a theory for the optical formation of the refracted image of the Sun in Venus' atmosphere (the arc) similar to the one proposed by Sharonov, and he also argued that asymmetry of the light distribution over the arc was due to atmospheric conditions, in particular, greater brightness is observed at the polar areas of Venus, and he concluded that Venus rotates around its axis in the same direction as the Earth and other planets (which we now know to be incorrect). Among the deficiencies of Link's analysis of the old observations is that he omitted most of the details and did not comment on them except for short accounts of Chappe d'Auteroche (1761-1762) and Smith et al. (1769); and instead of including original drawings he presented simplified sketches of his own of selected observations made by just four eighteenth-century observers, Bergman, Chappe d'Auteroche, Rittenhouse and Wargentin). This led Link to reach several false conclusions, particularly relating to Lomonosov. For example, he wrote:

Lomonosov observed this transit with a small telescope (4½ ft. long) of bad optical quality

> giving colored images outside the optical axis. Before the egress, when the limb of·Venus was at a distance by 1/10 of its diameter from the solar limb, Lomonosov detected at the solar limb a kind of swelling or blister becoming more distinct as the planet was approaching the egress. A short time afterwards the blister disappeared and the planet was visible without any special feature at the solar limb. Lomonosov explained this phenomenon by the refraction in the planetary atmosphere which is, according to him, equal if not more important than the terrestrial atmosphere. 113 years later the British astronomer Bigg-Wither observed a very similar phenomenon at the egress. When Venus was approaching the egress the planet seemed to push before it a kind of light ring. This feature was observed at the moment of the computed internal contact. Soon after, when the disk was outside the Sun, the ring in the form of a crescent was visible. Both Lomonosov's and Bigg-Wither's phenomena show a remarkable resemblance to each other and have probably the same origin in the irradiation which takes place on the limit of two areas of very different brightness observed under bad conditions. In addition, the explanation given by Lomonosov is not valid as it pre-supposes the refracting atmosphere at the height of 1/10 of diameter (= 1200 km), which is impossible, thus making it clear that Lomonosov never saw an atmospheric phenomenon which is different from the appearance observed by him and Bigg-Wither. We feel 1) that Lomonosov proposed though somewhat incautiously an explanation by atmospheric refracttion for the phenomenon observed by him which was, however, not of atmospheric origin, and 2) that his contemporaries having observed the true atmospheric phenomenon proposed independently but with more caution the same explanation. Neither Lomonosov nor any other astronomer has established (1761) any theory or brought to light any evidence to support their findings. The schematic outline of refraction presented by Lomonosov cannot, therefore, be considered as a form of theory and if it should be according to Sharonov, then this theory will have led to false conclusions about the importance of the Venusian atmosphere as quoted above. Hence we may admit under the denomination of Lomonosov's phenomenon only for the irradiation blister observed by him and later by Bigg-Wither and not for the true aureole observed in 1761 by nearly a dozen other astronomers. Thus, Sharonov, having collected and published a very copious documentation about Lomonosov's contribution, has not convinced the present author of its scientific value, neither has it convinced Struve who, some years ago, carried out an independent investigation; he, too, came to similar conclusions. (Link, 1969: 215-216).

Let us go through Link's misconceptions one by one: firstly, although Link was not aware of Nemiro's 1939 publication which asserted the high quality of Lomonosov's telescope (a Dollond achromat) he still could have inferred this from the thickness of the arc observed by Lomonosov (the smallest among all the observers in 1761). Secondly, the reference to the 1/10th of Venus' diameter distance was made to the disturbed edge of the Sun, as indicated in Lomonosov's *Fig. 3* and especially *Fig*. *4* (see our Figure 1), and one can see in the latter that the leading edge of Venus is about 1/10 of its diameter beyond the line where the unperturbed limb of the Sun would be, and the distance between the leading edge of Venus and the perturbed Sun's limb (the outer edge of the 'blister') varies from about 1/10th of Venus' diameter (in *Fig. 3*) to about 1/15th (in *Fig. 4*). The most outrageous claim, though, is the similarity between Lomonosov's observations and those made by Captain A.C. Bigg-Wither (1844–1913), an engineer with the Indus Valley Railway who was living in Multan in what is now Pakistan (see Kapoor, 2014). Figure 13 shows the original 1874

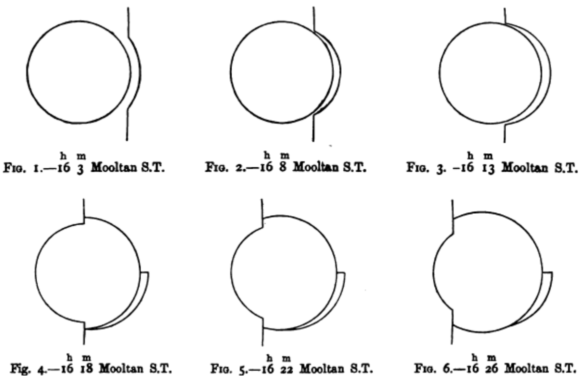


Figure 13: Bigg-Wither's drawings of the 1874 transit showing his observations at egress (after Bigg-Wither, 1883: 98-99).

drawings of Bigg-Wither (1883: 98-99), and one can see that contrary to Lomonosov's observations (and many others), Bigg-Wither's has two remarkable oddities: an arc which is thick in the middle and very thin at the ends touching the Sun (Figs. 2 and 3) and the reduction of the arc to one half during the later stage of egress (Figs. 4 to 6). It is very hard to find any reasonable explanation for these observations (as admitted by the observer himself),[6] and even harder to suggest that they are in any way similar to Lomonosov's *Fig. 4*. Again, as Link presented modified and overly-simplified versions of Lomonosov's *Figs. 3, 4* and *5* side-by-side with only the first three of Bigg-Wither's (also slightly modified) in his book, one might think that he believed there were similarities between Bigg-Wither's Fig. 1 and some of Lomonosov's drawings. But he could not have been paying attention to outstanding differences between the other images. Also, it is hard to explain Link's reference to Struve, who first of all was uncertain about the physics of Lomonosov's arc (was it caused by refraction or scattering?) and secondly, was not willing to draw any firm conclusions—let alone express a flat denial. Sharonov (1960) pointed to these obvious flaws in Link's arguments, and we tend to agree that it is hard to consider them seriously.

In 1966 the noted University of Leicester historian of science Professor A.J. (Jack) Meadows published a much more systematic analysis based on a true scientific evaluation. First of all, he presented original plates of Lomonosov's figures (and, for comparison, a plate from the later publication by Bergman (1761-1762)); gave an English translation of the most relevant part of Lomonosov's 1761a paper, and correctly identified 15 July 1761 (in the Julian calendar) as the date of this pioneering publication. Despite confusion over what "… the 1/10th of the Venus diameter distance ..." refers to (just like F. Link—see above), he considered the disturbance of the solar limb shortly before the ingress (*PII*) as a true indication of the atmosphere of Venus; confirmed in 1769 by Hirst; and concluded that "… Lomonosov's description of refraction in the hypothetical atmosphere of Venus was undoubtedly the best available at the time." (Meadows, 1966: 125). He considered that the appearance of the line of light at the second contact (*PIII*) was an optical illusion, which also was witnessed by several observers of the nineteenth century transits. Many observations of the arc and/or aureole were (even briefly) discussed in this paper (e.g. the 1761 transit reports by Bergman, Chappe d'Auteroche, Desmares, Dunn, Ferner, Fouchy, Hirst, Le Monnier, Mairan, Planman, Rumovsky and Wargentin, and the 1769 transit reports by Dunn, Dollond, Hirst, Hitchins, Horsley, Mairne and Maskelyne). Meadows also attempted to sort them out and separate optical illusions (e.g. observations of the aureole during the whole passage across the Sun—phenomenon *PIV*) from true atmospherically-induced effects (i.e. *PI*, the arc). Still, there were some misidentifications. For example, Dunn's aureole observation was considered to be similar to the effect reported by Bergman, and Chappe d'Auteroche was cited as giving the most exact reference to an atmosphere, while he obviously did not. Meadows (ibid.) then considered the reaction among astronomers after the eighteenth century transits and noted that

> … it is evident that most astronomers were not prepared to accept the evidence from the transits as certain proof of an atmosphere round Venus. They were deterred by the discrepancies between different observers … [and] the reports conflicted so greatly.

Unfortunately, Meadows in 1966 did not try to address the reason for the discrepancies—something that would only be fully understood almost half a century later (see Shiltsev et al., 2013)—merely concluding that "… in this sense, nobody discovered the atmosphere of Venus."

Of course the first of the two transits of the twenty-first century, on 8 June 2004, represented a huge step forward for observers, as modern imaging technologies were available for the first quantitative analysis of the atmosphere-induced aureole and its comparison with a simple refraction model and with observations of the 'Lomonosov arc' obtained in the past. A number of images of the aureole captured by CCD cameras through relatively large and good-quality telescopes were analyzed, where it was noted that

> … visual observers under good sky conditions and employing a magnification higher than ~150× had no particular difficulty in identifying the bright aureole outlining the Venus disk between 1st and 2nd contact, while it was crossing the solar limb ... Skilled observers immediately noticed the non-uniform brightness of the aureole along the planet disk. (Tanga et al., 2012: 208).

Yet analysis of the 600 or so entries from about 80 amateur observers located in Russia and Ukraine and posted on the forum http://www.astronomy.ru/forum/index.php/topic,4790.0.html revealed far from uniform success in seeing the aureole, even in favorable atmospheric conditions: only 30 people reported observing the arc, using instruments with apertures varying from 40 mm to 312 mm, and magnifications from 33× to 200×. One person indicated that it was only when he exchanged a standard M5.0 solar filter for a much weaker one that he was able to detect the arc.

5 CRITICISM OF THE PAPER BY PASACHOFF AND SHEEHAN

A few months before the 2012 transit, the American astronomers Professor Jay Pasachoff and Dr William Sheehan (2012a) published a paper in this journal where they bluntly denied Lomonosov's observations, arguing that his discovery was an erroneous claim. They then attempted to assign the credit to other observers. Subsequently, this paper stimulated extensive discussion by members of the History of Astronomy Discussion Group (HASTRO-L).

Here we consider only the major issues (with the page numbers generally referring to Pasachoff and Sheehan's 2012a paper).[7]

(1) Lomonosov's telescope was claimed to be inadequate, based on a misreading of the source material and ignorance of the facts on the subject. For example, on page 5, it is said that Lomonosov "... used a non-achromatic refractor ... that consisted of little more than two lenses (objective and eyepiece)." Later, the same authors

state:

> We think that what he [Lomonosov] saw was an artifact of his relatively primitive and small telescope rather than the aureole that is sunlight refracted toward Earth by Venus' atmosphere … (Pasachoff and Sheehan, 2012b: 11).

These claims are not correct, as shown in Section 2 above where it is established that Lomonosov's telescope was a good quality Dollond refractor with two lenses in the objective. There is also indirect evidence. The description "… two lens telescope …" is found in all translations which simply follow word-for-word the language of the original translations (Marov, 2005: a "… two-lenses tube …"; and Shiltsev, 2012b: a "… telescope with two glasses …"). Although there is some ambiguity in this description, it almost certainly refers to the achromatic objective of the telescope, not the telescope and eyepiece together, because in 1761 it was possible that a single objective could be used but an eyepiece with a single lens would have been unusual and inadequate. Multiple-element eyepieces were commonly used long before the mid-1700s, and it is hard to believe that a serious and well-connected astronomer like Lomonosov—a member of the ruling Chancellery of one of the best-funded scientific academies in the world at the time—would have used an inferior eyepiece for a major observation such as the 1761 transit. Therefore, it is hard to doubt that the term "two lenses" describes the objective. It is unclear why Pasachoff and Sheehan (2012a) hedged their bets by describing Lomonosov's telescope as "… little more than ..." two lenses. This incorrect description was then used as the basis for a sweeping rejection of his observations, because of "… the poor quality of this instrument."

(2) On page 6: "... Lomonosov, in particular, makes clear that his own instrument was of marginal quality. It clearly suffered from chromatic aberration." All refracting telescopes of that era exhibited chromatic aberration, especially during solar observations. The 2012 replication of Lomonosov's observations also produced a similar reference: "... the color fringe effect was noticeable only at the edge of the field of view (at approximately ¾ from the center of the optical axis) …" (Koukarine, et al., 2012). It seems that Lomonosov was just demonstrating that he was a careful observer when he noted this problem, which most probably was caused by aberrations in the ocular (Petrunin, 2012), and he effectively addressed this by centering his telescope on Venus:

> … during the entire observation the tube was permanently directed in such a way that Venus was always in its center, where its [Venus'] edges appeared crispy clear without any colors. (Shiltsev, 2012b).

(3) A revealing argument is made on page 6 that telescopes of that era were generally inadequate to the task because

> ... since the total apparent angular height of Venus' air is only about 0.02 arc seconds, it is, despite its brilliance, a delicate feature, and would presumably have been beyond the range of most eighteenth century observers with the small instruments available to them.

The first part of this statement seems to reflect a misunderstanding of the physics of the phenomena—indeed, the minuscular angular size of the object does not prevent it from being detected (think, for example, of point-like stars); it is the total brightness of the diffracted image that matters. As for the second part of the sentence, it is even more confusing as the authors themselves later note similar observations of the arc which were made in 1761, by Chappe d'Auteroche, Bergman and Wargentin (and, as we have shown above, many others), and accepted them as genuine. The arc indicating Venus' atmosphere is visible in telescopes smaller than that used by Lomonosov, as was shown by varous groups in the USA, Russia and Canada during the 2012 transit (and for a discussion of the 2012 observations see Section 6, following, and references therein).

(4) Pasachoff and Sheehan seem to have misread their own translation of Lomonosov's report and are preoccupied with the "… hair-thin luminous sliver …" seen by Lomonosov at second contact (phenomenon *PIII*), concluding that it "… refers to nothing more than the flash of sunlight between the trailing limb of Venus and the limb of the Sun marking the end of second contact." (page 7). We agree that such a phenomenon alone can hardly be used to conclude the existence of a Venusian atmosphere, and this is exactly what Lomonosov himself avoided referring to when making his claim. Indeed, this luminous sliver seen at ingress is not even illustrated in Lomonosov's figures. Instead, Lomonosov describes phenomena *PI* and *PII* (the arc, and the smeared Sun's limb at the points of the first and fourth contacts) as evidence of Venus' atmosphere, arguments which have been neglected by Pasachoff and Sheehan.

(5) On page 7 Pasachoff and Sheehan write that "... at no time did Lomonosov report any phenomena that resembled the phenomena seen during the transits of 2004 and 2012, with an arc above Venus' external limb …", but this statement is incorrect as most of the observations of the twenty-first century transits of Venus (and, in that regard, of other transits) were qualitatively similar, as a comparison of Lomonosov's *Fig. 4* (see our Figures 1 and 2) and the above discussion shows.

In conclusion, there is no basis for Pasachoff and Sheehan's (2012a: 7) claim that

> ... Lomonosov's observational data were flawed, [and] his detailed geometrical treatment also proves to have been spurious ... We have now shown definitively that ... Lomonosov arrived at the correct conclusion but on the basis of a fallacious argument.

Moreover, the successful replication of Lomonosov's observations during the 2012 transit of Venus raises further doubts about these statements, and Pasachoff and Sheehan's attempts to assign discovery priority to other observers (e.g. Chappe d'Auteroche, or Rittenhause, or Wargentin and Bergman) are unwarranted.

6 EXPERIMENTAL REPLICATION OF LOMONOSOV'S DISCOVERY DURING THE 2012 TRANSIT OF VENUS

Lomonosov's discovery was experimentally replicated during the transit of Venus on 5-6 June 2012. A thin arc of light on that part of Venus off the Sun's disc during the ingress has been successfully detected with original eighteenth-

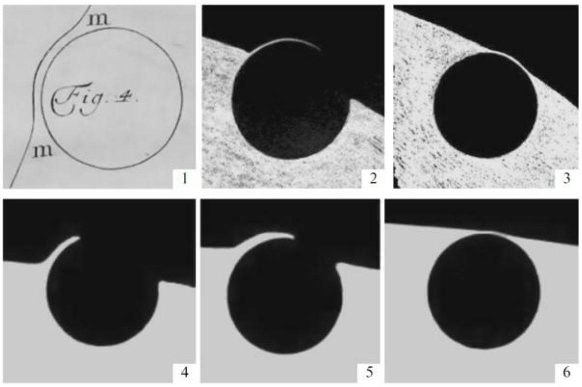


Figure 14: 1) shows 'Lomonosov's arc', the bulge on the Sun's limb at egress noted in 1761 (after Lomonosov, 1761b); 2) and 3) show 2012 observations at Lick Observatory with a 67-mm antique Dollond achromatic refractor and a weak filter; 4) to 6) show 2012 observations in Illinois with a 40-mm antique Dollond achromatic refractor and weakly-smoked glass filter (left), at 17:16, 17:19 and between 17:21 and 17:22 (all times in CST = UT–5) (after Kukarin, et al, 2013: 529).

century Dollond achromatic refractors similar to that deployed by Lomonosov and with his experimental techniques carefully emulated (e.g., lightly-smoked glass filters, and periodic rest for the eyes to maintain sensitivity) (see Koukarine, et al., 2012; Kukarin, et al., 2013). The experimental re-enactments resulted in successful detection of the aureole effect, a thin arc of light on that part of Venus off the Sun's disc when the planet was in transit—see Figure 14.[8] Despite having small apertures by modern standards, the old achromatic refractors were found fully adequate for the task of detecting the light refracted around Venus. Several factors combined to allow replication of Lomonosov's discovery of the Venusian atmosphere. The Dollond achromats were found to be of remarkably good quality, and had sufficiently large apertures and suitable filters. Care was taken to reduce the stray light and to assume comfortable viewing postures that would minimize eye strain. Simultaneous observations with high-quality modern doublet refractors with apertures as small as 50 mm revealed the aureole, and demonstrated that systems designed with modern software, employing modern optics and coatings did not significantly out-perform the older instruments (Rosenfeld et al, 2013).

The replication also allowed us to understand the inconsistent success in the detection of Lomonosov's arc, now and in the past (Shiltsev et al., 2013). When observed through a telescope, the brightness of the arc is determined by how much its width is spread due to diffraction, an effect inversely proportional to the aperture diameter, and to atmospheric turbulence (which is independent of the telescope's parameters). As with any extended object, the brightness of the arc and the Sun should not depend on the optical system's magnification. Observations of the arc with modern doublet refractors and a standard 1/100 000 filter in Saskatchewan (Rosenfeld et al., 2013) supported the above analysis and confirmed that aperture diameter plays the critical instrumental role in the detection of the aureole, while the magnification used was found to be a less important variable. Because of the non-linear response of the human eye, the optimal filter to be selected depends on the observational goal. To see the arc around Venus, the weakest filter that allows for comfortable and safe viewing should be used. A stronger filter would be better suited for studying the Sun over a long period, but it would reduce the arc's perceived brightness so much that the arc would be invisible against the background. The use of attenuating filters makes ambient glare from sunlight while viewing at the eyepiece a relatively large nuisance; it is important, therefore, to reduce stray light.

Unlike Lomonosov, most observers in the eighteenth century directed their attention exclusively to timing the contacts of Venus with the solar disk. The longer observation periods needed to achieve that goal demanded stronger filters than that used by Lomonosov for detection of the arc. Finally, not all of the instruments used at that time could match the optical quality of the Dollond achromats.

7 CONCLUSIONS

As shown above, during observations of the transits of Venus there were several optical phenomena that could be attributed to the atmosphere of the planet: an arc of light around that part of Venus that was off the Sun's disc at the ingress and egress; the blurriness of the Sun's limb at the times of the 1st and the 4th contacts; a thin bright radiance close to the times of the internal contacts; and the circular aureole around Venus when it was fully on the Sun's disc. The first of these, the 'arc', is caused by refraction of sunlight in the Venusian atmosphere, and was observed and described in similar terms by a dozen astronomers in 1761 and by many during the following transits, including the last one, in 2012. Mikhail Lomonosov stands out among the observers as he was the first to publish a scientific report of the phenomenon, understand it was due to refraction, and conclude from this that Venus possessed an atmosphere. As he providing the correct physical explanation for this and a detailed description of his methods of observation, astronomers were able to replicate his discovery more than two and a half centuries later. Our analysis of the 1761 observations of the transit and subsequent discussions show that the use of the term 'Lomonosov's arc' seems appropriate as he is the one who should be credited with the discovery of Venus' atmosphere.

Lomonosov's discovery was experimentally replicated during the 5-6 June 2012 transit of Venus when a thin arc of light on that part of Venus lying off the Sun's disc during the ingress was successfully detected with original antique telescopes similar to the one used by Lomonosov. The replication also shed additional light on why detection of the aureole was so capricious in the past, and it showed once again that a great discovery involves deep insight into physics on the part of the discoverer, the right instruments and techniques, and a little luck. From what we have learned through restaging his historic 'enlightenment' experience, Lomonosov seems to have been the only one to discover the Venusian atmosphere not by mere accident but by designing an experimental protocol that made it possible.

8 NOTES

1. N.I. Nevskaya (1973; 2000: 152-156) suggests that Lomonosov's thinking about possible experimental techniques to detect atmospheres of planets began even earlier, in the mid-1740s, during collaborative astronomical studies under the renowned French astronomer, Joseph-Nicolas Delisle (1688–1768), who was Professor of Astronomy at the St. Petersburg Academy from 1725 to 1747.
2. Dunér (2013: 158) claims that Lomonosov

   > … was neither the first, nor the only one, to conclude that the phenomena were caused by a Venusian atmosphere. Bergman and others published their results first.

   This claim simply is not true. As we have seen, Lomonosov actually began writing his first paper (in Russian) about the transit the day after the event, and this paper, and his later one, in German, were both published in 1761, in July and August respectively. Only the papers by Hellant, Strömer et al. and Le Monnier also were published in 1761, the first two in the third quarterly issue of *Kungliga Vetenskapsakademiens Handlingar* for that year (i.e., no earlier than July), while Le Monnier's paper was published even later in the year. In contrast, the papers in the *Philosophical Transactions of the Royal Society* by Bergman and Wargentin only appeared in 1762.
3. One can add that even at the very end of the nineteenth century the confusion over the cusp observations was quite valid. For example, H.N. Russell (1899: 298) concluded from his own observations that the elongation of the cusps was significantly smaller than reported by Schröter, only 1° 10′, which indicated that Venus' atmosphere "… (could not be)…more than one third as dense or extensive as the Earth's."
4. Extensive literature exists on the circumstances surrounding and instrumentation used during the nineteenth century transit expeditions. For example, see the popular books by Lomb (2011), Maor (2000) and Sheehan and Westfall (2004) and bibliographies therein, or the series of papers in this journal: Clark and Orchiston (2004), Cottam et al. (2012); Débarbat and Launay (2006), Duerbeck (2004), Edwards (2004), Kapoor (2014), Lu and Li (2013), Orchiston and Buchanan (2004); Orchiston et al. (2000), Pigatto and Zanini (2001; 2004), Stavinschi, 2012; Sterken and Duerbeck (2004) and Tobin (2013).
5. Besides O. Struve, the phenomenon of an indistinct or hazy edge of the Sun at the point and time of Venus' entry onto the solar disc was considered and analyzed as a true atmospheric optical phenomenon by Professor A.I. Lazarev from the Vavilov State Optical Institute, St. Petersburg Russia. He wrote (Lazarev, 2000: 431):

   > ... the first phenomenon [*PII* in our nomenclature – V. Shiltsev] was explained only in 1970 as the Fresnel reflection of the Sun from the Venusian atmosphere, which is especially strong at small glancing angles, i.e., specifically under conditions where Venus is close to the solar disk (Lazarev, 1976). This explanation appeared after [Soviet cosmonaut] A.A. Leonov discovered the Fresnel reflection of the Sun from the Earth's atmosphere from the Voskhod-2 spaceship and subsequently explained it together with us. (Lazarev and Leonov, 1973).

6. Bigg-Wither (1883: 98-99) stated: "… I am unable to form an idea of the cause of this crescent."
7. There are also several minor factual errors such as reference being made to 2012 transit observations on page 7 (in a paper that was published *before* the 2012 transit); mix-ups with the contact numbering (page 7); the absence of an explanation as to why E. Stuyvert's observations of the 1882 transit were indicative of "... the double cause of the black drop ..." and how they relate to Lomonosov's observations when they are so different (page 7); the absence of critical discussions of the transit observations by Chappe d'Auteroche in 1761 and by Rittenhouse, Green and Cook in 1769 (pages 8-10); mis-spellings of the last names of F.U.T. Epinus (Aepinus) and V. Sharonov on pages 11 and 14; etc.
8. It is to be noted that weather did not co-operate with several of the observers who prepared antique achromats for the 2012 transit—their bad luck replicated that of more than a few eighteenth century observers. Some of them encountered cloud cover and did not observe the aureole (see Koukarine, et al., 2012), while others obtained ambiguous results due to significant air turbulence (see Nesterenko, 2013).

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INDIAN ASTRONOMY AND THE TRANSITS OF VENUS. 2: THE 1874 EVENT

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Abstract: This paper is about sightings and astronomical observations of the 1874 transit of Venus made from the Indian region. The sources of the information presented here range from some classic texts and historiographies, publications and records of institutions, and chronicles, to accounts by individuals. Of particular interest is the fact that the transits of 1761 and of 1874 both provided independent evidence of an atmosphere around Venus in observations made from India, and the transit of 1874 led to spectroscopic confirmation of the presence of this atmosphere.

Keywords: 1874 transit of Venus, India, A.C. Bigg-Wither, S. Chandra Sekhar, C. Ragoonatha Charry, J.B.N. Hennessey, Rev. H.D. James, N. Pogson, E.W. Pringle, G. Strahan, P. Tacchini, J.F. Tennant.

1 INTRODUCTION

The present work, the second part of the account of transits of Venus relating to those observed from India, is specifically about the transit of Venus of 1874, and is an extension of an earlier work (Kapoor, 2012). Part 1 dealt with transit observations up to and including the transit of 1769 (Kapoor, 2013a).

2 THE 1874 TRANSIT OF VENUS

Interestingly, in 1672 astronomers had attempted to measure parallaxes from observations of Mars made simultaneously from different locations. However, the results ranged from 20″ to 9.5″, and were not accurate, and even were questionable (see Dick et al., 1998). The 1761 transit produced a solar parallax that had much less uncertainty, but it did not cheer up the astronomers. Meanwhile, the 1769 transit provided an improved value for the solar parallax, but a divergence of results remained that implied a not so exact value for the distance to the Sun. A detailed discussion is given in Dick et al. (1998) and in Orchiston (2005).

The astronomers hoped that the next transit pair, falling in 1874 and 1882, would reduce the scatter. After all, a century had passed, the techniques for angular measurements and geopositions and instrumentation had improved greatly, and more observatories had been built. On the other hand, the Solar System itself had grown larger with the discovery by Sir William Herschel (1738–1822) of Uranus on 13 March 1781 and of Neptune by Johann Gottfried Galle (1812–1910) and Heinrich Louis d'Arrest (1822–1875) on 23 September 1846. The science of astrophysics came into being in the nineteenth century with the introduction of spectroscopy and photography to astronomy. In India, it was pursued in due course. In this regard, the most notable development was the first use of a spectroscope during the total solar eclipse of 18 August 1868, and the identification at that time of a new line in the solar spectrum by Norman Pogson (1829–1891), who carried out his observations from Masulipatam.[1]

The forthcoming transits of Venus gave rise to widespread excitement, and scientific activity of even greater magnitude. Observatories braced themselves for the observations, whereas a number of expeditions to far-off lands also were planned. The transit of Venus was going to be observed for the first time using photography and spectroscopy. Observations by British observers gave parallax values ranging from 8.75″ to 8.88″. Simon Newcomb (1835–1909) then worked on the results derived from the 1761, 1769, 1874 and 1882 transits and came up with a value of 8.794″ for the solar parallax, which is remarkably close to the modern value of 8.794148″ that was adopted by the IAU in 1976 (see Dick et al., 1998).

In India, the plan was to observe the 9 December 1874 transit of Venus from several different places. The most prominent among these, the Madras Observatory, was suitably equipped for the occasion. In comparison, the Colaba Observatory in Bombay was not as well equipped as it had fewer instruments. Observations were planned also at the headquarters of the Great Trigonometrical Survey in Dehra Dun. The interest and the preparatory activity can be gauged also from the references to the forthcoming transits of Venus in the meetings of the Asiatic Society of Bengal during 1873 and 1874. In its meeting of February 1873, T. Oldham, Esq., LL.D. (1816–1878), in his Presidential Address, impressed upon the members as to how significant the observations of the rare transit events would be, which were planned to be carried out from regular and makeshift observatories at various places the world over, and that

> … the Government of India have, on representations made to them of the value of a series of observations especially photographic in the clearer atmosphere of some high elevation in North India, at once sanctioned the necessary

expenditure for instruments, and have telegraphed for their immediate preparation.

In connection with this, the General Committee of the British Association at their meeting in 1872, August last, requested the Council to take such steps as seemed desirable to urge the Indian Government to prepare these instruments, with the view of assisting in the Transit of Venus in 1874. (*Proceedings of the Asiatic Society of Bengal*: 58-62 (1873)).

Table 1: Details of the 1874 and 1882 Transits of Venus.

Date	Transit Contact Times (UT) 1 h:m	2 h:m	Greatest h:m	3 h:m	4 h:m	Minimum Sep. "	Sun RA h	Sun Dec °	Transit GST h	Series
1874 December 09	01:49	02:19	04:07	05:56	06:26	829.9	17.056	–22.82	5.182	6
1882 December 06	13:57	14:17	17:06	19:55	20:15	637.3	16.881	–22.56	5.025	4

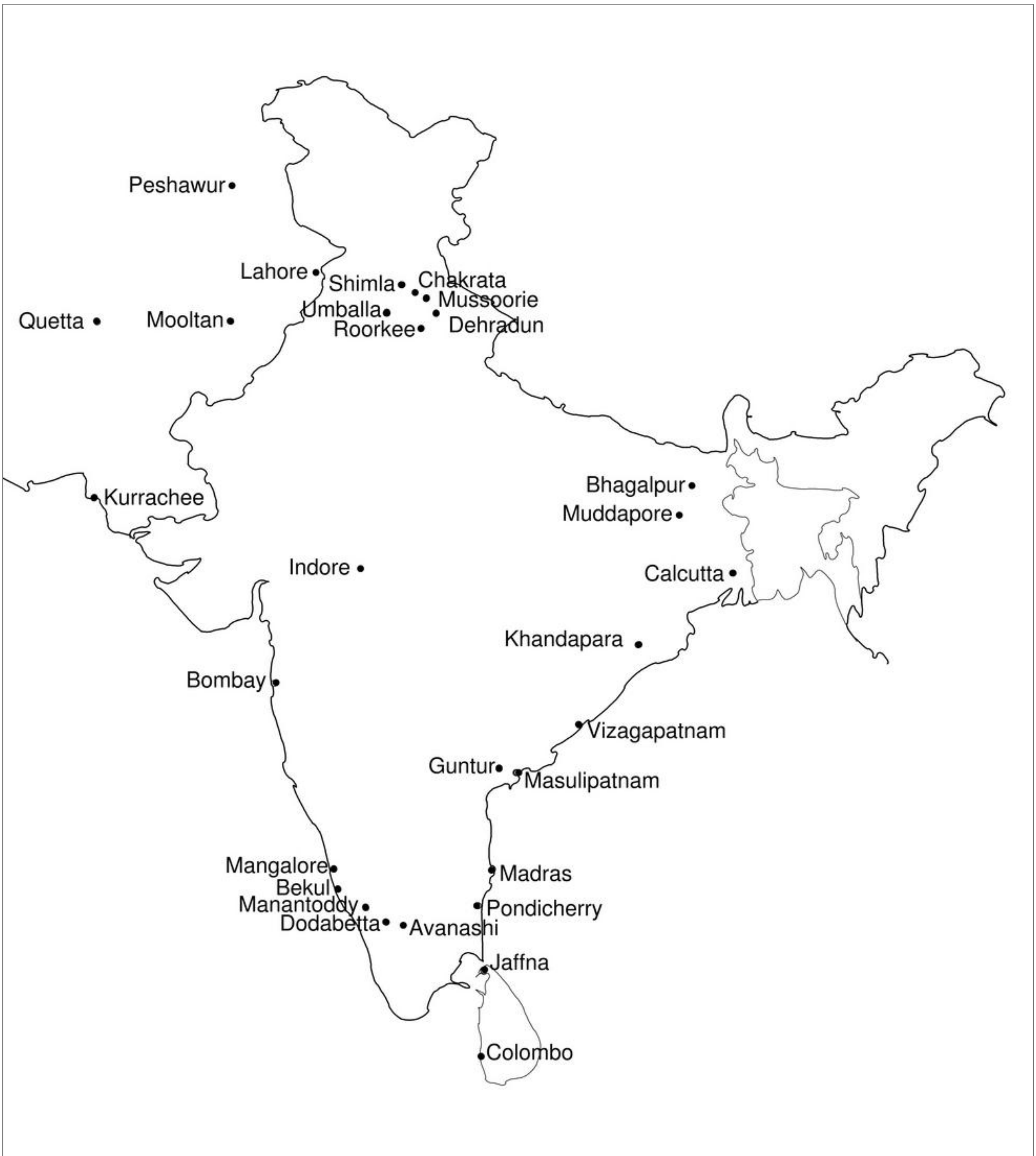


Figure 1: Outline map of the Indian Subcontinent showing localities mentioned in the text. Note that Kurrachee, Lahore, Mooltan, Peshawur and Quetta are now in Pakistan, and Colombo and Jaffna are in Sri Lanka.

The British Association had urged the Government of India to establish a solar observatory, and suitable locations for it existed in the mountain ranges (*Proceedings of the Asiatic Society of Bengal*, 1873; 1875). Colonel H. Hyde (Royal Engineers) succeeded Dr Oldham as the President of the Society, and in his address at the February 1874 meeting he stated that

> In India, however, Spectroscopic observation is making some progress in the Department of the Great Trigonometrical Survey and the atmospheric lines of the Solar Spectrum are being observed.
>
> Mr. J.B.N. Hennessey has continued observing and mapping the atmospheric lines of the Solar Spectrum, employing in super-session of the instrument formerly used, an excellent three-prism (compound) spectroscope with automatical adjustment belonging to the Royal Society of London. This instrument is placed at a height of about 6,500 feet above sea level, on a projecting spur of the Himalayan range on which the Sanitarium of Mussoorie is located, so that a clear view is obtained of the Sun down to the very horizon … (*Proceedings of the Asiatic Society of Bengal*: 46-48 (1875)).

As a ready reference, the circumstances of the 1874 and 1882 transits are listed in Table 1 (after Espenak, 2012),[2] and localities in the Indian region mentioned in the text are shown in Figure 1.[3] Note that the transit of 6 December 1882 would not be visible from India. For example, first contact was at 19:27 hrs (UT+5:30) whereas the Sun, and Venus, had set at Madras by 17:40 hrs.

3 THE MADRAS OBSERVATORY AND THE 1874 TRANSIT

The Madras Observatory staff made elaborate arrangements to observe the transit. However, for most of the event clouds frustrated these preparations. The Observatory has no publiccation about the observations except for a brief account that forms part of the Administration Report of the Madras Observatory for the year 1874, and Norman Pogson's letter to *The Astronomical Register* (1876b) where he reports on the failure, but also lays emphasis on determination of the solar parallax from observations of Mars when it is at opposition. But let us first have a glimpse at some history.

The earliest scientific astronomical observatory in India was established in 1786. This was a private facility erected at Egmore in Madras (now Chennai) by William Petrie (1747–1816), an officer with the East India Company. The first observation on record, on page 164 in the MS Observations in the Indian Institute of Astrophysics Archives, dates to 5 December 1786 and pertains to the determination of the coordinates of the Masulipatam Fort flagstaff. In 1789 the East India Company took over Petrie's observatory, and in 1792 it was shifted to new premises at Nungambakkam, designed by the Company's new Astronomer and Marine Surveyor Michael Topping (1747–1796), and renamed Madras Observatory (see Figure 2).

In *A Memoir on The Indian Surveys*, the noted British geographer Sir Clements Markham (1830–1916) has this to say:

> The Madras Observatory is now the sole permanent point for astronomical work in India, and the only successor of the famous establishments founded by Jai Sing. It has been presided over by a succession of six able and accomplished astronomers, it has produced results which entitle it to take rank with the observatories of Europe, and its present Director is engaged in the prosecution of labours which are of great importance to astronomical science. (Markham, 1878: 323-341).

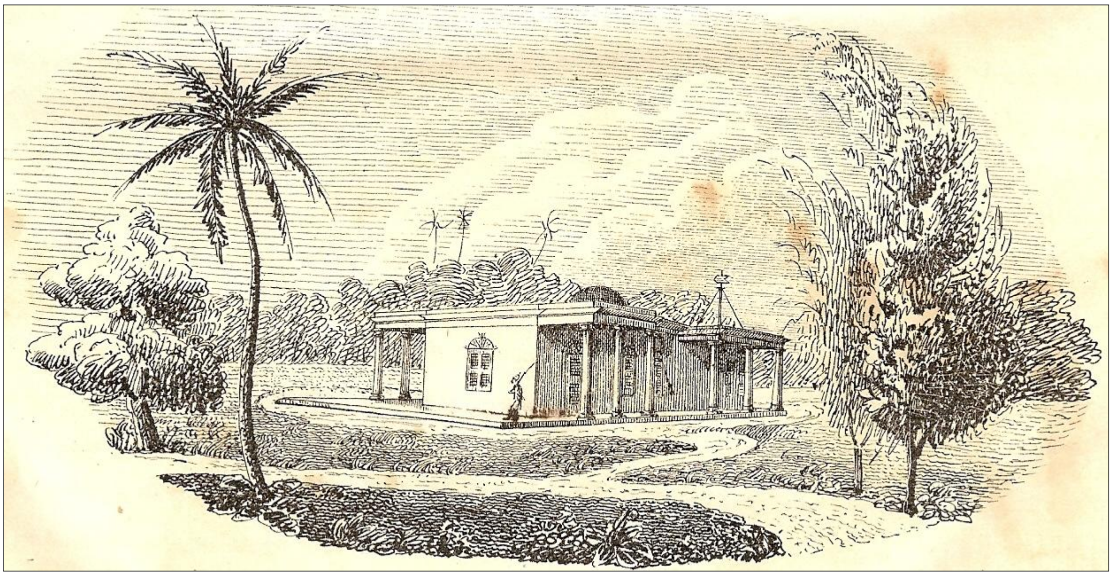


Figure 2: The Madras Observatory at Numgambakkam (after Taylor, 1838: front cover; courtesy: Indian Institute of Astrophysics Archives).

Figure 3: Norman Pogson, 1829–1891 (courtesy: Indian Institute of Astrophysics Archives).

The Director referred to in the above quotation is Norman Robert Pogson (Figure 3), who occupied the post from 1861 until his death on 23 June 1891. Pogson started his career as an astronomer at George Bishop's South Villa Observatory in London where he trained under John Russell Hind (1823–1895). Then followed fruitful days at the Radcliffe Observatory in Oxford from the close of the year of 1851, and at the Hartwell Observatory, beginning 1 January 1859. Although his name is well known as the 'founder' of the modern logarithmic magnitude scale (see Pogson 1856; cf. Reddy et al., 2007), while at the Madras Observatory, he also used the new 8-inch Cooke equatorial to discover five asteroids and seven variable stars. At Madras, he also rediscovered the lost asteroid *Freia* (D[reyer], 1892). In addition, his assistant, C. Ragoonatha Charry (1828–1880),[4] made a notable astronomical discovery in January 1867: that R Reticuli was a variable star (Markham, 1878: 333-334; see, also, Kameswara Rao et al., 2009). Pogson was awarded the Lalande Medal by the French Academy of Sciences for his discovery in 1856 of asteroid *Isis* (42) (named after his daughter), and later was honoured when a lunar crater and asteroid (1830) Pogson were named after him. In 1860 he was elected a Fellow of the Royal Astronomical Society and on 1 January 1878 he became a Companion of the Indian Empire. One can find more about Pogson in the obituary which was published in *Monthly Notices of the Royal Astronomical Society* (see D[reyer], 1892).

The Madras Observatory (Figure 4) continued to evolve during and following Pogson's Directorship, eventually becoming the Indian Institute of Astrophysics (IIA). Now there is nothing but a conspicuous monument in Nungambakkam to mark the original buildings (Figure 5). For further details of the Observatory's history see Kochhar 1985a and 1985b.

Figure 4: The Madras Observatory at Numgambakkam during the period 1860-1890 (courtesy: Indian Institute of Astrophysics Archives).

4 THE TRANSIT OBSERVATIONS

4.1 Norman Pogson's Report on the Transit

Well before the transit of Venus was to take place, Pogson was concerned that it be observed from various stations in India. The following is from the 'Notes' in *Nature* (Notes, 1873):

> We learn from the Times of India that Mr. Pogson, the Government Astronomer of Madras, has written a long letter to the local Government, suggesting that some special arrangements should be made for observations of the Transit of Venus in December 1874, in Northern India, independently of the Madras Observatory. The letter has been forwarded to the Government of India for consideration.

Post-transit, Pogson's account of the transit and comments form part of the "Administration Report of the Madras Observatory for the year 1874" (Indian Institute of Astrophysics Archives). First he says:

> The two equatoreals, by Messrs. Troughton and Simms and by Messrs. Lerebours and Secretan; the silver glass reflector by Browning, and seven smaller telescopes, four of which are provided with portable equatoreal stands, were all in good order and ready for the long-expected Transit of Venus on December 9th, which, however, was not observable at Madras owing to cloudy weather …

Furthermore:

> *Transit of Venus* – As at almost every other observatory in the world at which the important event was visible, very complete and careful preparations were made in anticipation of the Madras Observatory contributing its share to the general results. The valuable aid and experience of Colonel A. Ritherdon, Mr. G.K. Winter, and Mr. F. Doderet, all so signally successful on the occasion of the last total eclipse of the sun at Avenashy in 1871, were enlisted, but in vain. Venus was briefly seen once or twice during the transit, but only through thick clouds which rendered photographs or measurement of any kind impossible. The second internal contact, noted by Miss E. Isis Pogson and C. Ragoonatha Chary, was the only record obtainable after all the trouble incurred; but had the undertaking been crowned with success and the Transit photographed and observed throughout in an unclouded sky, the geographical position of Madras, or indeed any part of India, would have rendered such results only of very secondary importance compared with those secured by astronomers at the southern island stations of Kerguelen and elsewhere; which, combined with other equally valuable observations at the northern stations of Russia and China, would have amply sufficed to determine the solar parallax without the interference of any midway observers at all, so far as the method is capable of yielding the solution of this great problem. For two centuries past the Transits of Venus have been popularly regarded as the only means available for settling the precise value of the solar parallax, and thereby the earth's mean distance from the sun; but this delusive prejudice is now breaking down, and certain insurmountable drawbacks in the favorite method will probably lead to a more just recognition of the superior advantages offered by other means, of more frequent recurrence, and which involve no costly expeditions to remote parts of the earth. The oppositions of Mars, already observed here on five unfavorable occasions, but which in 1877 and 1879 will be especially favorable, will probably yield as good a determination, when discussed, as all the late Transit observations put together; though after all it is very questionable whether any direct method of observation will ever achieve more than a mere verification of the latest value of the parallax deduced by the triumphant theoretical researches of M. Le Verrier of Paris.

Figure 5: The Madras Observatory monument photographed by the author in July 2011.

The excitement of this rare event notwithstanding, Pogson was clear that the precision achievable by its observations was limited and that the method for determining the mean Earth-Sun distance from oppositions of Mars was better, more convenient and more accurate. His reference to Kerguelen is in respect of the Royal Observatory's expedition to Kerguelen Island in the southern Indian Ocean that was led by the Reverend Stephen Perry (1833–1889). Despite the failure of the observations due to bad weather, Pogson provided valuable help to observers stationed elsewhere through telegraphic determination of their respective longitudes, and in his words, "… one of the most important and yet the most difficult of all the requisite data for rendering their observations available for the determination of the solar parallax." Telegraph lines from London to India had been laid and connected only recently, in January 1870, first to Calcutta and then to Bombay and Madras (see Karbelashvili, 1991). Pogson's longitude work subsequently was published in 1884.

Of the two observers that Pogson mentions, Elizabeth Isis Pogson was his daughter, who

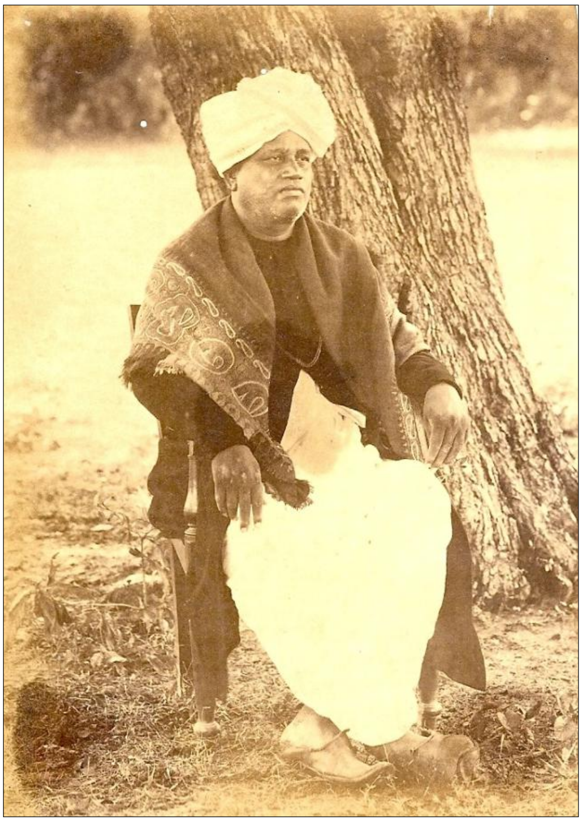


Figure 6: C. Ragoonatha Charry (courtesy: Indian Institute of Astrophysics Archives).

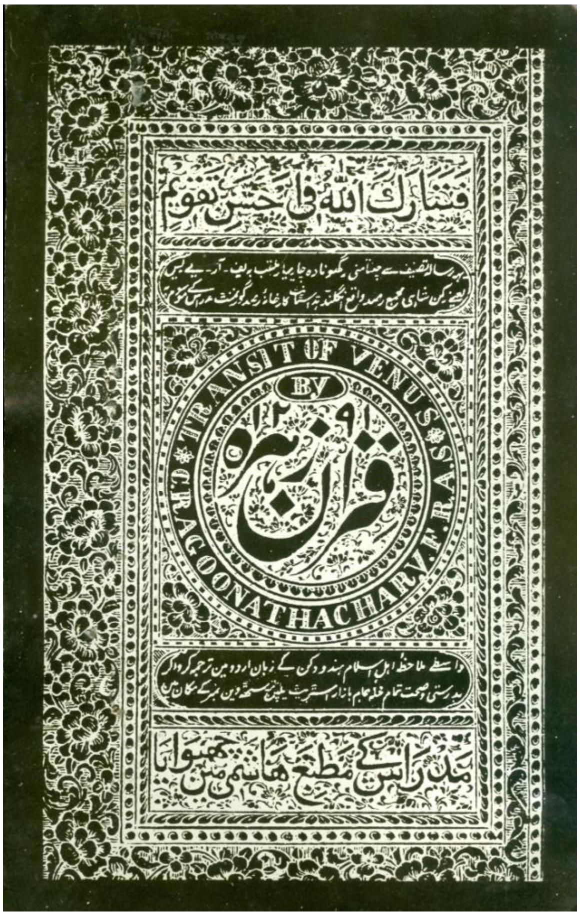


Figure 7: The cover page of the Urdu version of Ragoonatha Charry's pamphlet on the 'Transit of Venus' (courtesy: Indian Institute of Astrophysics Archives).

worked at the Observatory as an Assistant Astronomer (*Nature*, 1873: 513) whereas Ragoonatha Charry (Figure 6) was the First Assistant to the Astronomer. Charry came from a family of almanac-makers and when about eighteen years of age, in 1847, he had joined the Observatory (during T.G. Taylor's time as Director). Pogson (1861) spoke highly of Charry. In 1874, as the transit date drew near, Charry prepared a 38-page pamphlet titled *Transit of Venus* which was written in English, Kannada, Urdu and other languages (e.g. see Figure 7). As he states in the preface to the English edition:

> Having been accustomed for many years to discuss astronomical facts and methods verbally with Hindu professors of the art, my present sketch has naturally, as it were, taken the form of a dialogue; but in the Sanscrit, Canavese, Malayalum, and Maharathi versions I have found it convenient to vary the arrangement. The sketch was first drafted in Tamil, and then translated into English and the other languages.

Through several figures, the pamphlet beautifully explains the transit to the lay public. The English version is presented as dialogue but the style differs when he presents the versions in the local languages. The 'pamphlet', as he called it, was printed but was not published as such. It includes Charry's passionate address at the Pacheappa's Hall, Madras, on 13 April 1874 (one day after the Tamil New Year) to a large gathering of 'Native Gentlemen'. Here, he urges them to support a modern *Siddhānta* that he wished to bring out; the establishment of an observatory for which he offers a few crucial instruments of his own; and the formation of a society along the lines of the Royal Astronomical Society. A favourable review of the pamphlet appeared in *The Astronomical Register* (see Ragoonatha Charry, 1875).[5]

4.2 Observations by J.B.N. Hennessey and the Reverend H.D. James

A brief account of the observations of the transit from various other stations in India also is given in Markham (1878: 339-340). He writes that from Mussoorie (Masauri) in the Shivalik Hills, 6,765 ft above mean sea, the transit was observed by J.B.N. Hennessey (1829–1910; Figure 8) from The Great Trigonometrical Survey of India. Hennessey

> …. was appointed to the Indian Trigonometrical Survey in 1844, and in the times of the Mutiny was under arms and on a harassing duty for five months protecting a large number of ladies and children. In 1863, when on leave in England, he entered Jesus College, Cambridge and worked under Profs. Adams, Challis, and Walton to improve his mathematical and astronomical knowledge … (H[ollis], 1910).

At Dodabetta in the Nilgiri Hills, Hennessey and Captain James Waterhouse (1842–1922) had photographed the solar corona during the 1871 eclipse, under the superintendence of Colonel James Tennant. Solar physics was then in its infancy. At the compound of the Survey of India's Geodetic Branch Office in Dehra Dun the Hennessey Observatory still exists (Figure 9). This originally was established in 1884 to carry out photoheliography and take 30-cm images of the Sun. Nowadays, all the instruments are gone, but the dome remains, and it and the building require conservation.

Hennessey's main objective was to observe the transit of Venus from a high altitude, hence his decision to locate his observing station near Mussoorie. He used an 'equatoreal' telescope from the Royal Society given him by Captain John Herschel, R.E. (1837–1921), an alt-azimuth telescope, a mountain barometer and a thermometer. In the course of his professional duties, he was already in the Shivalik Hills at a location some 22 km from Mussoorie. He chose an observing site, then determined its altitude, latitude and longitude, and carried out observations to rate his chronometers. Mary Villa at Mussoorie, where he placed the equatorial, was appropriately named 'Venus Station'. Its coordinates, namely, 30º 27′ 36″.3 N, 78º 3′ 3″.2 E, and a height of 6,765 feet above sea-level, place the station south of the Municipal Garden, the erstwhile Company Bagh. Hennessey set up

Figure 8: John Babonau Nickterlein Hennessey, F.R.S. (after Phillimore, 1945-1968: V, Plate 23).

the equatorial in an observatory tent with a removable canvas top. By trial and error, he chose an eye-piece, one of 125 power, just suitable to view the ingress (when the Sun's altitude would increase from 2º 24′ to 7º 29′) as well as the egress (with the Sun at ~26º). He had two flat glasses to give a neutral and bluish field for ingress, and changing one of these with a deep red glass for egress (Hennessey, 1874). At the crucial moments of the transit, W.H. Cole

Figure 9: The Hennessey Observatory, Survey of India, Geodetic Research Branch, Dehra Dun (photograph: R.C. Kapoor, February 2013).

did the seconds count, audible for obvious reasons, and

> Baboo Cally Mohan Ghose took up a position by my side, pencil in hand, noting down such remarks as the phenomena, viewed through the equatorial, elicited from me. (Hennessey, 1873-1874: 318).

Hennessey had determined zenith-distances of the 'clock stars' α Tauri (east) and α Aquilae (west).

Hennessey enjoyed fine weather for his observations. He knew what was in the offing to the minutest detail and rehearsed his observations. As the moments of the transit drew near and Venus closed in, he noticed the beginning only after the planet had made a 'dent' on the Sun's disc. At 8½ minutes before the second contact he saw a thin luminous ring around the planet, but not the black-drop effect, despite the advantage of a high altitude (Hennessey, 1874-1875; for a comparison of their observations, see Tennant; 1877: 41). For about half an hour, he watched the planet and then he substituted a spectroscope for the eyepiece. Its slit placed across the centre of the planet gave a black band all through the length of a bright solar spectrum. However, when the slit was placed tangential to the disc, Hennessey got a faint glimmer, "… slightly brighter than the solar spectrum over which it appeared …", and the lines identical to those seen in the solar spectrum.

Table 2: Hennessey's contact times.

Contact	h	m	s
I[st] internal	14	17	09.0
2[nd] internal	18	05	32.6
2[nd] external	18	32	49.6

Reducing his local mean time to Greenwich Mean Time, Hennessey (1874-1875: 381) gives the contact timings listed above in Table 2.

The black-drop however was noticed clearly by Colonel James Thomas Walker (1826–1896), who, 16 km south of Hennessey, made his observations from 'Dehra Doon', in the foothills at 2,200 feet. At that time, Walker was Superintendent of the Trigonometrical Survey of India, but he rose to become the Surveyor General from 1878 until 1884.

The Reverend H.D. James observed the transit from Chakrata, a place in the Shivaliks at an elevation of 7,300 feet (30º 43′ N, 77º 54′ E) with a telescope of his own—made by Smith and Beck—with a 3.5-inch object-glass and a focal length of 4 feet. For timing, he used a pocket-watch that he says gained a minute in 12 hours. Chakrata lies 80 km by road west of Mussoorie. It was a cantonment of the British Indian Army, founded in 1866 by Colonel Hume and occupied in 1869. In the course of his observations, the Reverend was ably attended by his son, Henry. About the Reverend James, Hennessey (1874-1875: 381) says: "His station is distinctly visible from Mussoorie on a clear day." Hennessey cites from his correspondence with the Reverend James what the latter observed:

> When she (i.e. Venus) was about halfway on (at ingress) the sun we both noticed a fringe of white light illuminating that rim of the planet which was yet on the dark sky. When she went off we noticed the same fringe of light, but for a much shorter time, and when only about one eighth of her had passed the sun's disk. (Hennessey, 1874-1875: 382).

In his note to the Reverend James, Hennessey (ibid.) says: "I had seen a ring of light, but no "pear-drop" or other ligament, at internal contacts." The Reverend James subsequently wrote him (see Hennessey, 1874-1875: 382-383):

> When about half her orb had entered (alluding to ingress) my attention was attracted to the other half yet on the dark sky: to me it was dark; hence I infer that ray field was not so light as it ought to have been. Its outline, up to this time quite invisible to me, became now illumined with a fringe of white light. I then also noticed a much fainter, thinner, edging of light on the outline of the limb on the sun's disk, which soon ceased to be visible. The fringe external was rather less in width than 1/64 of the planet's diameter. The light somewhat resembled that which we see so plainly in India lighting up the dark side of the moon three or four days old; but it was brighter, not diffusive as that is, its inner edge being clearly marked. It remained visible as long as there was any appreciable portion of the planet beyond the sun's circumference.
>
> As the time for the internal contact approached, that half of the planet which was still entering appeared to lose its semicircular shape and to become oval. I compared it to the thinner half of an egg; but, since, I have examined several eggs, and find that my comparison would represent a distortion greater than I had intended. Just before the contact ceased, the end of the oval seemed as it were adhering to the sun's edge, and could not get free, rendering it difficult to decide when the contact ceased. Another impediment in the way of accurate timing was, that the outline of Venus looked woolly and wave-like, from a very annoying tremor in the air. Hence the notes we entered were, 'Internal contact ceased 7^h 41^m 20^s, quite clear 7^h 42^m.' As to the ligament which seemed to knit the two edges together, I am disposed to attribute it solely to the billowy motion of the planet's outline; for it had a hairy appearance, and sunlight could be seen through it.

Hennessey (1879) later supplemented his analysis of the observations.

4.3 Transit Observations by Colonel J.F. Tennant and Captain G. Strahan

On 21 March 1872, the Astronomer Royal, Sir George Airy (1801–1892), urged J.F. Tennant to arrange observations of the forthcoming 1874 transit of Venus from India, and especially to make use of photography. Consequently Tennant prepared to observe the transit from two stations: at Roorkee, where he would be based, and at Lahore, where he would send Captain George Strahan from the Royal Engineers.

Born in Calcutta, James Francis Tennant (1829–1915; Figure 10) joined the Bengal Engineers in 1849 as a Second Lieutenant, and was then attached to the Great Trigonometrical Survey of India (H[ollis], 1915). Tennant briefly directed Madras Observatory from 13 October 1859 until October 1860, when Norman Pogson was appointed Astronomer (subsequently becoming Director in February 1861). Tennant observed Donati's Comet (C/1858 L1) between 5 and 12 October 1858 from Mussoorie (30º 17′ 19″ N and 5^h 12^m 17.7^s E), and Halley's Comet (1P/Halley) on 16 May 1910 from "… somewhere in the Himalayas …" (Tennant, 1910: 297), at an altitude of 7,500 feet. Most likely, this observation was made from Lal Tibba, Mussoorie. In 1890 and 1891, Tennant was the President of the Royal Astronomical Society.

For the attention of the scientific world, Lieutenant Colonel Alexander Strange, F.R.S. (1818–1876) presented in *Nature* a detailed account of preparations and instruments being employed by Colonel Tennant at the Roorkee station (Strange, 1874). It was dated November 1874 but only appeared in print after the transit was over. Strange was Inspector of Scientific Instruments to the Government of India and he had superintended the manufacture of some of the instruments. He mentions also Peshawur (Peshawar, now in Pakistan) and Bombay as other transit stations, and more than one station in the southern part of the peninsula of India under the care of Mr Pogson, that are to be provided with sufficient equipments. Ragoonatha Charry (1874: 17) also mentions that

> The most important spot in India has been shown to be Peshawur, and accordingly both this station and Roorkee will be occupied by Colonel Tennant, F.R.S., assisted by officers of Trigonometrical Survey of India.

The city of Peshawar adjoins the eastern end of the Khyber Pass, the historical trade route that connects Pakistan and Afghanistan. Peshawur, however, does not figure in Tennant's (1877: 2) accounts, for, he says that

> When it was determined that I should be employed to superintend the observations, my first care was to select positions for the observing stations. The Punjab is often cloudy in December, and thus it was desirable not to go too far west.

At Roorkee, Tennant had Captain William M. Campbell, Royal Engineers of the Great Trigonometrical Survey, Captain James Waterhouse, Royal Engineers, Sergeant J. Harrold, Royal Engineers, Lance-Corporal George and Private Fox as part of the team. Tennant set up a solar observatory by installing the photoheliograph; an equatorially-mounted 6-inch Cooke refractor with a double image micrometer, sheltered in a circular building with a revolving roof; an altazimuth-mounted refractor; and a portable transit instrument and chronograph. The values adopted by him for the latitude and longitude of the transit pillar, 29º 51′ 33.81″ N and 5^h 11^m 31.09^s E, were determined with reference to the longitude of Madras. The spot where Tennant's observatory was sited is a few hundred metres north of where the present-day Dehra Dun-Saharanpur Road crosses the Right Bank Canal Road, and between the former and the Upper Ganga Canal, as we make it out from *Google Maps*. This is consistent with a sketch of part of Roorkee showing the location of the observatory, as given by Tennant (1877). Among the transit party, the tasks were divided as follows:

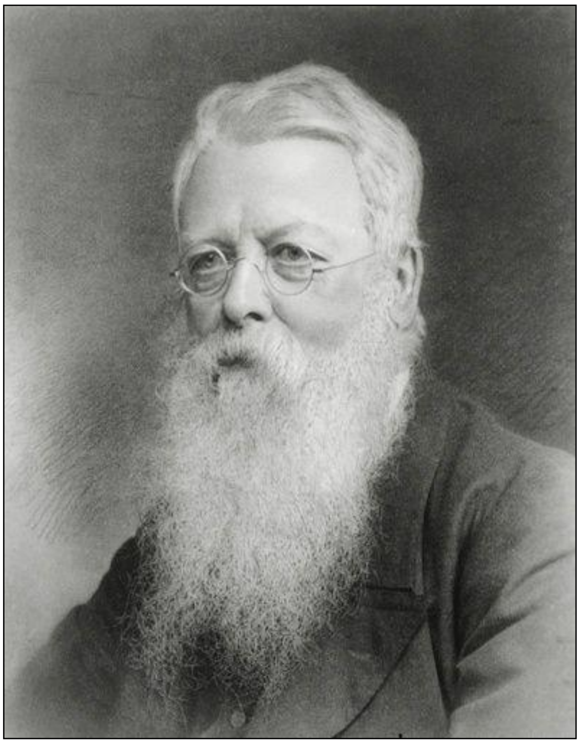


Figure 10: J.F. Tennant (courtesy: Indian Institute of Astrophysics Archives).

Time Determination:	Colonel Tennant
The Equatorial Telescope:	ditto.
The Alt-azimuth Telescope:	Captain Campbell
The Photoheliograph:	Captain Waterhouse

The team was later joined by Captain William James Heaviside, Royal Engineers, who also brought along the Royal Society's Slater Telescope. He was assigned responsibility for the chronograph: winding up the used record strips and their replacements when due. Besides, he was to observe the egress with the Slater Telescope. Regarding direct viewing, Tennant (1877: 44) held that

> ... where the spectroscope is not used, external contacts should be observed with a pale dark glass, so as to facilitate the seeing of Venus outside the Sun's limb, but that a smoke-colored glass (brown yellow) as deep in tint as is convenient should be used for internal contact to diminish, as far as may be, the irradiation and the haze round the planet.

Just when the transit began, with the Sun low, Tennant noticed the planet only four or five seconds after the first contact. However, he could observe the ingress in progress, and also the third and fourth contacts at egress. Tennant (1875a: 209) initiated micrometer measures of the cusps, obtaining sixteen measures of the chord joining the cusps at ingress, and also at egress. At the first internal contact, no black-drop or distortion was seen, that he had expected, and it was the same at egress. He even sent a telegram to Captain Strahan about this.

Table 3: Some values derived from the Indian observations of the transit made under Tennant's direction (after Tennant 1877: 44).

Observer	Venus' radius	Parallax
Tennant	30.87″	8.160″
Hennessey	31.18″	8.342″
Strahan	31.70″	8.260″

Tennant also measured the diameter of the planet, first horizontally so that it was free of refraction and atmospheric boiling, and later also in declination and in right ascension. The right ascension value exceeded slightly the one obtained in declination when corrected for refraction. He found a mean value of 63.948″ ± 0.0603″, for Venus as a sphere (Tennant, 1875b). Captain Waterhouse, assisted by 'Serjeant Harold', took 109 photographs while the transit was in progress and at the time of egress. Meanwhile, Captain Campbell observed the transit with the great theodolite.

Captain Strahan set up equipment in Lahore in the compound of a house occupied by Dr Calthrop that was known as Mr Elphinstone's house, the property of the Maharaja of Kashmir. Tennant deduced his position as 31º 23' 23.5″ N, 74º 19' 27.2″ E = 4h 57m 17.81s E. Strahan had a 6-inch Simms refractor and two solar and sidereal chronometers. Ingress was not visible here, but with favourable weather Strahan made his observations as the transit progressed. He, too, did not see the black drop effect at egress as such, but noticed the planet's atmosphere; to quote from his report and the notes presented in Tennant (1877: 36-38):

> As the planet moved towards the Sun's limb, she appeared to push away his edge before her, the cause of which became evident in a few seconds; the planet's edge was, in fact, encircled by a ring of light nearly as bright as the Sun, which prevented any contact, properly so called, from taking place at all … The part of the planet outside the Sun was palpably darker than the sky; dense black background being purplish. Its shape in no way distorted, magnified or diminished … It is difficult to account for the position of the strongest part of the ring of light being unsymmetrically situated with regard to the line joining the apparent centres of the Sun and Venus; but this is established beyond all doubt —indeed, the most unpractised eye must have noted the circumstance. It will be observed that the brightest part of it is almost exactly on the preceding portion of the disc reckoning along the line of the planet's motion; but whether this is a mere coincidence or a significant fact, is not readily apparent. The ring was visible up to the time of external contact, which enables one to make a rough estimate of the refractive power of the planet's atmosphere; inasmuch as the minimum (?) duration of a solar ray reaching the observer's eye after refraction when Venus is at exterior contact must evidently be the apparent diameter of Venus as seen from the Earth + the apparent diameter as seen from the Sun. This deviation, in the present case, amounts to about 1′ 27″.

Tennant provided a detailed account of the observations of the transit that were made under his charge, and he duly presented results in an 1877 report, together with a plan of the observatory that he had set up. The transit date printed in the report is 8 December 1874, which is according to the day that it commenced (Tennant 1877; see also Tennant 1875a and 1875b).

In the report, he used Hennessey's observations as well, and he deduced a few results for the three observing sites. The crucial ones are listed in Table 3. Based on these, he assigned a mean value of 8.260″ for π. It is of interest to note that this figure is not grossly dissimilar to the best figure for the solar parallax available at that time, Encke's 1824 value of 8.5776″, which was derived from observations of the 1761 and 1769 transits (see Dick et al., 1998: 223).

After the transit expedition, Tennant proposed the establishment of a solar observatory at Shimla, for spectroscopy and photography and observations of Jupiter's satellites, but his proposal was not accepted. However, arrangements were made to take daily photographs of the Sun with the Dallmeyer photoheliograph, under Colonel Walker's superintendence, and this is how the Dehra Dun Observatory came into existence.

4.4 Captain A.C. Bigg-Wither's Observations

Captain A.C. Bigg-Wither (1844–1913) was an engineer with the Indus Valley Railway, and he observed the transit of Venus on 9 December 1874 from his observatory at Mooltan in the Punjab (30º 11′ 5″ N, 4^h 45^m 59.5^s E; Multan—the current spelling—is now in Pakistan) where many gathered to watch the event. Bigg-Wither was a keen astronomer since his younger days, and he maintained a personal observatory for 45 years where he would carry out many different types of observations with his 5-inch telescope and a transit circle, so much so that

> At Quetta and Mooltan, his observatory was the scientific centre of the Civil and Military stations. After a long day in the Public Works Department he would be invariably found in the midst of calculations or working with his instruments till the night was far advanced. (*Monthly Notices of the Royal Astronomical Society*, 1914: 270).

Some details about him are provided by Gosnell (2012).

On the crucial day, Bigg-Wither observed the transit with a 4-inch equatorially-mounted Cooke refractor of 5 feet focal length using powers from 55× to 300× and a solar diagonal eyepiece, while the Sun rose with half of the planet's orb already on the disk of the Sun (Bigg-Wither 1883). He had fine weather, but even at the time of second contact the Sun and Venus were still very close to the horizon. Yet he was able to observe the black-drop effect, and he timed the second contact at 12^h 17^m 8^s Mooltan Sidereal Time, just when he saw the 7″ wide black band break.

As the transit progressed, he watched carefully to see if he could detect any trace of light on the disk of the planet. Only at its edge did he notice that "… the Sun's light appeared as if it were slightly encroaching …" (Bigg-Wither, 1883: 97). Over the disk of the Sun he also looked around the planet, though in vain, for any spot caused by a possible satellite.

At egress, he was surprised to notice no traces of the black drop effect. However, just as the planet reached the limb of the Sun,

> … she appeared to push before her a ring of light concentric with her disk; this was first noticed at about 16h 3m Mooltan Sidereal Time, when otherwise from her position Apparent Contact would have taken place; this ring soon appeared thicker in the middle, in fact taking the shape of a crescent, the inner edge of which was evidently the same as that of the planet's disk ... The appearance at this time, when the crescent was at its best, was very beautiful; the planet seemed to start out stereoscopically, with a kind of glow on its disk shaded like the light on a globe, so that I could see it was a sphere between the Earth and the Sun, an effect that no effort of the imagination could produce during the Transit … When the western part of the crescent vanished, as stated above, it appeared to leave exactly half, the thin end joining on to the Sun as before, and the other end corresponding to what was the middle. This appearance lasted some time; at 16^h 18^m the planet was about bisected by the Sun's limb, and the half crescent therefore covered about one-fourth of the planet's circumference. (Bigg-Wither, 1883: 98-99).

Bigg-Wither wondered how this crescent formed; it was not there at the ingress. Nor had he noticed this at the time of egress when he observed the transit of Mercury on 5 November 1868 with the same telescope, and while in England.

During the 1874 transit of Venus, the last external contact (contact 4) happened at 16^h 30^m 1^s, which Bigg-Wither says actually differed quite substantially from the calculated time.

4.5 Observations from Bushire, Calcutta and Kurrachee

We have little information on observations made at some of the other stations. According to Proctor (1882: 218),

> The whole transit was also observed by amateur astronomers at Kurrachee, Indore, and Calcutta, a fact rather showing what ought to have been done by official astronomers in England to strengthen the north Indian position, than (in all probability) adding much to the value of northern Halleyan operations.

Unfortunately we cannot identify these amateur astronomers, and we have no details of their observations.

David Gill also mentions observations of the transit made from Kurrachee (Karachi, now in Pakistan), Calcutta and also Bushire. These places are listed, together with Roorkee and Maddapore, in a table by Gill (1878: xxx-xxxii) showing stations where observations of the transit were carried out more or less successfully. He comments that the stations marked in his table with an asterisk had at least some persons present with previous training and good instruments. Of the stations mentioned above, Bushire and Calcutta are not so marked, and Gill raises the question as to whether the observations made without these conditions should be relied on. Bushire (Bushehr), we may recall, is situated on the Persian coast and was then a British India Political Residency in the Gulf. The *Astronomical Register* (Notes …, 1875) carried the latest information received by the Astronomer Royal, Sir George Airy through

Reuter's brief telegrams that he presented before the Royal Astronomical Society in its meeting on 11 December 1874. The telegram from Bushire merely said "The transit was beautifully observed …", and Airy lamented that the telegram

> … does not say by whom, and that is a misfortune attending most of Reuter's telegrams; though we shall hear more about them in time, no doubt. 'The interval from the commencement to the end of the apparent contact, 4h.37m.32s.; the interval between two internal contacts, 3h.42m.56s.'. And then comes the remark, which is worth notice, 'No black drop appeared'. (ibid.).

Airy then read out the content of a telegram from Calcutta that said the observations were excellent: mean time of the ingress centre: 7.56 a.m.; middle, 10.5 a.m.; egress centre, 12.13

Figure 11: Father Eugene Lafont (courtesy: en.wikipedia org).

p.m. The observer is unknown. While Madras reported a near wash-out due to clouds, Reuter's agency learnt from Kurrachee that the first contact happened before sunrise, at $6^h\ 10^m\ 26^s$. Airy commented that in such a case the observer, unable to observe it, would have taken the published time only and therefore one may pass over his other times. Lieutenant Stiff mentioned that the observer at Kurrachee was General Addison who used an equatorially-mounted Cooke refractor. Stiff said there might be some inaccuracy in the telegram itself as to the timing. Apparently, Stiff was referring to General Thomas Addison who had set up his own small observatory. According to Pogson (1884: 47),

> The telegraphic determination of the difference of longitude between Madras Observatory and Karachi was of two-fold importance and interest, from its being one of the Indian stations at which observations of the Transit of Venus, on 1874 December 8th, were arranged to be made; and still more as a means of comparison between Madras and Greenwich, in conjunction with the similar operations by Drs. Becker and Fritsch, members of the German Transit of Venus Expedition to Ispahan … His observatory was connected by triangulation with that of the Great Trigonometrical Survey, on Bath Island, and the latter was found to be 0.60 second further West of Madras … It is surprising, that with only three clock stars at Karachi such accuracy should have been attained.

The *Proceedings* of the Asiatic Society of Bengal for December 1874 carried a note from Captain Campbell detailing the equipment and the transit observations proposed to be made at Roorkee by J.F. Tennant et al. (Asiatic Society of Bengal, 1875: 241-44). Campbell's communication is followed by the Society's *Note*, as follows:

> The Transit of Venus having taken place since the above was written it may be interesting to state before going to press that the Transit was successfully observed in India, by Col. Tennant's party at Roorkee where 107 six-inch photographs and 6 Janssen plates were taken, with favourable weather; at Lahore by Captain G. Strahan R.E.; at Masúri by Mr. J. B.N. Hennessey, who obtained some interesting results with the spectroscope; at the Surveyor General's Office, Calcutta, where 39 photographs and several eye observations were made; at Muddapur by a party of Italian astronomers under the direction of Sig. Tacchini, the distinguished spectroscopist, and at Kurrachee by General Addision. At Madras the weather proved unfavourable.
>
> Tidings of the observations have also been received from the parties scattered in various parts of the world, mostly satisfactory.

The Calcutta observations mentioned above by Airy (The transit of Venus, 1875) may not be the same ones as in the *Note* in the *Proceedings of the Asiatic Society of Bengal*.

4.6 Father Lafont's Observations

Founded in 1860, St Xavier's College in Calcutta made a seminal contribution to the promotion of science and technical education. The Belgian Father Eugene Lafont (1837–1908; Figure 11) of the Society of Jesus began working in 1875 to establish the first spectro-telescopic observatory at St Xavier's College, having joined the staff in 1865 when he came there to teach. In 1867 he established a meteorological observatory and participated in the expedition organized by the Italian astronomer, Pietro Tacchini (1838–1905; Figure 12), to observe the transit of Venus on 9 December 1874 from Muddapore (Madhupur) in Bihar. In the process Father Lafont discovered the presence of water vapour in the atmosphere of Venus (Biswas, 1994).

Tacchini had persuaded Father Lafont to establish an astronomical observatory at the College and in 1877 he installed an equatorially-mounted 23-cm Steinheil refractor and an 18-cm Merz equipped with a Browning spectroscope, and a coelostat, etc., in a 22-ft diameter rotating dome erected on a terrace at the school (Udias, 2003).

In November 1874 Father Lafont was joined at St Xavier's College by a mathematician and astronomer, Father Alphonse de Penaranda. Until his death in 1896 Father Alphonse participated in the astronomical observations made by Father Lafont. These included: the solar eclipse of 17 May 1882 (magnitude 0.48 at mid-eclipse at 08:45 UT in Calcutta); the Mars-Saturn conjunction of 20 September 1889; the 17 June 1890 annular solar eclipse observed from Bhagalpur (magnitude 0.973, annularity 3^m 27.9^s, post-meridian; values from *Eclipse Predictions by Fred Espenak, NASA's GSFC*); the 10 May 1891 transit of Mercury; and the occultation of Jupiter by a Full Moon on 6 October 1892.

Biswas (1994) details Father Lafont's scientific work at St Xavier's College, and his contribution with Dr Mahendralal Sircar (1833–1904) in founding the Indian Association for the Cultivation of Science in 1876.

Of the transit of Venus expedition to Muddapore, Father Lafont wrote:

> After all the careful preliminary arrangements, we were all anxiously awaiting the rising of the sun; anxiously, for though the weather had been excellent almost every day since the arrival of Professor Tacchini, the clouds two or three days before had caused the astronomers great fear and anxiety. From 4 O'clock all were up, gazing at the sky, and the sight was not quite reassuring, light but numerous clouds overspread the horizon, and assumed rosy tinges as the sun began to rise. Nothing daunted however the four observers, who each with his chronometers in hand, entered their respective observatories to prepare for work. (Biswas, 2003: 97).

Pietro Tacchini was the Director of the Palermo Astronomical Observatory. Pigatto and Zanini (2001) have described in detail Tachini's expedition to India. On the basis of the maps provided in the 1874 edition of Richard Proctor's book on the transit of Venus and input from the Italian Consul in Calcutta, he decided to observe the transit from Bengal. Muddapore (24º 17′ 0″.96 ± 0″.34 N and 5^h 46^m 20.570^s E), the place they chose for their observations, is 300 km north-west of Calcutta. The high costs involved in mounting an international transit of Venus expedition prevented them from having a second station for the purpose of determining the solar parallax, and so they settled on making spectroscopic observations in order to obtain exact contact timings. Tacchini was accompanied by Alessandro Dorna (1825–1886; Figure 13) from the Observatory of Torino, Antonio Abetti (1846–1928; Figure 14) and Antonio Cagneto from Padova and Carlo Morso from Palermo. Italy's leading expert on astronomical spectroscopy, Angelo Secchi (1818–1878), could not come because of health issues. Tacchini's team had four instruments that required revolving observatories.

Figure 12: Pietro Tacchini (after Macpherson, 1905: facing page 77).

Figure 13: Alessandro Dorna (courtesy: www.torinoscienza.it/accademia/personaggi/alessandro_dorna_20107.html).

Tacchini had an equatorially-mounted refractor furnished with a spectroscope, as also did Professor Abetti. Father Lafont and Professor Dorna also had equatorially-mounted refractors, but they would use these visually to record the contact timings with the aid of rated chronometers. Despite frustration caused by clouds, Lafont and Dorna were able to time both pairs of ingress and egress contacts. Near the start of the transit, the clouds dispersed and allowed the observers to attend to their assigned tasks. Tacchini diligently observed and found evidence of water vapour in the Venusian atmosphere, an observation that was corroborated by Abetti. These observations from India provided the first *spectroscopic* confirmation of the existence of an atmosphere around Venus.

The idea was to detect the presence of the planet over the red chromospheric emission by keeping the slit of the spectroscope tangential to the solar limb just as the former entered and exited the slit, and time it. Tacchini commented that "… before the second contact, Venus was visible over the chromosphere …" (see Pigatto and Zanini, 2001: 49). Father Lafont (Biswas, 2003) further says

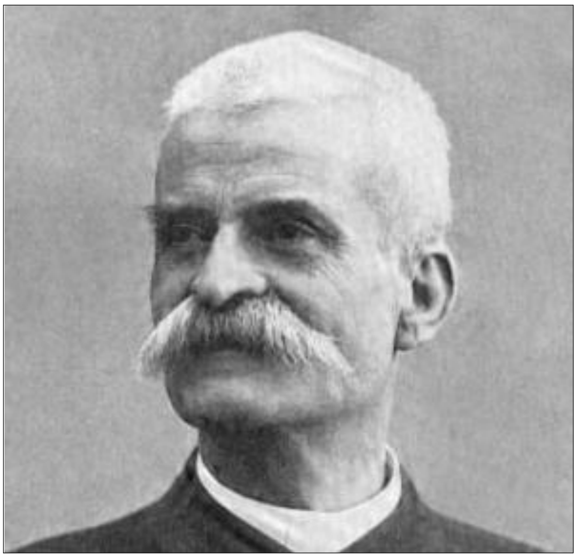


Figure 14: Antonio Abetti (courtesy: en.wikipedia.org).

> I may mention, before concluding, that Prof. Dorna observed the black dross both at ingress and egress, whereas not a trace of it was seen with the instrument I used, a German telescope by Starke, 52 lines aperture, and 6 feet focal distance. According to my results, the whole transit lasted 4 hours, 41 minutes, 1.5 seconds.

Tacchini and Abetti missed out on timing contacts 1 and 2 due to clouds, but what is remarkable is that between the five observers, spectroscopic contacts 3 and 4 occurred earlier than the telescopic ones. Tacchini concluded that when viewed through the spectroscope the Sun's diameter was smaller than seen visually in the telescope, a discrepancy that previously had been observed. In the following days, they measured the solar diameter visually and spectroscopically. The latter always turned out to be smaller, by an amount between 2.82″ and 4″ (Pigatto and Zenini 2001). Since the chromosphere lies above the photosphere, these observations are hard to reconcile with our current knowledge of solar physics.[6]

4.7 Transit Observations by Dr Mahendralal Sircar

Biswas (2003) mentions that Dr Mahendralal Sircar (Figure 15) also carried out telescopic observations of the transit. These may have been from Calcutta. At the insistence of Father Lafont, on 7 March 1874 Sircar acquired a telescope from a Dr J.N. McNamara. There is no information on the manufacturer or aperture of this instrument, which we can presume was a small refractor, except that it had an alt-azimuth mounting and five eyepieces: it was "… without equatorial … [and with] five powers …" (Biswas, 2000: 19). Apparently, Sircar would often observe planets with this telescope. Diary entries for the year 1882 also describe observations of a comet—which is not identified—but judging from the entries dating between 23 September and 9 October (see Biswas, 2000: 87) it must have been the Great Comet of 1882 (C/1882 R1) that even was visible during the day for part of this interval.

Observations of the transit of Venus listed in Sircar's diary (Biswas, 2000: 39), indicate that the total duration of the event was $4^h\ 37^m\ 30^s$, which is 3.5 minutes shorter than the duration reported by Father Lafont (see Table 1 in Pigatto and Zenini, 2001). Sircar's contact timings also differ from the corresponding ones of Father Lafont by between 7 and 10 minutes. Could Sircar have been so far off the mark? Maybe not. Tacchini's team did not use sophisticated equipment to time the transit, and they and Sircar may not have synchronized their chonometers. It is as well to remember that these observations date before British India adopted two time zones, with Calcutta using the 90º E meridian and Bombay the 75º E meridian. This scheme was only introduced in 1884, with Calcutta time set at GMT + $5^h\ 30^m\ 21^s$ and Bombay Time at GMT + $4^h\ 51^m$.

So what time system(s) did our transit of Venus observers use so that they could eventually match their observations? We cannot be certain, but we are inclined to believe that the various contact times recorded in Sircar's diary and reproduced here in Figure 16 are in local mean time. Notably, Sircar's times are consistently ahead of the Muddapore contact times (which were in Muddapore Local Mean Time).

The illustration which follows may therefore help. Calcutta local mean time (Greenwich Mean Time + λ/15º) is about $5^h\ 53^m$ ahead of GMT, so sunrise on 9 December 1874 was at 06:30 local mean time. If we factor in the longitudinal difference between Muddapore and Calcutta (~7 minutes), a more consistent set of contact times emerges, with the disparity in the respective contact times between Sircar and Father Lafont shrinking to within 3 minutes. In fact, the discrepancy decreases with each contact. The upcoming transit was a subject of great local interest (e.g. see Asiatic Society, 1873, 1875), and interactions with Father Lafont would have apprised Sircar of what to expect, and how to make meaningful observations and time the various transit contacts. We can only imagine that he viewed the transit through his telescope using a dark, coloured or smoked glass as a filter, or some sort of optical modification (e.g. a Herschel Wedge), or eyepiece projection, although Sircar does not specifically mention any of these. For one with a medical background who regretted that his telescope could not resolve Saturn's rings (Biswas, 2000: 27), we may judge that his account of the transit was a fair observation.

Interestingly, Father Lafont's own contact times also are consistently ahead of the predicted times by a similar magnitude, when we compare them with Espenak's (2012). Precision in computation of the circumstances apart, the fact is that to time exactly contacts 1 and 4 visually is very difficult, for both objective and subjective reasons. That is, because of the optical effects, namely atmospheric seeing and instrumental diffraction (e.g. see Proctor, 1882: 224); solar limb darkening (see Duval et al., 2005); and distortion of the silhouette of the planet's disk—the notorious 'black drop effect', these may seem to last from seconds to a minute (Maor, 2000: 95).

4.8 Nursing Row's Observations

As one keen to pursue astronomy with modern equipment, G. Venkata Jugga Row (1817–1856), an affluent *zemindar* (landlord), was a pioneer whose personal interest saw the erection of a private observatory in the backyard of his residence in Daba Gardens at Vizagapatnam in 1840 (see Figure 17) that continued to function under his descendants until the late nineteenth century. He acquired a Troughton transit circle and a chronometer, and the optics for a refracting telescope of 4.8 inches aperture and 5 feet 8 inches focal length telescope. Here, he carried out astronomical and meteorological observations, and he also determined the latitude and longitude of Vizagapatnam. On a nearby hill known as the Dolphin's Nose he installed a flagstaff to provide time signals for the public. Each

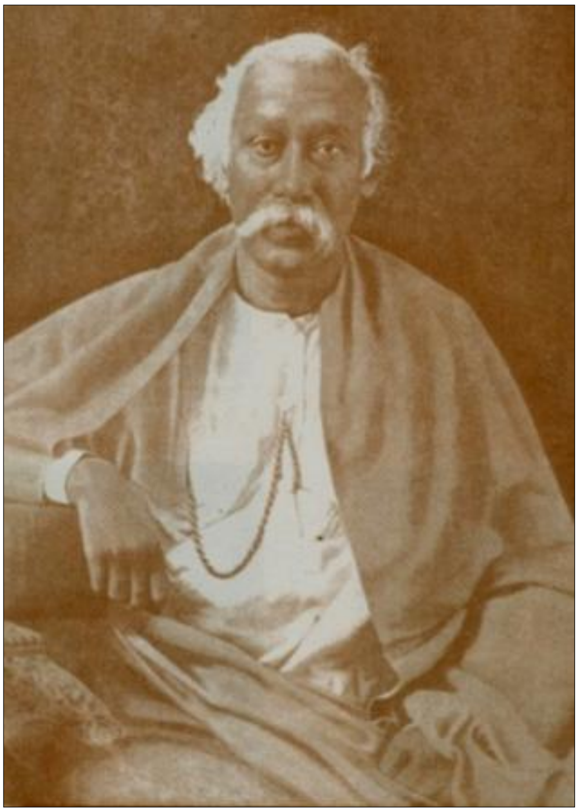
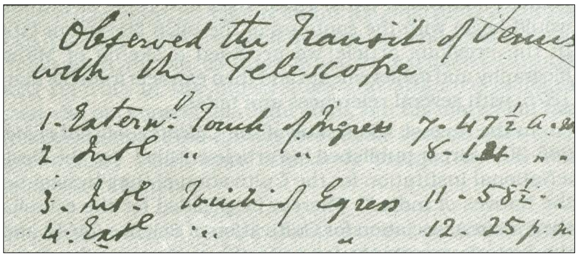


Figure 15: Dr Mahendralal Sircar (after Biswas, 2000: Plate 1).

day at 9 a.m. the flag was lowered, setting time for all who lived too far away to hear the report of the time-gun fired from the fort.

Jugga Row had assisted Thomas Glanville Taylor (1804–1848), the Director of the Madras Observatory, in observing Halley's Comet (1P/1835) in 1835, and he independently published a paper in the *Madras Journal of Literature and Science* in 1836 where he determined the mass of Jupiter to be 302 times that of the Earth, using the motion of the Jovian satellites and Kepler's laws of planetary motion (Kameswara Rao et al., 2011). This figure is close to the modern value of 317.83 times the mass of the Earth (Allen, 1976: 140).

Subsequently, A.V. Narsinga Rao (1827–1892, Figure 18), who is better known by his Anglicized name of 'Nursing Row', inherited the observatory from his father-in-law, Jugga Row. Nursing Row then carried out astronomical and meteorological observations, and he maintained



Observed the Transit of Venus with the Telescope

1. External Touch of Ingress 7-47½ a.m.
2 Intl .. .. 8-1[illegible] ..
3. Intl. Touch of Egress 11-58½.
4. Extl .. .. 12-25 p.m.

Figure 16: Excerpt from Dr Sircar's diary (after Biswas, 2000: 39).

Figure 17: The private observatory that G. Venkata Jugga Row erected at Daba Gardens in Visakhapatnam. However, this photograph was taken in 1874 by which time the observatory was owned by Nursing Row, and it shows European and Indian observers of the transit of Venus (adapted from Rao et al., 2011: 1575).

a local time service. To observe the solar eclipse of 18 August 1868, he assembled the 4.8-in telescope whose optics the observatory already had. He then published his observations, at the same time establishing contact with the Astronomer Royal of Scotland, Charles Piazzi Smyth (1819–1900) and one of England's foremost authorities on astronomical spectroscopy, William (later Sir William) Huggins (1824–1910). When the Government discontinued firing the time-gun at the Dolphin's Nose in 1871 Nursing Row came forward and maintained it at his own expense.

Figure 18: A.V. Nursing Row (courtesy: http://www.avncollege.ac.in/).

After erecting the 4.8-in telescope Nursing Row observed the 5 November 1868 transit of Mercury and published a report in *Monthly Notices of the Royal Astronomical Society* (Nursing Row, 1869). His subsequent papers in this journal speak of a keen interest in and knowledge of astronomy. He also observed the solar eclipses of 12 December 1871, 6 June 1872 and 17 May 1882; transits of Mercury on 8 November 1881 and 10 May 1891. He also carried out some astrophotography with the telescope.

By the time he observed the 9 December 1874 transit of Venus Nursing Row had replaced the original telescope in the dome room with a 6-inch, clock driven, equatorially-mounted Cooke refractor of 7½ feet focal length. Clouds allowed him to observe only the last thirty minutes of the transit, but including both egress contacts (Nursing Row, 1875: 318). He noted that

> After the second external contact, when the limb of the Sun had resumed its natural appearance of an arc, a slight indentation was directly formed in the Sun's limb. This indentation was not so dense as that caused by the planet, but more or less tending to an ash colour, and was apparently greater in arc than the previous one.

Nursing Row recorded the contact times shown here in Table 4. He surmised that the indentation was perhaps caused by the atmosphere of the planet.

In 1871, Nursing Row was elected a Fellow of the Royal Astronomical Society and the following year of the Royal Geographical Society. Today the Dolphin Hotel, which was established in 1980, stands on the site of the observatory.

4.9 E.W. Pringle's Observations

As the transit of Venus drew near, the journal *Nature* commenced a regular coverage of the preparations being made to observe it, then after the transit the journal reported in successive issues on successful observations made at various places throughout the world, and also referred readers to accounts that appeared in *The Times* newspaper.

One of the communications *Nature* received about the transit was from Manantoddy (Mananthavady) in India. The observations in question were carried out by E.W. Pringle (The transit of Venus, 1875), who employed a small Cooke refracting telescope of 24 inches focal length and a 53× eyepiece. Pringle's account does not mention contact timings or the geographical coordinates of his site, merely stating that he was located nine miles from Manantoddy on top of an 800-feet high hill and an elevation of 3,600 feet above mean sea level. In van Roode's (2011) maps, the site is tentatively pinpointed, but with the rider that Pringle's description of his location is vague. This location is in the Wayanad mountain ranges, in Kerala, about 40 km from Mangalore.

Pringle was an engineer with the Madras Public Works Department. We note that previously he had participated in the expedition to Bekul (Baikul) in South Canara that Britain's solar physics pioneer Norman (later Sir Norman) Lockyer (1836–1920) organized to observe the total solar eclipse of 12 December 1871 (Maclear, 1872). The *Illustrated London News* (see Loney, 2013) carried pictures of the expedition taken by Mr McC. Webster, the Collector of South Canara, that were featured also in the 1 February 1872 issue of *Nature* (see The eclipse observations …, 1872). These showed the fort where Lockyer and Captain J.P. Maclear had installed their instruments, with the men all at their posts and ready. Also seen therein are Mr Henry Davis and Dr Thomas Thompson, a botanist carrying out photographic and polariscopic observations. What is interesting to note is

> … the 9¼ reflector constructed by Mr. Browning, with a mounting by Cooke, and the double refractor, consisting of two telescopes of six inches aperture, mounted on one of the universal stands prepared for the Transit of Venus observations in 1874, and lent by the Astronomer Royal." (The eclipse observations …, 1872: 268).

Pringle timed the transit with the aid of an ordinary watch. There is a brief account of his observations in his letter from Manantoddy, dated 13 December 1874, to *Nature* and published in the 14 January issue (The transit of Venus, 1875). It says that Pringle was expecting equipment from England but this did not arrive in time so he had to make do with the little 24-inch long refractor. The morning of 9 December was clear and weather perfect. Pringle missed the first ingress contact, but he continued watching the ingress for the second contact. Then, when half the disc had moved onto the Sun he saw the whole disc become visible where the portion exterior to the Sun's limb showed up rimmed by a "… fine silvery ring like a minute corona." The observation also was verified by Pringle's brother, and they saw the same thing happen at egress. Regarding the black drop effect, Pringle (The transit of Venus, 1875: 214-215) reports:

> As first internal contact approached I looked carefully for the 'black drop', but, to my astonishment, the horns of the sun grew nearer and nearer, and at last seemed to fade into the last portion of the before-mentioned silvery ring, without my seeing the smallest vestige of the far-famed 'drop', or any apparent elongation of the limb of the planet. Had it existed to the extent of one hundredth of the diameter of Venus, I am confident I should have seen it ...

Table 4: Nursing Row's egress contact times.

Contact	h	m	s
2^{nd} internal	16	47	15.4
2^{nd} external	17	15	27.2
Disappearance of the slight indentation	17	15	54.0

He also mentions an attempt to detect absorption bands from the atmosphere of Venus during the transit, but had to give up for want of sufficient power and "… the difficulty of keeping the slit of the stellar spectroscope fixed, on the planet, with altazimuth motion." (The transit of Venus, 1875: 215).

In its 17 December 1874 issue, where reports from diverse groups appeared, *Nature* (1874: 121-123) transcribed a telegram giving an account of Janssen's transit observations. The transcription read "Nagasaki, Dec. 9: Transit observed and contacts obtained. Fine telescopic images. No ligament. Venus seen over sun's corona …" Pringle's (1875) subsequent letter to the Editor of *Nature* brings out his grasp of the phenomena observed during the course of the transit, where (referring to *Nature*, 1875: 122), he contests Janssen's observation that "Venus was seen over the sun's corona before contact …", first asking, "… which contact, external or internal, is unfortunately not mentioned." He says that the idea of a rim of light around the disc of Venus being due to the solar corona has not found favour with others. To explain his point, Pringle (1875) presents a diagram showing Venus at first internal contact, as also at half immersion. He says that he did not see the retreating edge of Venus after the last external contact. In fact, referring to his diagram, he says he noticed a brighter spot on the lower limb of the planet at about half immersion that could have been due to the atmosphere of Venus being freer of cloud and thus refracted more light.

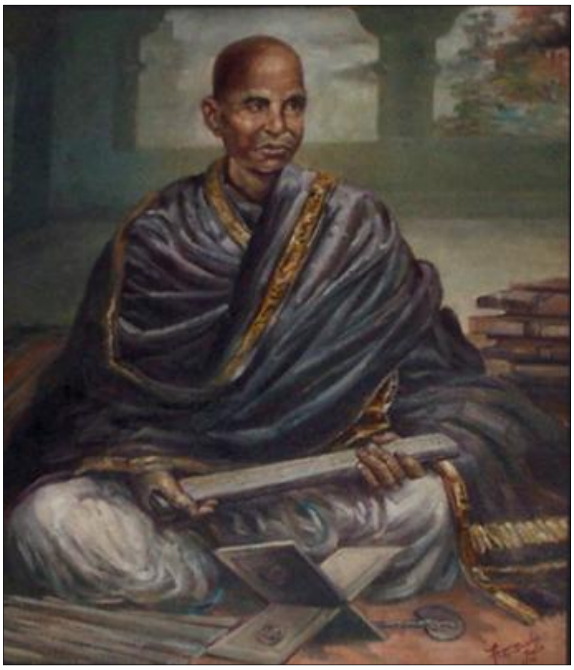


Figure 19: Samanta Chandra Sekhar Simha (http://www.iopb.res.in/~duryo/Samanta_Chandrasekhar/tn/Picture_1236.jpg.html).

4.10 Some Other Observations

Apart from Pringle's observations, *Nature* (The transit of Venus, 1875) mentions observations of the transit from some other places in the region. One of these was by George Wall from Colombo. A botanist and astronomer, George Wall (1820–1894) was a person of eminence in Ceylon (now Sri Lanka). As per the report, the observations recorded turned out to be similar to what Chappe d'Auteroche had made during the 1769 transit. Reporting on Wall's observations, the *Ceylon Times* (1875) remarked that "… it is clear that science will lose much from an incomplete discussion of all the observations made in 1761 and 1769."

The 'Notes …' (1875: 202) in the *Monthly Notices of the Royal Astronomical Society* about the 1874 transit of Venus cite places around the globe from which the Astronomer Royal received information that naked eye or photographic observations of the different phases of the transit were recorded. Places in India that he cited were: Indore, Calcutta, Kurrachee, Maddapore, Mooltan, Mussoorie, Roorkee and Umballa. Of these, we have not been able to obtain any information about the observations made at Indore and Umballa (Ambala).

5 SAMANTA CHANDRA SEKHAR AND THE 1874 TRANSIT OF VENUS

Samanta Chandra Sekhar Simha (1835–1904; Figure 19) from Odisha, popularly called Pathani Samanta, was a traditional *Siddhāntic* (theoretical) astronomer in a relatively modern age. He devised a number of instruments to carry out naked eye astronomical observations and gathered together his knowledge and experience in an invaluable tract, *Siddhānta Darpana*, which was written in Sanskrit. This work was published in 1899 by the Indian Depository in Calcutta (Naik and Satpathy, 1998). Chandra Sekhar's results compare well with the true positions and movements of the celestial objects, including their conjunctions etc., even though he had no exposure to modern scientific works or instruments (see for detail, Satpathy, 2003).

In the *Siddhānta Darpana* (XI, 110), Chandra Sekhar describes, in the stanza reproduced below in Figure 20, *Shukra* seen eclipsing the Sun in the Kali year 4975. Naik and Satpathy (1998) state that Chandra Sekhar predicted the eclipse from his computations and observed it with the naked eye. The observation may have been made from Khandapara in the Nayagarh district, where he was born. A translation of the stanza, by Upadhyaya (2012), follows:

> Solar eclipse due to *Sukra* (Venus) – To find the eclipse of the Sun due to *Sukra*, their *bimba* (angular diameter) and size of other *tara graha* (stars and planets nearby) is stated. In the Kali year 4975 (AD 1874) there was a Solar Eclipse due to *Sukra* (Venus) in *Vrischika Rasi* (Scorpio). Then *Sukra bimba* (Venus' shadow) was seen as 1/32 of the solar *bimba* (Solar shadow) which is equal to 650 *yojana* (a scale of several miles). Thus it is well proved that *bimba* of *Sukra* and planets are much smaller than the Sun.

To express numbers, Chandra Sekhar uses symbolical words, the traditional wont of Sanskrit scholars. The numbers for years and the size are

दृष्टं शुक्रस्य गाढास्तमचसमचजं मण्डलं चण्डभानौ कीटांशे पञ्चबिंशे गत बर्तिं कलितोहर्थाहद्रिगोहब्ध्यब्दबृन्दे ।
भास्वद् बिष्कम्भदन्तां शमितमित इदं खार्थषट् योजनं स्यात् । इत्यन्यजज्ञेचमस्मांत्तनब इन – तंनोस्तारका : कोर्ग्रहा : स्युः ।

Figure 20: Chandra Sekhar's description of *Shukra* seen eclipsing the Sun in the Kali year 4975.

given in reverse. To date the event, the conventional *Saka* year, or *Kalidina* (the number of days elapsed since a particular zero day—counted in Hindu astronomy from 17/18 February 3102 BCE when the astronomical *Kali* era commenced; see Somayaji 2000: 162) is not used. A description of this event which was unusual on all counts, and the timings of immersion (*sparsha*: touch) and separation (*moksha*) —which he would have deduced from computations, and possibly measured from observations —are not given.

Using *Solar System Live* (Walker, 2013), we get for Khandapara (20.26º N, 85.17º E) the Sun's altitude as 12.8º on 9 December 1874 when the transit commenced. By mid-transit (04:07 UT) it had reached 37.3º, and it was at 46.8º when the transit ended. From the Horizons System (Jet Propulsion Laboratory, 2012), we get the respective angular diameters of Venus and the Sun as 63.1″ and 1949.2″ at mid-transit, giving a ratio of 1/30.9. The word *danta* (dent) in Chandra Sekhar's stanza implies one of the 32 dents, and comes close enough when translated to mean 1/32 of the solar *bimba*. That is accuracy down to 1′, and is a remarkable result. Just how it is arrived at is not clear. If he had timed the events, say the ingress/egress, he had to know also the phenomenology beforehand. If it was from measurements with home-made instruments (Naik and Satpathy, 1998), we have no idea of their precision.

The *Sūrya Siddhānta* (ca. 400 CE - 12th Century; Burgess, 1860, VII: 13-14) defines the planetary diameter at the Moon's mean distance, where the brighter the object the greater the diameter. The unit used is *yojana*, a measure of distance. Its value is not standardised and different authors give different values in the classical Indian texts. Generally, it is taken to be equivalent to about 5 miles. Here, 15 *yojanas* make an arc minute and Venus is 4′, equivalent to 60 *yojanas*; Mars is similarly attributed 30 *yojanas*, etc. (see Burgess, 1860: 170). In the present observation, the planet, termed *bimba* in the translation, appeared as a black extended disc (on the *bimba* of the Sun) rather than a luminous disc. Chandra Sekhar assigns it a size again, also in *yojana*, and that must be the physical size. Chandra Sekhar could not have arrived at it without finding out the coveted distance. In the *Siddhāntas*, it is customary to express the circumference of a planetary orbit also in *yojana*. A distance to the Sun can then be deduced, where, ironically, one has to start from a certain value assigned to its orbital circumference, and the result turns out to be far less than the actual value (see Burgess, 1860: 126-127). One should refer to Naik and Satpathy (1998: 41) for the different values adopted in the various *siddhāntas*, including the *Siddhānta Darpana*.

At mid-transit, the modern computed true position of the Sun was λ = 257.0º (Horizons System). In the word *Keetāmsha* in the first line of the above-mentioned stanza, *Keet* stands for Scorpio, implying that the conjunction took place in Scorpio; *amsha* means part, but also 'degree'. The word *panchabinshe*, that appears next, means *25 of/in*. Taken as a phrase, *25 of/in Scorpio* implies that Chandra Sekhar probably meant the solar longitude to be 235º. That would be in the sidereal system, measured from a fixed Initial Point of the zodiac. From Chatterjee and Chakravarty (2000: 320-324), we learn of the attempts in the past by Indian classical astronomers to fix the position of the Vernal Equinox. These appear to have been made on three different occasions, circa 300 CE, 500 CE and 570 CE. It is not clear which one of the reference points Chandra Sekhar used. If it was the point 180º opposite the star *Chitrā* (Spica; epoch 1874.94 λ, β: 202.8º, –2.05º) which was fixed ca. 300 CE, we come very close to the computed tropical value of the longitude (the discrepancy is only ~0º.07) when we factor in the precession differential of Spica with respect to the position of the Vernal Equinox in 300 CE. Incidentally, this point was adopted in Varāhamihira's *Sūrya Siddhānta*, and possibly the founder astronomers of the *Sūrya Siddhānta* also used the same point (see Chatterjee and Chakravarty, 2000: 321). However, using ζ Piscium (epoch 1874.94 λ, β: 18.8º, –0.2º) as the Initial Point of the zodiac, fixed in ca. 570 CE, the corresponding position differs from the modern computed value for the longitude by 3.8º. We can imagine a consistency in Chandra Sekhar's computations, where the true position of Venus would match the true position of the Sun on the day so well that a transit would result. However, the longitude discrepancy translates into 4 days, a grave error that a *Siddhāntic* astronomer could not have committed. Chandra Sekhar's day of the event is, by implication, synchronized with the Gregorian date. Therefore, ζ Piscium as the reference is unlikely. We have also considered if by '*25*' he meant the *ayanamsha* (in degrees), the precession correction accumulated over a certain period since an initial epoch, that the Hindu astronomers needed to fix longitudes.[7] It may not be so; then the question is: why bring in an *ayanamsha* of 25º if one has merely to place the Sun in Scorpio?

With the Sun intense and high in the sky, how was the observation conducted? One may also like to question the precision of the instruments and their calibration where no standards were yet within sight, leading to astronomy of precision. As for timing the event, one can only wish that more than just the Kali year was given. These questions notwithstanding, what is commendable here is that Chandra Sekhar was able to recognize an unusual positioning of the planet —the *gāḍhāstamaya* (transit)—computed solely using the Hindu astronomical system, and then observe it. In a naked eye observation, it was rather unprecedented for a classical Hindu astronomer to witness a planet passing in front of the Sun, appreciate that it is an extended body and then express their relative sizes quantitatively. All this deserved more commentary from him. As an astronomer, Chandra Sekhar would know of the *Venus Pentacle*, but whether he realized the next such conjunction due eight years later in December 1882, and then worked out the circumstances, is not known. In the entire episode, we do find a keenness to confirm computations from observations that reminds us of Ibn Sīnā's observation of the transit of Venus in 1032 CE. We have worked out the phenomenology of the 1032 CE transit elsewhere (see Kapoor, 2013b) and parallels can be drawn.

6 CONCLUDING REMARKS: THE TRANSITS OF VENUS IN THE TWENTY-FIRST CENTURY

About the next pair of transits of Venus, Richard Proctor (1882: 231-32) concluded his book on a touching note:

> We cannot doubt that when the transits of 2004 and 2012 are approaching, astronomers will look back with interest on the operations conducted during the present 'transit-season;' and although in those times in all probability the determination of the sun's distance by other methods - by studying the moon's motions, by measuring the flight of light, by estimating the planets' weight from their mutual perturbations, and so on, will far surpass in accuracy those now obtained by such methods, yet we may reasonably believe that great weight will even then be attached to the determinations obtained during the transits of the present century. The astronomers of the first years of the twenty-first century, looking back over the long transitless period which will then have passed, will understand the anxiety of astronomers in our own time to utilise to the full whatever opportunities the coming transits may afford; and I venture to hope that should there then be found, among old volumes on their book-stalls, the essays and charts by which I have endeavoured to aid in securing that end (perhaps even this little book in which I record the history of the matter), they will not be disposed to judge overharshly what some in our own day may have regarded as an excess of zeal.

We are among the fortunate ones to have lived and experienced the transits of Venus in 2004 and 2012. Venus will next have a date with the Sun in 2117 on 11 December, and again in 2125, on 8 December.

7 NOTES

1. Some time after this eclipse the French physicist Jules Janssen (who had observed the event from Guntur) realized that the line was not associated with sodium, as he originally supposed, or with any known element. Lockyer then named it 'helium', after the source. It was only years later that the new element was isolated in the laboratory (see Nath, 2013).
2. As per international convention, in this paper contacts 1 and 2 refer to the first and second ingress contacts, and contacts 3 and 4 to the first and second egress contacts, respectively.
3. In most instances, the original spellings rather than the modern spellings are used here.
4. Various spellings of Ragoonatha Charry's name have appeared in print over the years. In this paper I have adopted the spelling of his name that Ragoonatha Charry used for his signature.
5. Near the time of the 2012 Transit of Venus the Indian Institute of Astrophysics brought out a reprint of the English edition of this pamphlet (see Ragoonatha Charry, 1874).
6. Professor Jagdev Singh from the Indian Institute of Astrophysics says (pers. comm., 2014):

   > … it is difficult to give a definite reason for this … result, [and] it might be a combination of the factors: (1) scattered light of the solar disc by the Earth's atmosphere dominating at the edge of the photosphere as compared to the chromospheric radiation that decreases exponentially with the distance from the edge of Sun; (2) the finite width of the slit; (3) the methodology of observations in defining the contact during the spectroscopic observations; and (4) scattered light in the instrument might affect the edge of Venus differently in the two cases.

   It is noteworthy that Tacchini's observations were never confirmed during any of the later transits, in 1882, 2004 or 2012.
7. The value for the precession rate Chandra Sekhar deduced was 57″.6/yr. Naik and Satpathy (1998: 42) mention that the year he used was sidereal, and correcting for the extra motion of the Sun over the tropical year, the rate came out as 49″.3/yr, which is much closer to the modern value of 50″.3/yr. To reach an *ayanamsha* of 25º, 1830 years should have elapsed since the reference epoch. In the context of classical Indian astronomy, the year 44 CE as the reference epoch does not quite fit. Also, it could not be the *Saka* era that is reckoned from the reign of the Kushana King Kanishka (r. 78-102 CE), i.e., 15 March 78 CE. The era came to

be used by Indian astronomers for astronomical calculations since the time of Varāhamihira and perhaps earlier (Saha, 1955: 255).

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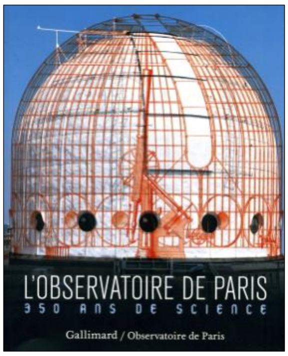
BOOK REVIEWS

***L'Observatoire de Paris: 350 Ans de Science*, edited by Laurence Bobis and James Lequeux; contributors: M. Combes, S. Débarbat, D. Egret, F. Launay and A, Saint-Martin (Paris, Gallimard/ Observatoire de Paris, 2012). Pp. 176. ISBN 978-2-07-013806-7 (softbound), 188 × 230 mm, €26.**



The Paris Observatory holds the accolade of being the astronomical observatory that has been in the longest uninterrupted operation on its original site. Since its foundation in 1667 and completion of architect Perrault's grand but impractical building five years later, the Observatory has been a principal actor in French astronomy; and with a permanent staff today of some 650, accounts for almost a third of the country's professional astronomy. Furthermore, many astronomers working elsewhere in France have passed through the Paris Observatory, which has also built equipment for other observatories at home and abroad.

Anyone investigating astronomical history or heritage in France is thus likely to find that the Paris Observatory crops up somewhere in the tale, but a problem has been the relative inaccessibility of works over-viewing the history of the Observatory. A history of the institution's 'equipment and personnel' (but not its science) up to the French revolution and the consequent end of the Cassini dynasty was published a century ago by Charles Wolf (1902), and is now available from more than one source on the internet. More recently, a series of four very useful articles variously authored by Débarbat, Grillot, Lévy and Morando (1980-1983) reviewed buildings, people *and* science up to 1963, but this work was published in a difficult-to-access local-history journal. At the same time, the first three of these authors published a summary history (1984). This 70-page booklet was a successor to earlier ones of broadly similar length and detail, and predecessor to later revisions, but they were all only available through the Observatory and difficult to acquire outside Paris.

All this has changed with publication of *L'Observatoire de Paris: 350 Ans de Science.* It has many praiseworthy qualities. Firstly, being co-published with Gallimard, it is easily available through on-line and other booksellers. Secondly, it reviews both institutional and scientific history from foundation to the present. We learn that the Observatory was initially under the control of the newly-established Academy of Sciences. In 1785 this link was lost, and the fourth Cassini became Director and was able to control research and train apprentice astronomers. But it did not last. The French Revolution broke out, the apprentice astronomers rebelled, and Cassini was squeezed out. Then in 1795 supervision of the Observatory passed to a newly-created organisation, the Bureau des Longitudes. (It is these periods of external control that explain why key Observatory figures—I'm thinking of the first Cassini in the 17th century, or François Arago in the 19th—were never 'Director'.) Authority stayed with the Bureau des Longitudes until 1854, when Urbain Le Verrier of Neptune-discovery fame was appointed Director by Napoleon III. The Observatory then began to expand beyond its Parisian home. The pre-existing Marseilles Observatory became a 'branch' at a new site in 1862. The astrophysical observatory at Meudon, created in 1875, became administratively part of the Paris institution in 1926. Expansion continued after WWII under the energetic leadership of André Danjon. In 1953, the Observatory co-created the Nançay radioastronomy station in eastern France, while in the 1960s it began to build instruments for space astronomy, and from 1972 to 1989 it ran the Centre d'Études et de Recherches en Géodynamique et Astronomie (CERGA) in the foothills of the French Alps. There have also been offshoots such as the Bureau International de l'Heure, now replaced by the International Earth Rotation Service. Scientifically, the Observatory's activity has included geodesy, discovering the finite speed of light (and two centuries later measuring it), mapping France, setting up the metric system, fundamental astronomy and celestial mechanics, issuing meteorological bulletins, guiding the *Carte du Ciel* project, disseminating time by radio and via the world's first talking clock, developing electronic cameras, laboratory astrophysics and of course modern astronomy across all wavelengths. Further, the Observatory has become involved in outreach, and the education of doctoral students.

A third praiseworthy quality of this book is that it is attractively laid out and beautifully and copiously illustrated, mainly in colour. Among the many illustrations that caught my eye are an oil painting from Versailles in which academicians and the Observatory are presented to Louis XIV, photographs of the complex stereotomy of parts of Perrault's building, a photograph of Janssen's 'photographic revolver' for observations of the 1874 transit of Venus, a dinner menu from the Congrès Astrophotographique in 1887 (the feast included tortoise and peacock), the Carte du Ciel plate-measuring ladies, a Lœwy and Puiseux photograph of the Moon, a cluster of balloons used by Dollfus to obtain solar photographs from 6000 metres altitude, iced-up antennas at Nançay, and old and modern timekeepers in the catacombs beneath the Observatory. Plans and an aerial photograph aid in understanding the layout of the Observatory site.

The fourth noteworthy quality of this book is that the text is very readable and does not shy away from delicate issues, such as the plunder of the library by the infamous 19th-century book-thief Guglielmo Libri; the long strike following the events of May 1968; the crisis of stagnating funding in the 1970s; and the 'stormy discussions' prior to setting up IRAM, the Institut de Radioastronomie Millimétrique (cf. Encrenaz et al., 2011). Explanation is available for those bewildered by French acronyms such as INAG, INSU, IMCCE, BIH or LPTF. A fifth praiseworthy feature of this book is that it is affordably priced.

L'Observatoire de Paris is aimed at the general reader, and visitors on the rare days when the Observatory is open to the public. By including the current and projected activity to the end of the decade, it lives up to its subtitle, *350 Years of Science.* For those interested in astronomical history and heritage it provides a splendid overview and a springboard from which to begin deeper studies. For these, let me mention (i) the six articles by Bigourdan (1928-1933) and thesis by Feurtet (2005) on the Bureau des Longitudes, which because of the interconnection of the two institutions contain much concerning the Paris Observatory; (ii) recent analyses such as those by Davis (1984) on the development of meteorological theory; by Chapin (1990) concerning the revolutionary period 1785-1795; by Canales (2001) discussing management styles and Wolf's *Histoire*; by Guinot (2000) on the Bureau International de l'Heure; by Aubin (2003) considering why the 19th-century Observatory did not move to a better observational site; and even my own work on the speed-of-light measurements (Tobin, 1993), and (iii) recent biographies of two key Paris Observatory scientists of the 19th-century, François Arago and Urbain Le Verrier (Lequeux 2008; 2009).

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