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Technology and the emergence of X-ray astronomy

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Abstract
X-ray astronomy went through a decade of impressive growth within the decade following the discovery observations of bright X-ray sources in 1962. The beginning of the discipline had to do with development of military rockets during World War II and the subsequent high interest in both military and civilian applications. The first X-ray sensing instruments were rooted in early nineteenth century technology but scientists quickly developed powerful new instruments that have sustained the discipline and provide the basis for future observatories. Entirely new instruments have been emerging that may provide for impressive new capability. The discipline provides a classic example of how a science discipline can emerge rapidly following an initial discovery and then settle into long middle age.

1 INTRODUCTION

In 1960 astronomy was very much a classical topic by current standards. The world's most advanced telescope was the 200 inch on Mount Palomar for which development had begun during the 1930s. Film was still the workhorse medium for recording information; phototubes and photomultipliers were just coming into use for photometry and spectroscopy. Radio astronomy was coming of age and just leading to the recognition of the prevalence of high energy, non-thermal processes in the Cosmos. No one could predict what was to emerge in the coming decade. Within a short time, quasars (1962), cosmic background radiation (1965) and pulsars (1967) were discovered, all with ground-based optical and radio instruments. Space astronomy was meeting its promise of providing an entirely novel vista from which to make observations, yielding yet other discoveries, most prominent of which were the bright X-ray sources (1962), entirely unpredicted and unexplainable. It is X-ray astronomy that I will discuss in this paper. What was the technology employed in the emergence of the discipline, how has it evolved and where may it be going?

2 THE FIRST DECADE

Observations from balloons in the early 1900s, intended to study natural radioactivity, led serendipitously to the discovery of cosmic rays. During the 1930s serious considerations led to the recognition that the Sun had to be a powerful source of ultraviolet and X-radiation in order to sustain the ionized region found at several hundred kilometres altitude above Earth's surface. Direct analysis of solar radiation led to the realization that the Sun's atmosphere had gas with a temperature of a million degrees. At that time balloons were the only technical means for carrying instruments to high altitudes, but they could only penetrate the stratosphere at ten kilometres or so, far short of the altitudes needed to see X-rays. Nevertheless the stage was set and with the availability of sounding rockets after World War II, scientists were able to carry instruments well above the sensible atmosphere.

One of the principal objectives of the earliest rocket experiments was the short wavelength radiation of the Sun. But it was only with the greatest ingenuity that information could be obtained; for example, Herbert Friedman and his colleagues at the Naval Research Laboratory enlisted the aid of the U.S. Navy to fire rockets during a solar eclipse from the back of a ship in the South Pacific and were able to establish that the Sun consisted of both a hot, tenuous atmosphere and small, bright regions of activity associated with sunspots (Chubb, 1960a). Another landmark observation of the Sun obtained by Friedman and his group at NRL from a rocket in 1960 was the image shown in Figure 1 (Chubb *et al.*, 1960b). This figure illustrates the power of imagery and the limitations of the then current technology. The optics was a pin hole and the recording medium was film. The rocket was aimed at the Sun but still was spinning; thus the image rotated during the exposure. Nevertheless the image shows specific features of the solar emission – an overall hot atmosphere that is revealed at the limb and the concentrated emission associated with active regions. Thus this single image revealed what had required a naval expedition and a solar eclipse.

Figure 1. Pinhole image of the Sun obtained on film by NRL during a sounding rocket flight in 1960. This is first image of the Sun obtained from above the atmosphere at X-ray wavelengths. The image is smeared because of rotation of the rocket during the exposure.

By 1960, space science, having received a tremendous boost from the US-Soviet space competition, was well into its 'second' generation. NASA had been founded, sensors were being flown on orbiting satellites and new groups were being encouraged to pursue space observing. The study of X-ray emission was a natural choice. The fact that the Sun was an X-ray source led to the idea that stars generally would be observable in X-rays. From a totally different vista, the observation of cosmic rays in the vicinity of Earth and of radio emission from both galactic and extragalactic objects, led to the recognition that observable X-rays (and even more energetic radiation) should be generated through various physical processes. Thus it was not surprising that by 1960 three different US agencies, NASA, the Navy, and the Air Force, had independently made the decision to provide support for technical developments aimed at measuring cosmic X-rays from space, as distinct from solar X-rays.

This research support reached fruition in June 1962 when a large and unexpected flux of X-rays was detected from an Aerobee rocket experiment devised by Riccardo Giacconi and his colleagues at American Science and Engineering (AS&E) in Cambridge, Massachusetts (Giacconi *et al.*, 1962), of which this writer was a member. The instrumentation consisted of three Geiger counters placed around the axis of the rocket. As the rocket spun, the counters scanned a swath of sky. Pointing consisted of waiting for the time when a given celestial location was in the right position with respect to vertical and firing straight up. Since the counters had a very broad field of view (about 60 degrees), it was hard to miss. The total collecting area was about 30 cm^2. These results were quickly confirmed and extended using similar, but larger instruments.

Aside from learning how to build larger instruments and how to plan experiments, there were two important innovations made within the first few years of the discovery flight. One was the switch to proportional counters from Geiger counters. The two are simple variants of gas detectors. Both work by arranging for a gas discharge upon the passage of a charged particle; however, proportional counters provide a signal proportional to the degree of initial ionization. This allows for measuring, albeit crudely, the energy of detected photons and allows for efficient background rejection techniques. Figure 2 shows a rocket payload developed by the AS&E group in 1967 that was used for scanning the Milky Way (Giacconi *et al.*, 1967). The collecting area was now about 1000 cm^2 and the detectors were collimated to ½ degree using closely-spaced latex sheets.

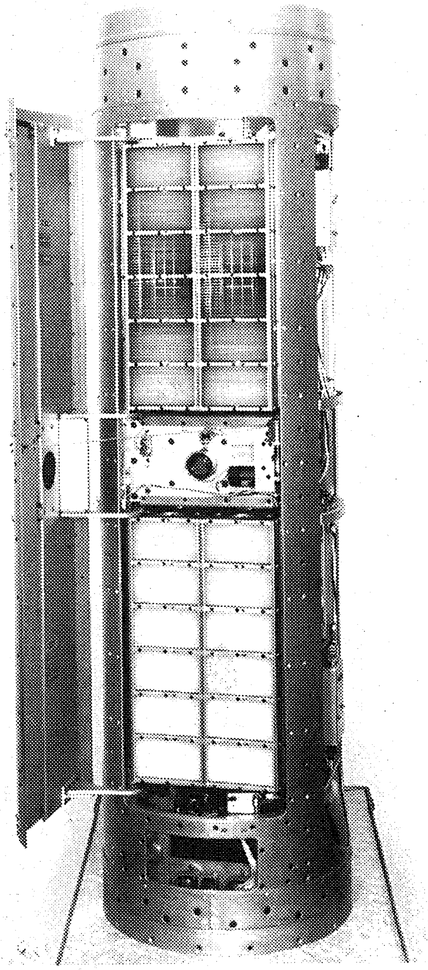

Figure 2. The sounding rocket payload used by the AS&E group to scan the Cygnus region of the sky in 1967.

The other innovation was the modulation collimator. The initial design consisted of two planes of wires with equal diameter and separation. Such collimators have multiple transmission directions. Following a proof of principle rocket flight, a modulation collimator instrument was used in 1966 to localize the bright X-ray source, Sco X-1, with arc minute precision, a landmark experiment that led to the optical identification of the bright X-ray source Sco X-1 and to the emergence of the recognition that binary systems with a collapsed companion star could be very luminous in X-rays. (Gursky *et al*., 1966). The data from that flight are reproduced in Figure 3 and show a few seconds of data with the source moving through the multiple fields accommodated by the collimator, each of 4 arc minutes width. Modulation collimators also introduced astronomers to the idea of spatial modulation and spawned a great variety of devices for mapping X-ray sources with high precision using relatively simple, mechanical elements.

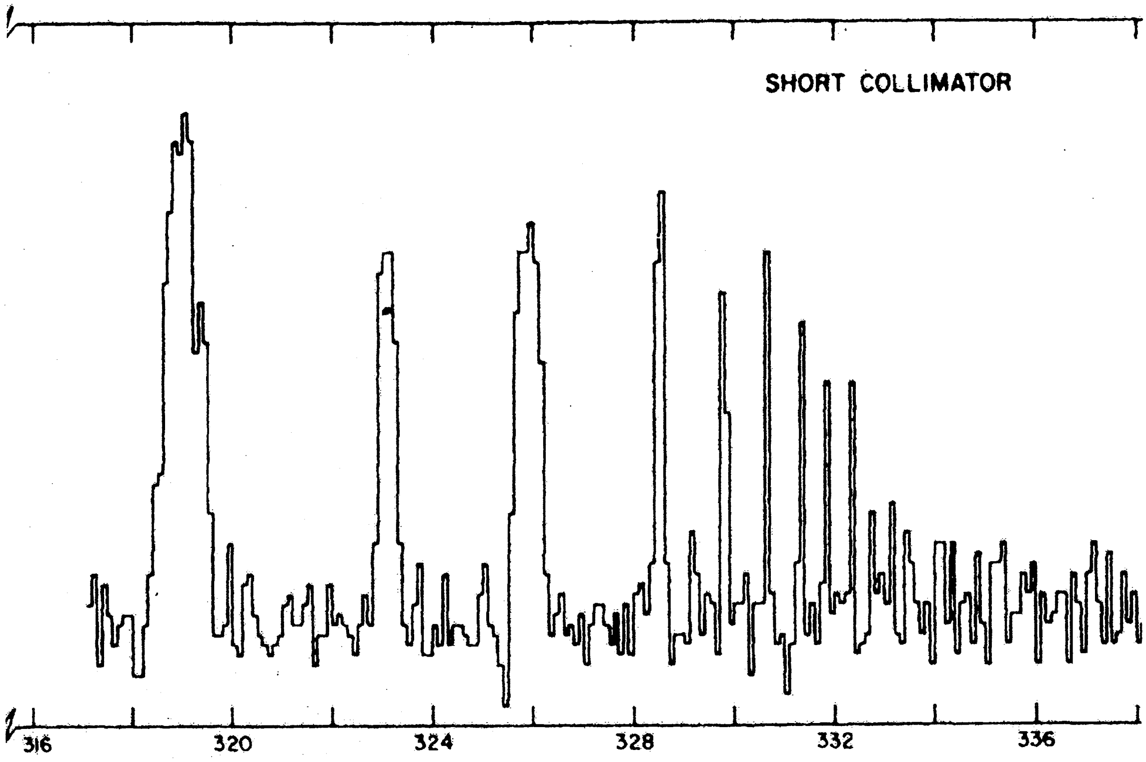

Figure 3. Data from the modulation collimator instrument flown in 1966 on a sounding rocket that led to a precise location for the bright source, Scorpius X-1, and its subsequent optical identification

The decade ended with the launch of the Uhuru satellite using instrumentation similar to that shown in Figure 2. The Uhuru data created a quantitative and qualitative change in the discipline. Each day in orbit, the satellite produced far more data than all the previous experiments to date and yielded important new discoveries, such as the pulsing, binary X-ray sources and the rich clusters of galaxy. The amount and quality of information produced by Uhuru brought X-ray observations into astronomy as a distinct discipline.

At the same time that astronomers were using rockets (and balloons) and gas counters to extend their knowledge of the X-ray sky, another development was taking place that would revolutionize the discipline; namely, that of X-ray optics and imaging detectors. Again the Sun was the key science driver and again there were independent trajectories, this time involving the Naval Research Laboratory, the Goddard Space Flight Center, and American Science and Engineering. I began this discussion by noting that the first information regarding the distribution of X-rays from the Sun came from rocket instruments flown during an eclipse and from a pinhole camera. During the 1960s the group at AS&E had begun to develop focussing optics that could produce proper images of X-ray emission, based upon the principle of total external reflection. The key ideas relating to X-ray optics were expressed by Giacconi and Rossi (1960) who noted the enormous improvement in point source sensitivity that resulted from the use of X-ray optics and by Wolter (1952) who described specific optical configurations that could yield images in X-rays.

The first X-ray optics were replicas taken from a steel mandrel and were used to observe the Sun from a sounding rocket. An example of an early image is shown in Figure 4. Except for the fact that the image was not smeared due to rotation of the rocket during the exposure, its quality was not much better than the one shown in Figure 1. However by 1968, high quality optics were obtained by AS&E using traditional polishing and figuring techniques on a glass blank. The same mirror technology was used in solar X-ray imaging experiments on NASA's SkyLab. The mirror blanks are shown in Figure 5; instead of flat discs that are the start of traditional astronomical mirrors, X-ray optics look like sections of large diameter pipe. Their inner surfaces become the figured mirror.

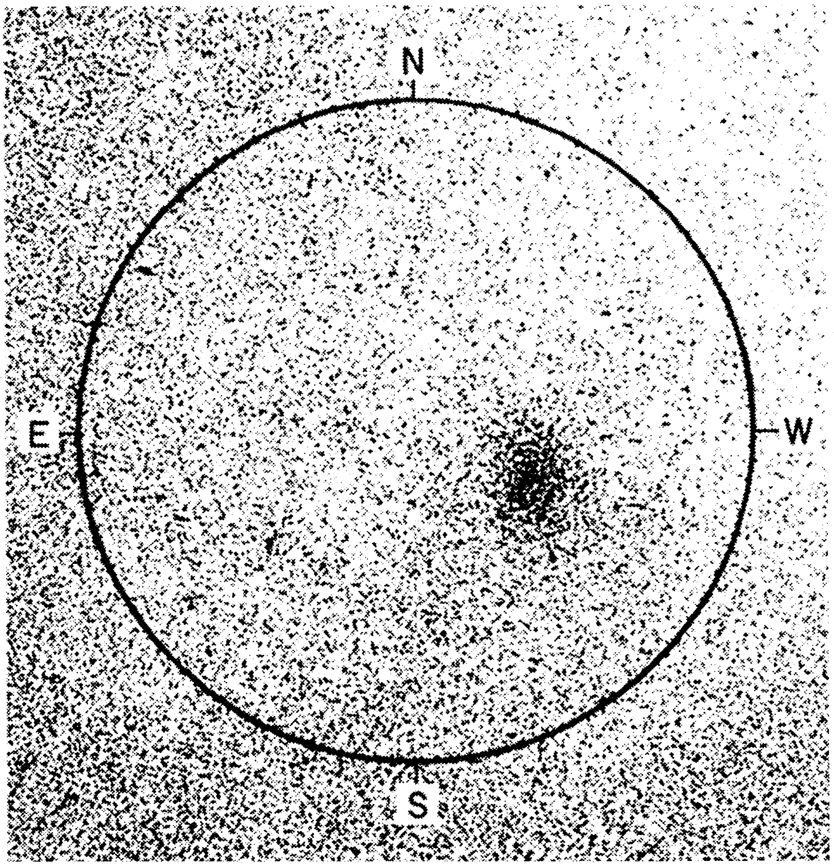

Figure 4. First solar image obtained with grazing incidence optics flown on a sounding rocket in 1967.

So for the purposes of solar investigation high quality X-ray optics had emerged. However the solar experiments, even Skylab, used film as the image-recording medium, totally unsatisfactory for the study of cosmic X-ray sources. Meanwhile, John Lindsey, who left NRL's solar research team when NASA was formed and started a solar research group at the Goddard Space Flight Center had introduced the idea of microchannel plate arrays as X-ray imaging devices. Each channel, and there are millions in the array, acts as an electron-multiplier when a voltage is applied across them. Thus a photon converting at or near the face of the array will produce a cascade of electrons. These devices do not provide any energy resolution. Leon Van Spoeybroek, Ed Kellogg and I employed such a device with the mirror used by the AS&E solar group, to image Sco X-1 from a sounding rocket in 1969. An image was formed by allowing the electron cascades from a multichannel detector to fall onto a scintillating screen, which was then photographed. Two camera frames from that flight are shown in Figure 6, each frame yielding a single event at the position of Sco X-1. A total of only four photons were detected during the flight. The result was reported at meetings but never published. Somehow I could never convince my colleagues that it was a very significant result.

The great power of telescopes was fully revealed with observations from the Einstein Observatory, the development of which was begun around 1970. Its point source sensitivity was a thousand times greater than that of Uhuru and other instruments using collimated proportional counters. Virtually every kind of astronomical object was seen as an X-ray source, including individual objects in external galaxies.

Thus within a few years after the discovery of cosmic X-rays with the simplest gas counters, astronomers had developed powerful new sensors and auxiliary devices for recording X-rays with very high sensitivity; including, proportional counters, modulation collimators, transmission grating spectrometers and microchannel plate detectors. However it is also the case that innovations in the technology of space access and NASA's expanding programme of space science drove X-ray astronomy in its first decade. Of special note was the technology relating to pointing rockets and spacecraft steadily at a fixed position in space.

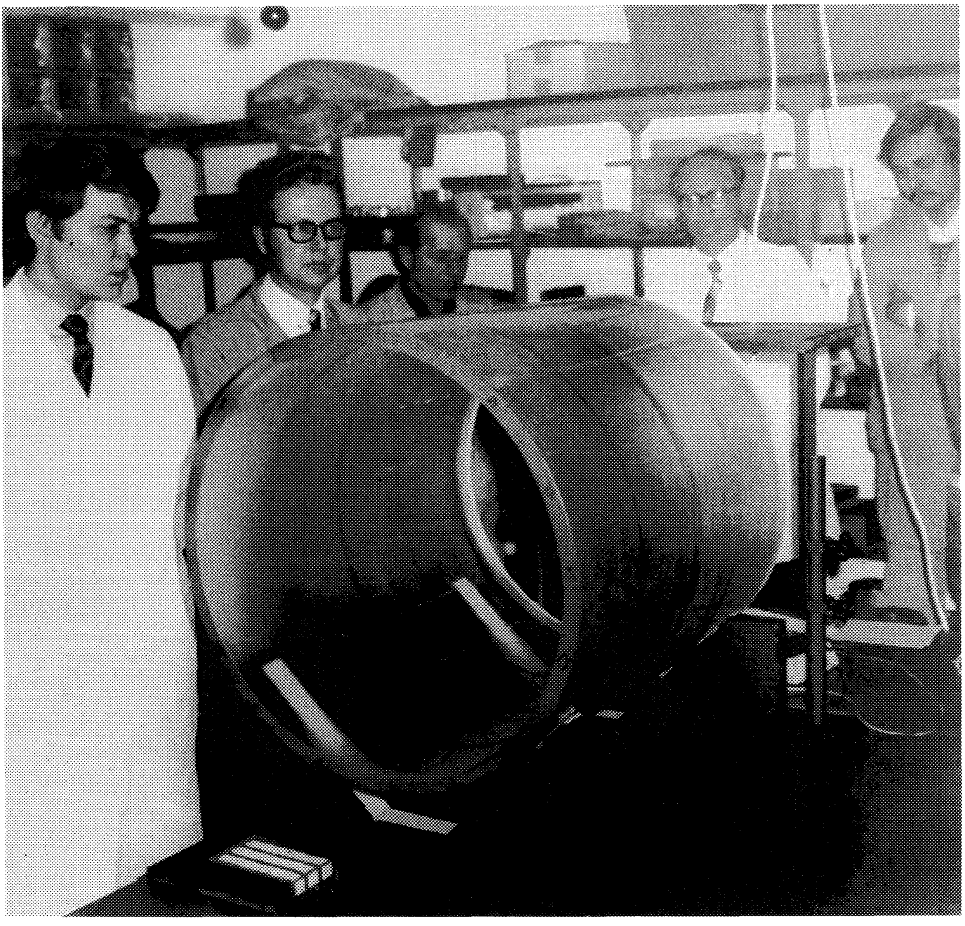

Figure 5. The blanks for one of the X-ray mirrors used on the Einstein X-ray astronomy mission.

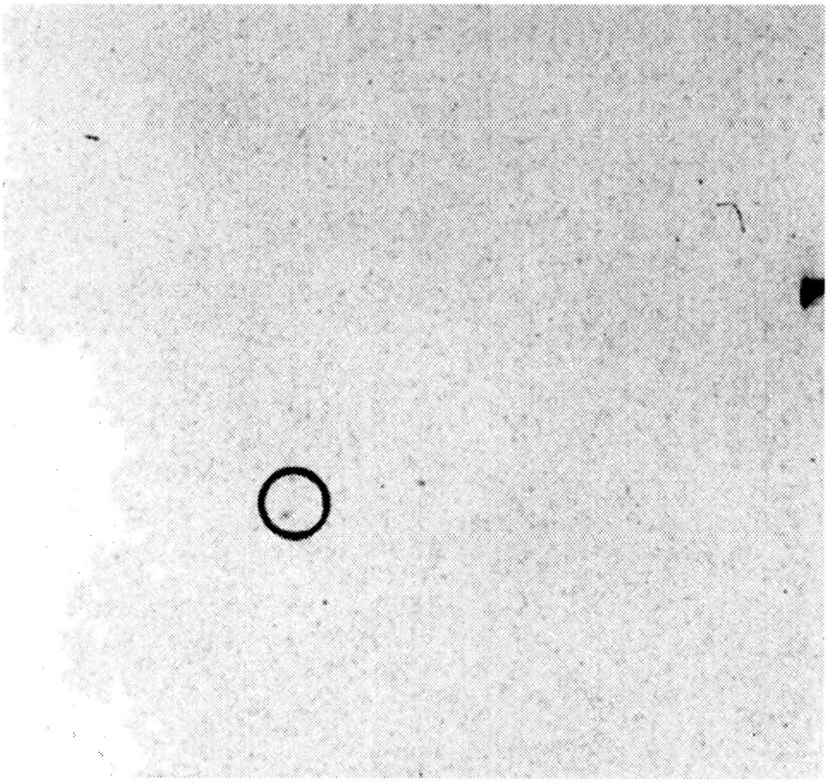

Figure 6. Photograph of a single photon obtained from Scorpius X-1 using grazing incidence optics flown on a sounding rocket.

3 MIDDLE AGE

These devices and their many variants would carry the discipline for the next two decades and down to the present time. This is revealed in Table I, which shows X-ray astronomy space missions that have both flown and are in the planning phase. The largest differences that are revealed in Table I are in the spacecraft themselves. The first space mission dedicated to X-ray astronomy, UHURU, used detectors identical to those flown in the 1967 rocket payload shown in Figure 2. The spacecraft was only spin stabilized, much like the first rockets used to study cosmic X-rays. The ANS satellite was the first to use inertial stabilization that allowed pointing continuously to single targets. By the 1980s all space missions were inertially stabilized. Another notable feature of this table is size growth of the missions. Uhuru was only a few hundred pounds and was flown on a SCOUT launcher; the recently-launched CHANDRA weighs over 10,000 pounds and took the entire bay of NASA's Space Shuttle. What has happened with the space missions is just what has happened with astronomical facilities on the ground; the development of larger and more sophisticated instruments in order to continue conducting state-of-the-art observations. The table reveals that space research is still a high-risk activity. Two recent missions, ABRIXAS and ASTRO-E, were total failures.

There were notable instrument developments that have provided a much different capability from their parents. One is the imaging proportional counter that was used in X-ray telescope systems for imaging. These devices were proportional counters in which the sensing wires were closely spaced, about 100 microns apart. The wires by themselves provide one dimensional data since the signal from photons converting in the gas would appear on a single wire; the second dimension was obtained by determining where along the wire the signal occurred, which was down by, for example, making the wire a delay line. Another advantage of imaging proportional counters was that they could be built large, or at least significantly larger than

Table 1. X-ray astronomy missions.

Programme	Nation	Launch Year	Instrumentation
Uhuru	US	1970	Collimated Proportional Ctrs, Spin Stabilized
ANS	Netherlands	1974	Collimated Proportional Ctrs, 3-Axis Stabilized
Ariel 5	UK	1974	Modulation Collimated Proportional Ctrs
HEAO A	US	1977	Collimated Proportional Counters
Einstein	US	1978	High Resolution Telescope
Hakucho	Japan	1979	Modulation Collimated Proportional Ctrs
Ariel 6	UK	1979	Collimated Proportional Ctrs
Tenma	Japan	1983	Gas Scintillation Proportional Counters
Exosat	Europe	1983	X-ray Telescope, High Elliptical Orbit
Ginga	Japan	1987	Collimated Proportional Counters
ROSAT	Germany	1990	High Resolution Telescope
ASCA	Japan	1993	High Throughput Telescope, CCDs
Rossi XTE	US	1995	Collimated Proportional Counters
BeppoSax	Italy	1996	Collimated Proportional Counters, Telescope
ABRIXAS	Germany	1999	High Throughput Telescope, Custom CCD
AXAF(Chandra)	US	1999	High Resolution Telescope, CCDs, High Elliptical Orbit
XMM	Europe	1999	High Throughput Telescope
ASTRO-E	Japan	2000	High Throughput Telescope, Bolometer
Constellation	US	Conceptual	High Throughput Telescope, Four Independent S/C
XEUS	Europe	Conceptual	High Resolution Telescope, Focal Plane, Mirrors are Separate S/C

microchannel plate detectors also used for X-ray imaging. As an example, the Einstein mirrors, with an eight-foot focal length required a detector almost ten inches in size to cover its one-degree field of view. The other variant was the high throughput telescope. The problem with X-ray telescopes as they were first developed during the 1960s was that they were massive and heavy. Each telescope only produced a small area and even though mirrors could be nested, only a small fraction of the frontal area could be utilized to collect photons. Thus the 'high throughput' variant emerged, mirrors designed so that large numbers, even hundreds, could be nested and much more collecting area achieved for a given frontal area. This was achieved by using thin metal or glass sheets as the collecting surfaces. But such surfaces cannot be manufactured or held to high mechanical precision; thus, their angular resolution has been limited to arc minutes compared to the arc seconds achievable with the more conventional mirrors.

The next substantially-new technology introduced into X-ray astronomy was the CCD as an imaging device for X-ray telescopes, which was first employed on the ASCA mission in 1993. X-ray astronomers have always counted photons with high efficiency devices, so the introduction of the CCD did not represent nearly the same shock as when optical astronomers switched from film to CCDs. CCDs have provided a substantial improvement over their predecessors since they provide for measurement of the energy of arriving photons with much higher precision than do imaging proportional counters, which means that some spectral features, especially the iron lines at 6 kev, can be cleanly recorded. Also CCDs offer superior spatial resolution to imaging proportional counters. The telescope missions, Einstein and ROSAT, used two different focal plane instruments, a microchannel plate detector for the highest spatial resolution and an imaging proportional counter for the best spectral resolution. On the Chandra Observatory, CCDs have replaced the imaging proportional counters.

It is in the area of spectral imaging that a spectacular new technology is emerging; namely, photon detectors that function by sensing individual phonons, which can be thought of as quanta of thermal vibration. Since energy resolution of single photon detectors is ultimately limited by the number of electrical carriers released per unit photon energy, the conversion of photon energy to phonons to charge carriers produces far more electrical carriers than do the processes in gas or silicon detectors which rely on ionization to produce carriers. Thus, instead of limiting energy resolution of kev of energy, these new detectors have the potential of producing energy resolution of ten electron volts or less (or spectral resolution of a few hundred, in terms commonly used by spectroscopists). For many objects, the combination of high temperature and opacity broadens spectral features to the point that higher resolution is not especially useful. These new detectors do not come without pain. They typically involve very small signals produced at very low temperatures; thus, the X-ray astronomers will suddenly have to deal with many of the technical problems that the space infrared astronomers deal with, at least in the focal plane.

The first of these new detectors to fly will be a bolometer developed by the University of Wisconsin and the Goddard Space Flight Center (Stahle *et al.*, 1993). This device measures directly the increase in resistance in a thermistor in thermal contact with a heat sink in which photons convert. Other devices make use of the changes in superconducting properties that accompany small temperature rises. The bolometer is scheduled for flight on the Japanese ASTRO-E mission. As with the first of anything, this detector is limited, comprising only a double strip of 16 detectors. However in principle large arrays of detectors can be constructed.

Other notable advances include advanced spectroscopic instruments. The US Chandra Observatory and the European XMM mission both include grating spectrometers. On Chandra they are of the transmission variety; and on XMM they are of the reflection variety at grazing angle.

4 THE FUTURE

Not surprisingly future X-ray astronomy missions are principally larger versions of current missions. In the US, the Constellation mission entails the launch of a number of independent X-ray telescopes, each with its own focal plane instruments. Common observing with each of the telescopes and co-adding data provides for the larger effective area. The use of independent telescopes allows for a shorter focal length compared to a single telescope with the same area. The Europeans have chosen a different approach; namely, eliminating the optical bench tying the telescope to the focal plane. Their future mission, XEUS, has the telescope and the focal plane on independent spacecraft and the alignment is maintained by station keeping between the two with laser beams and other aids. Thus the actual focal length of the mirror is not a factor in the development. Another feature of XEUS is maintenance by the International Space Station. The idea is that the focal plane spacecraft could rendezvous with the station on occasion for maintenance and refitting as needed. CCDs, bolometers, and other novel focal plane devices will further enhance the power of these new observatories.

The principal limitation for these new missions will be support from the funding agencies. These new missions are not particularly more complex than what has flown before, but they are much larger and will be more expensive than earlier ones. The world's major space science agencies, NASA, ESA, and ISAS, are under pressure to limit the cost of individual missions. NASA's new mantra – faster, cheaper, quicker – is not especially well suited to these super telescopes.

There is another kind of mission that is needed by the X-ray astronomers; namely, those like the Rossi XTE that are dedicated to observing the stronger sources. These can make do with traditional collimated detectors, although to some degree the same objectives can be met with missions like XMM where the mirrors are designed for maximum collecting area rather than the best possible angular resolution. It is also possible that new kinds of detectors based upon large sheets of silicon may become the detector of choice. NASA's proposed mission for energetic gamma ray observations, GLAST, will make use of 80 square metres of silicon strip detectors. For use with X-rays they will require cooling which will limit their applicability.

It is certainly possible that entirely new observing instruments may emerge of great power. One development is the use of multilayer coated optics that allow for normal incidence reflection in the soft X-ray range (Barbee, 1986). This is the same technology that is used to create very narrow pass band filters. The X-rays will reflect (and transmit) across each of the layers in the multilayer stack, allowing for constructive interference within a narrow pass band. Such multilayers have been used successfully in space solar instruments, the latest example being the instrument on NASA's TRACE satellite used to image the solar atmosphere at various temperatures. A portion of one of the TRACE images is shown in Figure 7 and shows how far the discipline has come in improving the quality of observing. The technique can also be used to create normal incidence reflection gratings of great power. Like other solar instruments, these are bound to find application in X-ray astronomy. However, because they currently function at 100 Å and longer, their cosmic span of vision is no more distant than about 100 parsecs or so. Interferometry may also find application in X-ray astronomy. It has already been demonstrated that fringes could be produced in X-rays using grazing incidence mirrors as a Michelson interferometer (Cash, 1999).

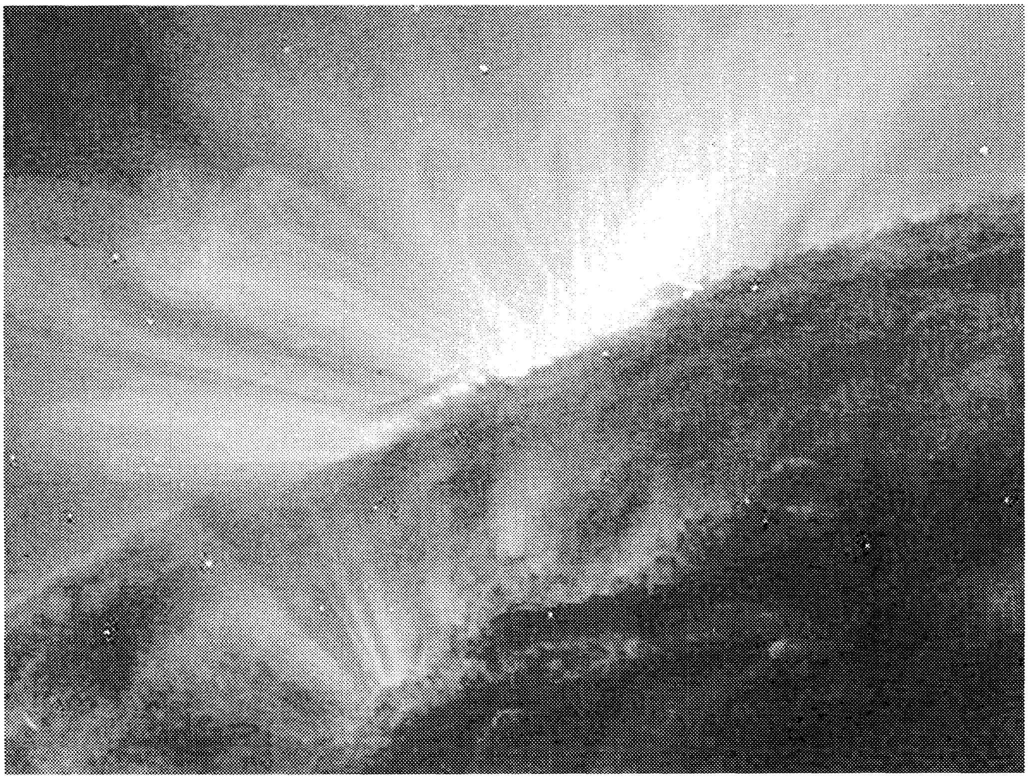

Figure 7. A portion of an image of the Sun in X-rays obtained from NASA's TRACE satellite.

5 SUMMARY

The principal factors relating to the emergence of X-ray astronomy were the rocket technology that developed during World War II and the interest in their continued

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development after the War. The technology that was utilized by scientists in the discovery observations was based upon concepts and instruments that had their origin early in the twentieth Century. In the decade after the discovery there was a period of intense development that yielded the devices that sustained the discipline for two decades. Only now are new devices in common use that did not exist in the 1960s.

The discipline is approaching a phase in which the next generation of major observing facilities being presented to the community are hardly novel, but are principally much larger versions of current facilities. These new facilities should provide significant advances in sensitivity over those that will be put into operation shortly, especially with the improved detectors and spectrometers now under development. However, if history is our guide, these more advanced concepts may have difficulty finding broad support; in particular, they will face tough competition with major facilities from other disciplines that offer novel concepts and new science.

I cannot leave a discussion of the history of one aspect of X-ray astronomy without commenting upon the human and social aspects of the discipline. As with the rest of astronomy, there was explosive growth during the 1960s. Indeed the CHANDRA mission had its origin then. One individual, Riccardo Giacconi, and the social environment in which he found himself in the early 1960s, can be credited with much of that growth; certainly with the development of large facilities based upon grazing incident telescopes. X-rays would have been discovered and the field would have developed without Giacconi and his colleagues – by 1960 there were too many people working on it and there was too much interest in exploiting space science for the field not to have emerged – however, not with the impressive pace that it did; certainly, not with the large, high quality, telescope missions such as Einstein. Several factors were present that provided for Giacconi's success. Firstly, it was the presence at MIT of a group of scientists and their collaborators, headed by Bruno Rossi, dedicated to studying cosmic rays; not just the particles but also the gamma rays. Secondly, it was the emergence of the Boston area as a breeding ground for scientists exploiting new technology, fed by MIT and Harvard and by military contracts. Thirdly, and in part due to the second, it was the attractiveness of the Boston area as place for scientists to work and live. Finally, it was the fact that much of the development took place in a private company, American Science and Engineering, which could pursue a range of applications, as opposed to the academic community that is frequently narrowly focussed. Giacconi stepped into this brew and exploited it for the benefit of his chosen discipline.

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