Journal of Astronomical History and Heritage, 14(3), 203-210 (2011).

EARLY ASTRONOMICAL SEQUENTIAL PHOTOGRAPHY, 1873-1923

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Abstract: In 1873 Jules Janssen conceived the first automatic sequential photographic apparatus to observe the eagerly anticipated 1874 transit of Venus. This device, the 'photographic revolver', is commonly considered today as the earliest cinema precursor. In the following years, in order to study the variability or the motion of celestial objects, several instruments, either manually or automatically actuated, were devised to obtain as many photographs as possible of astronomical events in a short time interval. In this paper we strive to identify from the available documents the attempts made between 1873 and 1923, and discuss the motivations behind them and the results obtained. During the time period studied astronomical sequential photography was employed to determine the time of the instants of contact in transits and occultations, and to study total solar eclipses. The technique was seldom used but apparently the modern film camera invention played no role on this situation. Astronomical sequential photographs were obtained both before and after 1895. We conclude that the development of astronomical sequential photography was constrained by the reduced number of subjects to which the technique could be applied.

Keywords: Sequential astronomical photography, astronomical chronophotography

1 INTRODUCTION

The histories of astronomy and photography are inextricably linked by the public presentation of the daguerreotype by the astronomer François Arago (1786–1853), on 19 August 1839 (Levitt, 2003). At the time, as it is well known, Arago correctly predicted the future use of photography in the astronomical fields of selenography, photometry and spectroscopy. Photographs of the Moon and the solar spectra were obtained in 1840 and 1843, respectively, while correctly exposed daguerreotypes of solar features were secured in the 1840s. Following these early achievements the number of astronomical applications of the new technique increased throughout the nineteenth century in tandem with the development of new photographic emulsions and instruments (Bajac and Saint-Cyr, 2000; de Vaucouleurs, 1961; Lankford, 1984).

As early as 1847, John Herschel (1792–1871) pointed out the advantages of applying sequential photography to the study of the solar surface variability (Herschel, 1847). He championed this idea in the following years, which ultimately led to the daily solar photography program started at Kew Observatory in the late 1850's and later elsewhere (Bonifácio, et al., 2007, and references therein). In this paper we will focus on sequences of photographs made to study either the motion or the variability of celestial objects on time scales of at most a few minutes. Sequential photographs actuated individually or automatically will be considered but only if made with instruments specifically built for the observation. Time-lapse photography, i.e. long-period sequences like, for example, daily solar photography programs, will not be considered. Equally beyond the scope of this paper is the quick succession of plates an observer could, for example, shoot during a total solar eclipse, by changing them manually in a standard photographic device. Sequential photographs obtained on celluloid strips via cinematographic apparatus (i.e. 'moving pictures'), will also not be discussed here.

The remainder of this paper is divided into three parts. In Section 2 we discuss single-plate and multiple-plate sequential photographs. Due to the readily-available literature (Launay and Hingley, 2005 and references therein) we start by briefly summarizing the main characteristics of Janssen's 'photographic revolver' and results obtained with it. We proceed with the description and analysis of other rotating-drum instruments. Next we discuss David Peck Todd's (1855–1939) automatic mechanisms developed to photograph total solar eclipses. We end this Section with an analysis of Harvard College Observatory's photographic program on Jovian satellites and lunar occultations of stars. In Section 3 we deal with data recorded on a continuously-moving photographic plate. We decided to include these records because they take sequential photography towards its conceptual limit of a null-time difference between consecutive photographs. In practice there is always a degree of integration and each point of the photograph is an average of the image moving on the plate. This technique was used, for example, to record the variability of solar spectra. Finally, in Section 4, we discuss our findings and present our conclusions.

2 SINGLE-PLATE AND MULTIPLE-PLATE SEQUENTIAL PHOTOGRAPHY

2.1 Janssen's 'Photographic Revolver'

On 10 February 1873 Jules Janssen (1824–1907) presented at the *Académie des Sciences de Paris* his plan to construct a new instrument to sequentially photograph the instants of contact between Venus and the Sun in the eagerly-anticipated 1874 transit (Janssen, 1873; cf. Janssen, 1876). His 'photographic revolver' was the first instrument that automatically took a series of photographs. It recorded 48 images in 72 seconds, via a clockwork mechanism, on daguerreotype circular plates (Braun, 1997: 151; Launay and Hingley, 2005).

At least nine photographic revolvers designed by either Janssen or Warren De la Rue (1815–1889) were used in the observation of the 1874 transit of

Venus (Janssen, 1883), but the results obtained were a disappointment (see Launay and Hingley, 2005; Mourão, 2005). Following the failure to improve on the value of the astronomical unit by using photography, in general, and the 'revolver', in particular, visual observations of the 1882 transit of Venus were preferred by many, including the official British and French parties that had previously used the 'photographic revolver' (Canales, 2002). Meanwhile, Janssen (1883) opted to perform astrophysical rather than astrometric observations in 1882 (see Launay, 2008: 160).

After the 1874 transit observation the 'revolvers' had almost no use. In fact, we are aware of only two other occasions where the 'revolvers' were employed. Launay and Hingley (2005) discovered that in 1875 an instrument of British design was deployed to the Nicobar Islands (Indian Ocean) to record—in combination with a spectroscope—the coronal spectrum during the total solar eclipse of 5 April, but the observations were hampered by bad weather. In the course of this research we came across an 1882 communication by Janssen to the Parisian Academy of Sciences, which claimed that a 'revolver' was in use at the Meudon Observatory to capture the motion of granulation in the solar photosphere (also see Launay, 2008: 118). However, we did not find any later reference to this work.

Janssen's 1879 suggestion that the 'revolver' could be used to register solar eclipse phases and solar meridian transits, and in the search for intramercurial planets, was apparently never put into practice (see Launay and Hingley, 2005). Despite this outcome, Janssen's 'photographic revolver' was an important step on the road towards the invention of cinema (Tosi, 2007a; 2007b).

2.2 The Toulouse University 1900 Solar Eclipse Expedition

Henry Bourget (1864–1921), Astronomer at the Toulouse Observatory, was in charge of the 1900 Toulouse University expedition to Elche (Spain). In order to obtain photographs of the solar corona during the 28 May eclipse the Observatory's technician, Mr. Carrère, built a "… revolver photographique [sic.] …" (Bourget, 1902: 472) allowing the use of eight photographic plates of 6.5 by 9 cm without loss of time (Figure 1). The system was moved by hand. During totality four different Lumière plates were exposed from 1 to 8 seconds. In his eclipse report, Bourget (1902) described the different solar features photographed, commented upon the plate and exposure combinations used and concluded that no unexpected celestial body was detected around the Sun.

2.3 Grubb's 1900 Eclipse 'Kinematograph'

A different approach was employed by the Royal Irish Academy and the Royal Dublin Society on their joint expedition to Plasencia (Spain) to observe the total solar eclipse of 28 May 1900 (Plummer, 1923). According to Arthur Alcock Rambaut (1859–1923),

> The object of the spectroscopic observations undertaken by us was to obtain two series of spectra, at second and third contacts, with the idea of determining the order in which various lines appeared in, and faded out of, the flash and chromospheric spectra (Rambaut, 1903: 77).

During a total solar eclipse, near to the time of the 2nd and 3rd contacts one can detect a chromospheric emission spectrum. This 'flash spectrum', as it was then known, was first observed by Charles Augustus Young (1834–1908) during the solar eclipse of 22 December 1870 and was photographed by William Shackleton (1871–1921) in 1896 (Anonymous, 1911; D.B., 1922; Langley, 1871). Studying the 'flash spectrum' was a popular research topic during the late nineteenth and early twentieth centuries. For example, in 1900 the Irish planned an eclipse expedition to test

> … whether the change from the absorption spectrum to the 'flash' spectrum took place simultaneously for all the lines, or whether some became reversed earlier than others, as might be expected to occur if the absorption of different lines took place at different depths in a reversing layer (Rambaut, 1903: 77).

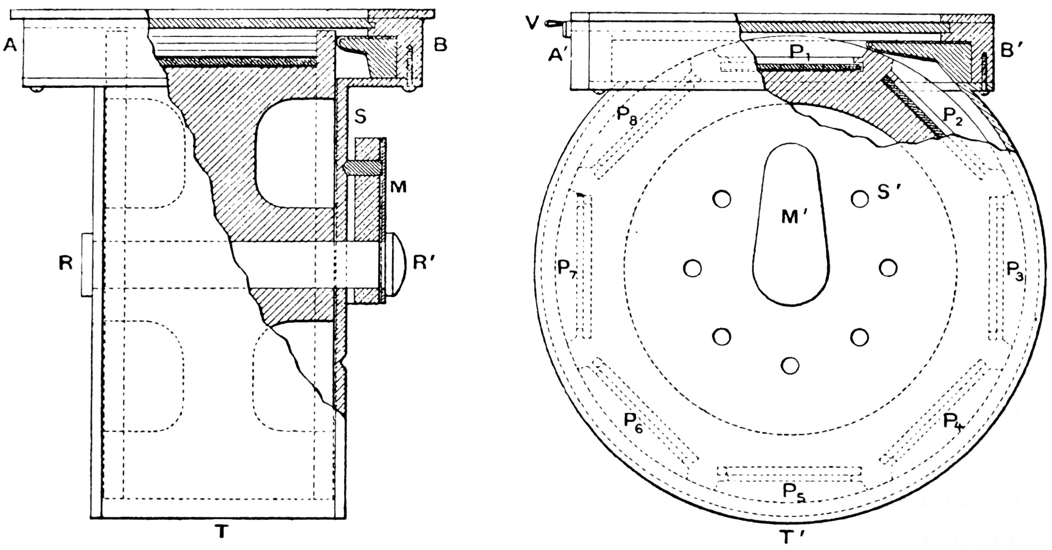

Figure 1: Side (left) and rear (right) diagrams of the Toulouse University 'revolver photographique'. The eight plates are numbered P1 to P8 and the system revolves around the R-R' axis. Motion is imparted by the handle M, M'. On the right hand image, plate P1 is in the correct position to be exposed. Note that the telescope is not represented (after Bourget, 1902: 473).

To attain this goal it was initially planned "… to project a very narrow spectrum upon a uniformly moving plate." (Rambaut, 1903: 77). This method was first used by Norman Lockyer (1836–1920) in 1896 (see Section 3). Due to Rambaut's late decision to join the expedition this plan was discarded in favour of "… a less complicated instrument, which could be more rapidly constructed …" (ibid.). According to Howard Grubb (1844–1931),

> It was required that some twelve photographic plates should be exposed to the image of the spectrum during about the same number of seconds, and that there should be absolutely no interval between the successive exposures, so that if any flash lines made their appearance, even for a moment, during those 12 secs., their images should certainly be impressed on some one of the plates. (Grubb, 1903: 73).

The instrument used two separate rotating hexagonal drums, each of which carried six photographic plates. A system of mirrors sent the light alternatively to each drum. To obtain a continuous registration for a while both plates, one on each drum, were simultaneously exposed. The system was activated by hand. Twelve spectra were obtained during second contact (Figure 2), giving an "… uninterrupted record of the changes in the chromospheric spectrum during the 17 or 18 seconds over which they extend …" (Rambaut, 1903: 81). The plate exposures varied from 1 to >2 seconds as the eclipse progressed. At third contact only five spectra were obtained, due to a drum malfunction and an over-exposed plate.

In his eclipse report Rambaut identified the spectral lines photographed, described their time evolution and estimated their visual intensity using an arbitrary scale (Rambaut, 1903).

2.4 More Rotating Drums

Heinrich Alfred Wolfer (1854–1931) had to observe alone during the total solar eclipse of 30 August 1905, and in order to obtain the largest possible number of coronal images he placed twelve 91 × 91 mm photographic plates upon a rotating drum and mounted this on a telescope. The photographs were shot at 15s intervals with exposures varying between 0.1 seconds and 3.0 seconds. Two different plate types were used. The system was apparently set in motion manually via a handle. The account of the expedition (see Wolf and Wolfer, 1906) describes a few of the images, while the discussion focuses on photographic rather than astronomical issues.

At Kalaa-es-Senam in Tunisia, Professor Ludwig Wilhelm Emil Ernst Becker (1860–1947) from Glasgow University observed the same eclipse equipped with a mechanism of his own design that allowed 10 exposures to be automatically made on a single plate. The shutter was rotated by spring-driven clockwork that was controlled by a pendulum clock. Half the plates were exposed for 1 second while the other five had exposures of 3, 9, 20, 46 and 89 seconds. Becker's plan was to study variations in coronal light intensity as a function of solar distance. Although the mechanism did not work flawlessly, two series of nine photographs were obtained. In a preliminary report Becker (1906) claimed to have measured the plates but, to our knowledge, no results were ever presented.

2.5 David Todd's Automatic Mechanisms

Following his 29 July 1878 solar eclipse observation D.P. Todd (1855–1939) realized that the number of photographs obtained was "… exceedingly meagre for an occasion when ... the money value of a single second is often hundreds of dollars …" (Todd, 1897: 318). As a consequence, over the following years he strove to increase the number of photographs taken during an eclipse by using various automatic apparatuses. In Todd's approach, at the beginning of an eclipse a single observer could automatically start up a 'compact' assortment of photographic equipment. The characteristics of the photographs to be obtained were already pre-defined.

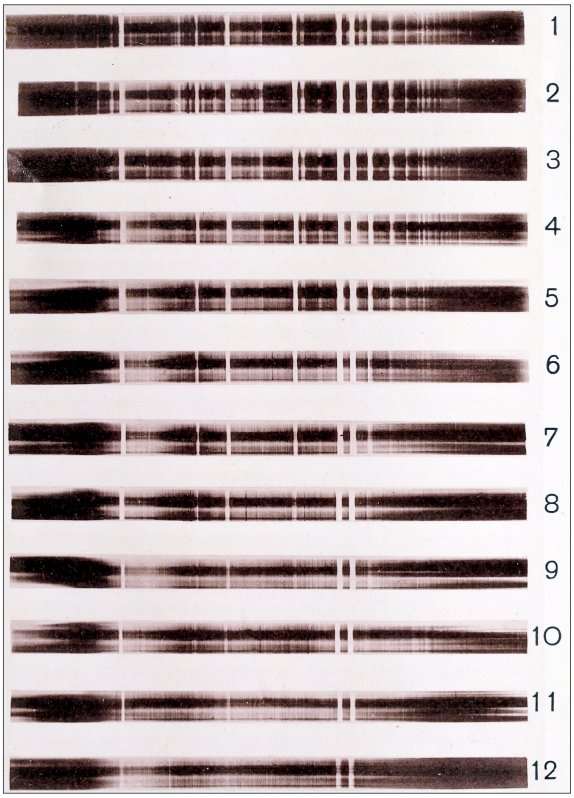

Figure 2: Twelve sequential spectra obtained at second contact by Grubb's 'kinematograph' during the 28 May 1900 total solar eclipse. The prominent pair of lines visible in all plates correspond to the chromospheric K and H calcium lines (after Rambaut, 1903: Figure 1, Plate VIII).

Upon returning from failed observations of the 19 August 1887 eclipse in Japan (Todd, 1888: 7), where a mechanical system was used to control the heliostat from a distance, Todd (1894: 178) again asked the question: "Why should it [i.e. changing plates and controlling the instruments] not all be done automatically?"

In 1889 Todd went to the west coast of Africa in today's Angola to observe the total solar eclipse of 22 December. Following "… much experimentation with different electric and pneumatic devices …" he selected a pneumatic valve system to control the photographic apparatus (Figure 3) (Todd, 1890: 382). A perforated paper ribbon moving along the mechanism fed the instructions to the machine in a process similar to the 'old' computer punch cards (Figure 4). When a perforation was opposite the corresponding pipe hole of the pneumatic system the air would flow

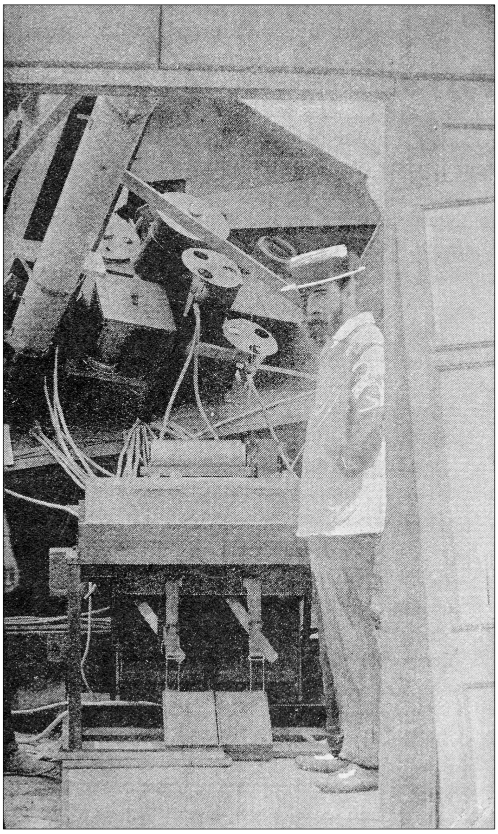

Figure 3: Partial view of the pneumatic commutator and photographic instruments (after Todd, 1894: 186).

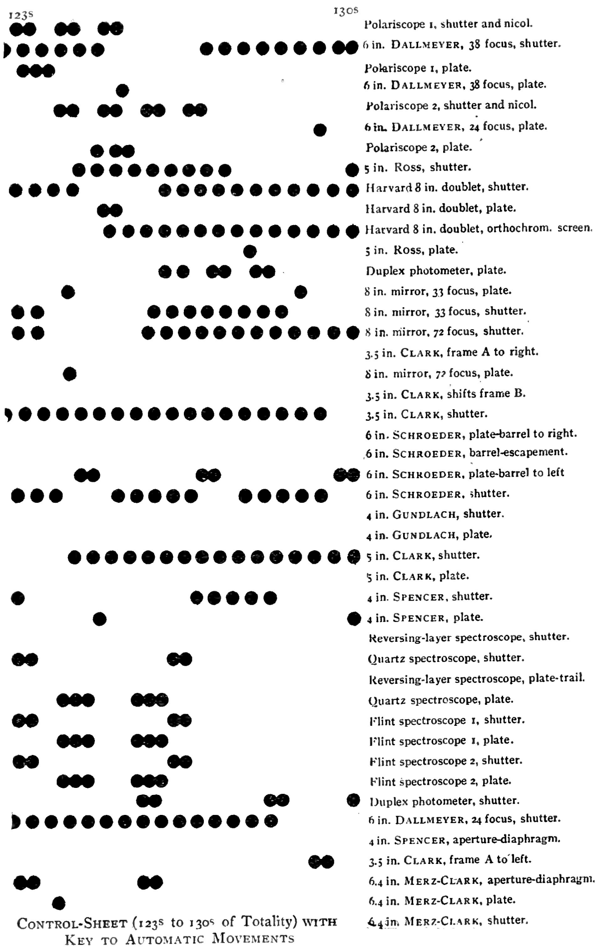

Figure 4: Partial control-sheet (123s to 130s of totality) with key to automatic movements (after Todd, 1894: 188).

and the photographic apparatus would be activated.

Figure 4 shows that in a seven second interval several photographs were planned for, at least, some instruments.

Despite the fact that bad weather prevented the photographs of the corona being obtained, more than one hundred exposures were made during the 190 seconds of totality. Consequently, Todd (1894) was upbeat about the future performances of his ‘automatic’ approach.

For his next attempt Todd returned to Japan to observe the total solar eclipse of 9 August 1896. On this occasion an electric commutator controlled the “… necessary instruments, about 500 in all.” (Todd and Lynn, 1899: 363). Once more, unfavourable weather conditions impeded the observation of the eclipse.

In 1900, Todd went to Tripoli (Libya) to observe the 28 May eclipse. Upon his arrival he developed *in situ* a “… crude and provisional …” mechanical system that used “… gravity as a motive power for the mechanical operation of shutters and plate-holders.” (Todd, 1900b: 674). Ironically, this time the skies were clear and over 100 photographs of the corona were obtained during the 51.5 seconds of totality. However, he did not enjoy this same good fortune the following year when he went to Singkep (Indonesia) to observe the solar eclipse of 18 May 1901 with a “… new type of mechanical commutator ...” (Todd, 1901: 364).

On 30 August 1905 Todd was again in Tripoli where a

> … three-and-one-half-inch Goerz doublet of thirty-three and one half inches focus, attached to one of the automatic movements used on my previous expeditions of 1896, 1900 and 1901, secured 63 fine pictures of the corona during the 186 seconds of totality. Some of these show the coronal streamers to exceptional length. (Todd, 1906: 458).

Unfortunately, while Todd published detailed accounts of his eclipse expeditions he never, as far as we know, analyzed his 1900 and 1905 photographic results.

2.6 Harvard College Observatory’s Photographic Occultations

Becker’s 1905 eclipse effort was not the first time that astronomical single-plate sequential photography had been attempted. Systematic observations of the eclipses of Jupiter’s satellites were performed at Harvard College Observatory from 1878, and eventually a decision was taken “… to make photographic observations …” of all eclipses visible at the Observatory, using the 11-inch Draper photographic telescope (Gerrish, 1895: 146). In a novel approach, in order to determine the eclipse times the telescope and/or the photographic plate were moved during the exposure in such a way that a discrete series of images of Jupiter and its satellites was recorded in a single plate. In principle, from the photometric analysis of the plate one could determine the disappearance and reappearance times of the satellites. The first measurable plate was photographed on 24 July 1888, and initially the slow motion in declination was moved by hand at intervals of ten seconds, the time being taken from a chronometer (King, 1917). The motion was of sufficient rapidity to ensure distinct, detached images of the satellites without the use of an exposing shutter, and was gauged to produce a displacement of the image on the plate of about 0.8 mm. This amount was doubled on the sixtieth second of each minute, thus dividing the chain of images into groups of six, each group representing one minute of time (Gerrish, 1895).

In the 1890s the process was automated, ten seconds being the typical exposure time. Observations started eight minutes before the computed eclipse time and continued for a few minutes afterwards (Figure 5) (Gerrish, 1895; King, 1917). The occultation times corresponding to half brightness, and the last photographic image were determined from the plates, but the photometric analysis proved difficult. In particular, the light reflected from the back of the photographic plates made the satellites appear on a background of varying density.

In 1917 Edward S. King (1861–1931) published the results of 122 eclipses and concluded that although "… discrepancies between the photographic and visual observations occur … [the method] may be useful in the solution of the general problem of the eclipses of Jupiter's Satellites." (King, 1917: 190).

On 25 February 1898 King recorded photographically the first lunar occultations of stars with a variation of the previously-described apparatus (Pickering, 1898). Once more the aim was to precisely time the occultation. The results would be used to test the contemporary precision of the lunar tables in order to improve them and to increase the accuracy of future predictions (King, 1912). The results of thirty-eight such events photographed between 1898 and 1908 were published in 1912. One immersion and one emersion of Saturn were also observed (King, 1912).

3 CONTINUOUSLY-MOVING PLATES

In the meantime and in order to investigate the possible effect of a lunar atmosphere on the measurement of the occultation times, King, devised an apparatus in which the photographic plate rotated at a constant rate. After one revolution, and to avoid superpositions, the centre of motion was carried near the point occupied by the star image. As a consequence a star traced a series of concentric arcs approaching the centre of the plate as time went on (Figure 6). The first emersion of a star recorded on this manner happened on 28 December 1904. King concluded that no appreciable atmosphere existed at a height of 1 mile above the lunar surface. If an atmosphere existed it would have a depth below the highest lunar mountains (King, 1912).

This was not, however, the first astronomical use of a continuously moving plate. For his observation of the 9 August 1896 total solar eclipse Norman Lockyer devised a 9-inch aperture prismatic camera with a 'dropping' plate. The plate was

> … to be exposed as near as possible ten seconds before the end of totality, and carried through until fifteen seconds after, the plate being moved slowly in the direction at right angles to the length of the spectrum. The object of this motion is to obtain an unbroken record of the changes in the spectrum during this interval of time.

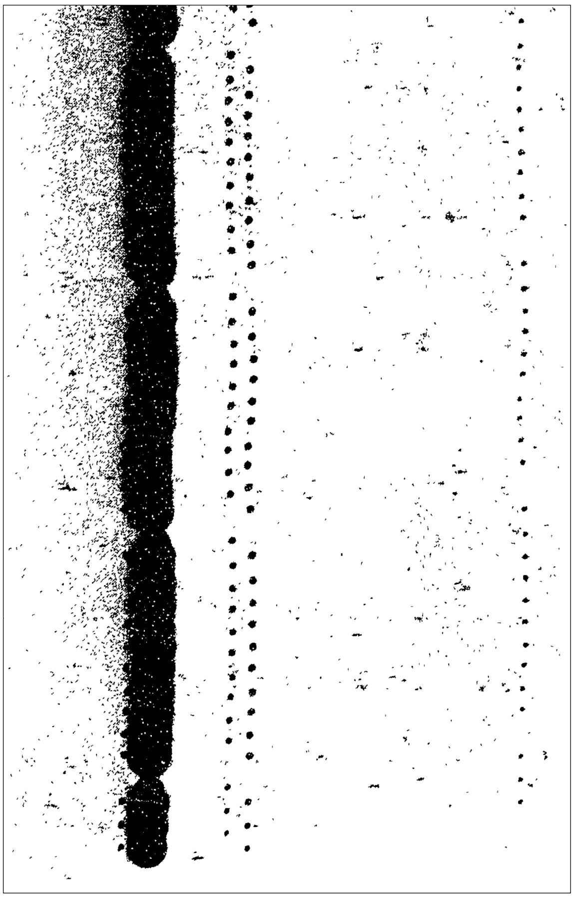

Figure 5: Photographic record of Io's disappearance on 14 April 1900 (after King, 1917: Figure 3, Plate I).

In this manner "… an unbroken record of the changes in the spectrum …" during that time interval would be obtained. The use of the camera was prevented by the poor weather at Kiö Island (Norway) on the day of the eclipse (Lockyer, 1897: 81).

Apparently William Wallace Campbell (1862–1938) was simultaneously working upon a similar idea but only had the chance to try it out at the 22 January 1898 total solar eclipse (Bingham, 1923; Campbell, 1898). A schematic of Campbell's apparatus is presented in Figure 7.

While the method unavoidably represented some degree of integration Campbell believed his approach provided a better description of the "… rapidly changing [flash] spectrum …" than a series of photographs

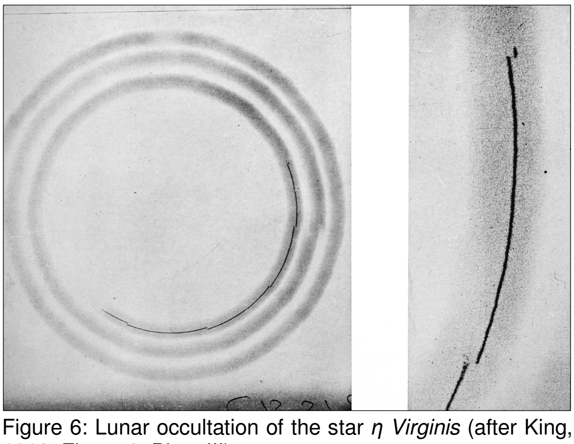

Figure 6: Lunar occultation of the star *η Virginis* (after King, 1912: Figure 3, Plate III).

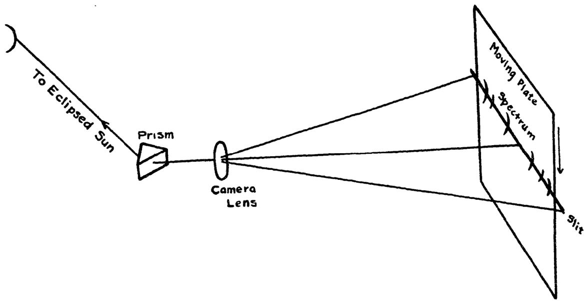

Figure 7: Diagram of the Moving-Plate Flash-Spectrum Camera (after Menzel, 1930: 3).

(Campbell, 1930: i). During the 30 August 1905 solar eclipse observation "… the plate-holder was moved by a hydraulic piston actuated by a weight …" (Campbell and Perrine, 1906: 27). Between 1898 and 1908 five successful plates were obtained on four different occasions by Campbell's Lick Observatory eclipse expeditions. Of those one was classified as poor, three as good and one as excellent (Table 1). The quality of the plates was highly dependent on obtaining accurate focus, which was very difficult to determine. The plate speed was determined by the required exposure. Speeds of the order of 1/16 inch per second corresponding to an exposure on any part of the plate of about half a second were typically used (Carpenter, 1927).

At the fourth conference of the International Union for Co-operation in Solar Research held at Mount Wilson in 1910 Campbell described his technique and presented at least the 1905 plate (Figure 8) (Anonymous, 1911). In the following years "… pressure of administrative and other duties …" prevented him from carrying out a full analysis of these plates (Campbell, 1930: vi).

Edwin Francis Carpenter (1898–1963) published some preliminary results in 1927, while a detailed analysis by Donald Howard Menzel (1901–1976) appeared in 1930-1931. In a work now recognized as a milestone in solar chromospheric studies (Osterbrock, et al., 1988: 170-172), Menzel (1930; 1931) emphasized the importance of turbulence and the high hydrogen abundance of the outer solar atmosphere (cf. Carpenter, 1927).

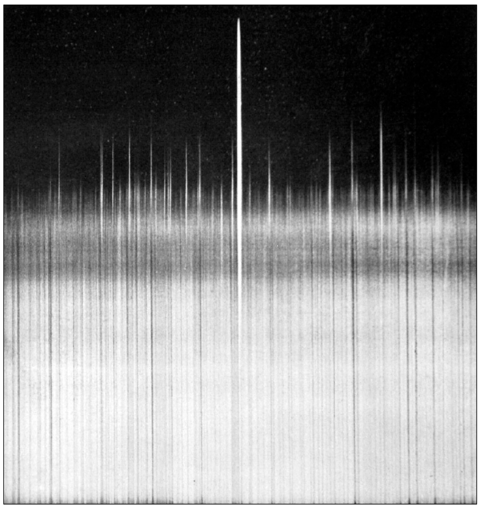

Figure 8: Enlarged section of the flash spectrum from the plate of 1905 (Spain). The most intense line is Hγ (after Carpenter, 1927: Plate IX).

Later Lick Observatory expeditions to the 21 August 1914 and 23 September 1923 solar eclipses were thwarted by poor weather conditions. On both occasions, amongst the instrumental apparatus transported to Brovary (Russia) in 1914 and Goldendale (Washingon state, USA) in 1923 there was a 'Moving Plate Spectrograph' for observations of the 'flash' spectrum. Due to the outbreak of WWI, the instruments of the Russia expedition were left behind and were unavailable for the 6 June 1918 total solar eclipse (Wright, 1923; Campbell and Curtis, 1914). This was unfortunate since on this occasion the weather allowed successful eclipse observations (Campbell, 1918). No reference to the moving plate spectrograph was found either in Campbell's papers about the 20 August 1922 solar eclipse observed from Wallal, Australia, nor in the 1927 and 1930 papers which analysed the plate spectra (Carpenter, 1927; Menzel, 1930). One may suspect that no such data were obtained, possibly because at the time Campbell's prime scientific objective was to confirm Einstein's predicted deflection of star light during a total solar eclipse. This approach was successful when photographs taken during the 1922 eclipse supported Einstein's theory (Burman and Jeffery, 1990; Crelinstein, 2006; Pearson, 2009; Pearson and Orchiston, 2008).

4 DISCUSSION AND CONCLUSION

The majority of celestial events occur on time-scales longer than a few minutes and as a consequence there are not, in practice, many astronomical applications open to sequential photography or cinematography. Notable exceptions are total solar eclipses, transits and occultations. In these latter events a series of photographs taken at very short regular intervals allows, in principle, precise determination of the contact times. In the former, sequential photography was valuable both for technical and scientific reasons. On the one hand, due to the short duration of total solar eclipses one could use different exposures and/or photographic plates in an attempt to better capture the phenomena. For instance the wide variation in the brightness of the solar corona made it impossible to correctly expose its inner and outer parts in a single photograph. On the other hand, a quick succession of images could capture the variability of solar phenomena. Obviously, in principle, a sufficiently large number of observers each furnished with their own equipment could obtain as many photographs as necessary, but this approach not only implied a higher cost—for instance in travel expenses—but its practicability was questionable since the 'human mechanism' needed to remain

> … unperturbed under the strain and tension of totality; but sad experience shows its frailty, as attested by numerous and unfortunate instances of slips in the execution of a perfectly arranged programme, no matter how constantly rehearsed. (Todd, 1897: 318).

It is therefore not surprising that this paper describes a small number of observations of total solar eclipses, transits and occultations. One should point out that apparently the development of cinematography did not play a role in this outcome, for two reasons. Firstly, cinematography itself was rarely used in this time period and secondly, photography, in general, and sequential photography, in particular,

Table 1: Summary of Lick Observatory's 'moving-plate' spectrograph eclipse observations.

Date	Location	Plate	Spectral Region (Å)
1898 January 22	India	Good	5150–5500
1900 May 28	Georgia	Good	3930–5180
1905 August 30	Spain	Poor	3200–5200
1905 August 30	Spain	Excellent	3800–5200
1908 January 3	Flint Island, Pacific Ocean	Good	3800–5100

allowed the use of larger plates, i.e. larger magnifications (Bonifácio, et al., 2010). It is also interesting to note that despite Todd's support for his 'automatic' mechanisms until at least 1914, he was aware, as early as 1900, of the 28 May 1900 eclipse film (Jacoby, 1907; Todd, 1900a; 1915). Furthermore, at the Seventieth Meeting of the British Association for the Advancement of Science, held at Bradford in September 1900, he presented a communication titled "On the Adaptation of the Principle of the Wedge Photometer to the Biograph Camera in photographing Total Eclipses." The idea was to compensate for the wide variation in brightness that occurs during a solar eclipse by using a wedge photometer (Todd, 1900a). To our knowledge, this proposal was not implemented.

Upon analyzing the attempts to use sequential photography in astronomy outlined here, one quickly realizes that several of them produced no results whatsoever, while in the case of those that did (e.g. the Harvard College occultations program and the Lick Observatory flash spectrum study) several years elapsed between the observations and the publication of the results.

We conclude that the lack of convenient objects explains the relatively small number of attempts that were made to apply sequential photography in astronomy. This technique could only be employed in very specific niche fields of research.

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