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A light history of photometry: from Hipparchus to the Hubble Space Telescope

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What is photometry?

Science, and in particular that branch known as physics, has its basis in measurement: that is quantifying a particular phenomenon so that it can be more fully described mathematically. In the case of light, we can use our own eyes to assess the phenomenon, but how can we describe what we see by way of numbers? How can we measure the *amount* of light we are experiencing? This is what I would like you to understand by way of the term 'photometry'. Let us go on a journey through time past and trace the developments that have taken place in photometry over the years.

Note that in the interest of brevity I shall limit this account to the measurement of light in the *visual* range of the spectrum. This will mean omitting the study of spectra and spectrophotometry, an examination of which might otherwise prove to be a distraction from the main theme, which is one of technological progress and human achievement.

Early beginnings and the magnitude scale

Hipparchus and the ancients

Although the constellations of the Zodiac were recognised by the ancients several millennia before the Christian era, the first known catalogue of the stars is attributed to the Greek astronomer and mathematician, Hipparchus of Nicaea (190–120 BC). Unfortunately, his original catalogue has not survived. Indeed, only one work of Hipparchus now remains, namely a *Commentary on Aratus and Eudoxus*. These two astronomers lived in the third century BC and described the 48 constellations known at that time. It is believed that Hipparchus' star catalogue contained about 850 stars, and was completed around 129 BC.[1] Importantly, he noted not only the positions but also the brightness of stars, classifying them as being either 'of brilliant light', 'of second degree', or 'faint': the very first step in the science of astronomical photometry.

Ptolemy's 'Almagest'

The first star catalogue of which manuscript copies now exist is the *Almagest*, which was produced by Claudius Ptolemy[2] and which lists 1028 stars for an epoch of about 137 AD, i.e. almost three centuries after Hipparchus' work (Figure 1). It was Ptolemy who coined the term 'magnitude', by referring to a scale of brightness extending from the 'first magnitude' to the 'sixth magnitude', the latter being the faintest stars that were recorded. His magnitude scale is believed to be based on the visibility of stars during the advancing evening twilight, in that the first magnitude stars showed themselves first. By dividing the time interval between the appearance of the first stars and the end of twilight into six parts, the faintest stars were assigned to the sixth magni-

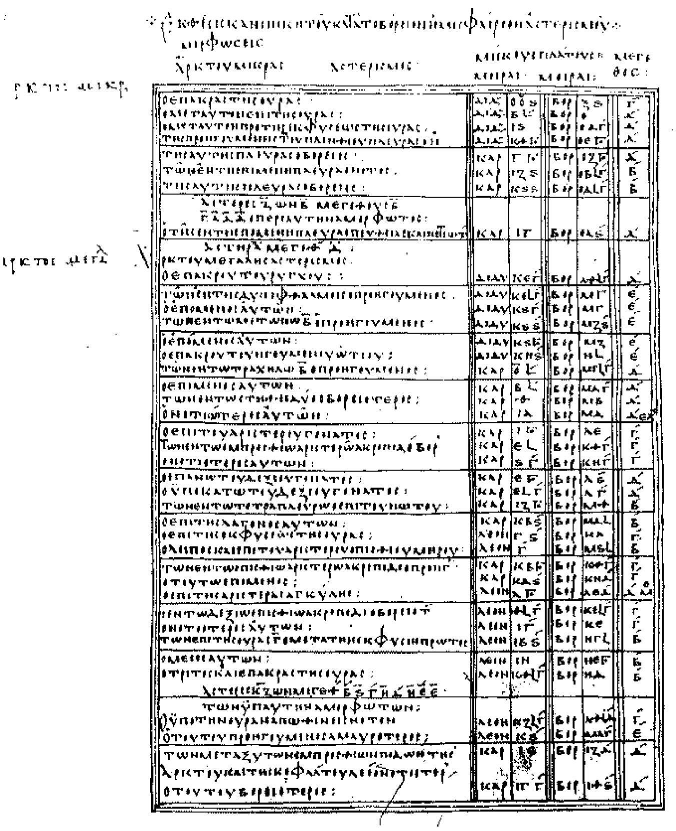

Figure 1. Ptolemy's *Almagest,* from the Paris Codex 2389 ninth-century Greek transcription.

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2007JBAA..117..172M

tude: hence as stars become brighter their magnitude *decreases*.

What is surprising is that the elegant numerical scale of magnitudes invoked by Ptolemy remained unsurpassed for the next fourteen centuries, and can be considered still to underpin the modern magnitude system that we all take for granted. Let us see how this happened.

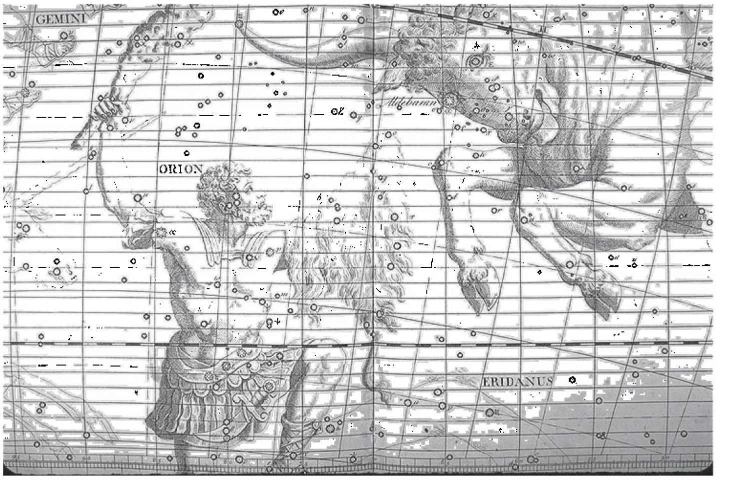

Figure 2. Orion the Hunter and Taurus the Bull as depicted in John Flamsteed's *Atlas Coelestis*, Edition 1721.

al-Sûfi to Tycho Brahé: star catalogues from 964–1603 AD

Through the centuries that passed, a number of astronomers produced star catalogues, in some cases estimating stellar brightnesses themselves. The most notable was by the tenth-century Persian, al-Sûfi (903–986), who produced his *Book on the Constellations of the Fixed Stars*[3] based on his own visual observations (Figure 3). However, he did use Ptolemy's positions precessed to the year 964 AD and added a few of his own, bringing the total up to 1151. His magnitude scale closely follows that of Ptolemy, with 374 stars being assigned 'less than' or 'more than' so as to subdivide Ptolemy's integral values. Comparing these two early catalogues with modern values, several authors have concluded that their random errors are typically better than ±0.4 magnitude, testimony to the skill of the observers.[4,5] It also showed that others found Ptolemy's magnitude scale to be practical and indeed the early catalogue of about 500 stars (epoch 899 AD) by al-Battani was based on magnitudes from the *Almagest*, whereas the medieval star catalogue of Ulugh Begh (1394–1449) copied magnitudes from al-Sûfi.[6]

We have to await the arrival of the great Tycho Brahé (1546–1601), whose astronomical interests were catalysed by the appearance of the very bright supernova of 1572. Tycho estimated its brightness and colour by comparing it to Venus, Jupiter and nearby stars in Cassiopeia. He later went on to create astrometric catalogues, his first containing 777 stars for the epoch 1600 AD. He re-estimated stellar brightnesses according to Ptolemy's magnitude system, interpolating between integral values, although his observations proved less precise than those of both Ptolemy and al-Sûfi with probable errors of about ±0.54 mag.[4] Johann Bayer (1572–1625) used Tycho's magnitude estimates to construct his famous star chart, *Uranometria* of 1603.

Dawn of the telescopic age and visual photometry

The advent of the telescope heralded the new age of astronomy beginning around 1608–1610, when it was shown, most notably by Galileo,[7] that many more stars existed fainter than magnitude 6. Using some of the very first telescopes, he was able to show that stars appeared over five magnitudes brighter through such instruments, implying a telescopic limit of about magnitude 11. However, Galileo did not attempt to quantify the magnitudes of these fainter stars.

Indeed, the invention of the telescope did not initially bring any improvement in the quality of stellar magnitudes in the 17th and 18th centuries. Edmond Halley (1656–1742) and John Flamsteed (1646–1719), two of the foremost observers of those times, used large sextants, some equipped with telescopic sights, to estimate stellar magnitudes.[8,9] The former produced a catalogue of 341 southern stars accurate to about ±0.4 mag,[4] and the latter made several catalogues including one of nearly 3000 stars, some of which extended the Ptolemaic scale to 7th and 8th magnitude (Figure 2).[9]

Early visual magnitude estimates cannot properly be classed as an attempt at visual photometry, but rather they were principally made as an aid to stellar identification, so little effort was made to improve their precision. Interestingly, Halley did appreciate the significance of quantitative estimates in that in 1721 he wrote that '*...and at ten times... which distance may perhaps diminish the light of any of the Stars of the first magnitude to that of the sixth*.'[10] Given that a difference of 5 magnitudes actually corresponds to a brightness change of 100, Halley even in 1721 recognised what we now refer to as the inverse square law governing the attenuation of light with distance.

Though the arrival of the telescope marked the dawning of a new age, a further 170 years or so passed before someone properly applied scientific principles to visual magnitude estimates, when William Herschel (1738–1822) produced the first reliable naked-eye estimates of the brightness of stars. He did this by devising the method of sequences. The motivations for Herschel at that time were two-fold.

Firstly, he was concerned for the accuracy of previous visual estimates. Earlier observers such as Flamsteed were not so intent on photometric accuracy and their estimates could be in error by up to 1.5 mag. Herschel wanted to do better. Secondly, and more importantly, Herschel wanted to determine the *change* in brightness of stars which were known to vary, and to discover whether other such variables existed. By 1780, many novae or 'new' stars had been observed, and some stars (four in all) were known to fluctuate in brightness over periods of days (Algol) or even months (Mira and chi Cygni) in a repetitive manner. The last such variable star known at that time was R Hydrae, discovered

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Figure 3. The constellation of Perseus from the tenth-century manuscript, *Book of the Fixed Stars* by Al-Sûfi. (*Bodleian Library, Oxford, MS Marsh 144*)

by Maraldi in 1704,[11] since when no similar objects had been found. Then during the early 1780s, new types of variables began to be discovered, including those by Edward Pigott and John Goodricke, two English amateurs working in partnership, who detected changes in eta Aquilae, beta Lyrae and delta Cephei, all in 1784.[12]

William Herschel too was on the lookout for these new types of star. He had already demonstrated that he was the pre-eminent observer of his age by discovering the planet Uranus telescopically after noticing its non-stellar appearance (apparent size of only 4 arcsec). In 1785, he achieved another feat of observing by detecting variability in the fainter component of the visual double star iota Boötis, now referred to as 44 Boo B,[13] even though its range of variability is only 0.6 mag (V= 6.5–7.1) and it is located relatively close to its brighter companion.

Visual estimation

Rather than trying to ascribe numerical magnitudes to stars, Herschel devised a system of notation to describe the relative brightness of a target star by judging the extent to which it differed in brightness from another star, expressing the difference as one of six discrete steps. Herschel's approach was later elaborated by Friedrich Argelander (1799–1875), establishing what is known as the step method for visual work, in which the magnitude differences are expressed as 1, 2, 3 or 4 steps, etc., each step corresponding to about one tenth of a magnitude. An alternative method also used to the present day is the fractional method, which can also be traced back to Herschel. In this the variable is bracketed between two stars, its relative brightness being defined as a fractional difference between the two. Thus the nomenclature A(3)V(2)B means that the variable is fainter than star A by 3/5 of the magnitude difference of stars A and B.

Pickering[14] investigated Herschel's observations of nearly 3000 stars and concluded that 'the error of a single comparison but little exceeds a tenth of a magnitude', testifying to Herschel's ability as a skilled observer. More recently, Zinner[4] was able to ascribe a typical probable error of ±0.17 mag to single observations by Herschel. John Herschel (1792–1871) continued his father's work by determining stellar sequences in both the northern and southern hemispheres, attaining an even higher precision estimated at ±0.12 mag for a single measure.[4] Present-day amateurs using modern comparison star sequences would be proud of achieving similar precision to that of John Herschel. It is generally accepted that ±0.1 mag is the practical limit of direct visual photometry, although a few amateurs may marginally better this under ideal conditions. It required the invention of specialised instruments, known as visual photometers, to improve visual work and place it on a more quantitative footing.

The era of the 'visual photometer'

Several astronomers experimented with using aperture stops or coloured glass of various thicknesses to facilitate visual observation, the aim being to render the apparent brightness of a target star the same as a nearby comparison. This approach takes advantage of the fact that it is easier to judge equality in brightness by eye than it is to estimate the difference in brightness of two sources. For many years these experiments, though interesting, failed to result in a practical instrument of general acceptance. We have to wait until the middle of the 19th century before real progress was

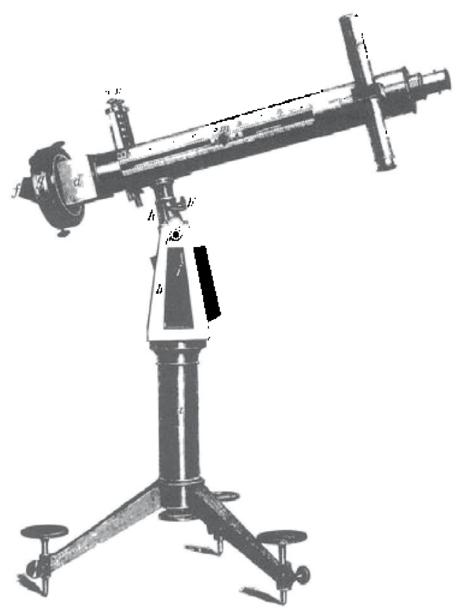

Figure 4. Carl von Steinheil's visual photometer of 1836.

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made in designing and building the first stellar visual photometers.

The era of the visual photometer can be considered to have begun around 1850 and to have lasted until the turn of the century, it eventually being displaced by the photographic plate. The names of Steinheil, Zöllner and Pickering are generally associated with having invented the most important visual comparative photometers.

The physicist Carl von Steinheil (1801–1870) first constructed such an instrument in 1836, it being a small refractor with a split objective lens, each half of the lens being able to slide along the tube (Figure 4).[15] Light from two stars was sent to each half-lens using prisms that could be moved independently. The images were defocused by an amount that depended on the position of the half-lens along the tube. By adjusting the relative positions of the two half-lenses it was possible to equalise the apparent brightness of the two extrafocal images. The relative difference in intensity of the two stars was then deduced from the relative displacement of the two lenses.

Unfortunately not only was this photometer of very small aperture, it was limited to the brighter naked-eye stars. In 1844, Ludwig Seidel began to put the Steinheil prism photometer through its paces. Eventually in 1866, Seidel published a catalogue of 208 stars, being a systematic study of all the brighter stars in the northern hemisphere complete to visual magnitude 3.3.[16] A fundamental advance made by Seidel was to take into account the relative dimming in the brightness of stars dependent on their altitude above the horizon. He corrected for this atmospheric extinction by calculating what the brightness would have been if the stars had been observed at the zenith. In this respect, he created the foundation of the method now termed 'absolute photometry'.

Though small in size, the Steinheil photometer was a fine instrument, furnishing accurate results in the right hands. Indeed, Zinner[4] estimated a probable error of ±0.05 mag for Seidel's photometric catalogue of bright stars: a great achievement for the time. However, this design of photometer had limited use in astronomy, so much so that prizes were offered by various societies, including the Academy of Sciences in Vienna, for someone to come forward with a device permitting numerous and accurate photometric determinations of the fixed stars. Friedrich Zöllner (1834–1882), then studying in Basel, put forward a new design[17] with two important innovations: (a) a kerosene lamp, which served as a standard source of illumination to produce an 'artificial star', and a crossed polariser and analyser (Nicol prisms) to reduce its intensity to that of the star being measured.[5] The Zöllner photometer was a success, becoming a standard in Europe for the remainder of the 19th century.

Most large observatories possessed a Zöllner photometer during the latter half of the 19th century, including Harvard College in the United States. However in 1877 Edward Pickering (1846–1919) became Director there and instigated an extensive programme of photometry. He soon grew dissatisfied with the performance of their Zöllner photometer in that the two objects being compared were very unlike in nature, especially when a star was bright: the real star presented a much smaller, intrinsically brighter disc, which often twinkled, and so it was difficult to compare this to a paler, larger and steadier object in the form of an aperture illuminated by a flame. Pickering developed new photometric instruments, the first of which was the '2-inch meridian photometer'. It was used to produce the *Harvard Photometry* of 4260 stars published in 1884 and consisted of a horizontal telescope with two 4cm objectives installed side by side in a common tube fixed in the East–West direction.[18] Starlight entered the lenses by way of tilting prisms, such that one always observed the Pole Star, the other observed any star near the meridian. Using special prisms the instrument brought both stars to a common focus in the field of view of a single eyepiece. Dimming of one of the stars was achieved by rotating a Nicol prism (the same technique as for Zöllner's device) and the intensity ratio of the two stars was calculated by applying Malus's law for the transmission of light through a polarising filter.

Edward Pickering was a remarkable and steadfast observer in that he pursued many lines of investigation, of which visual photometry was but one. Many studies were published in the *Harvard Annals* over the years, the most complete being the *Revised Harvard Photometry* comprising 9,110 stars over the whole sky brighter than 6.50 and 36,682 stars fainter than this magnitude limit.[19,20] By the end of his career in 1913, he had personally measured some 1,400,000 meridian photometer settings.[21]

As a postscript to the story of the visual photometer, its use continued well into the 20th century. For instance, Frank Bradshaw Wood (1915–1997) used a Zöllner photometer on the 23-inch Clark refractor at Princeton to make observations for his doctoral thesis in 1942.[22]

Pogson and the magnitude scale

It is remarkable that although the visual magnitude scale had its origin around two thousand years ago, it has persisted to

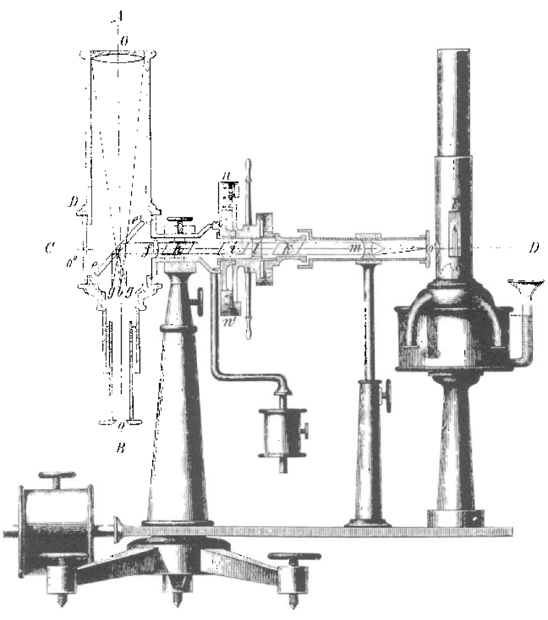

Figure 5. Diagram of the Zöllner visual photometer of 1861.

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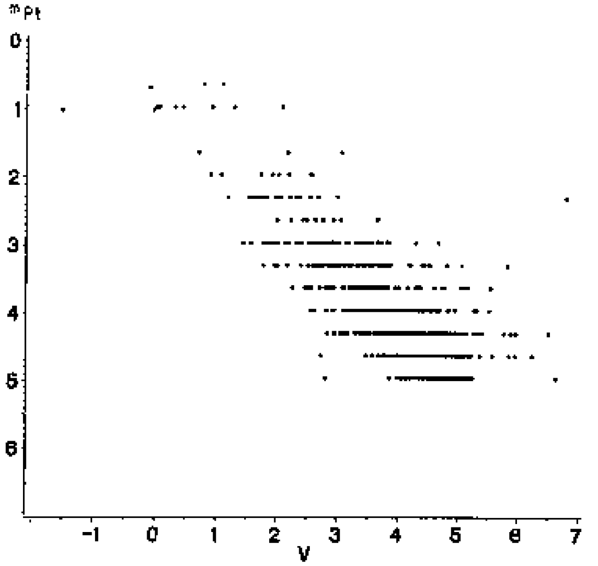

Figure 6. Correlation between Ptolemy's magnitudes and corresponding V magnitudes. (*Adapted from Sterken & Manfroid, Ref.31, Fig.1.11*)

the present day. Astronomers charting the sky tried to adhere to the Ptolemaic system of magnitudes and more recently extended them to telescopic stars. These efforts reached their culmination in the form of the sky survey conducted visually at Bonn Observatory under the direction of Friedrich Argelander, which comprised 324,198 mainly northern stars down to almost 10th magnitude, for which the positions and magnitudes (the latter to the nearest tenth) were estimated visually. This survey, known as the Bonner Durchmusterung (BD), was published between 1859 and 1862.[23] By this time, a great database of visual observations existed, each survey having assigned magnitudes on a semi-arbitrary scale. With the advent of visual comparative photometry, astronomers were obliged to convert measurements of relative intensities to magnitudes. But how to do this when no simple formula relating the two quantities existed? In particular, what is the relative intensity, R, of two stars that differ in brightness by exactly one magnitude?

Following the invention of the visual photometer, each observer seemed to have their own interpretation, which usually depended on comparing their own quantitative observations with existing visual magnitudes. At least 16 different values for R were suggested in the literature during the period 1836–1888.[24] Of all of these, only one proposal was adopted, namely that of Norman Pogson (1829–1891) who in 1856 suggested a value for R of 2.512.[25] Pogson, who at that time was an assistant at the Radcliffe Observatory, Oxford, arrived at this value in part as a mathematical convenience and in part justified by the fact that he estimated the mean of values cited in the existing literature to be 2.545. The mathematical simplification proposed was to adopt the following exact formula for converting intensity, I, to magnitude, m, namely:

$$m = -0.4 * \log(I) + \text{constant} \qquad \ldots[1]$$

This relationship models the response of the eye, the sensation of which varies in a logarithmic manner to the intensity of visual stimuli. (The human ear also exhibits this logarithmic response to sound, expressed in factors of 10, or decibels). The *exact* factor of 0.4 used in the above magnitude scale translates to an intensity ratio of about 2.512 per magnitude difference, and its adoption simplifies the calculation of the difference in magnitude of two sources, which if their intensities are expressed as I_1 and I_2 becomes:

$$m_1 - m_2 = -2.5 * \log(I_1 / I_2) \qquad \ldots(2)$$

This relationship is a somewhat arbitrary one, but it does happen to fit the visual magnitudes adopted by Ptolemy and his successors (Figure 6). It is also convenient in that an intensity ratio of 100 equates to *exactly* 5 magnitudes, something that Edmund Halley, as mentioned earlier, had postulated back in 1721.[10]

Photographic photometry

Advances in astronomical photometry depend on technological advance. Astronomers are always on the lookout for inventions which can be exploited in their quest to explore the universe. Photography is one such invention that has been utilised for the benefit of astronomy. Although the first 'photograph' dates from 1826, another 30 years would pass before photographic materials were sensitive enough to record starlight. In 1857, George Bond, the son of William Bond the then director of Harvard College Observatory, used the recently-introduced wet collodion process to take plates of the double star comprising Mizar and Alcor.[26] However, his experiments were brought to a premature end by the death of his father in 1859, and although others pursued the same goal, the wet colloidon plates proved to be slow and awkward to use so little progress was made.

The next key step in photography was the introduction in 1871 of dry silver bromide emulsions suspended in gelatine and supported on glass plates (Figure 7). Dry plates of this kind have been the mainstay of astronomical photography for more than a century, one spinoff of which has been photographic photometry. Interestingly some of the early pio-

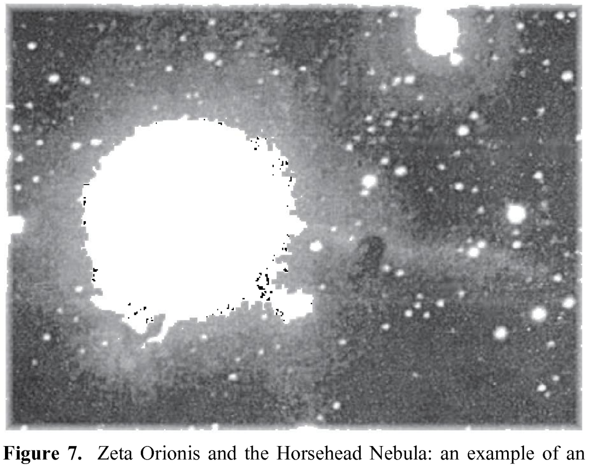

Figure 7. Zeta Orionis and the Horsehead Nebula: an example of an early astronomical photograph, taken in 1888. (*Harvard College Historical Photographic Archives Collection: by permission, and courtesy of Dr Martha Hazen*)

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neers who were instrumental in developing this new technique were amateurs, most notably the Revd Thomas Espin of the Liverpool Astronomical Society (LAS). In 1883 Espin set up a 114mm photographic lens at West Kirby in the Wirral, and recorded trailed images of stars. He utilised the visual estimates of two or more BD stars as standards so that the magnitudes of the other stars on each plate could be determined by visual inspection. In this way he was able to compile a catalogue of 500 photographic magnitudes, which was published in 1884.[27] (As an aside, Espin was the first to propose the formation of a society of amateur observers, in a letter to the *English Mechanic* in 1880.[28] This became a reality the following year when the LAS was formed, and later led to the foundation of the BAA in 1890: Espin was BAA member No.6.)

Espin's approach to photographic photometry of using trailed stars to estimate brightness was also adopted by Edward Pickering at Harvard, who in 1885 initiated extensive photographic surveys, including special studies of the Pleiades, stars close to the celestial equator, and stars within 1° of the North Pole. Pickering estimated the precision of magnitude estimates derived from polar trails to be about ±0.12 mag,[29] but this is likely to have been too optimistic since a correction had to be applied to allow for the different length of star trails. The correction depended on the cosine of a star's declination, but it was probably also affected by several other factors including seeing, edge effects and other plate-to-plate differences.

Although photography represented the vanguard of development in astronomy during the late 19th and early 20th centuries, its application to photometry proved to be very complex, and required years of devotion by many renowned astronomers at various great observatories around the world. One pioneer was Henrietta Leavitt (1868–1922), an assistant to Pickering, the work of whom on Cepheid variables led to the establishment of a distance scale to nearby galaxies.[30]

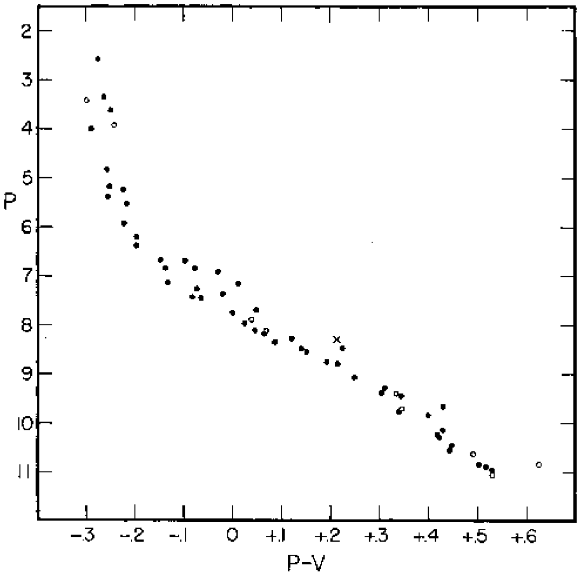

Figure 8. Example of an early colour-magnitude plot now known as a Hertzsprung–Russell diagram, of the Pleiades star cluster.

Gradually, the technique of photographic photometry became better understood and refined in its application. The methods employed included measuring trailed images, the diameter of stellar images and the degree of blackening (density) of defocused images. The difference in spectral sensitivity of photographic emulsions and that of the human eye was a major issue. Filters had to be used in conjunction with panchromatic emulsions to simulate visual response. For many decades, blue-sensitive photographic magnitudes derived from unfiltered exposures existed side by side with the visual/photovisual magnitude scale. Indeed, the difference in the two types of magnitude, sometimes referred to as the (b–v) colour index, became an important astrophysical quantity in helping to understand stellar evolution (Figure 8). By about 1930, it was possible to determine magnitudes to a precision of about ±0.02 mag, significantly better than was possible visually.[31]

Photography was exploited to create a new magnitude system based on a group of standard stars in the vicinity of the north celestial pole, known as the North Polar Sequence (NPS). Their magnitudes were defined so that the brightest stars in the sky would be close to the scale established using visual photometry. Secondary standards were established in 139 selected regions of the sky, largely from work at Mount Wilson Observatory. However, the NPS was doomed to failure as described later.

The reader might be expected to think that photographic methods have now been superseded but this is certainly not the case. The reason for this is the development of wide-field cameras such as the Schmidt camera, which can be used to make photographic surveys of the entire sky. The Palomar Observatory Sky Survey (POSS I) comprised 14-inch (35.5cm) square plates to create a photographic catalogue of mainly the northern hemisphere in 1950–1957. More recently other photographic sky surveys have been completed including POSS II, ESO and AAO Schmidt surveys covering the entire sky. Modern plate-scanning techniques have been used to digitise these plates and a sophisticated synthesis of these data from a total of 7435 Schmidt plates has been achieved by Dave Monet and Stephen Levine in the publication in 2003 of the USNO-B1.0 Catalog, which includes astrometry (including proper motions) and photometry on more than 1 billion objects.[32]

Photocells and the electrical measurement of starlight

Astronomers continue to go to great lengths to improve the precision and accuracy of photometry as well as to extend its application to ever fainter targets. Although photography has served them well to the present day, it is limited in both its ultimate precision and sensitivity. A new era was to open up by way of electrical and electronic techniques, starting slowly in the late 19th century

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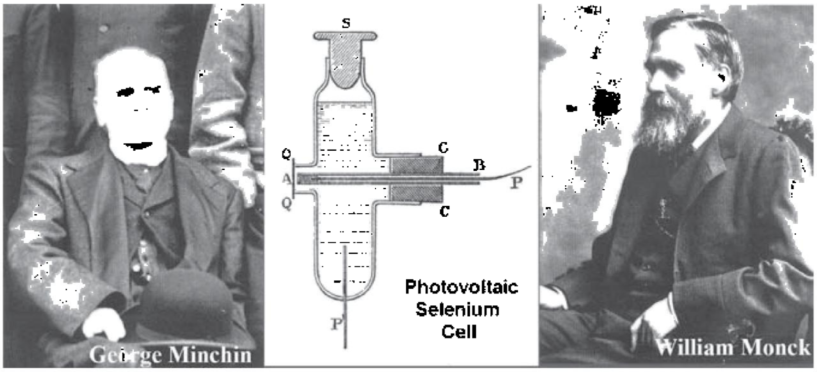

Figure 9. The earliest pioneers of photoelectricity, George Minchin and William Monck, and the photovoltaic cell.

but gradually building up momentum, aided by the technological advances of the 20th century. The remainder of this paper traces this evolution from the earliest pioneers through to the present.

Photocells of the first kind: photovoltaics

A photovoltaic cell is an electrochemical cell in which a voltage is produced on exposure to light. Strangely, although this effect was discovered by Edmond Becquerel in 1839, no-one appears to have utilised it for the benefit of astronomy until 1892. In this year, George Minchin (1845–1914), an Irishman working as a professor in London, had managed to make some photovoltaic cells and wished 'to test them on the stars'.[33] Minchin had been investigating 'photoelectricity' since 1877 and became skilled at making photovoltaic cells containing the element selenium. He arranged a visit to the observatory of his friend, William Monck (1839–1915), in Dublin and the very first measurements were made on 1892 August 28 when the relative brightness of Jupiter and Venus were measured using a 7½-inch aperture Clark refractor (Figure 9).[34] Monck was a founder member (No.12) of the BAA. Indeed, he was instrumental in the founding of the Association having written a letter to the *English Mechanic* in 1890 July advocating the formation of an amateur astronomical association with headquarters in London.[35]

Minchin's photocells were relatively insensitive and so a larger telescope was required to measure starlight. This was achieved in 1895–'96 when he tried his improved cells on the 24-inch reflector belonging to W. E. Wilson at Daramona, Co. Westmeath, Ireland. Observations were made of at least ten stars and three planets and Minchin concluded that 'there is little difficulty in obtaining fairly accurate measurements of the light of the stars of the first and second magnitudes'.[36]

Photocells of the second kind: photoconductive

Minchin's efforts to utilise photovoltaic cells in stellar photometry appear to have withered on the vine since no professional astronomer reacted to the reports of his work, which were published in the *Proceedings of the Royal Society* and in *Nature*.[36,37] The next venture in this area was made by Joel Stebbins (1878–1966), who in 1907 at Washburn Observatory began to exploit another new device, the photoconductive cell. This device also relied on the unusual properties of selenium, but it did so by applying a voltage across the cell and measuring the amount of current that flowed. This made it easier to utilise than the photovoltaic cell since small currents could be accurately measured using a Wheatstone bridge and a sensitive galvanometer.

Stebbins hooked up a commercially-available selenium cell to a 30cm refractor and proceeded to produce some staggering results, his best-known work being the observations of the eclipsing binary, Algol, in 1909–1910,[38] reproduced here in Figure 10. The photometric accuracy he attained of ±0.023 mag surpassed that of any previous visual or photographic method. Indeed by suitable averaging of measurements made outside of the eclipse, he obtained probable errors in the milli-magnitude range amounting to ±0.006 mag. In so doing, he revealed the presence of a secondary minimum for the very first time. It should be pointed out that Stebbins' achievement in defining the shape of Algol's lightcurve was the result of painstaking investigations through which he was able to optimise the performance of the selenium cell. For example, by accident (he dropped a cell on a hard floor causing it to break in two) he found that the smaller a cell was, the better was the ratio of the signal to noise.[39] Similarly, on cold nights he found the cell exhibited better sensitivity and lower noise, so he took to cooling cells with an icepack when mounted at the telescope.

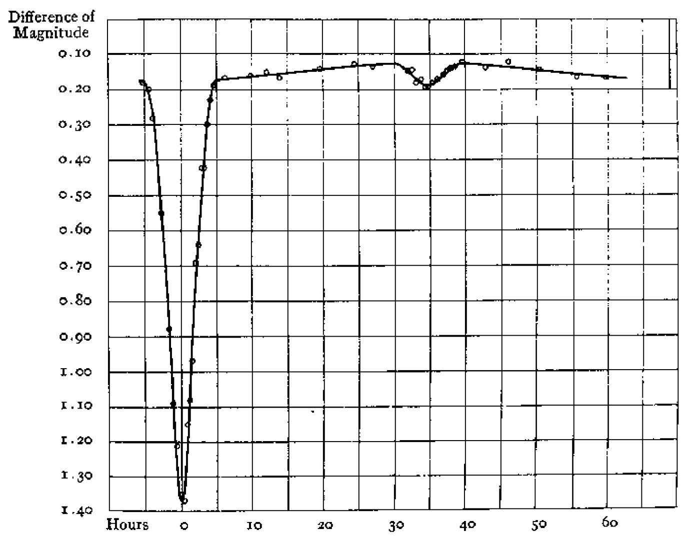

Figure 10. Algol lightcurve measured in 1909 by Joel Stebbins using a selenium photoconductive cell and 30cm refractor.

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Surprisingly, Stebbins did not continue his work with selenium cells after 1911, the reason being that a new device had been invented, which rapidly attracted interest around the astronomical community, namely the photoelectric cell.

Photocells of the third kind: photoelectric

Although the discovery of the photoelectric effect is attributed to Heinrich Hertz (1857–1894) in 1887,[40] Hertz did not study the phenomenon further and this was left to Wilhelm Hallwachs (1859–1922), who in 1888 demonstrated that ultraviolet light was able to discharge the negative charge on a zinc plate when illuminated in a vacuum.[41] Although the underlying process was then little understood (the electron had not been identified at that time), we now know how the photoelectric effect operates. Some elements have a single loosely-bound electron which can absorb a photon of light, the energy from which is enough to kick it away from the atom entirely allowing it to pass into free space as a 'photoelectron'. It is this photoelectron that can then be measured with a sensitive electrometer. The development of a device exploiting Hallwach's discovery was undertaken by Elster & Geitel, such that after four years they had constructed the first photoelectric cells having photocathodes comprising mixtures of sodium and potassium.[42] However, it was not until 1910 with the discovery that the hydrides of sodium or potassium were more sensitive to light than the metals themselves, that these devices saw their first application in astronomical photometry.[43]

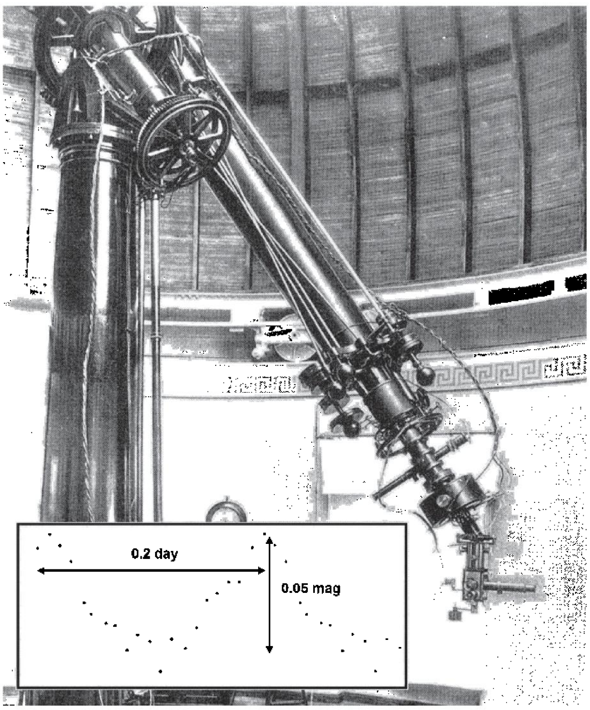

Figure 11. Guthnick & Prager's photoelectric photometer on the 30cm refractor at Berlin–Babelsberg Observatory. Inset shows their lightcurve of β Cephei of 1917. (*Ref.45*)

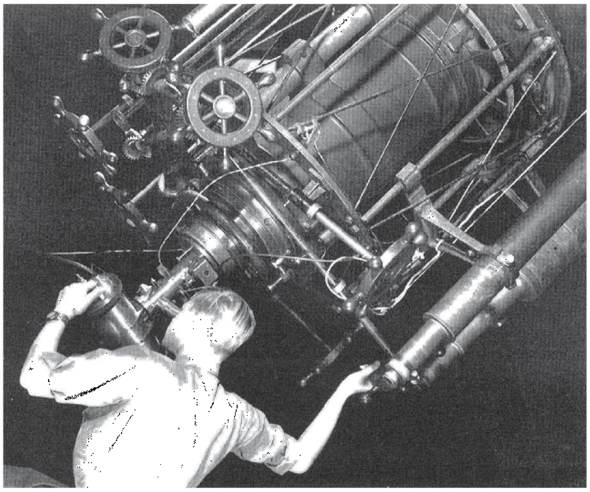

Figure 12. Gerry Kron with his photometer on the 36-in Lick refractor in 1938.

As an aside, I remember very clearly as an undergraduate at the University of Bristol in 1971, carrying out an experiment in the Physics Department which measured the photoelectric effect using light of different colours (mercury vapour emission lines). Little did I realise at that time that this phenomenon would occupy me greatly in later life when my interest in photoelectric photometry took off in 1981.

Between 1912 and 1940, only a few research groups worldwide pursued the development of photocells for use in astronomy. At Illinois, Stebbins collaborated with Jakob Kunz (1874–1939), who constructed the special cells, which though difficult to fabricate became increasingly refined in their design. Regular visits to Lick Observatory and Mount Wilson were made from 1915 onwards with many advances being made in variable star research, including the discovery of the 4th magnitude ellipsoidal variable, b Persei, which had a lightcurve amplitude of a mere 0.06 mag and individual measurements a probable error of about 0.003 mag.[44] Stebbins correctly attributed the changes in brightness not to that of an eclipsing binary system but instead to that of a tidally-distorted star in a close binary. Paul Guthnick (1879–1947), working at Berlin during the time of the Great War, undertook an extensive investigation of variable stars. He obtained a photoelectric lightcurve of β Cephei, which showed it to be variable with an amplitude of about 0.05 mag and period of about 0.2 day (Figure 11).[45] He incorrectly assigned this star to the RR Lyrae type of variable but we now know that it is the archetype of a new class of pulsating variable, the Cepheids.

Many new discoveries were made before 1940 using photoelectric cells, the design and operation of which evolved to include cooling with dry-ice and use of the latest thermionic valves to amplify the minute output currents of as little as 10^{-16} amp. Several different types of photocathode material were employed to increase sensitivity and to extend the width of spectral response into the near infrared. For those astronomers skilled in the art, unprecedented precision was possible. Gerald Kron (1913–), using a Kunz cell on the 36-inch (91.5cm) Lick refractor (see Figure 12) in a study of the Algol-type

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eclipsing binary YZ Cassiopeiae, attained probable errors as low as ±0.002 mag[46] for this 5th magnitude system on a night of average seeing. High precision was favoured by the juxtaposition of an ideal comparison star of similar colour to the variable, the pair being separated by less than 12 arcmin and high in the sky (Dec. +75°) as viewed from Lick. However, many astronomers were disappointed by their experiences with these new photocells as they encountered all manner of technical difficulties, which meant that by the late 1930s the large majority of stellar photometry continued to be based on photographic methods.

Early photometric systems: the rise and fall of the North Polar Sequence

By 1922, two photometric systems largely based on photography had become well established, one being the photographic magnitude, m_{pg}, responding to blue/ultraviolet light, the other being the photovisual magnitude, m_{pv}, obtained using isochromatic plates and taken through a yellow filter. A few years later, more red-sensitive emulsions became widely available and these spawned a red magnitude scale, m_{pr}, sometimes referred to as the photo-red system, but this was little used.

Most effort was invested in establishing a system of m_{pg} magnitudes, which by the early date of 1912 ranged from magnitude 2.7 to the remarkable value of mag 21 largely thanks the work of Henrietta Leavitt on the North Polar Sequence or NPS.[47] The idea behind establishing the NPS was to create standards that were relatively unaffected by changes in atmospheric extinction, and could be used to calibrate stars in other parts of the sky after applying a suitable correction to derive the corresponding brightness at the zenith. In 1913, the Pogson scale of intensity ratio was formally adopted for photographic photometry and the zeropoint was defined so that stars with Harvard visual magnitudes between 5.5 and 6.5 and spectral types A0 should have equal visual and photographic magnitudes.[48]

All seemed to be well at the time but this international system of photographic magnitudes was not built on firm foundations, as this type of astronomy was still in its infancy and few if any astronomers were fully aware of the various factors that could prejudice their endeavour. With the wisdom of hindsight, we can make a number of serious criticisms of the new system. These shortcomings included not specifying the type of photographic plate nor its spectral responsivity, as well as failure to properly allow for atmospheric extinction and 'seeing' effects, or for differences in reflectivity in going from silvered to aluminised mirrors. All of these factors conspired to degrade the accuracy of the photographic system, which could be subject to typical systematic errors of 0.2–0.3 mag and occasionally 0.5 mag, especially for stars in the southern hemisphere, where transfer of magnitudes from the NPS was problematical.

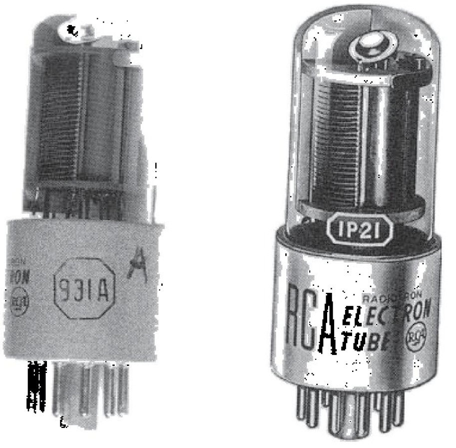

Figure 13. The RCA 931A and IP21 photomultiplier tubes.

The arrival of photoelectric (PE) methods and especially the photomultiplier in the late 1930s and 1940s was to mark the death knell of the NPS photographic system, as these new devices were capable of reaching unprecedented precision and accuracy. However, it took until the 9th General Assembly of the International Astronomical Union held in Dublin in 1955 for the international system of photographic magnitudes and colours to be finally laid to rest.[49] By that time PE methods had advanced sufficiently that the old system could be replaced, and for the next 30–40 years the photomultiplier would reign supreme.

The photomultiplier revolution

1P21 and all that

Many readers will be familiar with the thermionic valves used in early television sets to amplify signals. The photomultiplier tube has the appearance of such a valve except that it relies upon light to liberate photoelectrons from the cathode, and contains a series of plates or dynodes which are held under progressively increasing voltage so that photoelectrons are attracted to each dynode in succession where more electrons are liberated. The end result is that the original photocathode current is multiplied by as much as a million times.

The development of the earliest photomultiplier tubes (PMTs) which were destined for use in astronomy took place at the Radio Corporation of America (RCA) in New Jersey, beginning in 1936 by Vladimir Zworykin (1889–1982) and his colleagues.[50] In 1940, RCA produced tubes with caesium-antimony (Cs-Sb) photocathodes,[51] which were much superior to the old potassium hydride ones and these were produced commercially first as the nine-stage RCA 931 (later known as the 931-A) and then most famously as the 1P21, which became available commercially after the 2nd World War (Figure 13). Kron[52] incorporated the 1P21 into a photometer head, which he used on the Lick 36-inch refractor in 1946, where it was an immediate hit such that within a few years many other simi-

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lar photometers had been constructed and put into operation at observatories around the world.

The advantage of the PMT was threefold: it had a higher yield of photoelectrons (13% near 400nm), it had a broader spectral response (as far as 640nm towards the red), and the million-fold or so amplication of the photocurrent was essentially noise-free.

Figure 14. The IAPPP logo.

Once the usefulness of the PMT became apparent to astronomers, they were keen to develop the technology further and so tubes of various designs were produced utilising a variety of photocathode materials that extended the spectral response further towards the ultraviolet and importantly into the infrared. The amplification within the PMT was so large that it became possible to electrically discriminate between the arrival of pulses of photoelectrons at the anode that were associated with a *single* photon impinging on the photocathode and background noise. In other words, it became possible to count individual photons! This capability to pulse count or photon count grabbed the imagination of many astronomers, especially when it was shown in 1954 that photometry of stars as faint as 23rd magnitude could be obtained, admittedly when using the 200-inch Hale telescope at Mount Palomar.[53]

Pulse-counting versus direct current method

There are many pros and cons to be considered when choosing whether to pulse-count or to amplify the direct current (d.c.) at the anode. In the early days, pulse-counting was favoured by some because the signal was less sensitive to voltage drift, reduced effect of dark current and the output was in digital form. However as early as 1962, Harold Johnson (of Johnson UBVRI fame – see 'Photometric systems' below) argued that 'most of the supposed advantages of the pulse-counting method over d.c. methods do not exist'.[54] Early pulse-counting equipment was subject to radio interference and for bright stars, where the pulse rate was very high, 'pulse pile-up' took place and a correction had to be applied to compensate for this effect.

Figure 15. The author and home-built photometer attached to a Celestron 11 telescope at Mouldsworth Observatory, Cheshire, in 1982.

From the author's experience, developments in integrated circuits and computers through the 1970s and early 1980s, especially low-noise chopper-stabilised electronic amplifiers,[55] benefited the d.c. approach tremendously. Previously, the d.c. output was fed to the pen of a chart recorder and the deflection measured, but the use of low-cost voltage-to-frequency (V-to-F) converters permitted a digital output and computerisation became possible even amongst the amateur community.

Photoelectric photometry (PEP) and the amateur

Possibly the first amateur to undertake PEP was John Ruiz of the American Association of Variable Star Observers (AAVSO), who was tutored in the art by none other than Gerald Kron himself during the early 1950s.[56] A photoelectric photometer committee was formed by the AAVSO, which published a guide to the photometer in 1956[57] followed in 1962 by a manual,[58] and in 1963, the book *Photoelectric Astronomy for Amateurs* appeared, edited by Frank Bradshaw Wood.[59] However, although some professional astronomers went out of their way to encourage amateurs in the field, the topic was a difficult and rather expensive avenue for amateurs to explore. Indeed, during the 1960s and 1970s only a few amateurs took up the challenge and became active PEP observers, including one notable group in New Zealand, who held the first symposium devoted to small observatory photometry at the Carter Observatory, Wellington, in 1976, the proceedings of which appeared in a special issue of *Southern Stars,* the journal of the Royal Astronomical Society of New Zealand.[60]

Interest in PEP was gathering momentum stimulated by advances in electronics, so much so that the International Amateur-Professional Photoelectric Photometry (IAPPP) organisation was founded by Russ Genet and Douglas Hall in 1980 (Figure 14).[61] This author became a charter member in 1981 January and constructed a PMT-based photometer, which saw 'first light' in 1982 March (Figure 15).[62] Since these early days, many hundreds of amateurs (and professionals) have

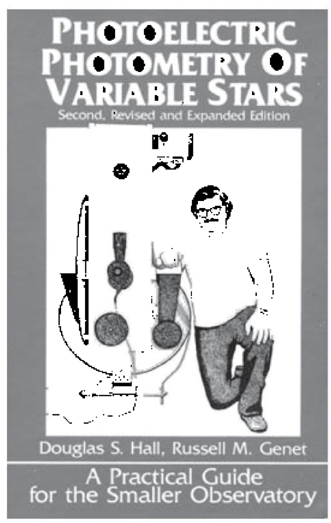

Figure 16. Hall & Genet's book, *Photoelectric Photometry of Variable Stars.* (*Ref.63*)

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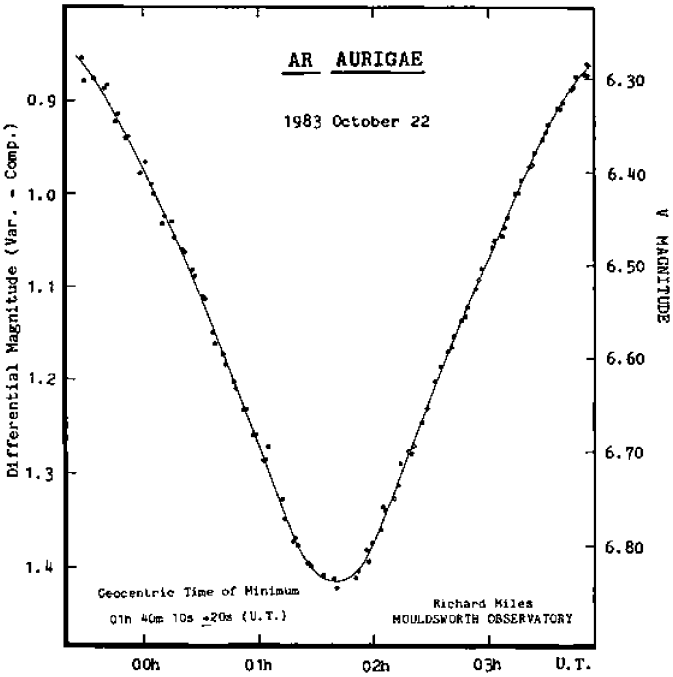

Figure 17. Lightcurve of the eclipsing binary, AR Aurigae from Mouldsworth Observatory in 1983.

joined the IAPPP, which continues to facilitate collaborative research between, amateur, student and professional astronomers. The organisation spawned various 'wings' affiliated to the IAPPP around the world, one being based in the UK. A joint BAA/IAPPP symposium was held in 1984 September, hosted by the RGO, Herstmonceux and attended by representatives from several European countries.[63] A landmark publication for amateurs was the book *Photoelectric Photometry of Variable Stars* by Hall & Genet in 1982 (2nd edition in 1988),[64] this being a practical guide for the smaller observatory which encouraged many amateurs to become involved in PEP (Figure 16).

The development of photometry in amateurs' hands is well described in the various IAPPP Communications and in the *Advances in Photoelectric Photometry* series of books published by the Fairborn Observatory. One particular noteworthy advance in the UK was made by BAA member Jack Ells, who with his son, Peter, constructed a semi-automated photoelectric telescope in 1986.[65] An example of my own early work is shown by way of the eclipsing binary lightcurve in Figure 17, which was made under ideal weather conditions. However, most nights were far from ideal so my own investigations turned to ways of improving photometry under poor skies, first in the mid-1980s by going to simultaneous two-telescope operation. Using d.c. photometers it was possible to measure objects of virtually any brightness, so that in the case of two-telescope observations of planetary satellite phenomena, the planet itself could be used as the 'comparison star'. Cases in point included the occultation of 28 Sagittarii by Titan in 1989 when Saturn was the comparison,[66] and a mutual eclipse of Jovian satellites, shown in Figure 18, when Jupiter itself was used. Subsequently, simultaneous three-telescope methodology was tried where one scope monitored the variable while the other two were separately trained on a comparison star and on the background sky – examples are Figure 19 and photometry of the asteroid (11) Parthenope.[67]

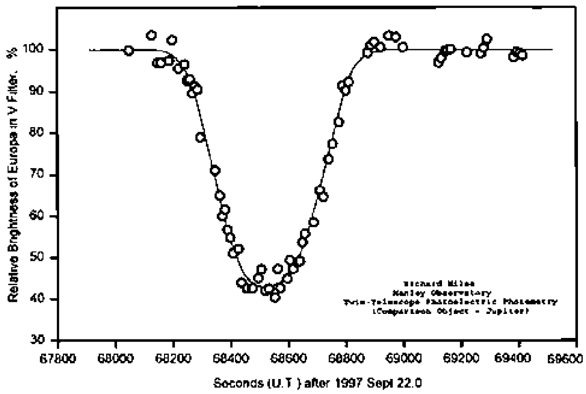

Figure 18. Two-telescope photometry of the partial eclipse of Jupiter's satellite Europa by Ganymede from Manley Observatory, Cheshire on 1997 Sep 22. Note that the comparison 'star' used at the time was the planet Jupiter.

Photometric systems

From the earliest years, coloured glass filters were used in PMT-based photometry so that observations could be related to the photographic system of magnitudes. Johnson & Morgan established the UBV broadband photometric system,[68] which is still in use today. The passbands had effective wavelengths in U of about 360nm, in B of 430nm and in V of 550nm. A combination of U and B were similar to the photographic m_{pg} scale, and that of V was similar to the photovisual m_{pv} scale. The system was enlarged to include R and I passbands using PMTs with extended red response,[69] and an important UBVRI catalogue of 1567 bright stars was published in 1966.[70] Many photometric systems were devised including intermediate and narrow-band ones. Hearnshaw[71] has tabulated 22 such systems established during the period 1943–1976. Systems working in the ultraviolet (U) region exhibited

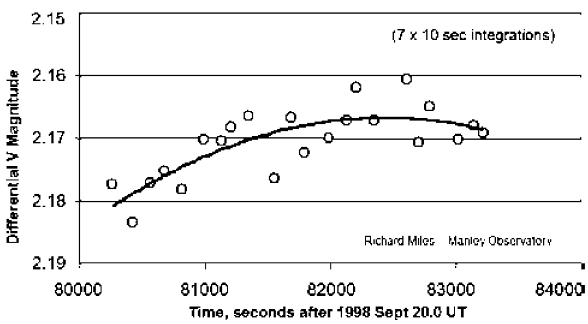

Figure 19. Example of three-telescope photometry: γ Equulei on 1998 Sep 20 from Manley Observatory. The differential V magnitude is measured relative to 6 Equ + a constant.

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important differences due to variations in the short-wavelength cutoff of the optics employed as well as significant atmospheric effects on airmass corrections. U-band photometry remains problematic even today.

Inconveniently, the original UBVRI system required two photomultipliers. More importantly, that used to measure the I passband was relatively insensitive in this region of the spectrum. The invention of the wide-response Ga-As photocathode came to astronomers' rescue, given its extended red response. In 1976, Alan Cousins utilised the RCA 31034A Ga-As photomultiplier to establish a new RI system at the Cape Observatory in South Africa.[72] His passbands in the red and near infrared were similar to those devised by Gerald Kron[73] back in 1951 and are usually referred to as the Kron–Cousins system, R_c and I_c. They were initially based on the use of an interference filter for the R-band and a Schott glass filter for the I-band (effective wavelengths of about 640nm and 800nm respectively).

The Kron–Cousins $UBVR_cI_c$ system was largely based on observations of stars in nine of the Harvard E regions centred at a declination of about −45°. Another set of standards located near to the celestial equator has been developed by Arlo Landolt at the South African Astronomical Observatory.[74] His later publications include fainter stars down to 16th magnitude as well as blue and red stars located in a small area of sky, which makes it easier to obtain transformation coefficients using CCD cameras on larger telescopes.

The first area detectors

From our vantage point here in the 21st century, we often take CCD cameras for granted even though their arrival on the photometric scene has been very recent. Previously, various approaches were pursued to enable intensity measurement using electronic means over an area of sky as opposed to the single-channel detection of a photomultiplier or photovoltaic device. The Lallemand electronic camera[75] was one such device, as were television systems based on the image orthicon and later the vidicon tube.[76] In the era before digital electronics and computers, images produced by these devices were recorded on photographic plates, and these were then measured using a microdensitometer. Merle Walker and Kron pursued stellar photometry using a Lallemand-type electronographic camera at the US Naval Observatory, Flagstaff, attaining better than ±0.1 mag accuracy at 21st magnitude in 20-min exposures on the 61-inch telescope.[77] Image-intensifier stages were also added to increase sensitivity.[76] Compared with PMTs, these early area detectors left much to be desired. Their dynamic range was constrained by the response of the photographic plate, with acceptable linearity extending over a brightness range of <5 magnitudes. They were also complicated, expensive and difficult to calibrate, and as such were never widely used for photometry.

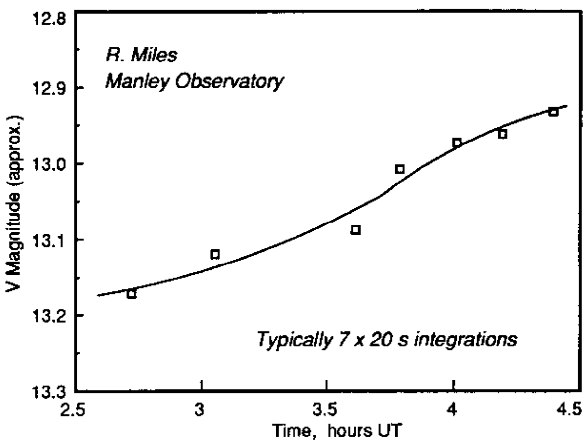

Figure 20. First steps in CCD photometry by the author using an ST-4 camera in 1992: Asteroid (402) Chloe has subsequently been found to have a rotation period of 7.11 hours and a lightcurve amplitude of up to 0.28 magnitudes.[82]

Figure 21. Santa Barbara Instruments Group model ST-4 thermo electrically-cooled CCD camera head and controller.

Make way for the CCD

Charge-coupled devices

In 1969, George Smith and Willard Boyle invented the charge-coupled device or CCD at Bell Laboratories in the USA.[78] By 1976, astronomers at several American observatories had begun to use commercially-available devices on large telescopes.[79] The CCD is fabricated from a single wafer of crystalline silicon, from which several units can be produced, hence the term 'CCD chip'. It is particularly useful in astronomy owing to its very high quantum efficiency, which may exceed 90% at some wavelengths, as well as its strong response in the near infrared. The digital nature of the image also facilitates numerical analysis by computer. The remarkable performance of the CCD camera was ably demonstrated by Dave Jewitt and Edward Danielson when they imaged Comet Halley on 1982 Oct 16, more than three years before perihelion, when the object was about 24th magnitude. To accomplish this feat, they used an 800×800 pixel CCD array developed as a prototype camera for the Space Telescope on the 5m Hale telescope at Mount Palomar.[80] By 1986, the CCD camera was being used not only to detect very faint objects but also to carry out quantitative photometry, the precision of which was comparable to that of conventional photometers at that time.[81]

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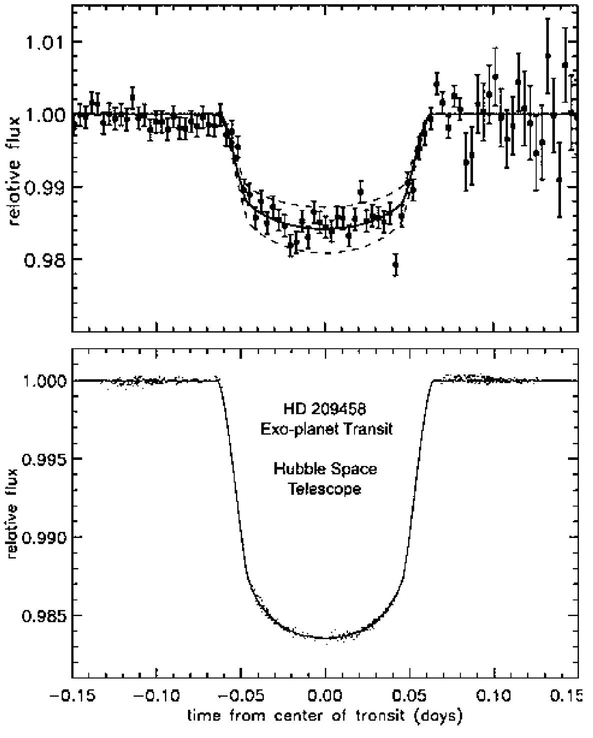

Figure 22. Transit of the planetary companion to HD 209458: Upper plot – discovery lightcurve by Charbonneau *et al.*[85]; lower plot – Hubble Space Telescope photometry. (*Courtesy STScI*)

CCDs and the amateur

By 1989, the first CCD cameras suitable for amateur use became available commercially, exemplified by the Santa Barbara Instruments Group device known as the ST-4 Camera/Star Tracker (Figure 21). This device utilised the Texas Instruments CCD chip TC 255, comprising 192×165 pixels, and was only about 3mm square in size. Larger chips were available, notably the TC 245 used in the *CCD Camera Cookbook* camera, which had to be assembled from kit form. During the early '90s, few observers exploited CCDs in photometry as their use was hindered by their relatively high cost, small fields of view severely limiting the choice of comparison star(s), and a serious shortage of software available to the interested amateur.

My first venture into CCD photometry involved using an ST-4 attached to a 35cm aperture Schmidt–Cassegrain telescope to record a time series of images of the 13th magnitude asteroid (402) Chloe on 1992 Nov 21 (Figure 20). I wrote my own software to read the pixel values within each image file and was thereby able to calculate the flux of the variable asteroid relative to a nearby 12th magnitude comparison star. About this time, a book by amateur astronomer Christian Buil entitled *CCD Astronomy*[83] appeared, explaining the construction and use of this revolutionary new device. The breakthrough in software however took until the end of the '90s when, for example, a comprehensive book was published by Richard Berry & Jim Burnell, entitled *The Handbook of Astronomical Image Processing*, which included a section on photometry and specialist image processing software.[84] As technology progressed, CCD prices reduced, chip size increased and software for reducing the images became available commercially, such that after a further 10 years or so this observer finally discontinued using the high-voltage PMT-based photometer in favour of the low-voltage, intrinsically more efficient CCD camera.

There are many excellent CCD cameras in use by amateurs today, many of which produce remarkable images of extended objects. Although some are colour cameras equipped with a Bayer-type array of colour filters, others are 'monochromatic' devices and can be used either directly or in conjunction with colour filters to make photometric measurements, which can then be transformed to a standard system such as Kron–Cousins BVR_cI_c.

The future of photometry

The technological momentum in astronomy is dramatic at present, with major advances in both professional ground-based and space observatories. One incentive has been the search for planets orbiting nearby stars, the presence of which can be detected if the planet happens to transit across the star's disk as seen from the Earth. One of the earliest to be detected was around HD 209458, a 7th magnitude star located in Pegasus at a distance of about 150 lightyears. The discovery lightcurve shown in Figure 22 (upper plot) was made using a ground-based 10cm aperture telescope.[85] In contrast from space where no intervening atmosphere has to be contended with, much higher precision photometry is possible as exemplified by the equivalent observation using the Hubble Space Telescope (Figure 22 – lower plot).

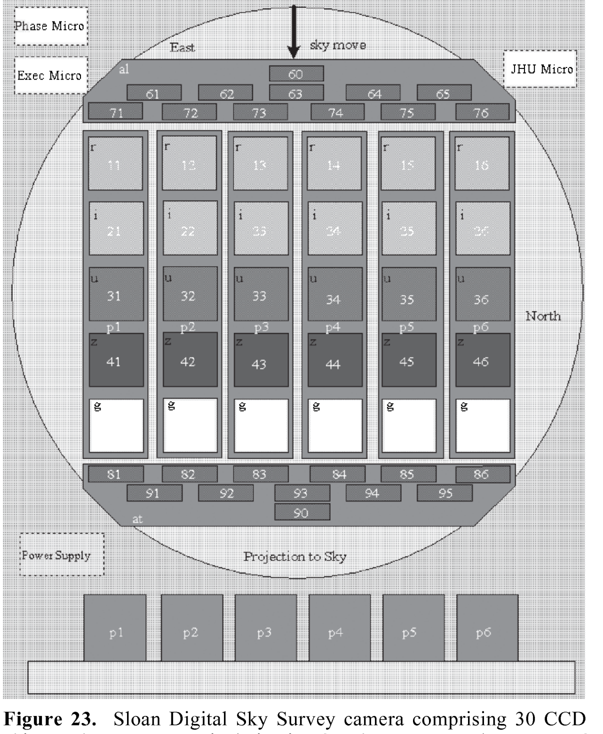

Figure 23. Sloan Digital Sky Survey camera comprising 30 CCD chips each 2048×2048 pixels in size for photometry, and an array of other CCD chips for astrometry and focus monitoring.[87]

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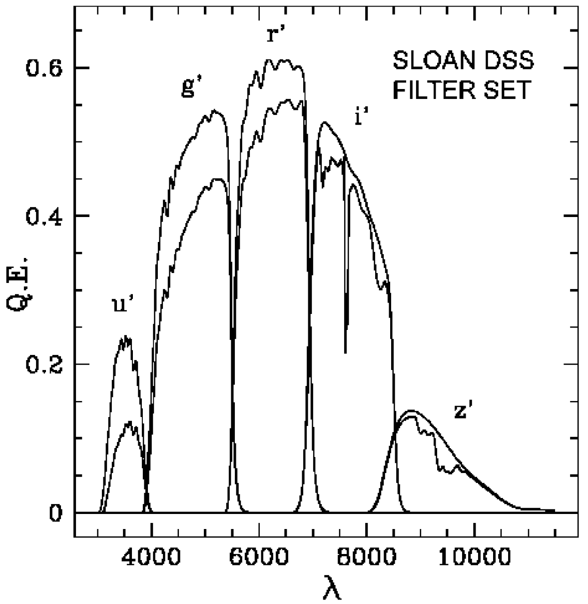

Figure 24. Plot showing the five passbands of the SDSS photometric system.[89]

Photometric surveys are an inevitable consequence of computerisation and automation,[86] examples being the MACHO and OGLE projects, which employ large-area cameras to monitor light variations in many millions of stars in search of transient gravitational lensing phenomena. The Sloan Digital Sky Survey (SDSS) is an important new survey which uses an array of 30 CCD chips for simultaneous photometry in five passbands (Figure 23). SDSS has in effect created a new CCD photometric system, namely the *u'g'r'i'z'* system,[87] which has proven popular with professionals (Figure 24). A review of the current and future perspective of standard photometric systems has been carried out by Mike Bessell.[88]

Spacecraft have been used to make very precise astrometric observations (measurements of stellar positions), most notably the *Hipparcos* mission during the 1990s, which also performed photometry. Following on its success, the European Space Agency is currently developing a new combined astrometric/photometric space-borne facility, namely GAIA (the Global Astrometric Interferometer for Astrophysics) due to be launched in 2011 December.[90] To overcome limitations of any one photometric system, light from objects will be dispersed to form spectra, the distribution of light within which will be measured. The spectral data can then be used retrospectively to calculate magnitudes in a range of photometric systems. The GAIA mission (see front cover) is planned to extend to at least the year 2020 and it is hoped that it will set new standards for many years to come.

Acknowledgment

This article is a brief summary of the historical development of photometry, as presented in my opening Presidential Address to the members of the BAA on 2006 October 25. In compiling my talk and this account, I have been guided by the definitive work on the subject, *The Measurement of Starlight* by Professor John Hearnshaw of the University of Canterbury, New Zealand.[6] This work is unique in that it is by far the most complete historical review of photometry from the earliest times through to around the end of the 1980s. I thank Professor Hearnshaw for the guidance his book has provided me as well as the opportunity to use selected photographs from the same.

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2007JBAA..117..172M

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