EVOLUTION OF THE "REAL" VISUAL MAGNITUDE SYSTEM

Ronald E. Zissell
Mount Holyoke College
South Hadley, MA 01075

Presented at the Annual Meeting of the AAVSO, October 25, 1997

Abstract

The historical development of the system of visual magnitudes is traced. The relationships among visual, PEP(V), and CCD(V) magnitude systems are examined.

1. Introduction

One hears the comment that some comparison star magnitudes on AAVSO charts prepared from PEP or CCD sequences do not match what the eye sees at the eyepiece; their labeled magnitudes do not match the "real" visual magnitude system. This kind of comment leads to the questions "What is the 'real' visual magnitude system and how or when was it defined?" and "Why do some stars appear to be out of sequence, even though they have been calibrated to within a few percent by modern electronic detectors?" This paper will attempt to answer these questions by tracing the historical development of the system of visual magnitude and showing the relationship between the visual magnitudes and the photoelectric and CCD(V) systems.

Anyone can define a photometric system by selecting a detector, some pieces of colored glass, and then measuring a number of stars that become the standards of that system. Another observer can obtain the same type of detector and filters and closely reproduce the measures of the standards. Such modern PEP and CCD systems are common today. The detector and filters are chosen to measure features in the stellar spectrum that have astrophysical significance. While modern photometric systems have been carefully planned, the visual magnitude system for stars developed slowly over the ages. The detector was, of course, the human eye, and the color filter was the natural color response of the human eye.

Originally, "astronomy" meant position measurement of the stars. The precise brightness of the stars was of lesser importance than their positions in the sky. After the development of the telescope, precise star brightness measurements gained importance with the discovery of variables and an ever-increasing number of faint stars visible through the eyepiece.

2. Ancient history

Any historical survey of stellar magnitudes begins with the work of Hipparchus of Nicea, who lived in the 2nd century BC. He divided the stars into six brightness classes called magnitudes. The brightest stars belonged to the first class, while the faintest were assigned to the sixth class. It is important to remember that these "magnitudes" were not the continuous real number scale we use today, but just classes or bins into which the stars were sorted. Anyone familiar with the night sky knows that there is a noticeable difference between the brightness of Sirius and Rigel, although both were classified as stars of the first magnitude. Therefore, stars of the first magnitude originally meant only the most conspicuous ones, and sixth magnitude meant the least conspicuous. The Greeks made a distinction between numbers and magnitudes. Numbers (integers) were pure concepts, while magnitudes (sizes) were considered common and beneath the consideration of true mathematicians. That the original magnitude divisions were not subdivided into fractional parts has its origins in this philosophy. Also, there was no need for a finer division of brightness at that time.

We have no ancient copies of Hipparchus's catalogue of stars. His work was adopted into the *Almagest* of Claudius Ptolomy, which appeared circa 138 AD. Ptolomy acknowledged the differences in brightness within a magnitude class by adding the terms "greater" and "lesser" to indicate position within a class (Bailey 1931). Again, star positions were the important part of the work; star brightness was secondary.

By the 10th century, many copy errors had corrupted the *Almagest.* Al Sûfi made a revision of Ptolomy's work and revised the magnitudes. To guard against future copy errors, he wrote the magnitudes in words instead of using digits. A copyist was more likely to make a mistake copying a digit than a word (Knobel 1917).

In 1437 Ulugh Bey made an improvement in Ptolomy's positions by measuring the star positions anew (Pannekoek 1961). His new catalogue retained the magnitudes from Al Sûfi (Knobel 1917). An example of these magnitudes are 3, 4, 3-4, 4-3, 4-5. This system indicates a rough position within a magnitude class but was still not a continuous scale (Knobel 1917).

Tycho Brahe published a new catalogue of stars, *De Nova Stella*, from his own observations made from 1564 to 1601. The brightness of 788 stars was listed in one-third magnitude steps (Pannekoek 1961). Why stop at one-third magnitude steps? Why not one-tenth magnitude steps? At this point a question presented itself. When was the decimal point invented, and when did decimal calculations become the accepted method of calculating? How were calculations performed in ancient times? These questions led to a fascinating side journey into the history of mathematics. A brief summary follows:

2.1. Mathematics

Ptolomy's *Almagest* included an extensive mathematical section that covered the solution of spherical triangles as applied to astronomy. "The fact that trigonometry was cultivated not for its own sake, but to aid astronomical inquiry, explains the rather startling fact that spherical trigonometry came to exist in a developed state earlier than plane trigonometry" (Cajori 1896). Ptolomy included tables of chords of circles that were used to calculate spherical triangles in fractions of a degree.

Leonard of Pisa (Fibonacci, 1175–?) published a book in 1202 covering most of the mathematical knowledge of the Arabic world. The section on algebra was entirely in prose; it contained no algebraic symbols (Cajori 1896). He favored the use of Arabic (Hindu) numbers over Roman or Greek notation for calculations. Two examples of his work follow: $x^2 + 5$ and $x^2 - 5$ are each square numbers. What is x and what are the square numbers? His solution was $(3\ 5/12)^2 + 5 = (4\ 1/12)^2$ and $(3\ 5/12)^2 - 5 = (2\ 7/12)^2$. He also gave a root of the cubic equation $x^3 + 2x^2 + 10x - 20 = 0$ as $x = 1^{\circ}\ 22^{i}\ 7^{ii}\ 4^{iii}\ 33^{iv}\ 4^{v}\ 40^{vi}$, where the exponents indicate powers of 1/60, just as we still use in our angle measurements. In decimal notation, this root was accurate to nine places. These examples show that fractions were the mode of expressing numbers. The most popular fraction denominators were 12 and 60, since they had more factors than 10.

The sixth volume of Copernicus's *De Revolutionibus*, published in 1543, uses only Roman numerals (Pannekoek 1961). Since the book was written in Latin, this would be expected. Old traditions are slow to pass away even though more efficient methods are available. After all, we still give stellar coordinates in degree, minute, second notation rather than in decimals of a degree.

The invention of decimal arithmetic is attributed to Simon Stevin (1548–1620) of Brugen, Belgium. In 1584 he published *La Disme*, in which he described the advantage of decimal fractions for interest calculations. It took another generation before the modern notation of the decimal point became established. (In European countries the comma is still used instead of the period.) *La Disme* was not translated into English until 1608 (Cajori 1896).

1998JAVSO..26..151Z

3. The age of the telescope

The publication of the discovery of variations of Delta Cephei by Goodricke in 1786 provides a good view of the state of visual photometry toward the end of the 18th century:

> Mr Goodricke’s first observation was Oct. 19 1784, and they were continued almost daily, till June 28 1785. From this series he settled, that the star has a periodical variation of 5d 8h 37½m, during which time it undergoes the following changes: 1. It is at its greatest brightness about 1 day and 13 hours. 2. Its diminution is performed in about 1 day and 18 hours. 3. It is at its greatest obscuration about 1 day and 12 hours. 4. It increases in about 13 hours. When it is in the first point it appears as a star of between 4th and 3rd magnitude; but its relative brightness does not seem always to be quite the same, being sometimes between zeta and iota Cephei, and sometimes only equal to, or something less than, iota Cephei, or between zeta Cephei and 7 Lacertae. In the third point it appears as a star of between the 4th and 5th magnitude; and its relative brightness is as follows: nearly equal to iota and xi Cephei, and considerably less than 7 Lacertae.... (Goodricke 1786)

Note that the period is given in days, hours, and minutes. This is not too unusual considering that his countrymen were comfortable doing business in pounds, shillings, and pence at this time in history. The light curve is given in words, not graphically or in a table. Also, Goodricke describes the maximum and minimum light relative to named stars, not in stellar magnitudes. William Herschel described the light variations of Mira in similar terms (Herschel 1780).

A promising lead to the magnitude notation used by William Herschel appeared in *On the Diameter and Magnitude of the Georgium Sidus* (Herschel 1785); but I found that “Size” referred to the angular diameter and that “Magnitude” referred to the actual diameter in miles. The original meaning of “magnitude” was size. Brighter stars appear bigger than the fainter ones. William Herschel used the symbols “ . ; - ” to indicate 0.1, 0.2, and 0.4 magnitude steps within a magnitude class, along with a few more complex symbols which were used so rarely that we cannot decode their precise meanings (Pannekoek 1961).

As the nineteenth century began, astronomers were on the verge of converting the magnitude steps of Hipparchus into a different system—that of a continuous scale of magnitudes. The greatest obstacle to this change was determining the zero point of the scale. Which stars of the fourth magnitude class are 4.0 and which ones are 4.9? The average of the fourth magnitude stars would not be 4.5, since there are more stars at the faint end of the class than at the bright end. Who would agree on which stars were exactly 4.0?

4. Modern stellar astronomy: photometry

The modern era of stellar photometry began with Argelander (1799–1875), who introduced the “Step Method” of estimating magnitudes. This method uses a brighter and fainter comparison star to bracket the variable. The interval is divided into a convenient number of steps. Argelander’s first results were published in 1843 in a paper on the light variations of delta Cep, beta Lyr, and eta Aql (Argelander 1843). An examination of the tabulated results shows that the brightness is given not in magnitudes, but in intensity, called “Grades.” The important concept introduced in this paper is that the brightness units were given on a continuous scale to one decimal place. In his later publications, Argelander transformed his brightness grades into magnitudes that were related to those of Hipparchus. The faintest third magnitude and brightest fourth magnitude stars of Hipparchus became magnitude 4.0.

While working in Bonn between 1852 and 1859, Argelander made a survey of stars of magnitude 9.5 and brighter with a 76-mm objective. The magnitudes of the stars were visual estimates given to one decimal place based on extrapolation of the step sizes of Hipparchus. The *Bonner Durchmusterung* (BD) contained 324,000 stars.

The magnitudes from the BD defined the zero point of the magnitude scale because of the vast scope of the survey. Later surveys with more modern instruments have shown that Argelander's magnitude steps were not consistent and had progressive systematic errors.

Argelander's successor at Bonn, Schoenfeld, continued the work down to -24° declination. In 1885 Thome' went to Cordoba, Argentina, to extend the survey to -62°. The various *Durchmusterungs*, collectively known as the DM, contain 579,000 stars and were of great importance to the advancement of stellar photometry studies. The DM were based on eye estimates which varied with observer color sensitivity and fatigue. A better method of photometry was needed to actually measure the brightness rather than just estimate it.

4.1. Instrumental photometry

In 1836 in South Africa, John Herschel used an "astrometer" to compare the brightness of stars to a reduced image of the moon. This was a true photometer, in that it contained a scale to read the brightness, and that one could compare equal intensities rather than estimating intensity intervals. An inaccurate theory of moon-brightness as function of phase limited its usefulness, along with its being able to measure only the brightest stars, since it could be used only while the moon was in the night sky (Pannekoek 1961).

In the first half of the 19th century, a number of astronomers investigated the relationship of a magnitude step to the change of brightness it represented. Figure 1 compares the telescopic magnitudes from a number of experienced observers (Webb 1962), with English astronomer and double star observer William Henry Smyth's (Bryant 1907) magnitudes taken as the standard (even though they are not necessarily any more correct than those of the other observers). We see that at 6th magnitude they agree quite well. The step size of Hipparchus was continued down to 10th magnitude, where they start to diverge. Argelander and Struve used increasingly smaller ratios than J. Herschel and Smyth. If Struve reported a star at 16th magnitude, Argelander would conclude that he could not see such a faint star.

In 1835, Steinhel opined that a magnitude step represented a fixed ratio of brightness. John Herschel came to the same conclusion in 1837 and suggested that the ratio be defined so that all observers could report consistent magnitude differences. In 1856, Pogson determined that the brightness ratio k for one magnitude varied from $2.24 < k < 2.75$ among astronomers. In terms of common logarithms, $0.340 < \log(k) < 0.440$; Pogson proposed that the standard ratio be adopted so that $\log(k) = 0.400$. This means that five magnitudes represents a brightness ratio of exactly 100 (Pannekoek 1961). This is the value we all use in our modern magnitude calculations.

It is one thing to define a constant, and another thing to apply it at the eyepiece of the telescope. Who could, by eye estimates alone, tell if two stars had a brightness ratio of 2.35 or 2.43? An instrument like Herschel's astrometer was needed by which one could read a calibrated scale.

4.2. Photometers

Seidel in Munich used a Steinhel photometer to compare 208 stars from 1844 to 1860. The Steinhel photometer varied an out-of-focus star image until it had the same surface brightness as an out-of-focus comparison star image. This only worked for stars

1998JAVSO..26..151Z

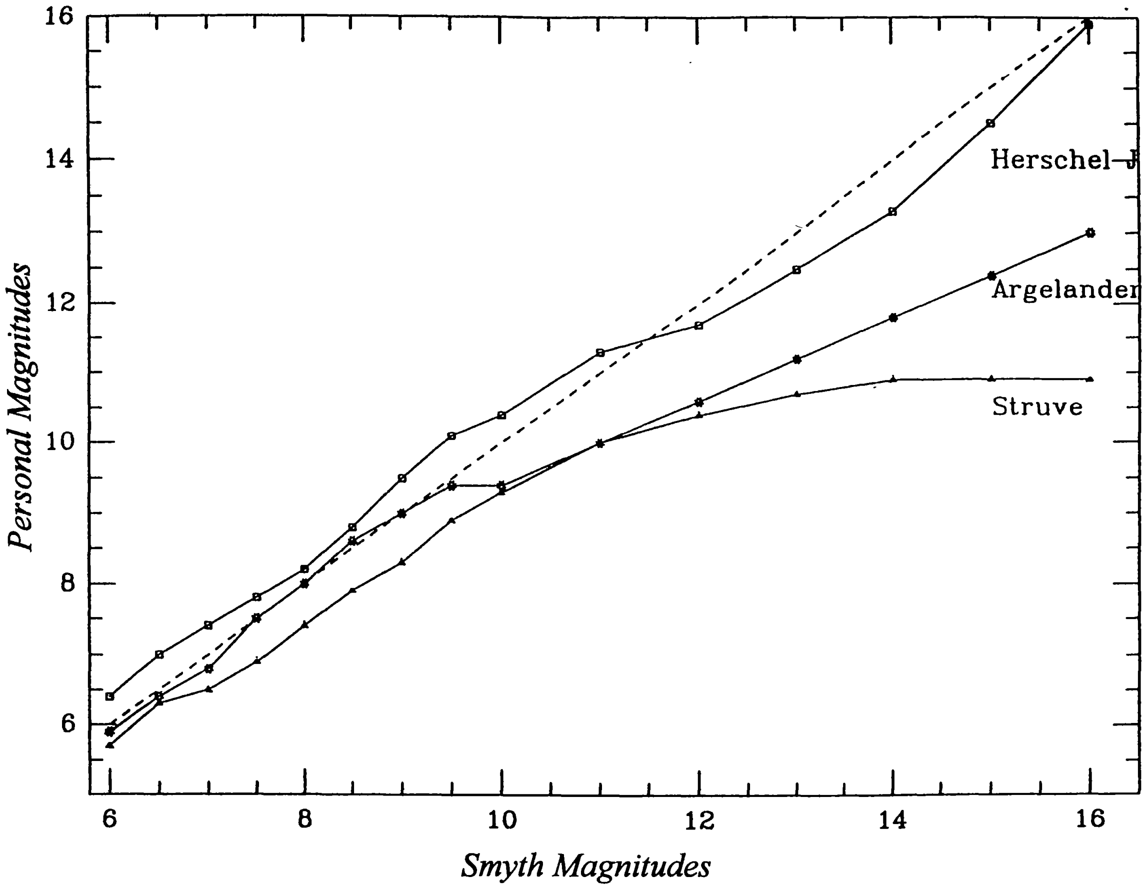

Figure 1. Comparison of the telescopic magnitude system of Smyth, Struve, Argelander, and J. Herschel. As the magnitudes become fainter there is greater divergence between observers. Magnitudes falling on the dashed line agree with those of Smyth. Any of the observers could have been chosen as the standard. (After Webb 1962.)

of magnitude 3 or brighter, since the bright stellar points were defocused into dim disks—the brightness of the disks being easier to compare than the brightness of the point images (Pannekoek 1961).

Another popular visual photometer was the "wedge photometer." This device used a piece of glass with an optical density gradient along its length. In use, the wedge would be oriented East-West, and the telescope drive stopped so that the star to be measured drifted into the field at the clear end of the wedge and passed into the darker end of the wedge as time elapsed. As the star entered the field, a stopwatch was started and then stopped when the star disappeared at some point within the wedge. For bright stars, an aperture stop could be used to attenuate the light by a known amount (Pannekoek 1961). This method was popular because it was simple and quick. Unfortunately, it had limited accuracy, since it relied upon the point of disappearance rather than a comparison of two equal brightnesses which the eye could distinguish to 5 percent uncertainty. Pritchard at Oxford used a wedge photometer to measure all the naked-eye stars visible from Oxford. The *Oxford Catalogue* was published in 1885 (Pannekoek 1961). The accuracy and scope of this catalogue was inferior to others being produced at the time.

The Zöllner photometer allowed the quantitative measure of stellar brightness by comparing two images of equal brightness. An artificial star formed by a lamp flame and a pinhole was projected into the telescope field of view. The brightness of this image could be attenuated by rotating one of a pair of polarizing prisms. The intensity changes in proportion to the square of the cosine of the angle of rotation between the prisms. By alternately matching the artificial star to two stars in the field, one could determine the brightness ratio of the two stars. As long as sky transparency remained constant, one could even compare stars in adjacent fields or in different parts of the sky (Bailey 1931).

The Zöllner photometer was invented before the age of the electric light. One disadvantage was the use of a flame for the light source. The flame was always vertical and flickering from slight breezes, while the photometer could be in any orientation at the eyepiece as the telescope pointed to various parts of the sky. Another disadvantage was the appearance of the artificial star. It did not appear the same as the real star since it did not undergo the effects of seeing. It is difficult to tell when both images are the same brightness when they have different appearances.

Even though there were disadvantages with the Zöllner photometer, it was a great step forward in accurate photometry. Wolff (Bonn 1869–1875) used it to catalogue the magnitudes of 475 stars.

What was needed was a large systematic survey of the entire sky on the scale of Argelander's with an accurate photometer. It takes much more time to use a photometer at a telescope than to make a visual estimate. Any large-scale survey would therefore occupy the resources of an observatory for a number of years, and careful preparation would be needed to minimize systematic errors and ensure that the most accurate results possible would be obtained.

Pierce at Harvard College Observatory tested a Zöllner photometer (1872–1875) to investigate the possibility of a comprehensive accurate survey. He repeatedly measured 494 stars in the declination zone +40° to +50°. His results appeared in "Photometric Researches" (Pierce 1878). This paper also contains 176 pages on the theory of light, color, and comparisons of the catalogues of Ptolomy, Ulegh Bey, Tycho, W. and J. Herschel, Seidel, and Argelander, as well as a determination of the intensity ratio each had adopted for a magnitude step.

The survey by Pierce encouraged the director of Harvard College Observatory, Edward C. Pickering, to undertake the Harvard Photometry project (1879-1882). Pickering devised an improvement on the Zöllner photometer. His Meridian Photometer was composed of two objective lenses of 1.6-inch diameter, 31-inch focal length. One lens was pointed at Polaris and the other pointed to the western horizon. A prism in front of the horizontal telescope brought any star on the meridian into the field of view. The image of Polaris also appeared in the same field as the program star. Polarizing prisms could attenuate either image until they were equal. Stars down to the sixth magnitude between -30° and +90° declination could be measured (Bailey 1931).

In practice two people operated the meridian photometer. One operated the meridian prism to select the star and acted as recorder. The second was at the eyepiece protected from stray light by a black cloth and rotated the prisms. Four settings were made on each star and counted as one observation. About sixty stars per hour could be observed. After one hour, the observer and recorder changed positions to guard against fatigue influencing the measures.

Polaris was initially assumed to have a magnitude of 2.00. After corrections for extinction and light lost in the prisms, the value was changed to 2.12. Polaris was later found to be a variable star with a period of about four days and an amplitude of 0.08 to 0.17 magnitude, but this problem had been anticipated by Pickering. At the beginning, middle, and end of each night a number of 5th magnitude stars from the BD were observed to determine extinction and calibrate the magnitude of Polaris (Bailey 1931). Thus the actual magnitude of Polaris was determined three times each night. As long as the variations in Polaris were longer than this interval, they would not affect the final magnitudes. The amplitude of the light variations of Polaris were at the limit of the accuracy of the meridian photometer and therefore not discovered in Pickering's survey.

The results of the survey published as "Observations with the Meridian Photometer during the years 1879–82" contained 4,260 stars 6.2 magnitude and brighter (Pickering 1884). The magnitudes were published to two decimal places along with the standard error of each entry. The magnitude of any one star was not accurate to two decimal places but the average of a number of stars of similar magnitude was better than one decimal place. The brightness ratio for one magnitude was the one proposed by Pogson and the zero point of the system determined from 100 circumpolar stars of 5th magnitude from Argelander's BD.

As soon as the northern survey was complete, Pickering sent the Meridian Photometer to the southern hemisphere to extend the catalogue. Sigma Octantis was the primary comparison star and the zero point was determined from equatorial stars calibrated in the northern survey. Eight thousand southern stars were measured.

In order to reach fainter stars, Pickering built a meridian photometer with four-inch objectives and remeasured the stars in Harvard Photometry (1891–1894). With this instrument he was able to extend the survey down to 9th magnitude. By 1906 more than one million comparisons of fifty thousand stars had been made. The mean values of all the Harvard surveys were combined into Harvard Revised Photometry (Pickering 1908). At the same time (1885–1905), Muller and Kemph at Potsdam used a Zöllner photometer to create a similar catalogue. This program was also prepared with great care and claimed a mean error of ±0.07 magnitude consistency, but covered only stars in the northern hemisphere (Pannekoek 1961).

Even the four-inch meridian photometer was insufficient to measure the comparison stars needed for the faint Mira variables that were being discovered telescopically. The observers at Harvard College Observatory used small photometers on the fifteen-inch refractor to calibrate these faint comparison stars. Their results are still seen today on many AAVSO charts.

A twelve-inch meridian photometer was also built and used to extend the Harvard Photometry to fainter stars. This instrument differed from the previous meridian photometers in that an artificial star was used for comparison instead of Polaris and a mirror was used to direct the star into the objective (Bailey 1931). The mirror was coated with silver and tarnished quickly from sulphur in the Cambridge air, a by-product of the coal fires used for home heating. As the mirror tarnished, its color transmission changed significantly.

The results were published in "Catalogue of 16300 stars observed with the 12-inch Meridian Photometer" (Pickering 1913). Comparisons of the DM and HCO magnitudes show a significant deviation from the Pogson steps for the fainter DM magnitudes. Examples are: 7.3DM = 7.24HCO, while 9.5DM=11.59HCO (Pickering 1913, p. 19). The catalogue contains some stars at magnitude 12.8 and an occasional 13.5.

Even while the visual photometry at Harvard was underway, the next technological step was being anticipated. "Investigations in Astronomical Photometry" was published at Harvard (Pickering 1895). This paper dealt with the new field of photography as applied to astronomical photometry.

Kapteyn, 1885–1890, used photography to catalogue 454,000 stars in the Cape Photographic DM. He used the image diameter as a function of magnitude. These magnitudes were not on any visual system but measured the blue intensities of the stars, not the visual intensities (Pannekoek 1961).

Pickering realized the impossibility of providing magnitudes for all the faint stars that could be observed. He proposed dividing the sky into 48 equal regions, to be known as the "Harvard Standard Regions." In each region, all the brighter stars would be classified by magnitude and spectral class, while a single sequence near the center of each region would define the faint end. Stars from sixth or seventh magnitude down to sixteenth or seventeenth magnitude defined the sequence at the center of each region.

The faint end of each sequence was produced from photographic plates which were calibrated such that "Photographic magnitudes coincide with photometric (visual) magnitudes on the Harvard System for stars having spectra of class A0 between the magnitudes 5.5 and 6.5, and are fainter than the photometric magnitudes by 1.00 magnitude for stars having spectra of class K0 between the same limits" (Bailey 1931).

"In the Draper Catalogue magnitudes were determined from measures of the photographic intensity of the spectrum near the line G" (Bailey 1931). This was an attempt to select a defined portion of the spectrum near the visual peak sensitivity to represent m_v. When photographic plates could be dyed to shift their spectral sensitivity and the proper cutoff filters were produced, it was possible to obtain magnitudes from photographic plates that were comparable to visual magnitudes over a wide range of spectral types.

Thus m_v and m_{pg} systems were both defined through Harvard Revised Photometry. The brightness ratio is that defined by Pogson, and the zero point as defined by the average magnitude of stars in the 5- to 6-magnitude range in BD. It would be hazardous to pick one star to be defined as the brightness standard, as all stars are variable on a long enough time scale and the standards must be observable from anywhere on the globe.

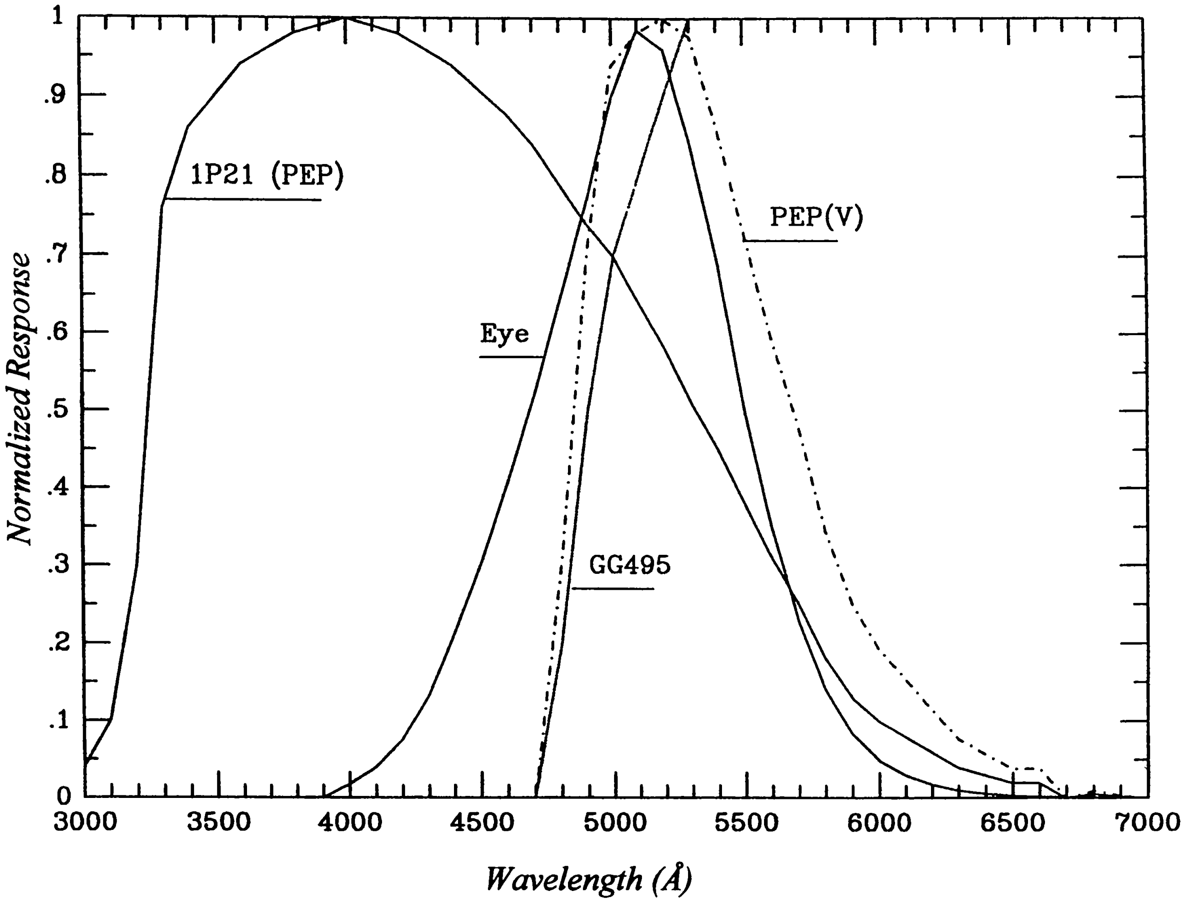

Figure 2. The normalized response of the dark-adapted eye is compared with the photocathode used in UBV photometry. PEP(V) is the V passband defined by the PEP response through the GG495 filter. The eye will see very blue stars as brighter than the published V magnitude, while very red stars will appear fainter than the published V magnitude.

4.3 Transformations

No two photometers produce exactly the same response from the input light, since the spectral response of the detector or pass band of the filter varies slightly. One must always apply a transformation formula to bring the local photometry to the standard system. A standard transformation formula would look like equation (1):

$$Mx = mx + Tx*CI + Zx\,, \qquad (1)$$

where Mx is the standard magnitude in bandpass x, mx is the measured magnitude in bandpass x, Zx is the zero point correction, Tx is the transformation coefficient operating on the color index CI. The best detector and filter system would have a small Tx. The size of the zero point correction depends on the units in which the star intensity is recorded (photon counts, mm on a chart recorder, milliamps on a digital meter, ...). One could define the visual magnitude of Sirius (V = -1.45) to be 0.00. The magnitude of Alcor (V = 4.03) would then be 5.48. The brightness ratio between the stars would be the same in either case; only the zero point of the system would have changed. It is important that all observers use the same zero point.

Even the Harvard Revised Photometry suffers from inconsistent measures of extreme-colored stars. The eyes of the observers differed in their response to deep red or very blue stars; the human eye has a much wider effective passband than the filters used in PEP or CCD photometry.

PEP and CCD magnitudes can be transformed to match each other accurately to better than a few percent. Figure 2 shows the relative response of the eye as a function of wavelength. The response of an RCA 1P21 photomultiplier (PEP) that defined the UBV system is also plotted along with the passband through a GG495 filter. The effective V passband differs somewhat from the response of the dark-adapted eye. The sharp filter cutoff at the short-wavelength end of the passband means that very blue stars would appear brighter to the eye than the published V magnitudes. Red stars would appear fainter than the published V magnitudes. Equation (2) gives a transformation formula for the correction of V magnitudes to the visual system, m_v, as a function of the B-V color index (Stanton 1981). The two systems differ by only 0.032 magnitude for A0 stars where B-V = 0.00, while a difference of 0.24 magnitude would be observed for a very red star with B-V = 1.5.

$$m_v = V + 0.182\,(B-V) - 0.032 \qquad (2)$$

Figure 3 shows a similar plot for the eye and CCD response. The CCD chip response differs greatly from the 1P21 photocathode. The CCD chip is quite efficient in the deep red end of the spectrum, whereas the photocathode is most efficient in the blue. This difference in response requires different filters to isolate the V band. A combination of GG495 which blocks the blue light and a BG39 filter which blocks the red light gives a reasonable bandpass for V, although it still passes too much at the red end. An interference filter can be made that would give a better passband, but interference filters are much more costly than dyed glass filters and therefore are not usually employed in broadband photometry. A transformation equation similar to equation (1) would apply to the m_v vs CCD(V) observations, with the corrections being in the same sense as those of the PEP(V).

5. Conclusions

The visual magnitude system evolved through history. It was not originally defined by standards developed through the use of modern electronic detector systems, but rather, the zero point of the m_v system was defined by the visual estimates of the fifth-magnitude stars of Argelander in the BD. The Meridian photometry at Harvard was the basis for what we now call the "real" visual magnitude system.

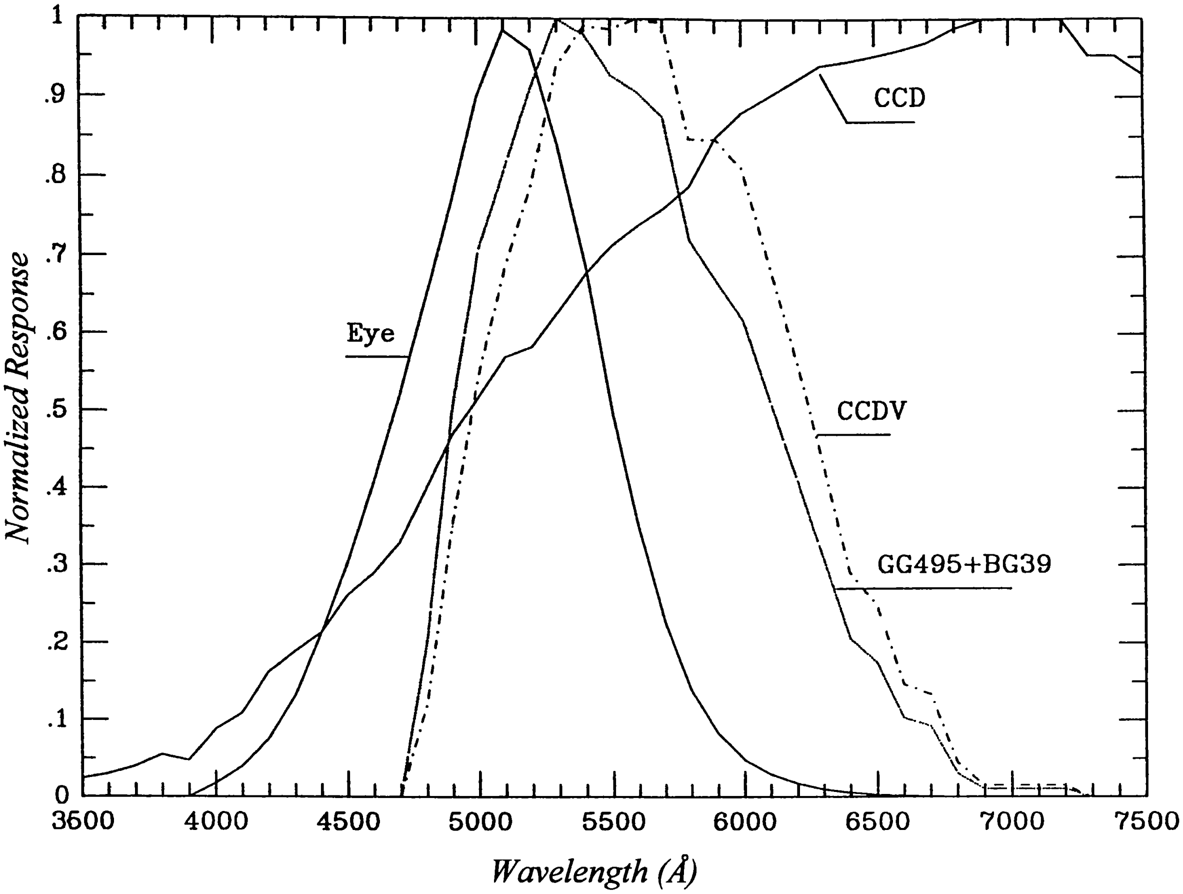

Figure 3. The normalized response of the dark-adapted eye is compared with the silicon photodiode response of a CCD. CCDV is the V passband defined by the PEP response through a GG495 and BG39 filter combination. The eye will see very blue stars as brighter than the published CCD(V) magnitude, while very red stars will appear fainter than the published CCD(V) magnitude.

The human eye is a broadband detector that varies from person to person and with age. It must be kept in mind that the color of a star has an effect on the perceived magnitude. This is the most significant reason for comparison stars appearing to differ from their PEP(V) or CCD(V) calibrations.

Ideally, all the comparison stars should be of the same color and be close to the color of the variable, but in the real world this condition can rarely be achieved. The comparison stars on early charts were chosen to give small magnitude intervals for ease in making variable star estimates, but even this condition could not be met on many charts.

The early AAVSO charts were prepared at HCO and used HR photometry, with magnitudes that should appear normal to the eye. If sequences calibrated by PEP(V) or CCD(V) magnitudes were transformed to the m_v system by equation (2) before being listed on AAVSO charts, many sequence problems would disappear. Even then, there would still be some visual observers who would not find such charts satisfactory, because their eyes differ from the average color sensitivity.

References

Argelander, F. 1843, *Astronom. Nach.*, **455**, 595.

Bailey, Solon I. 1931, *The History and Work of Harvard Observatory 1839 to 1927*, McGraw-Hill Book Co., Inc., New York and London.

Bryant, W. W. 1907, *A History of Astronomy*, E. P. Dutton & Co., New York.

Cajori, F. 1896, *A History of Elementary Mathematics*, The MacMillan Company, New York.

Goodricke, J. 1786, *Phil. Trans. Roy. Soc. London* (abridged), **16**, 56. C. and R. Baldwin, Blackfriars, London.

Herschel, W. 1780, *Phil. Trans. Roy. Soc. London* (abridged), **14**, 689. C. and R. Baldwin, Blackfriars, London.

Herschel, W. 1785, *Phil. Trans. Roy. Soc. London* (abridged), **15**, 325. C. and R. Baldwin, Blackfriars, London.

Knobel, E. B. 1917, *Ulegh Beg's Catalogue of Stars*, Carnegie Inst. of Washington Pub. No. 250, Gibson Bros., Washington, DC.

Pannekoek, A. 1961, *A History of Astronomy*, Simon Hand Ltd., London.

Pierce, 1878, *Ann. Harvard Coll. Obs.*, **9**.

Pickering. E. C. 1884, *Ann. Harvard Coll. Obs.*, **14**.

Pickering, E. C. 1908, *Ann. Harvard Coll. Obs.*, **50**.

Pickering, E. C. 1913, *Ann. Harvard Coll. Obs.*, **74**.

Pickering, W. H. 1895, *Ann. Harvard Coll. Obs.*, **32**, pt. 1, 30.

Stanton, R. H. 1981, *J. Amer. Assoc. Var. Star Obs.*, **10**, 1.

Webb, T. W. 1962, *Celestial Objects for Common Telescopes, Vol. II: The Stars*, 7. Ed. and rev. M. W. Mayall, Dover Publications, Inc., New York.