VISUAL PHOTOMETRY: COLOUR AND BRIGHTNESS SPACING OF COMPARISON STARS

by Alan B. Whiting
University of Birmingham

A significant amount of data on the historical and current behaviour of variable stars is derived from visual estimates of brightness using a set of comparison stars. To make optimum use of this invaluable collection one must understand the characteristics of visual photometry, which are significantly different from those of electronic or photographic data. Here I show that the dispersion of estimates among observers is very consistent at between 0.2 and 0.3 magnitudes and, surprisingly, has no apparent dependence on the colour of comparison stars or on their spacing in brightness.

Introduction: Visual Photometry

Measuring the brightness of an object is one of the most basic of operations in astronomy and doing it accurately is one of the most important. For most of the history of the science it has been accomplished by the human eye, supplemented for about the past century by photographic and electronic methods. These are certainly more accurate and objective than visual estimates, but they have not entirely supplanted the eye for two major reasons. First, many historical records are only visual in nature; the best CCD in the world today cannot measure Eta Carinae in 1835. Second, even in this age of large-scale, rapid surveys, visual estimates may be the only way of getting the desired temporal coverage. Observers from the American Association of Variable Star Observers (AAVSO), for example, are routinely called upon to alert professional astronomers to outbursts or other behaviour of objects in support of observing campaigns. In this way an amateur with a small telescope may trigger the use of the Hubble Space Telescope and visual data may be combined with far more sophisticated measurements. As a recent example, Humphreys et al. used visual estimates of Eta Carinae in conjunction with instrumental photometry and spectroscopy from a variety of telescopes.

But the human eye is not a simple detection and measuring system. In a sense, there is no such thing as raw visual photometric data; everything is heavily processed before it can be recorded. While this automatic processing is no doubt useful in a terrestrial environment it is occasionally annoying to the photometrist. Known effects include the tendency for red stars to appear

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brighter if stared at for a time and for a star placed vertically above a similar one in the visual field to appear brighter. And, even more than instruments, people differ among themselves.

To better understand the workings of the visual photometry system here I concentrate on two features of comparison stars, motivated by experiences of my own in making visual estimates.

All the data analysed were produced using the current visual method as practised by the AAVSO and similar organisations. The observer is provided a chart of suitable scale, centred on the variable star of interest. On it are marked comparison stars whose $V$ magnitude has been measured by electronic means, the latter given to one decimal place. The observer picks stars brighter and fainter than the variable and then judges whether it is closer to one than the other in brightness, and by how much; converts this to an estimated magnitude; then reports that estimate. While some exceptional observers can reliably see smaller differences, all data are reported to a tenth of a magnitude. Photometry of comparison stars in other bands is also readily available, mostly for the use of CCD observers.

The first feature we investigate is best illustrated by an anecdote. The author, AAVSO chart in hand, was making an estimate of Eta Carinae standing next to a student. The latter, using the same comparison sequence at the same time, was firm in giving an estimate of 5.1; the author, equally firm at 5.0. Neither could convince the other. A plausible explanation comes from the fact that the lens of the eye yellows with age, so the student was seeing more blue light than the (much older) author, and thus made Eta with its strong H-alpha emission relatively less bright. The first investigation seeks the effect of the colour of the comparison stars on the spread of visual estimates. The hypothesis to be tested holds that the dispersion of estimates will increase as the colour of the comparison stars differs from that of the variable.

The second investigation stems from the perceived difficulty in placing a variable when there is a great difference in brightness between the bracketing comparison stars. The unreliability of the human eye when there are no nearby guides is suggested also by a table given by Webb\textsuperscript{2}, comparing the magnitudes assigned to telescopic stars by four outstanding visual observers of the nineteenth century. Extrapolating the generally agreed system of six naked-eye magnitudes, the four (F. W. Argelander, F. R. W. Struve, Adm. W. H. Smyth and Sir John Herschel) disagreed at the half-magnitude level by about 6.5, sometimes by a full magnitude at 8.5 and worse at fainter levels. The second investigation therefore seeks how much disagreement in visual estimate can be traced to large differences in brightness between comparison stars. The hypothesis to be tested asserts that the dispersion among estimates will increase as the difference in brightness between the bracketing comparison stars increases.

The Sample and Processing

While there are several organisations worldwide of dedicated variable-star observers, the largest and the one with the most accessible data is the American
Table 1: Summary observational data on the stars analysed.

| Star                      | Starting JD | No. of Observations |
|---------------------------|-------------|---------------------|
| R Leonis                 | 2455472.0   | 756                 |
| R Aquarri                 | 2455032.8   | 148                 |
| R Bootis                  | 2455231.5   | 622                 |
| R Canum Venaticorum       | 2455223.5   | 319                 |
| R Hydræ                   | 2455170.8   | 67                  |
| S Coronae Borealis        | 2455301.2   | 407                 |
| T Ursæ Minoris            | 2455400.5   | 414                 |
| R Ursæ Majoris            | 2455404.5   | 344                 |
| T Ursæ Majoris            | 2455400.2   | 468                 |

Association of Variable Star Observers, whose data were used exclusively for this study.

For the investigation we need variable stars with many observations (to give a good delineation of the spread of estimates) and a variety of comparison stars. The latter translates directly into a large variation in brightness. These conditions essentially limit us to bright Mira-type variables. We must then bear in mind that what we find could, in principle, be different for a different type of star; but it immediately simplifies the colour analysis, since essentially no comparison stars will be redder than the variable.

Nine stars were chosen from the AAVSO list fitting the requirements and I downloaded from the website one to two periods of visual observations each. For each observation the Julian date and time; the reported brightness; and the brightness of the two reported comparison stars were extracted.

I initially tried to fit a polynomial to produce a smooth curve for reference (as did Price, Foster & Skiff), but found no number of terms that would reproduce well the overall form without adding artifacts due to unfortunate or badly-placed odd observations. In the end I used a top hat smoothed version, its width depending on the density of observations. For each observation (not the corresponding magnitude on the smoothed curve) I determined, from AAVSO photometry, the $B-V$ colour of the comparison star nearest in brightness. (The $V-R$ colour might have been more directly applicable to visual observations of Miras, but was unavailable for many stars.) Also for each observation, I recorded the difference in magnitude between the bracketing comparison stars.

In subsequent displays time is presented in days from the first observation used. Table 1 gives the starting Julian Date and number of observations for each star analysed, to allow connections with other investigations and to give an idea of the quantity of data available.

R Leonis will serve as an example of the method of analysis. First the observations were combined with a smoothed curve, shown in Fig. 1. The curve generally follows the centreline of the observations, but by the nature of smoothing underestimates the brightness at maximum and overestimates that at minimum. The two possible problem areas are kept in mind during subsequent work.
Next, the difference in magnitude between each observation and the smooth curve is plotted against the colour of the closest comparison star (in brightness and in the sky, where two comparison stars are listed as the same brightness). Here in Fig. 2 we see at $B - V \sim 0.743$ a clear displacement toward positive differences, a result of the smoothed-curve error at maximum, and at $B - V \sim 1.05$ a displacement toward negative differences from a similar effect at the minimum. It is not clear from this plot that there is any systematic difference between the estimates based on very blue comparison stars (left of the plot) and those based on red stars (on the right), though the overlap of plotting symbols can hide a great deal.

For that reason the data were binned (in the obvious bins, though at times neighboring colours were combined in order to have enough observations) and the standard deviations calculated about the mean, which gets rid of the systematic offsets at maximum and minimum. The resulting plot of standard deviation against colour appears in Fig. 3. Formal error bars are calculated as $\Delta \sigma = \sigma / \sqrt{n}$, with $n$ being the number of observations in the bin, and are probably optimistic as a measure of actual uncertainty. The outstanding feature of this plot is its featurelessness: there is no clear trend of dispersion of estimates with colour. (A slight trend downward to the right can be imagined, but it is not significant.)

Postponing a discussion of this result until the data on the other variables are presented, we turn to the question of the magnitude gap between comparison stars. The differences between the observations and the smoothed curve are shown in Fig. 4 plotted against the corresponding gap. We note that there are
Figure 2: Deviations of visual estimates of R Leonis about the smoothed curve, as a function of the $B - V$ colour of the closest comparison stars. The systematically high residuals at 0.743 are due to the failure of the smoothed curve to trace the maximum accurately, as the systematically low residuals at 1.05 come from the minimum.

Figure 3: Standard deviation of observations of R Leonis about the average, plotted against the colour of the closest comparison star. Error bars are assigned based on the number of observations in each bin.
comparatively few observations with a gap as large as a full magnitude, some show up at 2.7. Again, the piling up of symbols in columns makes interpretation unclear, so as before the standard deviations of the bins (sometimes combined) are plotted in Fig. 5.

Again we note a lack of any apparent correlation, and again we postpone discussion until the results of all the variables have been collected.

Results

The combined results of all nine stars are presented in Fig. 6 and Fig. 7 produced as in the last section. For several variables the observations were much sparser than for R Leonis, resulting in fewer bins. In each plot there are a handful of points well above the general trend; these (all above about $\sigma \sim 0.4$) can be traced to an individual or a few wild points, where an obvious mistake has been made in star identification or perhaps in entering a Julian Date. (Some come from the failure of a smoothed curve to bridge a long gap between observations accurately.) They have been left in as a reminder that we are dealing with human data.

There is, very obviously and firmly, no trend of dispersion among the observations with either comparison star colour or spacing of comparison star magnitudes. This is very surprising. Consider what it means.

First, with colour: for all the known problems with red stars and the known differences among people in colour perception, it does not seem to matter whether an $M$ Mira variable is compared with another $M$ giant or a $B$ star; the variation in estimate among observers will be the same. The 0.1-magnitude
Figure 5: Standard deviation of the difference between observations and smoothed observations of R Leonis in bins based on the magnitude gap between comparison stars. As before, error bars are based on the number of observations in each bin.

Figure 6: Standard deviation of brightness estimates for all nine variable stars as a function of $B - V$ colour of the nearest comparison star.
disagreement in the anecdote is dominated by some other effect, or effects, that produce a 0.2-0.3 magnitude dispersion quite reliably.

This result appears to be in flat contradiction to that of Price et al., who found a strong difference in the standard deviation of visual estimates among stars of various spectral classes. But their work classified by the colour of the variable, not the comparison stars, so we are not doing the same thing. (There are several other differences between their treatment and this one, making any detailed comparison impossible here.)

Second, it makes no apparent difference to the dispersion of estimates among observers how far apart the comparison stars are in brightness. This is very surprising to an observer. One certainly has a feeling of being on firmer ground when placing one’s variable on a stepladder of several stars 0.1-magnitude apart, rather than reaching into the wide spaces of whole magnitudes. But this doesn’t appear to be true, at least when comparing the estimates of several observers. Up to a gap of 2.7 magnitudes, visual estimates do not suffer the same dispersion by interpolating that they seem to do when extrapolating.

For comparison, consider that an electronic detector, if limited by shot noise in the comparison star, will have twice the uncertainty if the comparison is made 1.7 magnitudes fainter, and three times the uncertainty for a 2.7 magnitude drop. The situation is not, of course, directly comparable; which is indeed the point.

Perhaps the best way to sum up these results is that the human eye-brain system does not work like any easily-modelled detector when performing photometry.
Implications

It should be borne in mind that these surprising results apply only to the observations of several or many observers taken together; there is both anecdotal and more systematic evidence (Skiff et al.4) that observers taken individually are significantly more reliable (with some offset) than the 0.2-0.3 magnitude dispersion found here.

But consider the implications. Given a ladder of stars reliably measured as magnitude 8.1, 8.2, 8.3 and 8.4, a set of observers will put them in any order with roughly equal probability. More to the point here, an observer can estimate a variable as being simultaneously brighter than a 9.1 comparison star and fainter than a 9.2 comparison star. Not only will this dent the confidence of a new observer, it can puzzle an experienced one: what number should be reported?

On the other hand, the dispersion appears to be immune to the obvious problems one might expect from inconvenient comparison stars. Perhaps this result will encourage more observations of variables now regarded as difficult and under-observed!

A deeper matter is the source of the dispersion. Where does it come from, and how does it behave? There is a great deal of work yet to be done on visual photometry.

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