OBSERVING BRIGHT CEPHEIDS WITHOUT OPTICAL AIDS

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Abstract

The eye can distinguish brightness differences as small as ±0.1 magnitude near the limit of vision. Bright variable stars can therefore be studied effectively without optical aid, provided such a restriction is satisfied. That conclusion has been confirmed by backyard observations of the bright Cepheids δ Cephei, ζ Geminorum, and η Aquilae made during 1998–99 using newly-generated reference charts tied to photoelectric *V*-magnitudes rather than the usual "visual" magnitudes included on AAVSO charts. The derived light curves for the three bright Cepheids exhibit surprisingly little scatter, and are of potential scientific value for the study of period changes in the variables.

1. Introduction

The human eye is sometimes perceived to be relatively unreliable as a photometric detector. Introductory books and articles on variable star observing (Percy 1993; Levy 1998) generally claim that uncertainties in eye estimates of brightness can be as small as ±0.1 magnitude for experienced observers, whereas the characteristic scatter in published variable star light curves based solely upon eye estimates is typically ±0.2 magnitude or more. Of course, many factors can account for the larger scatter, including observer inexperience and different color sensitivities for the eyes of individual observers. The question remains, "How reliable are variable star light curves generated by a single experienced observer?" This paper addresses that question.

2. Background to the present project

During February 1996, the author carried out an experiment on limiting visual magnitude as part of a one-semester course on observational astronomy offered at Saint Mary's University. The experiment was based upon identical observing exercises performed by the author as a graduate teaching assistant at the University of Western Ontario and as a faculty member at Laurentian University. The basis for the experiment is a relationship for the visual threshold for telescope observing given by Baum (1962) in a chapter in *Astronomical Techniques* on "The Detection and Measurement of Faint Astronomical Sources." The relationship is based upon previous work by Bowen (1947), and in its simplest form is expressed as:

$$m_0 = \text{constant} + 2.5 \log D + 2.5 \log M , \tag{1}$$

where m_0 is the limiting magnitude, D is the aperture size, and M is the magnification. Note that, according to the above relation, the effects of either doubling the aperture of a telescope or of doubling its magnification should be identical for the purposes of detecting fainter stars visually. Such expectations are confirmed by observation, at least to within the usual limits for magnification that apply to telescope-eyepiece combinations.

The effect of changing the magnification of a telescope is perhaps best understood as a signal-to-noise ratio effect. Increasing the magnification of a telescope does not affect the signal from an unresolved star on the eye's retina, but does spread the background light from the sky (the noise) over a larger surface area, thereby reducing its intensity at any point on the retina. The resulting gain in signal-to-noise ratio allows one to detect fainter stars than is the case with a smaller magnification.

The observational experiment conducted in 1996 consisted of using the campus 0.4-m reflecting telescope (effective aperture 37.4 cm) at Saint Mary's along with a selection of eyepieces (to vary the magnification) and a temporary front-end mask designed to reduce the effective aperture of the telescope to 8.5 cm. The telescope was aimed at the open cluster NGC 1893, which lies in reasonable proximity to the zenith on clear winter evenings, and a record was kept of the faintest detectable numbered cluster star as a function of the aperture size and magnification in use at the time. In each case the detection was made using averted vision in order to assure that the eye was working at the true limit of vision. The results are presented in Table 1 in a format that lists the published photoelectric *V*-magnitude of the faintest detected star (from Hoag *et al.* 1961), the *V*-magnitude of the next faintest cluster star (which was not detected at the specified aperture and magnification), and the corresponding constant calculated from equation (1). The data are from the author's observations alone. Undergraduate students who performed the experiment with the author sometimes obtained different results, presumably because of their relative inexperience or their different eye sensitivities.

Table 1. Limiting magnitude estimates for NGC 1893 using the 0.4-m reflector at Saint Mary's University.

Aperture, D	*Magnification, M*	*V, faintest star*	*Constant*	*V, next faintest*	*V-Step*
8.5 cm	120x	11.23	3.71	11.61	0.38
8.5 cm	184x	11.61	3.63	11.78	0.17
37.4 cm	120x	12.91	3.78	13.14	0.23
37.4 cm	184x	13.19	3.60	13.49	0.30
37.4 cm	368x	13.53	3.70	13.55	0.02

Mean values for Constant and Magnitude Step = 3.68 ±0.07 s.d.; 0.22 ±0.14 s.d.

The mean value obtained for the constant term in the limiting magnitude relationship is 3.68 ±0.07 s.d., while the mean difference between the last detected star and the next fainter cluster star is 0.22 ±0.14 s.d. magnitude. The *V*-Step value provides a measure of the "coarseness" of the cluster sequence in terms of steps in star brightness. Since the steps in star brightness from one cluster star to another in the NGC 1893 sequence are of order 0.1 to 0.3 magnitude or more, the small scatter of ±0.07 magnitude obtained for the constant term in the limiting magnitude formula is all the more remarkable. It implies that the eye, or at least the author's eye, is capable of establishing stellar limiting magnitudes to a precision of ±0.1 magnitude. Clearly the human eye can attain a photometric accuracy of ±0.1 magnitude, as has been argued in the literature many times previously.

The experimental results imply that a precision of ±0.1 magnitude is the practical limit for observations made by the author with the unaided eye. There is also the implication that the author's observations are a reasonable match to photoelectric *V*-band observations, although that is difficult to test using NGC 1893, a young cluster where most stars are of similar color. The close match of the author's eye estimates of magnitude to photoelectric *V*-band observations was pointed out previously in connection with observations of the bright variable δ Cephei (Turner 1999).

The derived constant for equation (1) also permits one to establish the limiting magnitude at the site for observations made without optical aid. For that one substitutes a magnification of $M = 1$ and an aperture of $D = 0.7$ cm (*i.e.*, twin eye apertures of 0.5 cm) in equation (1), and obtains a visual limit of 3.3. If account is taken of light losses in the telescope optics amounting to 20–30% or more, the inferred limiting magnitude for the site is closer to 3.5 or 3.7. Both values are in close agreement with experience. The Burke-Gaffney Observatory at Saint Mary's is located in the midst of a bright light pollution umbrella from downtown Halifax, and the faintest stars visible from the site rarely include fourth magnitude stars.

3. Observations of bright Cepheids

A program of observation for bright Cepheids was begun in December 1998 as a means of testing some of the conclusions reached from the limiting magnitude test. Results for δ Cephei have been published previously (Turner 1999), where the ideal features of that Cepheid for observations without optical aid were emphasized. Although observations of δ Cephei and other bright Cepheids have been promoted elsewhere (*e.g.*, Percy 1993; Percy and Mattei 1994; Mattei *et al.* 1997), a modification made here consisted of charts of reference stars based upon photoelectric *V*-magnitudes to two decimal places. Similar charts to that for δ Cephei (Turner 1999) were constructed for the Cepheids ζ Geminorum and η Aquilae, even though the reference stars near the latter objects are not as conveniently located as those for δ Cephei. The data for the photoelectric *V*-magnitudes of the reference stars were taken from *The Bright Star Catalogue* (Hoffleit and Jaschek 1982).

The reason for using two-decimal photoelectric *V*-magnitudes for the reference stars was twofold. First, the limiting magnitude experiment had already suggested that the photometric sensitivity of the author's eyes might be a reasonably close match to the photoelectric *V*-band system. Second, the extra decimal made it possible to estimate the brightness of each variable to the nearest tenth of a magnitude—or, where warranted, to the nearest twentieth of a magnitude (±0.05 magnitude)—without concern about prior rounding of the magnitudes for the reference stars. The use of 0.05-magnitude steps was adopted on those occasions when the estimated brightness of the Cepheid fell midway between two (or more) standards such that the averaged magnitude rounded naturally to a twentieth, rather than a tenth (see Turner 1999).

Although preliminary results for δ Cephei have already been summarized and presented elsewhere (Turner 1999), additional observations for the star were continued during the summer and fall of 1999. The full set of observations covering the interval from December 5, 1998, to February 24, 1999, and from August 2 to November 11, 1999, is presented in Figure 1. Similar observations for ζ Geminorum and η Aquilae are presented in Figure 2. The observations for ζ Geminorum were made from January 16 to May 3, 1999, and those for η Aquilae were made from August 2 to November 11, 1999.

Previously published light curves for bright Cepheids based upon visual estimates (*e.g.*, Percy and Mattei 1994; Percy and Rincón 1996) exhibit much larger scatter than that evident in Figures 1 and 2. The difference can be accounted for by the specific approach adopted here. Each observation was made soon after entering the dark environment of the author's backyard from the brighter but subdued lighting environment of a house interior. Although some time was taken to become dark-adapted on each occasion, the magnitude estimates were made as soon as reasonably possible after the start of observing to assure that the eyes were always working close to the instantaneous visual limit. That is where brightness differences of ±0.1 magnitude were most easily detected by the author.

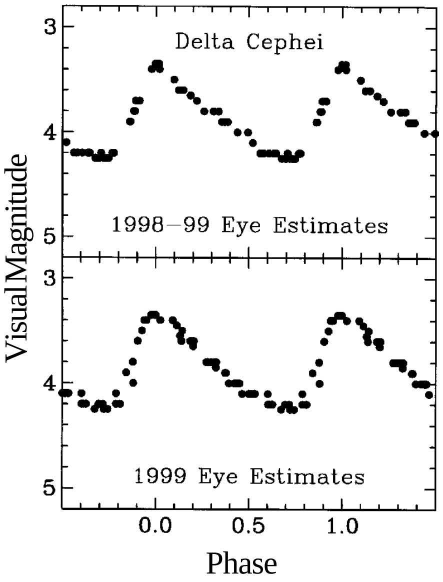

Figure 1. Observations of δ Cephei made by the author without optical aid during the interval from December 5, 1998, to February 24, 1999 (upper graph), and from August 2 to November 11, 1999 (lower graph).

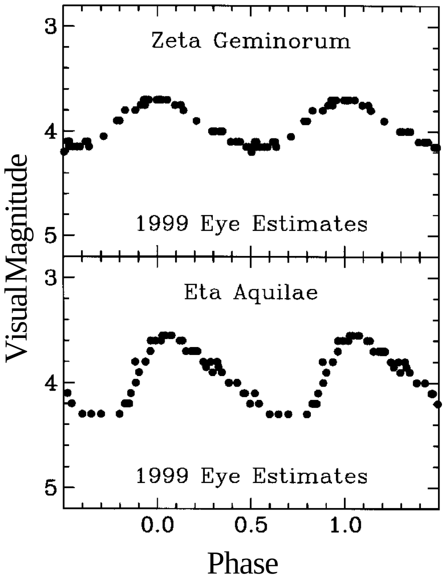

Figure 2. Observations of ζ Geminorum (upper graph) and η Aquilae (lower graph) made by the author without optical aid during the interval from January 16 to May 3, 1999 (ζ Geminorum), and from August 2 to November 11, 1999 (η Aquilae).

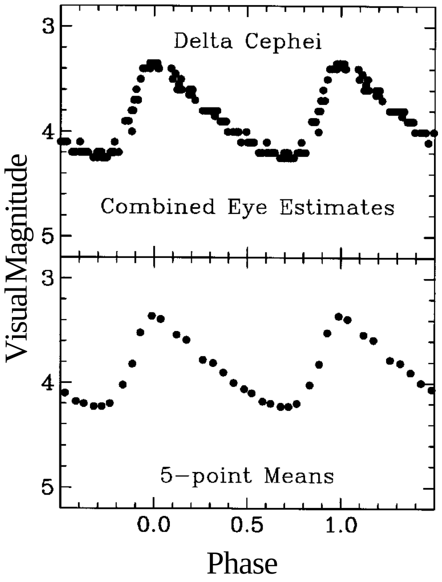

Figure 3. Combined observations of δ Cephei made by the author without optical aid during the interval from December 5, 1998, to November 11, 1999 (upper graph), and five-point means of the same data (lower graph).

As the author became familiar with the reference stars in each field, the field of each variable was examined in turn, and a note was made of the sequence of appearance of the reference stars and variable as the eyes gradually distinguished fainter and fainter objects. It was a simple matter to establish the brightness of each Cepheid on a given night by noting the brightness of the reference stars that became visible just prior to and immediately following the appearance of the Cepheid. That procedure was always carried out in conjunction with the use of averted vision to compare specific reference stars in turn with the variable, with both stars symmetrically placed on the sensitive portion of the eye's fovea (see Turner 1999).

Since the practical visual magnitude limit for "day vision viewing" is about 4.1 (Schaefer 1993), the adopted method of approach guaranteed that the eyes never became fully dark-adapted when estimates were made. Since similar conditions also applied during the limiting magnitude experiment mentioned earlier, one should expect a similar result, namely a precision of about ±0.1 magnitude in the estimates. There were occasions when extended sessions made it possible to reach a dark-adapted state, but estimates for the brightness of the program Cepheids were generally noted to be less reliable and less precise at such times. In those circumstances the variable was typically a magnitude or more brighter than the visual limit, and was in general found to be more difficult to compare with the reference stars in terms of finding a close match in apparent brightness. Those results invariably were found when there were two program stars being observed on a given night, with the first-observed program star being near minimum light and the second near maximum. While steps were taken to reverse the order of viewing on such nights, those particular estimates are probably only good to ±0.2 magnitude.

Additional details on the observations for δ Cephei and ζ Geminorum are given by Turner (1999). δ Cephei is easily the most ideal candidate Cepheid for observation because of the closeness of suitable reference stars. ζ Geminorum, on the other hand, is the worst of the three Cepheids to observe because of the lack of suitable reference stars, the large separation between them and the variable, and the fact that the region is lost in the glare of the Moon for several nights each month. η Aquilae proves to be midway between the two in terms of ease of observation. The region of η Aquilae contains more suitable reference stars than is the case for ζ Geminorum, but like the latter they tend to lie at large separations from the variable. It is possible to observe all three bright Cepheids successfully, but the features of δ Cephei make it the best of the three to observe.

It should be noted that there is no intent made here to advocate the adoption of artificial techniques to decrease the magnitude limit of one's eyes for the observation of bright variables, for example by staring at a terminal screen or by shining a light in one's eyes. In the author's experience such techniques only hamper the procedure of making eye estimates. Also, what works well for one observer may not necessarily work well for another. In general, the optimum techniques for an individual observer are those that have proven to be successful based upon practical experience.

4. Data analysis

The amount of observational scatter that is evident in Figures 1 and 2 is small enough to be of only marginal importance in an analysis of the Cepheid light curves. For each variable the data were phased using ephemerides given by Szabados (1980, for δ Cephei and η Aquilae; 1981, for ζ Geminorum). Once complete light curves had been constructed for each variable, estimates were made for the times of light maximum by applying Pogson's method of bisected chords (see Hoffmeister *et al.* 1985) to the phased observations. In each case the calculated offset in the phase for light maximum was used to calculate a value for the difference between Observed and

Table 2. Newly-derived O-C residuals for bright Cepheids.

Cepheid	*JDmax*	*E*	*O-C*		*Weight*	*Data Source*
δ Cep	2451192.234	+1572	$-0^{\mathrm{d}}.032$	$\pm0^{\mathrm{d}}.107$	1	Turner (1999)
	2451433.630	+1617	-0.119	±0.109	1	This Paper
ζ Gem	2451245.711	+735	-0.082	±0.205	1	This Paper
η Aql	2451435.736	+1204	+0.174	±0.145	1	This Paper

Computed times of light maximum (O-C). That value was then used to establish an estimate for the time of light maximum occurring near an epoch centered towards the middle of the observing season. The uncertainty was estimated from the experimental scatter in the calculated phase of light maximum. The results are given in Table 2.

The new O-C data resulting from this investigation are accorded a weight of 1.0 in Table 2 by analogy with the weighting scheme used by Szabados (1980, 1981). For each Cepheid the resulting O-C data are fully consistent with recognized long-term trends. δ Cephei exhibits a decreasing period, and both new O-C estimates agree closely with the well-established trend for the star. ζ Geminorum also has a decreasing period, and the single new O-C datum is in excellent agreement with its recognized rate of period change. η Aquilae is the only one of the three bright Cepheids to exhibit an increasing period, and the single O-C datum obtained for it is a good match to the well-established trend.

Although the two seasonal light curves for δ Cephei plotted in Figure 1 seem to have slightly different shapes, a superposition of the data reveals no obvious differences in the magnitude estimates obtained from the two separate observing seasons. The combined light curve for δ Cephei resulting from observations over the full twelve-month interval is shown in the upper part of Figure 3, and the lower portion of the figure illustrates what results from taking running five-point means from the original estimates. In such a situation one expects the resulting scatter in the combined visual estimates to decrease by a factor of $n^{1/2}$, *i.e.*, to roughly ±0.04 magnitude (±0.03 magnitude if one takes the results of Table 1 at face value). That is certainly confirmed by the low scatter in the data. The light curve for δ Cephei depicted by running averages of visual estimates (the lower portion of Figure 3) is not very different from photoelectric light curves for the star. Clearly eye estimates for variable stars obtained without optical aids can be of scientific value, provided they are obtained in a consistent fashion and analyzed with due consideration for standard sources of error.

5. Conclusions

Unaided visual observations have a very long history in the study of variable stars. Until the advent of photoelectric photometry in the 1950's and the arrival of CCD photometry in the 1980's and 1990's, most observations of variable stars were made using photographic photometry or visual estimates. In the search for trends in O-C data for variable stars on baselines of a half-century or more, the question can arise as to the reliability of older visual estimates. It seems clear from the present results, however, that, in the proper circumstances, light curves for variable stars constructed solely from visual estimates can be of reasonably high quality. For Cepheids, in particular, some of the high-scatter light curves published in recent years (*e.g.*, Percy and Mattei 1994; Percy and Rincón 1996) are not representative of the true state of the art. It has been the author's experience that, if bright Cepheids are studied by a single experienced observer using techniques designed to assure that the observations are always made under circumstances in which the eye appears to attain its greatest photometric precision, the resulting light curves can exhibit relatively small scatter. The present study demonstrates that unmistakably.

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