The Power of Archival Astronomy

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Abstract Examples are given of the extreme usefulness of the Harvard College Observatory Photographic Plate Collection for the study of variable stars that possess only limited published observational data. Program objects studied with the aid of archival photographic data include: (i) the eclipsing binary HD 174403, (ii) the semiregular variable BC Cygni, (iii) V439 Cygni, now recognized as a γ Cassiopeiae variable, and (iv) the classical Cepheid T Antliae. In the case of T Antliae, the plate archives yielded not only data for the star's brightness variations but also for the spectral characteristics of all stars brighter than $B = 12$ in the field.

1. Introduction

The world's collection of archival photographic plate material comprises an enormous wealth of useful information that is readily available for the study of variable stars, yet is often overlooked or underutilized. Worse still, some astronomers may question the value of old, scratched, and grainy photographic emulsions from the last century in the present era of fast, ultrasensitive, and precise photometric instrumentation. Many variable star observers presently make use of new detectors and new instruments to study variable stars with unprecedented detail and precision, yet there is still a crucial role played by archival material. For the last few years the author has made use of the Photographic Plate Collection of the Harvard College Observatory primarily to study period changes in Cepheids. On a recent trip to the plate stacks, however, some time was allotted to the study of a small sample of other variables, all of which were relatively unstudied since their discovery years earlier. The present paper summarizes the early results of an analysis of the resulting data and is intended to illustrate the extreme usefulness of the Harvard Plate Collection for the study of overlooked variable stars.

It can be pointed out that archival astronomy is an observational astronomer's dream. As a type of ground-based astronomy, it offers the advantages of no interruptions by clouds, no restrictions on when you can collect data, and no need to process observational material (photographic development, photon counting, or image processing), and also provides observations over a large temporal baseline that typically exceeds the active lifetime of an average astronomer: usually sixty years or more. Data can also be collected with a minimum of instrumentation; a good viewing eyepiece and a light table are usually sufficient. No astronomer with even a minimum interest in the study of variable stars should have trouble finding ways to utilize the boundless supply of information available in archival photographs. Examples are provided below.

2. HD 174403

HD 174403 is a seventh magnitude B-type star (B8 II–III) lying only 1.5 arcminutes from the slightly brighter 6.6-day Cepheid BB Sagittarii on the outskirts of the open cluster Collinder 394. Star counts and photometry for the cluster suggest that both stars are probably outlying cluster members (Turner and Pedreros 1985). Since HD 174403 is the only star of comparable brightness to the Cepheid lying in the general vicinity, it has often been used as a reference star for observations of BB Sgr, despite a marked difference in color. It was on one such night of observation, HJD 2444439.4978 (July 1980), when photoelectric photometry was being made of BB Sgr, that Gieren (1981) found HD 174403 to be a few tenths of a magnitude fainter than usual. Turner and Pedreros (1983) made a similar discovery less than a year later, on HJD 2444738.7824 (May 1981), and a period of variability for the newly discovered eclipsing binary system was estimated to be one-fifth of the temporal difference of 299.2846 days from searching for a reasonable spectroscopic orbit within the restrictions of the five radial velocity observations that were available for the star (Lloyd Evans and Stobie 1971; Turner and Pedreros 1983). The initial ephemeris adopted for the star was:

$$\mathrm{HJD}\,(V_{\mathrm{min}}) = 2444738.7824 + 59.8569\,E, \tag{1}$$

where E is the number of elapsed cycles, under the assumption that the eclipse observation of Turner and Pedreros occurred close to minimum light for the system. But all subsequent attempts to confirm the period of variability for the system were frustrated by the long interval between eclipses and a lack of clear skies whenever photometric runs on the star were possible. The passage of years also meant that the initial ephemeris for HD 174403 might be of little use in planning future observing runs for the star.

The solution to the problem was obvious. Instead of searching for future eclipses of the system, why not use the Harvard Plate Collection to search for past eclipses of the system? Even within the optimistic limitations of the ±0.1- to ±0.2-magnitude precision that is possible from eye estimates off photographic plates (in many cases, particularly for bright stars and grainy emulsions, the precision is much worse), it was anticipated that one or two earlier eclipses of the system might be detected by an experienced worker.

The results far exceeded initial expectations. A very obvious reduced brightness for HD 174403 was noticed on a plate taken on HJD 2416679.694 (July 1904), and on several other plates there was a clear suspicion of slightly shallower eclipses in the system. The 1904 eclipse was immediately useful for refining the orbital period of the system. The time difference from the 1981 eclipse observation of 28,059.088 days corresponds to a difference of 468.77 cycles. Figure 1 illustrates the phased light curve for the system from the Harvard plate estimates using: (i) the original ephemeris, (ii) a revised ephemeris corresponding to a difference of 468 cycles between the 1904 and 1981 eclipses, and (iii) a revised ephemeris corresponding to a difference of 469 cycles between the 1904 and 1981 eclipses. It is clear that the last trial generates the most realistic result, and also reveals for the first time that secondary eclipses occur in the system. The original study by Turner and Pedreros (1983) predicted, on the basis of the radial velocity data, that secondary eclipses would occur near phase $\phi = 0.585$. Instead they occur near phase $\phi = 0.467$. The difference appears to originate in the published radial velocity data for the star, which do not sample the orbit of the system in smooth temporal fashion—as might be expected from a sample of only five velocities.

Further study of the results is continuing in conjunction with the radial velocity data and photometry from the Hipparcos/Tycho data sets. A new working ephemeris for HD 174403 is:

$$\mathrm{HJD}\,(V_{\mathrm{min}}) = 2444738.7824 + 59.827485\,\mathrm{E}. \qquad (2)$$

Detailed information on HD 174403 and its eclipses is of more than passing interest, given that it may provide an independent estimate for the distance to the Cepheid BB Sgr. There is considerable interest at present, for example, in the use of eclipsing systems to establish the distances to nearby galaxies (e.g., Guinan *et al.* 1998). In the case of HD 174403 and BB Sgr, an actual physical association is strongly implied by the information available on Collinder 394 (Turner and Pedreros 1985). HD 174403 has the colors and brightness of a star lying at the tip of the evolved cluster main sequence, while BB Sgr has parameters consistent with the age of Collinder 394. A match in radial velocity for the two stars with those for cluster members would strengthen the case, but to date only the systemic velocity for BB Sgr is known, whereas the systemic velocity for HD 174403 is tied to the orbit inferred from the existing radial velocity sample. Improved orbital parameters for the latter are therefore essential for further testing of the case for a physical association with the cluster.

3. The variables of Berkeley 87

Berkeley 87 is an interesting young cluster that contains a selection of unusual stars (Turner and Forbes 1982). The use of zero-age main sequence fitting has resulted in a reasonably accurate estimate for the distance to the cluster, which means that the evolutionary masses and ages of its member stars, including the variables, can be established with reasonable precision (see Turner *et al.* 2001). Given the general lack of detail regarding the light curves of some of the stars, however, it was decided to use the Harvard Plate Collection to solidify the background information available on their light variations.

BC Cygni is a red semiregular variable of spectral type M3.5 Ia, which is almost certainly a member of Berkeley 87. The mass of stars just reaching the end of their main-sequence lifetimes in Berekeley 87, which has an age of ~4×10^6 years based upon its main-sequence turnoff at spectral type O9, is 40 $M_\odot$ according to the relations of Meynet *et al.* (1993). BC Cyg, as a post main-sequence object, presumably has a mass slightly in excess of that value. It is listed in the *General Catalogue of Variable Stars* (GCVS) (Kholopov *et al.* 1985) as a SRC variable, i.e., type C semiregular, with a period of variability estimated to be about 700 days. The listed parameters for the star refer to a thirty year old study by Alksnis *et al.* (1973), who found a brightness range from 11.3 to 13.8 photographic. Type C semiregulars are all late type supergiants (typically spectral class M) with periods in excess of 30 days and amplitudes of order one magnitude. Their brightness variations are typically rather erratic, with some having been classified previously as irregular variables.

For the present study, the brightness of BC Cyg was estimated on available Harvard plates of the field with reference to a sequence of non-variable stars in Berkeley 87 covering the brightness range from $B = 11$ to $B = 14.5$ on the Johnson system, where the magnitudes are from the study by Turner and Forbes (1982). The cluster is heavily reddened, so the reference stars for BC Cyg all have very red colors, much like the variable itself. For the sake of uniformity, the brightness of the variable was always referred to the same set of standards, which form a consistent set with small but noticeable differences in apparent brightness, and most estimates were also made from plates taken with the same telescope. Magnitude estimates for red variables from photographic plates are always a challenge given the potentially deleterious effects of the various lens/emulsion combinations on the amount of light recorded for a star in any particular wavelength band. No obvious problems were noted for the plate estimates obtained here, although it can be remarked that there were a few discordant estimates that arose during the process and which were readily identified with the use of different telescopes or different plate emulsions. Those estimates were omitted from the final sample.

It was possible to obtain 434 estimates for the brightness of the star on the Harvard plates. The data are plotted in Figure 2, where it can be seen that the observations tend to contradict the parameters listed in the GCVS. The brightness range indicated here for BC Cyg is from $B = 12.2$ to $B = 13.5$, in contrast to what was found by Alksnis *et al.* (1973) and closer to expectations for a semiregular variable.

The variability is indeed rather erratic for BC Cyg, but certain trends are evident, even by eye. For example, when the data were inspected in an Excel plot, there appeared to be a long period wave in the brightness data on a time scale of almost a decade, with shorter period variability of slightly larger amplitude superposed. The short period variability was evident during the original sampling process, since it appeared as noticeable changes in the brightness of the star over the course of a single observing season.

A periodogram analysis was made of the data using AAVSO software (program TS, Foster 1996), with the results presented in Figure 3. Three dominant periods are found: $P = 696$ days (the strongest signal), $P = 239$ days, and $P = 3417$ days (the weak long-term signal evident to the eye). The dominant period is close to that found by Alksnis *et al.* (1973), but is much better defined by the data obtained from the Harvard plates. The secondary light variations, possibly arising from overtone pulsation in combination with the fundamental mode pulsation (?), are revealed for the first time by the Harvard data. Figure 4 presents the data of Figure 2 with a model light curve superposed, where the amplitudes for the various periodic components were taken from plots of the light curve variability as a function of individual period. The match is reasonably good, given the limitations of the data, and the model curve at least illustrates the rather erratic nature of the light changes typical of semiregular variables.

Also of interest as a member of Berkeley 87 is the curious variable star designated as V439 Cygni. V439 Cyg was detected photometrically as a variable star by van Schewick (1941) and designated as a cool semiregular because of its red color. Its spectral appearance in 1958 from an objective-prism exposure by Peraud and Pelletier (1959) implied that it is a cool carbon star, but more recent *UBV* data (Turner and Forbes 1982) indicate instead that it is a highly reddened early-type star. Confirmation of the photometric interpretation was subsequently provided spectroscopically by English *et al.* (1983), who detected a featureless continuum with $H\beta$ emission superposed. A 1984 blue spectrum of V439 Cyg (Turner 2003) closely resembles that of a rapidly-rotating B0 star (i.e., B0 V:nnep), which helps to clear up some of the confusion surrounding the star that existed previously. V439 Cyg has been studied spectroscopically at longer wavelengths by Polcaro and collaborators (Polcaro *et al.* 1989, 1990, 1991a, 1991b), and has recently been suggested to exhibit features like those of a luminous blue variable (Polcaro and Norci 1998). From all the available spectroscopic evidence it appears that the star undergoes periods of spectral veiling (Turner 2003). But why was the star originally designated as a semiregular variable?

The original description of the variability of V439 Cyg by van Schewick (1941) can be translated from the German as follows: "Semiregular. The light variations execute a long flat-bottomed wave of 260^d duration that, as the small number of observations permit one to judge, is not confidently established. Observations of maxima occurred on JD2425570 and JD2425810. Between JD2427280 and JD2427400 there was a brightness increase. The star is red."

Our own brightness estimates for V439 Cyg obtained from the Harvard plates are illustrated in Figure 5. The data were obtained from most of the same plates used for the study of BC Cyg. The observations cover a much greater time span than those of van Schewick (1941) and appear to bear little similarity to the characteristics described by him, although the star is indeed variable. There are 393 new magnitude estimates available, most of which cluster near a minimum brightness of $B \approx 13.8$, which presumably represents the star in an "unexcited state." There are occasional brightenings, possibly reaching $B \approx 12.2$, but they occur infrequently and irregularly. The time coverage of the data is not ideal for studying the fine features of the star's light curve, but flare-ups appear to occur over intervals spanning a few days to a week, following which the star gradually returns towards minimum brightness over the course of a few weeks or more. No periodicity is evident in the data according to a periodogram analysis. V439 Cyg can now be categorized as a GCAS (γ Cas) variable on the basis of the available spectroscopic and photometric data. A more detailed study of its brightness variations appears to be warranted.

4. Cepheid period changes

Cepheids are ~3–30 $M_{\odot}$ post-main-sequence stars evolving through the instability strip in the Hertzsprung-Russell diagram. Both the mass and strip-crossing mode of a Cepheid dictate the rate and direction of its period changes, so a knowledge of the rate of period change for individual Cepheids is of tremendous value for establishing both evolutionary status and position in the instability strip, as well as for testing stellar evolutionary models (see Turner 1998; Turner *et al.* 1999). Archival data are essential for such work since the rates of period change for most Cepheids are so small that they are difficult to establish from recent observations alone. Lengthy temporal databases are also essential for detecting random changes in period that have been found for a small selection of Cepheids. Although such changes are relatively common in cooler classes of pulsators (Mira and RV Tauri variables) according to the work of Percy *et al.* (1997), Percy and Hale (1998), and Percy and Colivas (1999), there has not been to date much analysis of the effect in Cepheids.

A good example of the usefulness of the Harvard Plate Collection for the study of Cepheid period changes is provided by work completed for T Antliae. The variable has had a rather uncertain classification because its galactic latitude of $11\overset{\circ}{.}12$ places it somewhat more distant from the galactic plane than most classical Cepheids. It is designated as a possible classical Cepheid (DECP:) in the GCVS (Kholopov *et al.* 1985), but with a note suggesting that it might also be a Type II Cepheid, or long period W Virginis variable (CWB). A recent Baade-Wesselink study of the star by Laney (1995) confirms its Population I (DCEP) status, but the star's southern hemisphere location and distance from the galactic plane have resulted in it being overlooked in many photometric surveys. There is therefore only a limited set of photoelectric observations available for the star, all of which postdate 1953.

There is a good deal of field overlap for the region of T Ant in the patrol series plates of the Harvard Plate Collection, so it was possible to obtain 734 estimates of photographic magnitude for the Cepheid relative to a selection of nearby stars used as references (with magnitudes taken from the *Hipparcos Catalogue*), of which 699 were accurate enough to track the star's brightness changes reliably. The data set was binned according to year. Examples of the light curve from 1915 and 1944 are illustrated in Figure 6, along with the star's photoelectric light curve for comparison. The $\pm 0\overset{m}{.}1$- to $\pm 0\overset{m}{.}2$-magnitude uncertainty typical of the best eye estimates from the Harvard plates is evident in the data, but that is still adequate for tracking the period changes in the Cepheid. Figure 7 illustrates the O–C diagram for T Ant derived from fitting all available photometric data to a light curve template for the Cepheid. It can be seen that the quality of such data based solely on plate estimates is closely comparable to what is obtained using photoelectric data. That is because of the excellent phase coverage of the light curve of T Ant provided by the Harvard patrol plates.

The O–C data for T Ant are closely matched by a parabolic trend indicative of a period increase for the pulsator. The relationship depicted in Figure 7 is described by:

$$HJD_{max} = 2436120.761 + 5.897912E + 4.77 \times 10^{-8} E^2, \quad (3)$$

where the inferred rate of period increase is +0.511 ±0.017 s yr^{-1}. T Ant can be identified as a Cepheid in the third crossing of the instability strip on the basis of its rate of period change. An added bonus for the star exists in the Harvard Plate Collection, namely an objective prism plate of the field obtained from Harvard's Boyden Station in Bloemfontein, South Africa, on the evening of February 7/8, 1946. The plate contains spectra of stars within several degrees of T Ant, at a dispersion of about 350 Å mm^{-1} at $H\gamma$, to a limiting magnitude of about $B = 12$. Many of the faint stars in the field of the Cepheid are indicated to be B-type stars according to their objective prism spectra, with numbers in excess of that expected for a selection of field B-type stars lying at a galactic latitude of 11°. The plate is therefore of considerable value in helping to confirm an impression gained from a visual inspection of the field that there is a sparse cluster of stars, possibly a loose B association, near T Ant that in all likelihood contains the Cepheid as a member (Turner and Berdnikov 2002). Details will be presented elsewhere.

5. Summary

The examples provided here should illustrate the extreme usefulness of archival data for learning more about variable stars for which only limited data are available otherwise. In each case data obtained from the Harvard College Observatory Photographic Plate Collection provided observations essential for sorting out some of the more perplexing questions related to the star. For HD 174403 it was a problem of establishing an accurate value for the time between eclipses, with the discovery of secondary eclipses in the system being an added bonus. For BC Cygni it was a problem of establishing the semiregular variable's light curve parameters more reliably, with secondary periods of variability being revealed by the data. For V439 Cygni it was a matter of trying to discover why the star was misdesignated as a late-type variable star for so long when it is now recognized as a γ Cas variable. And for T Antliae the plate collection provided invaluable data for establishing the Cepheid's rate and direction of period change. An added bonus was the discovery of an objective prism plate for the field of T Antliae that is useful for studying possible cluster membership for the Cepheid.

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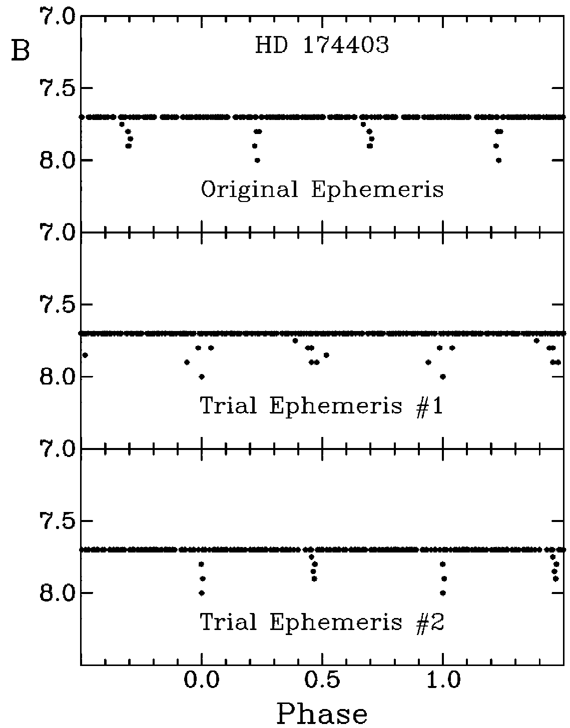

Figure 1. Harvard plate estimates for HD 174403 phased using the original ephemeris with P = 59.8569 days (upper graph), a trial ephemeris using P = 59.9553 days (center graph), and a trial ephemeris using P = 59.8275 days (lower graph). The brightness of the star was assumed to be B = 7.7 when it appeared to be at normal brightness.

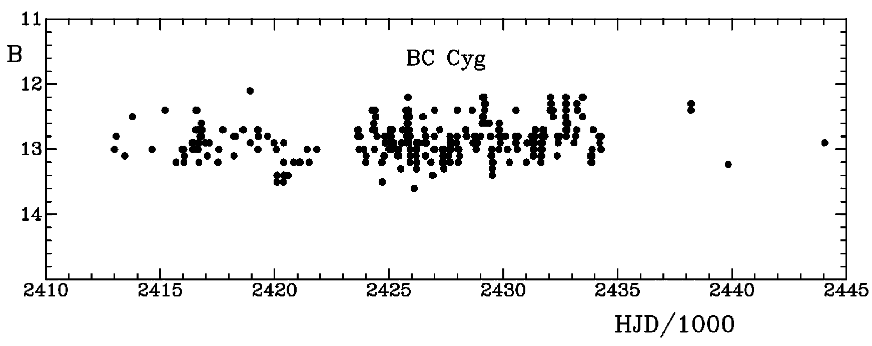

Figure 2. Harvard plate estimates for BC Cygni plotted as a function of Heliocentric Julian Date. The 434 magnitude estimates are tied to data for other members of Berkeley 87 with published photometry. The most recent estimate is from a plate in the author's collection.

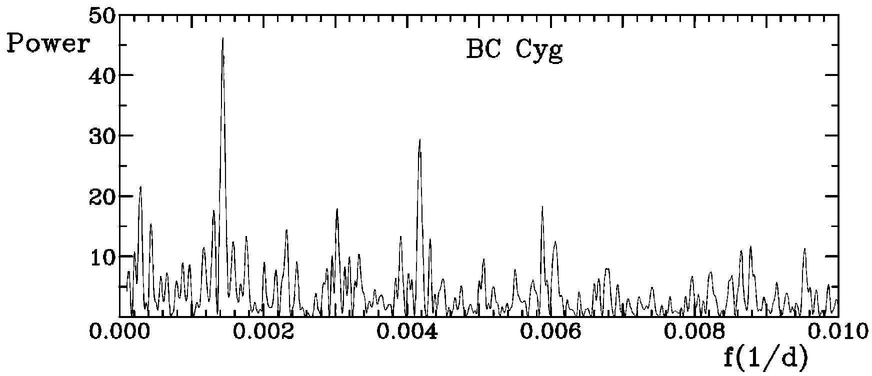

Figure 3. A periodogram analysis of the data for BC Cygni. The three largest peaks in the power spectrum correspond to periods of 696 days, 239 days, and 3417 days, respectively.

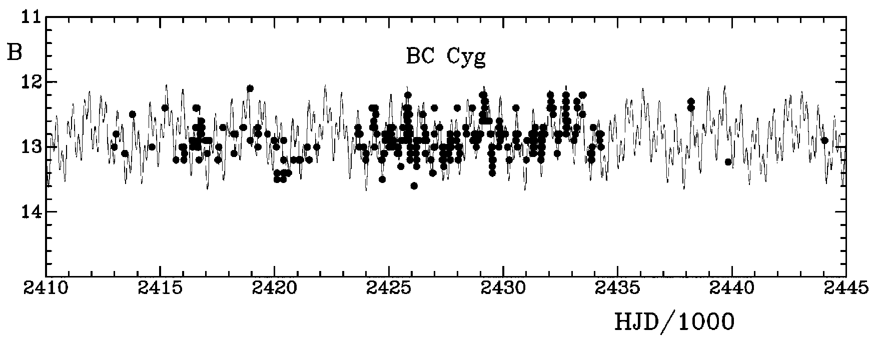

Figure 4. The Harvard plate estimates for BC Cygni from Figure 2 plotted with a model light curve generated using the three periods obtained from the periodogram analysis.

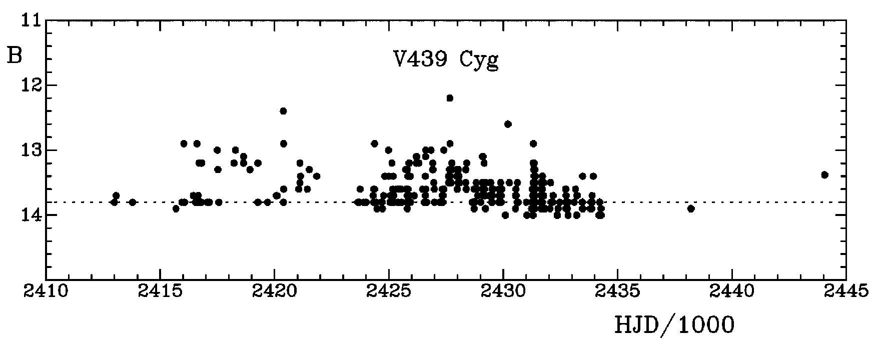

Figure 5. Harvard plate estimates for V439 Cygni plotted as a function of Heliocentric Julian Date. The 393 magnitude estimates are tied to other members of Berkeley 87 with published photometry. The most recent estimate is from a plate in the author's collection. The brightness of V439 Cyg in its "unexcited state" is $B \approx 13.8$.

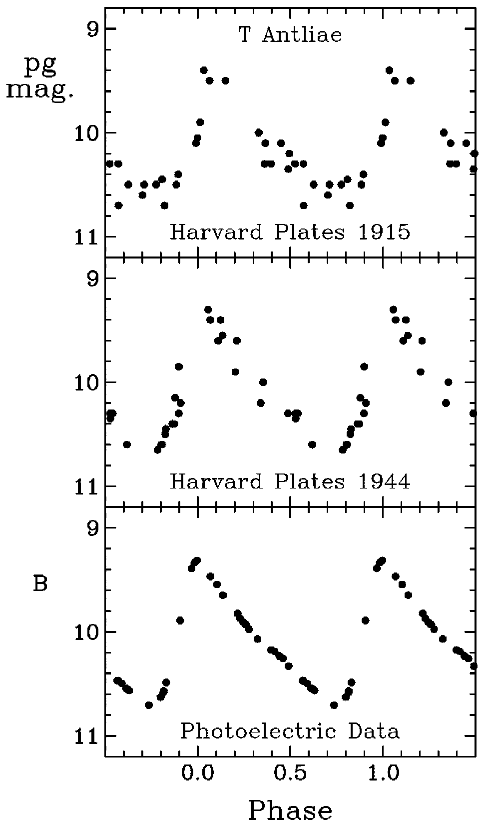

Figure 6. Photographic light curves for the Cepheid T Antliae derived from estimates from Harvard patrol plates for 1915 (upper) and 1944 (middle), relative to the photoelectric light curve (bottom).

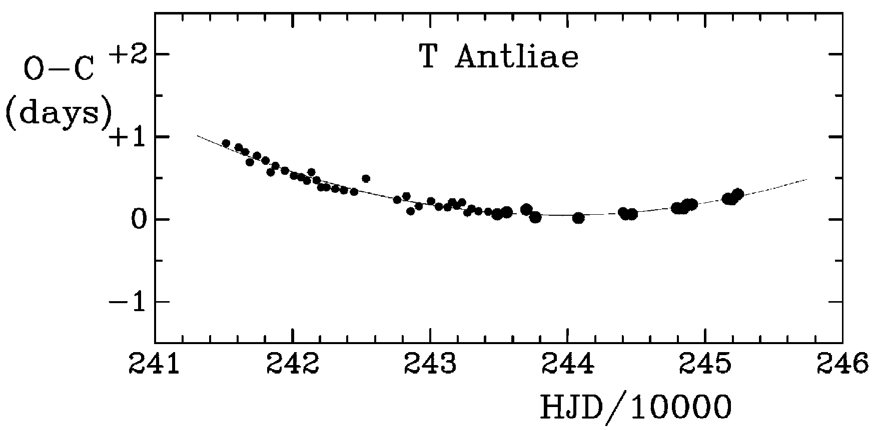

Figure 7. O-C data for T Antliae plotted as a function of the observed Heliocentric Julian Date of light maximum. Small symbols denote data obtained from the analysis of archival Harvard plates, while large symbols denote data obtained from an analysis of published photoelectric observations.