A NEW MAPPING OF THE CEPHEID INSTABILITY STRIP

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ABSTRACT. Results are presented for a new mapping of the instability strip for Milky Way Cepheids based upon field reddenings for 40 stars (mainly members of open clusters and associations), color excesses for 53 stars obtained from reddening-independent systems, and photometric reddenings for 200 additional Cepheids tied to the new system. The data provide new insights into features of the Cepheid instability strip and indicate that photometric reddenings for Cepheids are generally not of high accuracy.

Key words: Stars: variable: pulsating: Cepheids.

1. Introduction

Two unresolved issues raise concerns about the use of Cepheids as extragalactic distance indicators: "How important are metallicity differences between stars?" and "How well is interstellar (or intergalactic) reddening established?" Distances to galaxies derived from Cepheids, for example, are normally tied to a subset of Magellanic Cloud Cepheids for which reddenings are uncertain and the chemical compositions differ from those of Cepheids in the spiral galaxies targeted by the *Hubble Space Telescope* (HST) Key Project. Both features could affect the calibration of the Cepheid period-luminosity (*PL*) and period-luminosity-color (*PLC*) relations, which would affect distance estimates in a systematic fashion.

The question of Cepheid reddenings has been addressed many times in the literature. At present most adopted color excesses for Milky Way Cepheids are taken from a compilation by Fernie (1990a) based upon a scale of reddenings (Fernie 1987) linked to Strömgren system photometry by Feltz & McNamara (1980). Turner et al. (1987) discussed problems with some of the Strömgren system data of Feltz & McNamara, and Turner (1995) noted sizable differences between the resulting reddenings of Fernie (1990a) and well-established space reddenings for the same objects.

Presented here are the results of an empirical study of the instability strip for classical Cepheids in the Galaxy tied to a separate scale of interstellar reddening for such objects. The new system is defined by space reddenings (E_{B-V}) for 40 Cepheids (mainly members of clusters and stellar groups) and color excesses for 53 Cepheids obtained from reddening-independent indices. Photometric reddenings for an additional 200 Cepheids have been tied to the new system by regression techniques using published data on the *UVBGRI* (six-color), *BVRI*, Walraven, DDO, Geneva, Strömgren, Washington, and *VHK* systems, often involving recalibration of the system reddenings. The basic premise behind such a step is examined here in light of the fact that one expects a natural spread in colors for stars populating the instability strip.

2. Details of the Reddening System

The 40 Cepheids for which field reddenings are available originate from photometric studies of the surrounding fields (by Turner and collaborators) in which the exact form of the reddening law was established beforehand. It is an important caveat given that no single relationship accurately describes the reddening in all regions of the Galaxy (e.g., Turner 1989). Many published studies of Cepheids in clusters followed the more traditional use of fixed reddening relations to analyze the photometric data; they were excluded from the resulting sample. An added concern in some studies is the question of potential uncertainties in the standardization of the photometry (Turner 1990).

Full details of the study will be presented elsewhere, but it can be noted that all field reddenings obtained from early-type stars in the Cepheid fields were adjusted to values appropriate for the Cepheids themselves. The 53 color excesses obtained from reddening-free indices (Kraft 1960; Turner et al. 1987; Spencer Jones 1989; Sasselov & Lester 1980; Krockenberger et al. 1998) were adjusted, where necessary, to the system defined by Cepheids with field reddenings. A final step was to add photometric color excesses to the data base, after such values were normalized to the present system using the 93 Cepheids above as standards.

Fernie (1990b) has argued that $\langle B-V\rangle_0$ is better correlated with effective temperature for Cepheids than $(\langle B\rangle-\langle V\rangle)_0$, the latter being designated as the better temperature index by older stellar atmosphere studies (e.g. Karp 1975). The problem was tested using the sample of 93 Cepheids of well-established reddening. The results are presented in Fig. 1, which plots unreddened color as a function of Cepheid pulsation period. The scatter in the $(\langle B\rangle - \langle V\rangle)_0$ data is similar to that in the $\langle B - V\rangle_0$ data, but is about 5% larger for the latter. If small scatter is taken as a positive test for a correlation with effective temperature of stars in the Cepheid instability strip, then it appears that older model atmosphere studies of Cepheids are correct in asserting that the optimum temperature indicator is $(\langle B\rangle - \langle V\rangle)_0$.

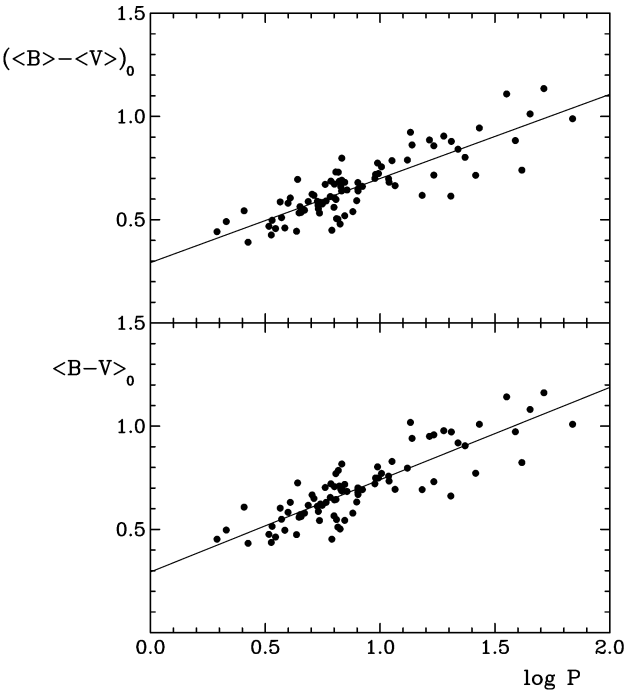

Figure 1: Derived intrinsic colors for $(\langle B\rangle - \langle V\rangle)_0$ (upper) and $\langle B - V\rangle_0$ (lower). The dispersion for the latter is about 5% larger than that for the former.

The final period-color relation is depicted in Fig. 2, in which the best-fitting relation is given by:

$$(\langle B\rangle - \langle V\rangle)_0 \;=\; 0.330(\pm 0.132) \,+\, 0.369(\pm 0.140)\log P.$$

The intrinsic dispersion in the data is ± 0.076, although the full color width of the strip is more like 0.25, comparable to what was found by Fernie (1990b).

3. Radii and Effective Temperatures

An empirical map of the instability strip for Milky Way Cepheids can be made once a system of reddening is established, but an important step involves the derivation of effective temperatures and absolute bolometric magnitudes for individual objects. The transformation of $(\langle B\rangle - \langle V\rangle)_0$ to effective temperature was made here using the sixth order polynomial given by Gray (1992, eqn. 15.14), which provides an excellent fit to stars of all luminosity classes for which good model atmosphere data are available. An examination was made of the various alternative linear relationships established for Cepheids in the literature, but none were any better than Gray's relationship, and most provided poor fits to Cepheids of very red color.

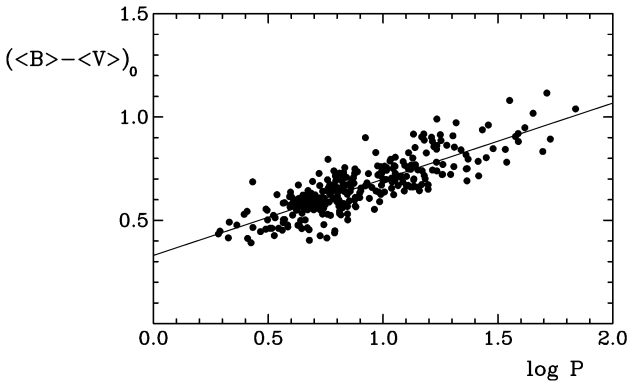

Figure 2: Derived intrinsic colors for the full sample of Cepheids, with the best-fitting relation depicted.

Rather than depend upon an uncertain PLC relation for Cepheids, we estimated absolute bolometric magnitudes for Cepheids in our sample from their derived luminosities, through a combination of the inferred mean effective temperature of the variable (from its mean dereddened color) with a value calculated for its average radius, in other words from:

$$\langle L\rangle \;=\; 4\pi\langle R\rangle^2\sigma\langle T_{\rm eff}\rangle^4.$$

Such an approach does not properly account for abundance differences between stars, which presumably affect their $(\langle B\rangle - \langle V\rangle)_0$ colors, but such effects are difficult to include in any event.

Mean radii were established in simple fashion from each star's pulsation period using the period-radius relation established below. That step entailed knowledge of whether an individual star was pulsating in the fundamental mode or first overtone, but suitable tests are available to establish that characteristic.

The most reliable radii for Cepheids are generally those established from variants of the Baade-Wesselink (BW) method, although one must be wary of subtle assumptions in some versions of the BW method that may invalidate a feature of the approach adopted. Perhaps the best BW radii published for Cepheids are those of Laney & Stobie (1995) and Laney (1995) based upon *VJK* observations in conjunction with published radial velocity data.

A variant of the BW method developed by Turner (1988) uses published narrow-band *KHG* spectrophotometry from Feltz & MaNamara (1980) to isolate phases of identical effective temperature in Cepheid light cycles. The method employs an empirical correction factor to adjust for systematic effects on the V magnitudes and $B-V$ colors during the cycles, and has some similarities to the inverted BW method of Ivanov (1984). An advantage of the *KHG* version is that the main assumptions of the BW method appear from tests to be fully satisfied in practice, while the external uncertainties in the results seem to be no larger than about 2–4%, compared with 5–8% in most other variants.

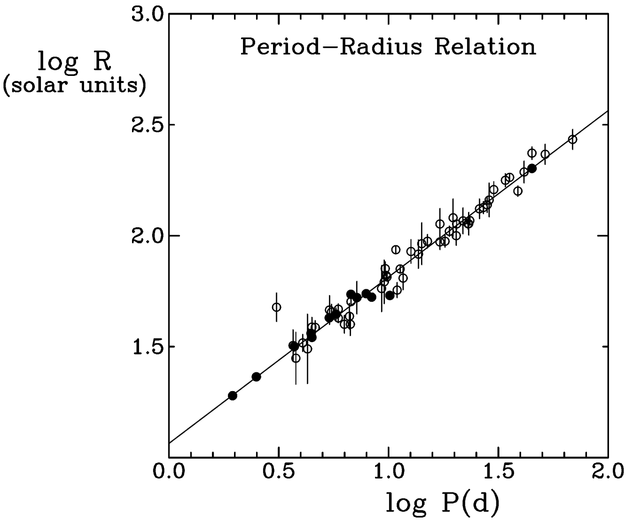

Figure 3: Derived BW radii from the *KHG* method (solid circles) and from Laney (1995) and Laney & Stobie (1995) (open circles), with the best-fitting relation depicted.

The original application of the *KHG* variant of the BW method provided a radius only for δ Cep, but unpublished results are available for ten additional Cepheids, the only objects for which good *KHG* data are available and the technique yields reliable results. The full set of BW radii for those stars, along with the independent BW radii published by Laney & Stobie (1995) and Laney (1995), are plotted in Fig. 3. The best-fitting relation, established by means of regression and non-parametric techniques, is:

$$\log\langle R/R_{\odot}\rangle \;=\; 1.064(\pm 0.006) + 0.750(\pm 0.006)\log P_0.$$

Such a simple relationship between radius and pulsation period ($R \propto P^{3/4}$) appears to be valid for δ Scuti variables as well (Fernie 1992).

A survey of the data for main-sequence companions of Cepheids in open clusters (Turner 1996) noted that Cepheid mass correlates with pulsation period, namely $M \propto P^{1/2}$. From the discussion above it follows that the average surface gravity for Cepheids should also vary with period, i.e., $\langle g\rangle \propto P^{-1}$, and, from the period-density relation, that the pulsation constant $Q \propto P^{1/8}$.

4. Results

The resulting data for all Milky Way Cepheids in the complete sample are illustrated in Fig. 4, which plots the derived average bolometric magnitude for each variable as a function of inferred effective temperature, with symbol size increasing in direct proportion to observed blue light amplitude. Hidden in the scatter of Fig. 4 are a variety of features. The width of the strip, for example, appears to widen with decreasing temperature, although not to the extent indicated by Fernie (1990b). In fact, the temperature width of the strip remains essentially constant ($\sim$ 870 K) as a function of Cepheid pulsation period. There is one isolated point in Fig. 4 lying well outside the instability strip boundaries at $(\log T_{\rm eff}, M_{\rm bol})$ = (3.784, –8.94). That is V810 Cen, which is clearly a Cepheid-like supergiant rather than a true Cepheid.

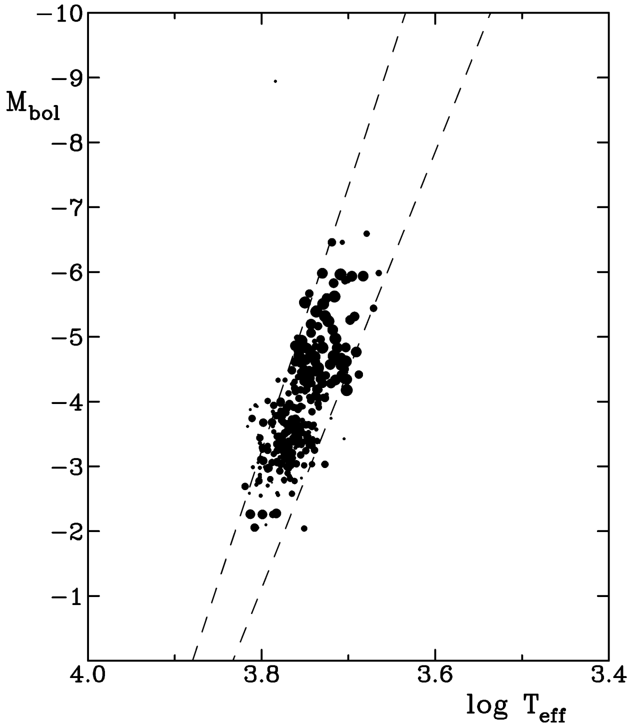

Figure 4: The new empirical map of the instability strip tied to the system of Cepheid reddenings described here. Symbol size increases in direct proportion to observed blue light amplitude.

Close examination of the data in Fig. 4 also reveals that the location of a Cepheid in the strip correlates with light amplitude, as argued previously by Pel & Lub (1978). The evidence for that is illustrated in Fig. 5, which plots blue light amplitude versus inferred effective temperature for individual Cepheids at specific pulsation periods, $P = 15^{\rm d} \pm 1^{\rm d}, 8^{\rm d} \pm 0^{\rm d}.5, 6^{\rm d} \pm 0^{\rm d}.5$, and $3^{\rm d}.5 \pm 0^{\rm d}.5$.

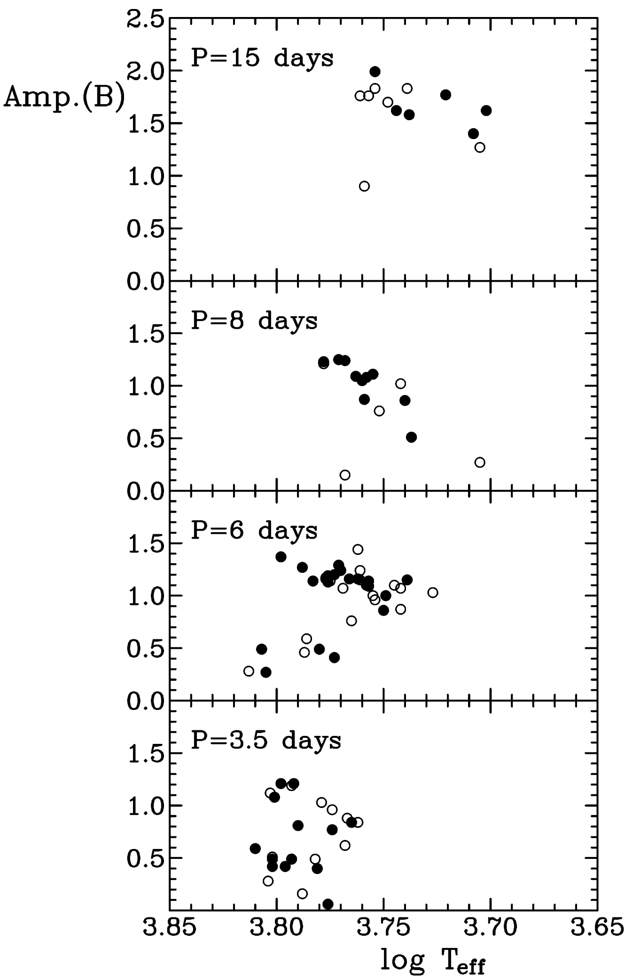

Figure 5: Plots of Cepheid light amplitude as a function of temperature for isolated cuts through the instability strip at $P = 15^d, 8^d, 6^d$, and $3^d.5$. High weight points are represented by filled circles, low weight points by open circles.

It seems clear from Fig. 5 that there is a tendency for light amplitude to increase dramatically on the blueward (hot) side of the Cepheid instability strip and to fall off gradually toward the redward (cool) side, where surface convective layers presumably become more efficient at damping out pulsation. The evidence is strongest for the longer period Cepheids; for shorter period pulsators there is increasing contamination by small-amplitude Cepheids lying near the middle of the strip. The contamination is mostly illusory, however, and arises in large part from Cepheids for which only photometric reddenings are available. Since most photometric color excesses are derived from period-color relations, there is a natural tendency for the values to cluster objects towards the center of the instability strip, independent of light amplitude. The same systematic effect can account for the fact that Fernie (1990b) was unable to find any evidence for a temperature dependence of light amplitude in his system of photometric reddenings, and argues that purely photometric reddenings should not be used where high accuracy is required.

There are a few high-weight points in Fig. 5 that also contribute to the low-amplitude contamination for Cepheids with periods of $3^d.5$ and 6^d. In some cases they represent objects of intermediate weight that have several independent photometric reddening sources. The systematic effect identified above probably applies to those stars as well. Stars for which the color excesses originate from the 93 standards are interesting cases. Two of them in the $P = 3^d.5$ group are Polaris (α UMi) and EV Sct, both of which are suspected overtone pulsators. The problem disappears if the stars are overtone Cepheids. The last object is V367 Sct, a double-mode pulsator in the heavily reddened cluster NGC 6649. It is conceivable that the space reddening for this Cepheid is in error, given the large and often patchy extinction that is present along the line of sight to cluster stars. NGC 6649 is a difficult cluster to observe photometrically, however, so an immediate resolution to the problem for V367 Sct is not envisaged.

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