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The Galactic Cepheid Period-Luminosity relation from Hipparcos parallaxes and proper motions

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Abstract. A Bayesian model of Cepheid kinematics has been applied to the Hipparcos parallaxes and proper motions to obtain an independent estimate of the Galactic Cepheid Period-Luminosity relation for visual magnitudes. The resulting estimate includes a slope that differs significantly from those of Magellanic Cloud Cepheids, suggestive of a lack of universality amongst galaxies in Cepheid P-L calibration.

1. Introduction: the problem

Although the Cepheid Period-Luminosity (P-L) relation constitutes a cornerstone of the cosmic distance scale it has not been directly calibrated, a consequence of the rarity of these extreme Population I objects in the solar vicinity. No reliable ground-based trigonometric parallaxes are available for any Cepheid, so that prior to Hipparcos the Galactic P-L relation was based on a combination of distances inferred from putative open cluster/OB association memberships and comparison with Magellanic Cloud Cepheids. But there are serious concerns about the applicability and reliability of both of these. The cluster/association distances yield a large scatter to the P-L relation (Feast 1999) and naively imply, by themselves, a relation that differs significantly from those of the Magellanic Clouds: the "calibrating Cepheids" of Laney & Stobie (1994, Table 4), for instance, are best fit with a P-L slope of ~ -3.1, quite different from the LMC/SMC slopes. Furthermore, the two Clouds may not share the same slope to their Cepheid P-L relations (Caldwell & Laney 1991), possibly a consequence of systematic metallicity differences (Tanvir 1990). As a consequence the Galactic Cepheid P-L relation remains uncertain at the level of a few tenths of a magnitude, sufficient to introduce some uncertainty into Cepheid-based calibrations of the Hubble constant.

One might hope that the relatively high precision of Hipparcos parallaxes would resolve the issue, but such has not been the case: nearly all Hipparcos Cepheid parallaxes are so small (in comparison with their standard errors) as to naively imply significant formal probabilities of negative parallaxes, and (with one exception) are too small to permit Lutz-Kelker bias corrections. Feast & Catchpole (1997) have employed a clever transformation to estimate the P-L zero-point from these data, but their estimate is of uncertain statistical properties and, in any event, cannot be extended to estimate the slope, which they take to be that of the LMC Cepheids (and whose chosen value strongly influences the zero point thus deduced).

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2. Method: Bayesian analysis

The probabilities of very small or negative parallaxes implied by most Hipparcos Cepheid measurements arise largely from measurement errors and are inconsistent with both the expected spatial distributions and peculiar velocities of Galactic Cepheids. This suggests enhancement of the physical information content of observed parallaxes by employment of a Bayesian model that utilizes the relatively well-known thin disc properties of Cepheids in the form of prior information to, for example, exclude risible probabilities of Galactic Cepheid distances on a physically sound basis independent of inferred luminosities. Schematically, the appropriate model is one of probabilities of parallaxes given the observed parallax and its standard deviation, *and* of the resulting implied peculiar velocities: the well-defined velocity dispersions of these extreme Population I objects allow significant constraint of parallax probabilities. The resulting model is a straightforward Bayesian model with a kinematically based prior; it is most productive to model both parallaxes and proper motions in a single, trivariate Bayesian model that correctly accounts for estimated errors in proper motions as well as parallaxes, and the correlations between their measurements, as reported in the Hipparcos catalog. The resulting parallaxes (and consequent luminosities) are the most accurate available for the Hipparcos Cepheids, and should suffer no luminosity bias (other than Malmquist bias arising from brightness-limited observational selection).

3. Results: The Galactic Cepheid P-L relation

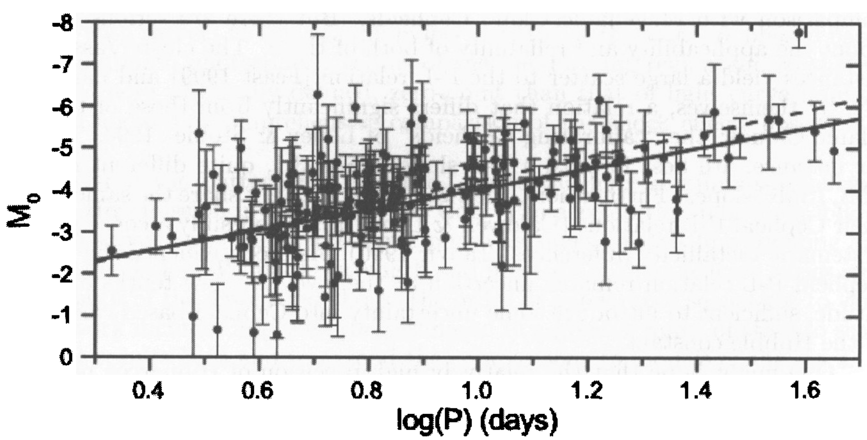

Figure 1. The Galactic Cepheid P-L relation. Solid line: maximum likelihood estimator to these data. Dashed line: Feast & Catchpole (1997). The error bars are the equivalent of $\pm\sigma$.

The results for the 194 Hipparcos Cepheids to which the kinematic Bayesian model is applicable are shown in Fig. 1. The solid line is the P-L relation inferred from these data by a maximum likelihood estimator employed because of the

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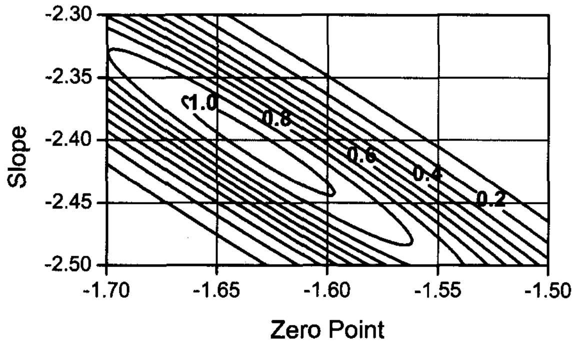

Figure 2. The P-L relation parameter likelihoods (arbitrary scaling).

skewness of many of the individual absolute magnitude distributions; it does not differ significantly from the least-squares solution resulting from treating the individual distributions as Gaussians. The linear P-L fit is better than appears to the eye: the reduced chi-square statistic is 1.082, indicating that the scatter in the figure is consistent with the hypothesized linear relation.

The likelihood surface, as a function of the P-L parameters, is shown in Fig. 2; the maximum likelihood parameters are –1.63 for the zero point, –2.41 for the slope. These raw parameters must be corrected for Malmquist bias using the observed apparent magnitude distribution of Hipparcos Cepheids (which rolls over sharply at $V \sim 10$), corrected for extinction. The resulting best estimates are (in the notation of Feast & Catchpole):

$$\begin{array}{rll} \text{Zero Point:} & \rho = -1.58 \pm 0.13 & \text{(s.e.)} \\ \text{Slope:} & \delta = -2.42 \pm 0.14 & \text{(s.e.)} \end{array}$$

These estimates are highly correlated, as can be appreciated from the ridge-like structure of the likelihood surface: $\sigma_{\rho+\delta} = 0.04$ mag, which reflects the likely error in luminosity estimation of, for examples, a Cepheid of $\log P = 1$.

4. Discussion: can this be true?

This result is quite different from what was expected: estimates of the P-L slopes for the Magellanic Cloud Cepheids range from -2.87 (Laney & Stobie 1994, both Clouds) to -2.63 (Caldwell & Laney 1991, SMC), with a more-or-less nominal value of -2.81 being used for both Clouds in most applications. Estimates of the Galactic Cepheid zero-point range from the value of approximately -1 implied by the (cluster/association) calibrating Cepheids of Laney & Stobie (1994, Table 4) to the aforementioned Hipparcos value of -1.43 deduced by Feast & Catchpole (1997). But this work's calibration estimate is not in conflict with any credible independent estimates: the slope in particular is the first credible and direct estimate for Galactic Cepheids; there is independent evidence of differences in P-L slope amongst different galaxies (Caldwell & Laney 1991; Sekiguchi & Fukugita

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1998); and the mean absolute magnitude implied for Galactic Cepheids (~ -4) is reasonable. The parallaxes deduced by the Bayesian model appear credible in all respects: the peculiar velocities they imply have the overall distributions expected of Cepheids, and – independent of the kinematic prior employed – the distances above/below the disc midplane implied by the deduced parallaxes have the expected exponential distribution with scale length ~ 0.06 kpc. Finally, the parallax deduced for δ Cep is much closer to the accurately observed HST value (Benedict et al. 2002) than is the raw Hipparcos measurement.

No luminosity biasing effect other than Malmquist bias (on the order of 0.02–0.05 mag) seems likely, especially in regard to the slope. In particular, since the stars observed and analyzed were *not* selected on the basis of observed parallax, there is no Lutz-Kelker bias in their overall luminosity distribution. There thus seems to be no reasonable way of reconciling the P-L relation deduced here with the canonical calibration of Feast & Catchpole (1997), which lies about 2.5σ from the maximum likelihood implied by the Bayesian kinematic model. But note that the Feast & Catchpole zero point is largely a consequence of their choice of slope, which derives mostly from the LMC; and is susceptible to systematic errors in the Hipparcos parallaxes on the order of 0.1 mas (which cannot be ruled out). The susceptibility to such errors is much less for the results reported here, largely because of the use of additional distance information in the form of the kinematic prior.

The main consequence of this result – if it holds – is that Cepheid P-L relations are not universal, and that local P-L calibration is of limited use of itself in calibrating the distance scale to other galaxies. Complete details of the statistical model and its application to Hipparcos Cepheid parallaxes will be published elsewhere (Heacox 2004).

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