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Evidence for a universal slope of the period-luminosity relation from direct distances to Cepheids in the LMC

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Abstract. We have applied the infrared surface brightness (ISB) technique to derive distances to 13 Cepheid variables in the LMC which have periods from 3-42 days. The corresponding absolute magnitudes define PL relations in VIWJK bands which agree exceedingly well with the corresponding Milky Way relations obtained from the same technique, and are in significant disagreement with the observed LMC Cepheid PL relations, by OGLE-II and Persson et al., in these bands. Our data uncover a systematic error in the p-factor law which transforms Cepheid radial velocities into pulsational velocities. We correct the p-factor law by requiring that all LMC Cepheids share the same distance. Re-calculating all Milky Way and LMC Cepheid distances with the revised p-factor law, we find that the PL relations from the ISB technique both in LMC and in the Milky Way agree with the OGLE-II and Persson et al. LMC PL relations, supporting the conclusion of no metallicity effect on the *slope* of the Cepheid PL relation in optical/near infrared bands.

Key words. Cepheids — distance scale — galaxies: distances and redshifts — Magellanic Clouds

1. Introduction

Cepheid variables are key objects for the calibration of the extragalactic distance scale. Using the period-luminosity (PL) relation as a tool, Cepheid distances to galaxies out to about 25 Mpc can currently be measured (Freedman et al. 2001). These measurements rest on the assumption that the PL relation is universal, or that a possible effect of metallicity on the slope/zero point of the PL relation can be well controlled.

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An alternative way to measure the distances to individual Cepheids is offered by the infrared surface brightness (ISB) technique. This method uses the light-, colour- and radial velocity-curves of Cepheids to calculate their distances and mean radii. It is nearly independent of errors in reddening, and can be applied on any individual Cepheid for which the necessary datasets have been obtained. Very importantly, the relation between surface brightness and colour has recently been put on a solid foundation by means of interferometric angular diameters of Cepheids (Kervella et al. 2004a, Nordgren et al. 2002).

A disturbing issue over recent years has been the fact the the slope of the PL relation derived from the ISB method for Milky Way Cepheids (Storm et al. 2004, Gieren et al. 1998) has turned out to be *steeper* than the slope determined from LMC Cepheids by the various microlensing projects, particularly by the OGLE-II project (Udalski et al. 1999), hinting at a possible metallicity effect on the *slope* of the PL relation. One way to check on this intruiging possibility, which would imply a strong complication in the use of Cepheids as standard candles, is to measure the distances to a number of LMC Cepheids directly with the ISB technique, and compare the resulting LMC PL relation to the results from the OGLE-II project, and to the results of Persson et al. (2004) who have established accurate Cepheid PL relations in the LMC in the near-infrared JHK bands.

2. Infrared Surface Brightness Distances to LMC Cepheids

We have used the ISB technique to determine the distances to 13 LMC Cepheids with periods in the range 3-42 days. Details on the stars, and on the different datasets used in these calculations can be found in Gieren et al. (2005a). A detailed description of the ISB technique can be found in Storm et al. (2004), and in the paper of Barnes et al. in these proceedings.

When plotting the absolute magnitudes of the LMC Cepheids derived from their ISB distances against period, it turns out that in all bands from V through K, the sequences are exceedingly well described by slopes which are identical to the Milky Way counterpart relations, and in significant disgreement with the slopes found by the OGLE-II project in the V, I and the reddening-free Wesenheit (W) bands, and by Persson et al. (2004) in the near-IR J and K bands. This is shown for the W band in Fig. 1. When plotting the individual, tilt-corrected true LMC Cepheid distance moduli against period, a significant trend of the moduli with period is apparent (Fig. 2). We interpret this unphysical trend as a clear sign for the presence of a systematic, period-dependent error in the ISB method.

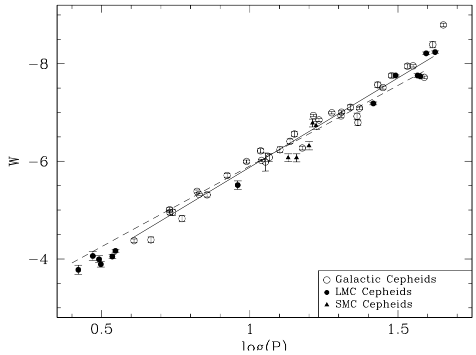

Fig. 1. Absolute W-band magnitudes derived from the ISB distances of 38 Milky Way, 13 LMC and 5 SMC Cepheids. The canonical p-factor relation was used for the ISB distance calculation for all stars. The solid line is the best fit to the Milky Way data. The dashed line is the W-band PL relation in the LMC from the OGLE-II project, for an assumed LMC distance modulus of 18.50. The ISB-based PL relations both in Milky Way and LMC are significantly steeper than the OGLE-II LMC relation.

There are two sources of systematic error which can in principle introduce such a period-related effect on the distances. The first is a wrong calibration of the surface brightness relation used in the ISB technique; the other one is a period dependence of the p-factor law which is different from the one we assumed. Regarding the possibility of a systematic error in the surface brightness relation, the recent interferometric work of various groups has nailed down the surface brightness-colour relation to an accuracy of 2%, and has

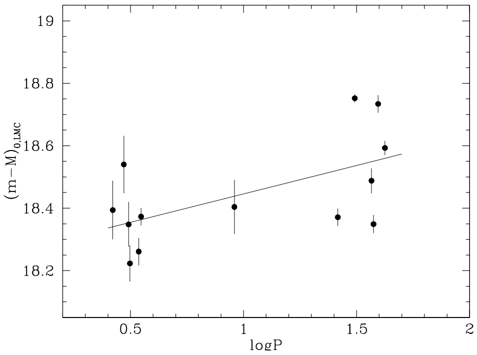

Fig. 2. ISB-determined true distance moduli for LMC Cepheids, calculated with the canonical p-factor law. The distance moduli have been corrected for the tilt of the LMC plane with respect to the line of sight. There is a significant trend of the distance moduli with period.

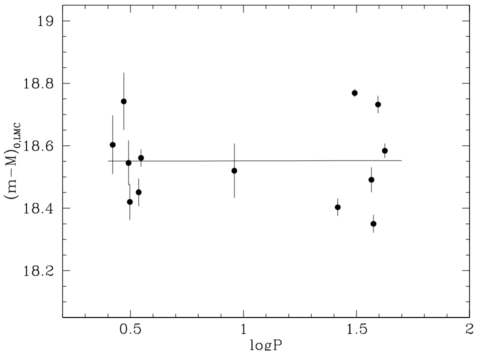

Fig. 3. As Fig. 2, but now distance moduli calculated with the revised p-factor law of this paper. The trend in Fig. 2 has disappeared.

confirmed the Fouqué & Gieren (1997) relation used in our work at this level of precision. A direct comparison of the interferometrically determined angular diameter variation of the nearby Cepheid ℓ Car with that prediced by the ISB method has yielded agreement at the 1% level (Kervella et al., 2004b). Any remaining systematic uncertainty on the surface brightness-colour relation for Cepheids can therefore not explain the trend observed in Fig. 2.

Regarding the p-factor law, we have assumed p=1.39 - 0.03 logP (P in days), as established by Gieren et al. (1993) from the theoretical models of Hindsley & Bell (1986). Our current work suggests that the assumed period dependence in this law is seriously flawed. We have therefore re-determined the period dependence of the p-factor law by requiring the trend seen in Fig. 2 to disappear. Since we cannot be confident of the zero point of the adopted p-factor law either, in view of our new results for the LMC Cepheid distances, we chose to use twelve well-established open cluster Cepheids in the Milky Way which have both ZAMS-fitting and ISB distance determinations to set the zero point of the p-factor law, by the requirement that the average difference between the ZAMS-fitting and ISB distances be zero for this sample of stars (see Gieren et al. 2005a for details). Actually, the derivation of the slope and zero point of the new p-factor law are not completely independent from each other. Our result for the *revised p-factor law* is p=1.58 (± 0.02) - 0.15 (± 0.05) log P, suggesting that the p factor to be used in Baade-Wesselink work on Cepheid variables depends more strongly on period (and thus luminosity) than previously thought. The expression for p is also tied to an assumed LMC distance of 18.56 mag.

We have re-calculated all ISB distances (LMC Cepheids, and Milky Way Cepheids) with the revised p-factor law. Fig. 3 displays the corrected LMC Cepheid distance moduli, plotted against the periods of the stars - evidently, there is no trend anymore. When we re-calculate the slopes of the PL relations in the different bands, we find that the excellent agreement between Milky Way and LMC relations persists, but now these relations are all shallower than before, and agree with the OGLE-II and Persson et al. PL relations *within the combined* 1σ *uncertainties*. This is demonstrated in Fig. 4 for the K band.

3. Conclusions

Our current results strongly suggest that the previous problem with Milky Way Cepheid PL relations from the ISB technique being steeper than LMC and SMC relations was caused by an erroneous calibration of the p-factor law

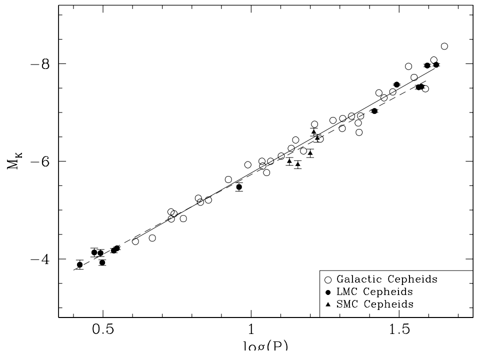

Fig. 4. Absolute ISB-based K-band PL relations in Milky Way and LMC, calculated from the revised p-factor law. Solid line is the best fit to the Milky Way data. This line fits also the LMC data very well. The dashed line is the Persson et al. PL relation for LMC Cepheids, which now agrees very well with the ISB-based Milky Way and LMC PL relations.

used to convert the observed Cepheid radial velocities into their pulsational velocities. With the corrected law, the discrepancy disappears, and we now get Milky Way PL relations from the ISB technique in all bands which agree with the PL relations observed in the corresponding bands in the LMC by the microlensing projects, and by Persson et al. in the near-infrared. Adding to this excellent agreement between Milky Way and LMC our current knowledge about the PL relations in more metal-poor galaxies, like IC 1613 (Udalski et al. 2001), there seems now solid evidence that the *slope* of the Cepheid PL relation in the optical VIW bands is independent of metallicity, at least in the metallicity regime from -1.0 dex to solar. In order to investigate if this is also true for near-infrared bands, more work on near-IR PL relations in nearby galaxies must be done. The Araucaria Project discussed by Pietrzyński et al. elsewhere in these proceedings will provide such studies in the very near future. One recent example is the near-IR Cepheid work in NGC 300 (Gieren et al. 2005b).

In order to address remaining concerns with our present work, we need to obtain ISB distances to a significant number of additional Cepheids in the LMC, in order to improve the statistics of our results. Such a program has recently been started. In particular, it will be important to analyze a number of short-period Cepheids in the general LMC field which are not related to each other as the ones in our current study, all which are all members of the same cluster, NGC 1866 (see Storm et al. in these proceedings).

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