

# Determining the Cepheid Period–Luminosity Relation Using Distances to Individual Cepheids from the Near-infrared Surface Brightness Method

Jesper Storm<sup>1</sup>  
 Wolfgang Gieren<sup>2</sup>  
 Pascal Fouqué<sup>3</sup>  
 Thomas G. Barnes<sup>4</sup>  
 Thomas Granzner<sup>1</sup>  
 Nicolas Nardetto<sup>5</sup>  
 Grzegorz Pietrzyński<sup>2,6</sup>  
 Didier Queloz<sup>7</sup>  
 Igor Soszyński<sup>6</sup>  
 Klaus G. Strassmeier<sup>1</sup>  
 Michael Weber<sup>1</sup>

<sup>1</sup> Leibniz-Institut für Astrophysik  
 Potsdam (AIP), Germany

<sup>2</sup> Universidad de Concepción, Chile

<sup>3</sup> L'Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse, France

<sup>4</sup> University of Texas at Austin, McDonald Observatory, USA

<sup>5</sup> Laboratoire Lagrange, UNS/CNRS/OCA, Nice, France

<sup>6</sup> Warsaw University Observatory, Poland

<sup>7</sup> Observatoire de Genève, Switzerland

The near-infrared surface brightness method has been applied to 111 Cepheids in the Milky Way, the Large Magellanic Cloud and the Small Magellanic Cloud, and distances and luminosities to the individual stars have thus been determined. As the Cepheid populations in these galaxies have significantly different metallicities, the effect of metallicity on the Cepheid Period–Luminosity (PL) relation can be directly determined. We show that the *K*-band PL relation is very insensitive to abundance and argue that it is the best Cepheid PL relation for distance determination.

## Motivation

The Cepheid Period–Luminosity relation provides a crucial step on the distance ladder in the quest to determine accurate distances out to cosmologically relevant distances and thus constrain the value of the Hubble constant. It also allows accurate distances to be measured to nearby galaxies, providing the luminosities of other scientifically interesting objects found in these galaxies and allowing quantitative investigations of the physics

of these objects. One of the more elusive aspects of the PL relation is the effect that metallicity has on the luminosity of the Cepheids. It has long been argued that there is an offset in the luminosity depending on metallicity, but in spite of much effort there is still no unanimous agreement even on the sign of the effect. Storm et al. (2004) applied the near-infrared surface brightness method to Milky Way Cepheids and found that the slope of the resulting PL relation differed from that seen in Large Magellanic Cloud (LMC) PL relations, a finding that would have significant implications for the use of the relation as a distance indicator. Any improvement in our understanding of this relation is thus very important and has far-reaching consequences.

## The near-infrared surface brightness method

The near-infrared surface brightness method takes advantage of the fact that a Cepheid star is radially pulsating. By observing the light curves in the visual and near-infrared (NIR), we determine the variation of *V*-band luminosity and (*V*–*K*) colour as a function of phase. These data can be used to determine the surface brightness of the star and thus the angular diameter as a function of phase. This relation is well established from interferometric observations of non-pulsating stars (Fouqué & Gieren, 1997) and was later confirmed by Kervella et al. (2004) by measurements of the angular diameters of Cepheids using the Very Large Telescope Interferometer (VLT).

Observing the radial velocity curve for a star allows us to determine the pulsational velocity curve for that star by applying the so-called projection factor to the observed radial velocities. The projection factor accounts for the fact that the observed light from the radially pulsating star originates from the whole visible hemisphere of the star and not just the intercept between the stellar surface and the line connecting the observer and the stellar centre. From the pulsational velocity curve we can compute the variation of the stellar radius as a function of the phase. We thus have the angular diameter variation from the photometry

and the corresponding absolute variation of the radius from the radial velocities. By relating the observed angular diameter, the radius of the star and the distance to the star geometrically we can solve the equations for the distance and the mean stellar radius. In this sense the method is similar to the Baade–Wesselink method for determining distances to pulsating stars.

In Figure 1 we plot the angular diameters against the radius variation with the best fit over-plotted for the LMC star HV877. For all our fits we disregard the phase interval between 0.8 and 1.0 where the star is contracting and the stellar atmospheres often exhibit signs of shocks (emission lines in the spectra) which can affect the angular diameter measurements. In the lower panel of Figure 1 the angular diameter is shown as a function of phase and it is clear that the match between photometric angular diameter (the dots) and the angular diameter inferred from the radial velocity curve and the best fit distance (the blue curve) agree rather well, except for the aforementioned phase region between 0.8 and 1.0.

The great advantage of the near-infrared surface brightness method over, e.g., trigonometric parallaxes, is the fact that it can be applied to stars in other galaxies as well as to nearby stars. The price to be paid is that the method is very demanding in observing time as precise light curves are necessary at both optical and near-infrared wavelengths as well as precise radial velocity curves.

## A lot of data

Over the years a lot of data for Milky Way Cepheids has been collected by many workers in the field. This has allowed the near-infrared surface brightness method to be applied to many Galactic stars. The first application to a small sample of extragalactic (Small Magellanic Cloud [SMC]) Cepheids was successfully attempted by Storm et al. (2004). Gieren et al. (2005) then applied the method to a number of Cepheids in the LMC. The sample was still too small to delineate a definitive PL relation for the LMC and so we found it necessary to expand the

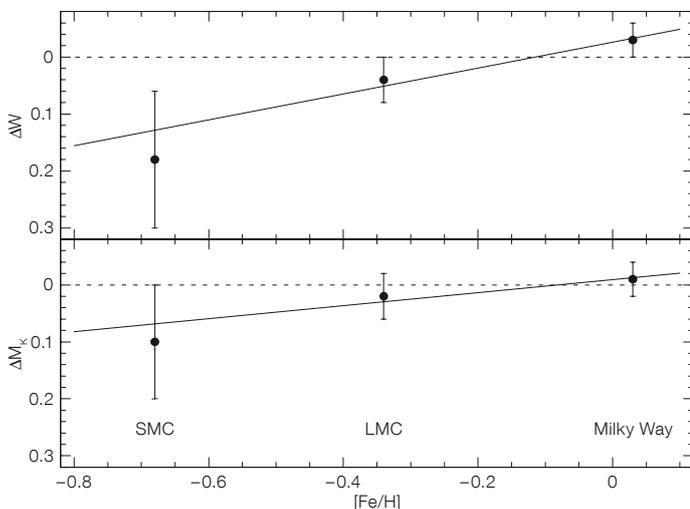
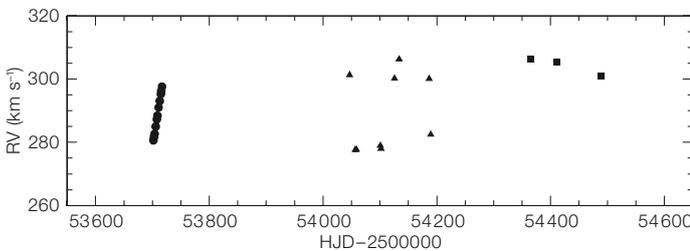
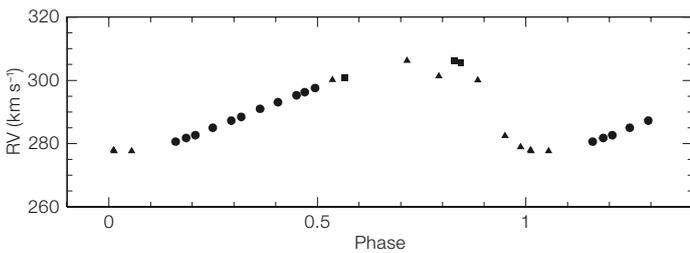
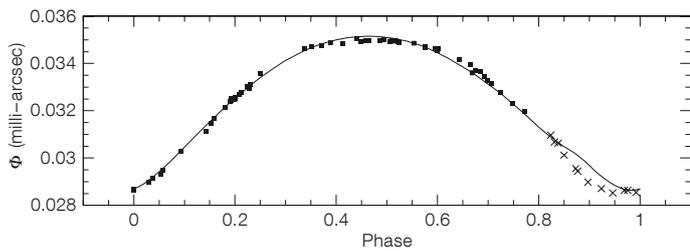
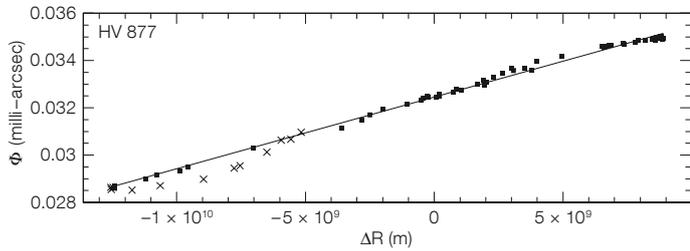


Figure 1. The upper panel shows the angular diameter versus the radius variation for the Cepheid HV877 with the best fit over-plotted. The lower panel shows the angular diameter as a function of phase. The phase interval from 0.8 to 1.0 is always omitted from the fit due to the possible presence of shocks in the stellar atmosphere.

Figure 2. The upper panel shows the radial velocity curve for HV877 as observed with HARPS. In the lower panel the epochs of the individual observations are plotted. The different observing seasons have been coded by different symbols and the coding is the same in both panels.

Figure 3. The zero-point offset of the PL relations in the  $K$ -band (lower panel) and in the Wesenheit index (upper panel). The three points correspond to the SMC, LMC, and Milky Way samples.

sample significantly. At this time new precise light curves in both the optical (Soszyński et al., 2008) and in the NIR (Persson et al., 2004) became available, so radial velocity curves were called for. We were granted time with HARPS on the 3.6-metre telescope at La Silla over three observing seasons. Over the first season we had 16 consecutive photometric (!) half-nights in which the shorter period stars were well covered; in the next seasons the observations were carried out in service mode with the diligent support of the La Silla staff.

In Figure 2 an example of a radial velocity curve is shown; again we have chosen the LMC Cepheid HV877 which has a pulsation period of 45.2 days. The good phase coverage is very important and the observations in the last two observing seasons were carefully planned to fill the gaps remaining from the first campaign. The lower panel in Figure 2 shows the timing of the observations, and it becomes obvious that this kind of work demands very careful scheduling to succeed and that the instrument is available not just in a few long blocks of time, but also for single observing blocks distributed throughout the semester. Thanks to the flexibility of the La Silla support staff the programme could be completed in three seasons. For our 20 target stars we obtained more than 450 data points with HARPS.

### The effect of metallicity

With the new data in hand, we have determined luminosities for a total of 36 LMC Cepheids with periods ranging from 3 to 80 days and can determine a PL relation in any of the observed photometric bands (Storm et al., 2011b). For the Cepheids in the Milky Way we have proceeded in exactly the same fashion (Storm et al., 2011a), supplementing the available data with new radial velocity measurements from the echelle spectrograph on the STELLA robotic telescope on Tenerife, Spain and analysing a total of 70 fundamental mode Cepheids in a similar period range. It turns out that the slopes of the two samples are very similar and we do not find significant evidence that the slopes should be different. This

is a very important point to establish when applying the PL relation as an extragalactic yardstick, especially as our earlier work suggested that such an effect was present. We then compare directly the luminosities of the stars from these two samples as well as the five Cepheids in the SMC, which we have re-analysed using the exact same procedure as for the other stars.

The resulting offset from the mean PL relation in the  $K$ -band and in the Wesenheit index from our study is shown in Figure 3 (in the lower and upper panels respectively). The Wesenheit index is a reddening-insensitive colour index based on the  $V$ - and  $I$ -band photometry, which has been employed in particular by the Hubble Space Telescope Key Project on the extragalactic distance scale (Freedman et al., 2001). We find a significant effect in the sense that metal-poor stars are fainter than metal-rich stars by  $0.23 \pm 0.1$  mag per dex. The size of the effect is similar to the most recent one adopted by the Key Project group. This is a very reassuring result as our method is entirely independent from the methods that they have employed. In the case of the  $K$ -band, the effect is significantly (a factor of two) smaller and a null effect is consistent with the data. From the plot it is obvious that the constraint on the metallicity effect could be made even stronger by expanding the sample of SMC stars and thus decreasing the size of the error bar on this point. In fact this would probably provide the strongest constraint that is currently achievable.

### The projection factor problem

In our first application of the method to Milky Way and SMC Cepheids, we could only determine the slope of the PL relation for the Milky Way sample, since the five SMC Cepheids all had about the same pulsation period. However, we found that the slope of the Milky Way PL relations differed significantly from the slopes of the PL relations obtained for LMC Cepheids, based on their apparent luminosity and assuming the same distance to all the LMC Cepheids. If this were to hold true, the PL relation would be a very poor extragalactic yardstick.

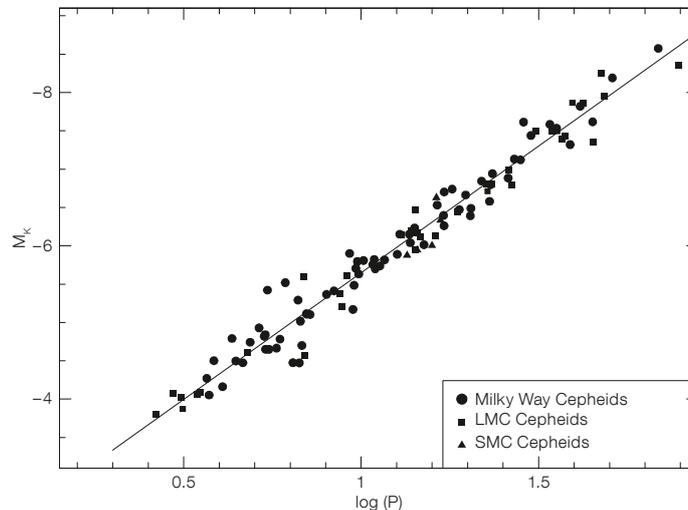


Figure 4. The universal  $K$ -band period–luminosity relation based on 111 Milky Way, LMC and SMC Cepheids is shown.

Gieren et al. (2005) applied the method to LMC Cepheids and found the first evidence that the slopes are in fact the same in both the Milky Way and in the LMC, but due to the availability of observations for only a few stars, the conclusion was not very firm. With the new data we confirm our findings from 2005, namely that the slopes are the same for the two samples, but the projection factor has a stronger period dependence than originally anticipated, or at least there is a period dependence of the method which earlier had not been accounted for. Using the Benedict et al. (2007) method, and taking trigonometric parallaxes for ten Cepheids to set the zero point and insisting that the distances we derive for LMC Cepheids are independent of pulsation period, we can well constrain the period effect and include it in the projection factor. Nardetto et al. (2011) and references therein discuss from a theoretical point of view the possible stellar atmosphere physics entering into the projection factor and they actually find a steeper relation than adopted in the past, albeit not as steep as we find from our purely empirical approach. This difference implies that there is some physics somewhere which is still not well understood.

### The universal PL relation

With the modified projection factor from above and the knowledge that the

effect of metallicity is very limited for metallicities between that of the SMC and the Milky Way, we can then combine the  $K$ -band luminosities for all 111 Cepheids from the Milky Way, the LMC and the SMC. In Figure 4 we show the relation. The dispersion is about 0.22 mag and is dominated by distance errors from our analysis. However the resulting relation is based on 111 stars so the slope and zero point are statistically very well-defined. The LMC Cepheids provide an LMC distance modulus of  $(m-M)_0 = 18.45 \pm 0.04$  mag.

Persson et al. (2004) found the dispersion for their LMC PL relation in the  $K$ -band to be less than 0.1 mag, so the  $K$ -band PL relation is an extremely powerful distance indicator, even for individual Cepheids. As the  $K$ -band is only weakly absorbed by interstellar dust and, as shown here, the PL-relation is only weakly dependent on metallicity, it has all the characteristics of an excellent distance indicator.

### References

- Benedict, G. F. et al. 2007, *AJ*, 133, 1810
- Fouqué, P. & Gieren, W. 1997, *A&A*, 320, 799
- Freedman, W. L. et al. 2001, *ApJ*, 553, 47
- Gieren, W. et al. 2005, *ApJ*, 627, 224
- Kervella, P. et al. 2004, *A&A*, 428, 587
- Nardetto, N. et al. 2011, *A&A*, 534, L16
- Persson, S. E. et al. 2004, *AJ*, 128, 2239
- Soszyński, I. et al. 2008, *Acta Astr.*, 58, 163
- Storm, J. et al. 2004, *A&A*, 415, 531
- Storm, J. et al. 2011a, *A&A*, 534, A94
- Storm, J. et al. 2011b, *A&A*, 534, A95