The Classical Cepheid Distance scale in the NIR bands

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Abstract. The Period–Luminosity (PL) relation of classical Cepheids is one of the most popular standard candle, being the first rung of the cosmic distance ladder. We discuss both theoretical and empirical features of the PL, Period–Luminosity–Color (PLC) and Period–Wesenheit (PW) relations using the largest optical ($V, I$; OGLEIII) and near-infrared (NIR, $J, H, K_S$; IRSF/SIRIUS) data sets ever collected for classical Cepheids in the Magellanic Clouds (MCs). The MCs are indeed a fundamental benchmark to calibrate the cosmic distance scale. We found that the PW relations are linear over the entire period range and show a very low dispersion. Moreover, their slopes appear independent of the metallicity since they attain similar values in the MCs and in the Galaxy. This indicates that Cepheids in NIR bands obey to universal PW relations.

1. Introduction

Classical Cepheids play a key role in constraining the cosmic distance scale. They are yellow supergiant variable stars, they can be observed at great distances and they obey to a well known Period–Luminosity (PL) relations. Since its discovery by Miss Henrietta Leavitt in the 1912, the PL relation has played a pivotal role in constraining Galactic and extra-galactic distances, leading to the discovery of the expansion of the Universe by Edwin Hubble. However, after one century the universality of the Cepheid PL relations is still under debate. This means the possibility to use the Galaxy-calibrated Cepheid PL relations to estimate the distance of any galaxy containing Cepheids, independent of its chemical composition. During the last ten years theoretical and observational efforts were devoted to investigate the dependence of the Cepheid pulsation properties on metallicity. Indeed, a metallicity dependence could introduce systematic errors in the evaluation of extragalactic distances, and in turn on the Hubble constant, $H_0$ [3].

In this investigation, we briefly summarize some of the main problems affecting the Cepheid distance scale in the near-infrared (NIR, $J, H, K_S$) bands. In particular, we analyze the PL
relations in the NIR bands for the Cepheids of the Magellanic Clouds (MCs), using the largest NIR data set ever collected.

2. The PL and PLC relations

At the basis of all Cepheid distance determinations lies a Period–Luminosity–Color (PLC) relation:

\[ M_\lambda = \alpha_\lambda + \beta_\lambda \log P + \gamma_\lambda (CI)_0 \]  

(1)

where \( M_\lambda \) is the magnitude in the \( \lambda \) photometric band (i.e. \( \lambda = B, V, I, J, H, K_S, \ldots \) ) and \((CI)_0\) is the mean intrinsic color index. Traditionally, the relation widely used to estimate Cepheid distances is the PL relation found by H. Leavitt: \( M_\lambda = \alpha_\lambda + \beta_\lambda \log P \). This relation is the projection on the Period–Magnitude plane of the correct PLC relation. Since only the PLC relation can account for the Cepheid pulsational properties, the PL relation is expected to have an intrinsic dispersion. The PLC relations is a simply restatement of the Stefan’s law that is applicable to stars on individual basis. The Cepheid instability strip defines a range of luminosity, colors and periods over which pulsation is a stable mode for the star and is therefore an observable: these constraints control the statistical properties of the ensemble of Cepheid variable stars. Recent theoretical predictions based on nonlinear, convective Cepheid models indicate that the instability strip boundaries in the Period-Magnitude planes are better described by quadratic P–L relations [1]. If we look at the Fig. 1 we note that at each given luminosity the pulsation instability occurs over a finite range of effective temperatures. This finite width of the instability strip and particular distributions of Cepheids within the instability strip cause indeed an intrinsic scatter in any PL relation.

![Figure 1](image-url)  

Figure 1. The evolutionary track for stars with different masses. The red and the blue boundaries of the instability strip, according to [1], are also overplotted (blue and red solid lines). The tracks of the intermediate \((5M_\odot)\) and \((8M_\odot)\) mass stars cross the instability strip three times and the \((10M_\odot)\) stars crosses it once, while the track of low mass star \((2M_\odot)\) do not cross the strip at all.

Moreover, when we consider the observable quantities, we have to take into account the effect of interstellar reddening and absorption. It’s difficult to separate the effects of extinction from the effect of metallicity in equation 1 (this is the so called: metallicity–reddening degeneracy). However, the debate on the role played by the chemical composition on the pulsational properties of Cepheids is still open, with different theoretical models and observational results leading to markedly different conclusions. The atmospheres of stars like Cepheids, having effective temperatures typical of G and K supergiants, are affected by changes in the atmospheric metal abundance (these changes in chemical composition produce also a change in the overall stellar structure). Thus, it is expected that the colors and magnitudes of Cepheids, and their
corresponding PL relations, should be a function of metallicity. At each given luminosity an increase in the metal content shifts the instability strip toward cooler effective temperatures. This implies that metal-rich pulsators have on average longer periods than metal-poor ones with the same mass and luminosity. It turns out that the mean bolometric magnitude, at fixed period and for an uniformly populated instability strip, increases at larger metal contents. Owing to the dependence of the bolometric correction on the effective temperature, this effect is further enhanced when visual magnitudes are taken into account.

2.1. The NIR bands
Recent theoretical models predict that NIR PL relations are almost completely unaffected by metallicity and show also a smaller dispersion due to the reduced width of the instability strip [1]. These models predict a metallicity dependence of the PL relations in V and I, but empirical analyses of the metallicity corrections to Cepheids distances have not yet achieved a firm result. Moreover, reddening and absorption are much smaller at longer wavelengths. At the J, H, Ks wavelengths, interstellar reddening and absorption, and the sensitivity to heavy-element abundance are all much smaller. We also have to observe that, as a results of the physical proprieties of Cepheids, the PL Relations in the infrared show less scatter because the width in temperature of the instability strip is narrower. Moreover, the pulsation amplitude of a single Cepheid decreases for increasing wavelength. These means that we can approximate the mean NIR magnitude with the single epoch measurement taken at a given pulsation phase. A huge amount of data collected by the automatic surveys become available in the NIR bands, and the use of these single epoch measurements leads to a larger statistical significancy of the PL relations.

3. The PW relations
The Wesenheit indices was introduced by [4], who define a Wesenheit magnitude, W, by:

$$W(V, I) = V - R_{VI} \times (V - I);$$

where the ratio of total-to-selective absorption $R_{VI} = A_V / E(V - I)$ is adopted by [2], $A_V$ is the absorption and $E(V - I)$ is the color excess or reddening. By construction this Wesenheit parameter is reddening-free:

$$W(V, I) = V_0 + A_V - R_{VI} \times (V - I)_0 - R_{VI} \times E(V - I) =$$

$$= V_0 - R_{VI} \times (V - I)_0 + A_V - R_{VI} \times E(V - I)$$

where $A_{VI} = R_{VI} \times E(V - I)$ in the last term, so $W(V, I) \equiv W_0(V, I)$, which is the de-reddened W magnitude. Thus, W, for any given star, is dimmed only by distance and it is unaffected by extinction by its definition, but only to the degree that $R_{VI}$ is known and is universal. Similarly any Wesenheit parameter based on an apparent magnitude, color, and a given reddening law can be computed for any combination of optical/near-IR bandpasses. The advantage of using these parameters is that uncertainties in the amount of extinction toward any given Cepheid, whether in the Magellanic Clouds or within the set of Galactic calibrators, is avoided once that the reddening law, which controls $R_V$ and the analogous ratios for other Wesenheit parameters ($R_{\lambda_1, \lambda_2}$), is chosen. Cepheids obey to the Period-Wesenheit (PW) relation:

$$W(\lambda_1, \lambda_2) = \alpha_{\lambda_1, \lambda_2} + \beta_{\lambda_1, \lambda_2} \log P$$

where $\lambda_1, \lambda_2$ are any pair of photometric band. Theoretical predictions [1] show that these relations are quite tight, and show several additional advantages: they are almost independent
of the pulsator distribution within the instability strip; they are linear over the entire period range; the effects of the mixing-length \( l/H_p \) at fixed metal (Z) and Helium content (Y) on both the slope and zero-point are negligible; the adopted Y, at fixed Z and mass-luminosity relation, only affects the zero–point of the relations, while their slopes turn out to be almost independent of the chemical composition.

4. The PL and PW relations for the MCs

For this work we have used the OGLE - III Catalog of Variable Stars (CVS) and the IRSF/SIRIUS Catalog. The OGLE-III CVS [8] is a free catalog that can be downloaded at http://ogledb.astrouw.edu.pl/ogle/CVS/. The InfraRed Survey Facility (IRSF) is located at the Sutherland observing station of the South African Astronomical Observatory (SAAO). It carried out an imaging survey of the MCs in the NIR bands \( J \) (1.25 \( \mu \)m), \( H \) (1.65 \( \mu \)m) and \( K_S \) (2.14 \( \mu \)m). The single–epoch \( J,H,K_S \) magnitudes for the OGLE-III FU Cepheids were extracted from the IRSF/SIRIUS Survey by [5]. We have then collected a sample of 3042 for the Large Magellanic Cloud (LMC) and 4150 for the Small Magellanic Clouds (SMC) Cepheids with \( V,I,J,H,K_S \) single–epoch measurements (see Fig. 2,Fig. 3 and Fig. 4). Using this dataset we can analyze the main features of the PL and PW relations. The data showed in Fig. 2 compare the PL(\( V \)) and PW(\( V,J \)) relations in the Optical bands for the LMC. According to the theoretical predictions discussed in the above section, thePW relation in Fig. 2 is tight and linear over the entire range of period. When we move to the NIR bands, we find that the PL is narrower [9]. The data showed in Fig. 3 compare the PL(\( J \)) and PW(\( J,K_S \)) relations in the NIR bands for the LMC. The dispersion around the PL(\( J \)) relation (left panel) is still large, due to the reddening effects, while the PW(\( J,K \)) (right panel) relation is very tight, as expected. The comparison between the PL(\( J \)) and PW(\( J,K_S \)) relations in the NIR bands for the SMC is given in Fig. 4. The dispersion around the PL(\( H \)) relation (left panel) and the PW(\( H,K_S \)) relation (right panel) are quite similar (a detailed discussion on the PW relations for MCs is given in Inno et al.,2012, in preparation). In the case of the PL(\( H \)) relations the dispersion can be related to the reddening, while for the PW relations, it is due to the intrinsic feature of the SMC, since the galaxy is elongated along the line of sight [10]. According to theoretical predictions, we can assume then that the dispersion around the PW relation is due only to the individual distances of Cepheids. The PW relation can than be used as a tool to investigate the geometry and the three dimensional structure of the MCs.

**Figure 2.** Comparison between the PL(\( V \)) (left panel) and PW(\( V,J \)) (right panel) relations for the LMC. Red dots display OGLE-III mean magnitudes for FU pulsators and green dots are the mean magnitude for FO pulsators. The solid lines show the linear fits. The dispersion around the PL is large and also non linear effect are evident, while the PW(\( V,J \)) relation shows linearity and also a very low dispersion.
Figure 3. Comparison between the PL($J$) and PW($J,K_S$) relations for the LMC. Red dots display IRSF/SIRIUS mean magnitudes for FU pulsators, while purple dots are the mean magnitude for 41 Cepheids by P04. The green dots are the mean magnitude for FO pulsators. The solid lines show the linear fits. The dispersion around the PL relation (left panel) is still large, due to the reddening effects, while the PW($J,K_S$) (right panel) relation is very tight.

Figure 4. Comparison between the PL($H$) and PW($H,K_S$) relations for the SMC. Red dots display IRSF/SIRIUS mean magnitudes for FU pulsators, and the green dots are the mean magnitude for FO pulsators. The solid lines show the linear fits. In this case we find that the dispersion around the PL($H$) relation (left panel) and the PW($H,K_S$) relation (right panel) are quite similar. This is due to the intrinsic properties of the SMC.

5. Conclusions
The main aim of this work is to investigate the properties of the Cepheids as distance indicators. Classical Cepheids play a key role in distance determinations, and the Magellanic Clouds are the fundamental benchmark to calibrate the astronomic distance scale. In particular we focused on the PL relations for the MC Cepheids and we find that, when we move from Optical ($V$) to NIR bands, the dispersion due to non-linearity effects is lower, according to theoretical models. Moreover, metallicity effects on the PL relation are expected to decrease in amplitude with increasing wavelength. Although the extinction term is also reduced in the NIR bands, we need to correct the PL for reddening effects. Another approach is to use the Wesenheit functions. In studying the PW relations for MCs Cepheids we find that they are linear over the entire range of the period, as predicted by theoretical models. Moreover we find a very low statistic dispersion around the PW relation, suggesting that the Wesenheit function can be safely used to derive individual Cepheid distances (see also [6]). The last and most important finding is that the PW relations in both the MCs are very similar, supporting the theoretical prediction that the slope of the PW relations is metallicity independent. Current finding thus suggest the possibility of a universal PW relation for Cepheids.

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