

Cepheid distances from the Baade–Wesselink method

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Abstract. Recent progress on Baade–Wesselink (BW)-type techniques to determine the distances to classical Cepheids is reviewed. Particular emphasis is placed on the near-infrared surface-brightness (IRSB) version of the BW method. Its most recent calibration is described and shown to be capable of yielding individual Cepheid distances accurate to 6%, including systematic uncertainties. Cepheid distances from the IRSB method are compared to those determined from open cluster zero-age main-sequence fitting for Cepheids located in Galactic open clusters, yielding excellent agreement between the IRSB and cluster Cepheid distance scales. Results for the Cepheid period–luminosity (PL) relation in near-infrared and optical bands based on IRSB distances and the question of the universality of the Cepheid PL relation are discussed. Results from other implementations of the BW method are compared to the IRSB distance scale and possible reasons for discrepancies are identified.

Keywords. Cepheids, distance scale

1. Introduction

Since its original conception by Baade (1926) and Wesselink (1946), the Baade–Wesselink (BW) method has been used, and refined over time, to calculate the radii of and distances to radially pulsating stars, in particular classical Cepheid variables. The method fits the observed radial velocity curves of Cepheids to their angular-diameter curves (derived interferometrically or by some equivalent means). This allows to establish an independent astrophysical distance scale, which is extremely useful to check Cepheid distances derived using other methods, particularly based on Cepheids in open clusters, and to independently establish period–luminosity (PL) relations in both the Milky Way and the Magellanic Clouds (e.g., Storm *et al.* 2011a,b). In this paper, we review the state of the art in BW distance determination, focusing on using the most recent calibrations of the method reported in the literature.

2. Distances based on the infrared surface-brightness (IRSB) version of the Baade–Wesselink method

The infrared surface-brightness (IRSB) version of the BW method was introduced by Fouqué & Gieren (1997). It employs the $(V - K)$ color of Cepheid variables to calculate their surface brightnesses, from which the angular diameters at the corresponding pulsation phases are derived. In this way, VK photometry of a Cepheid through its pulsation cycle provides its angular-diameter curve. In the original calibration of the surface-brightness–color relation of Fouqué & Gieren (1997), interferometrically determined angular diameters of non-pulsating giants and supergiants with colors similar to Cepheids were used. The surface-brightness–color relation later obtained from phase-resolved angular diameters of a sample of nearby Cepheids by Kervella *et al.* (2004a) with the European Southern Observatory’s (ESO) *Very Large Telescope Interferometer* demonstrated that the relation, obtained directly from the Cepheids, agrees to better than 2% with that derived from stable giants (Kervella *et al.* 2004b). An example is shown in Fig. 1 for ℓ Car, the Cepheid with the largest angular diameter in the sky.

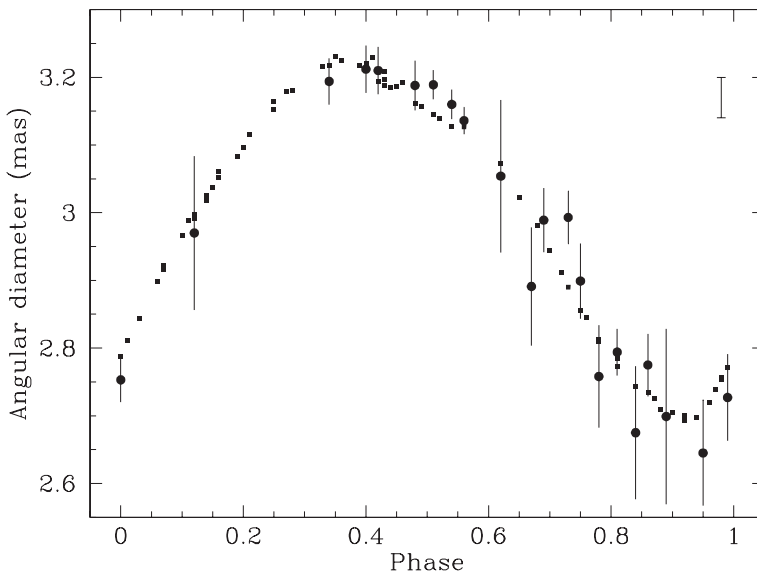


Figure 1. Black bullets: Interferometric angular-diameter measurements for the Cepheid ℓ Car. Blue squares: Angular diameters calculated using the IRSB technique. The agreement is at the 1% level (see Kervella *et al.* 2004b).

To calculate the radius variation of a Cepheid from its observed radial velocity curve, the p factor—which converts a radial to a pulsational velocity—must be known for the star of interest. In earlier work (Gieren *et al.* 1993, 1997, 1998; Storm *et al.* 2004), a slightly period-dependent p factor was adopted based on the models of Hindsley & Bell (1986). In Gieren *et al.* (2005) the IRSB technique was applied for the first time to a small sample (13 stars) of Large Magellanic Cloud (LMC) Cepheids, producing an unexpectedly significant and unphysical period dependence of the distance moduli of LMC Cepheids. This suggested a stronger dependence of the p factor on pulsation period than predicted by Hindsley & Bell (1986) and led to the relation $p = 1.58 - 0.15 \log P$ (days). Storm *et al.* (2011a,b) confirmed the Gieren *et al.* (2005) result of a steep p -factor law by extending the analysis to 36 Cepheids in the LMC for which very accurate radial velocity curves were obtained with the HARPS instrument at ESO/La Silla, and

for which accurate photometry was available from Persson *et al.* (2004) in the K band and from OGLE III in the V band. Simultaneously, Storm *et al.* (2011a,b) also obtained new radial velocity data for a number of Milky Way (MW) Cepheids. Based on the combined MW and LMC Cepheid data set, the IRSB technique was re-calibrated using the two constraints that (i) the IRSB Cepheid distances must agree with the *Hubble Space Telescope* parallax distances of 9 MW Cepheids (Benedict *et al.* 2007; the binary Cepheid W Sgr was excluded because its bright blue companion produces a spurious IRSB solution), and (ii) that the tilt-corrected (van der Marel & Cioni 2001) LMC Cepheid distances do not depend on their pulsation periods. These requirements led to a p -factor law, $p = 1.55 - 0.186 \log P$ (days), which agrees within the uncertainties with the Gieren *et al.* (2005) result.

Storm *et al.* (2011a,b) used their new calibration of the IRSB method to provide PL relations for the MW and LMC Cepheid samples in the optical V , I , and $(V - I)$ Wesenheit bands and in the near-infrared J and K bands. Particularly in the near-infrared bands, the Galactic and LMC PL relations show excellent agreement for both their slopes and zero points. In the K band, the relations are $M_K = (-3.33 \pm 0.09)(\log P - 1) - (5.66 \pm 0.03)$ (MW), and $M_K = (-3.28 \pm 0.09)(\log P - 1) - (5.64 \pm 0.04)$ (LMC). There is also excellent agreement with the slope observed by Persson *et al.* (2004) for the LMC K -band PL relation (-3.26 ± 0.02) . These results suggest that the K -band PL relation for classical Cepheids is universal across the metallicity range from solar down to the typical LMC Cepheid metallicity (approximately -0.4 dex; Luck *et al.* 1998; Romaniello *et al.* 2008). The excellent agreement of the MW and LMC PL relations at K allows us to construct a common PL diagram, which is shown in Fig. 2 and can be used directly for distance determination to galaxies containing sizeable samples of classical Cepheids. The distance to the LMC's barycenter implied by the Storm *et al.* results is $(m - M)_0 = 18.45 \pm 0.04$ (statistical) mag. The MW and LMC PL relations in the optical V and I bands agree within their uncertainties, but there is a marginally significant metallicity effect in the W_I band, -0.23 ± 0.10 mag dex $^{-1}$ (more metal-rich Cepheids are more luminous for a given period than their more metal-poor counterparts).

3. Comparison of IRSB and cluster zero-age main-sequence-fitting Cepheid distance scales

IRSB distances were calculated for 18 Galactic open cluster Cepheids whose cluster membership was established with a high level of confidence. Their zero-age main-sequence (ZAMS)-fitting distances were adopted from Turner (2010) and supplemented with the recent ZAMS-fitting distances to the cluster Cepheids TW Nor (Majaess *et al.* 2011), SU Cas (Turner *et al.* 2012), δ Cep (Majaess *et al.* 2012a), and ξ Gem (Majaess *et al.* 2012b). From these data, we find a mean difference, $(m - M)_{\text{ZAMS}} - (m - M)_{\text{IRSB}} = +0.07 \pm 0.09$ mag, showing that the IRSB and cluster Cepheid distance scales currently agree at the 3% level. This excellent agreement between the two completely independent distance scales is exemplified by Fig. 3.

4. Results from other implementations of the Baade–Wesselink method

Other recent implementations of the BW method, such as that used by Groenewegen (2007) or Joner & Laney (2012), have found (on average) rather similar distances to individual Cepheids despite their use of different p factors for the conversion from radial to pulsational velocities. Groenewegen (2007) finds evidence of a constant p factor of

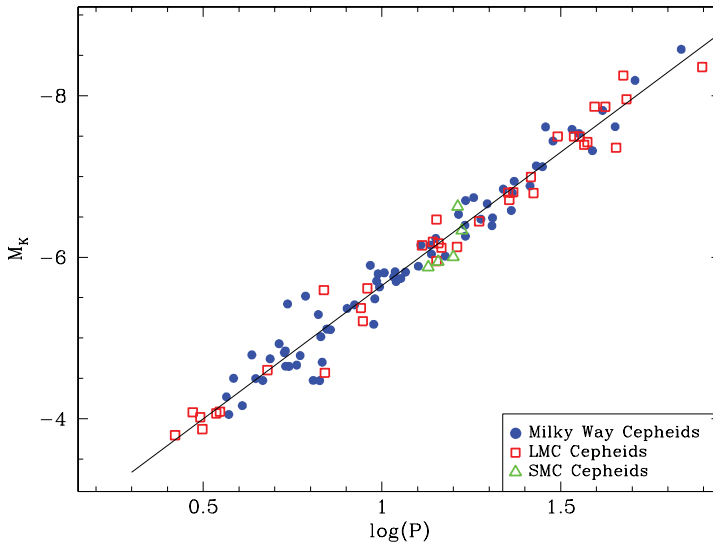


Figure 2. Composite K -band Cepheid PL relation obtained from IRSB distances to 70 Cepheids in the MW, 36 in the LMC, and five in the Small Magellanic Cloud (SMC). The K -band PL relation is independent of metallicity in the range from solar to the typical SMC Cepheid metallicity.

1.27 (albeit with a large scatter for individual Cepheids) based on his calibrating sample with adopted distances from their known parallaxes. Jonev & Laney (2012) adopt a slope of -0.07 , which is in good agreement with the theoretical prediction of Nardetto *et al.* (2009). Both versions of the BW technique actually derive the mean radii of the Cepheids, which are then transformed to luminosities and distances adopting a particular effective temperature scale.

Very recently, the CORS method (Caccin *et al.* 1981) was re-calibrated by Molinaro *et al.* (2011) and applied to the massive young LMC cluster NGC 1866, which contains more than 20 classical Cepheid variables (Molinaro *et al.* 2012). The CORS BW technique is a semi-theoretical approach; it uses Walraven photometry and calibrates the Cepheid surface brightness using a grid of atmosphere models. Adopting $p = 1.27$, the V -band magnitudes of Molinaro *et al.* (2012) are systematically brighter, by approximately 0.2 mag, than the V -band magnitudes of Storm *et al.* (2011a). The likely overestimation of Cepheid absolute magnitudes, and, thus, their distances based on the CORS method becomes evident in the application of the technique to five Cepheids in NGC 1866 with periods clustering around 3 days, that are in common with the Storm *et al.* (2011b) sample. If Storm *et al.* had used $p = 1.27$ instead of $p = 1.46$ as predicted by the IRSB p -factor law for Cepheids of $P \sim 3$ days, the IRSB distance modulus of NGC 1866 would become 18.14 mag, which is clearly unreasonably short, and ~ 0.4 mag shorter than the CORS mean distance for these five variables. On the other hand, the CORS distance modulus to NGC 1866 is 18.57 mag, which is only 0.12 mag larger than the average LMC distance derived from the IRSB method by Storm *et al.* (2011a,b).

It is important to stress that the only version of the BW method which has used LMC Cepheids as a constraint for the calibration (demanding that LMC Cepheid distances must be independent of their periods) is the IRSB technique as calibrated by Storm *et al.* (2011a,b), which places additional weight on this particular BW method.

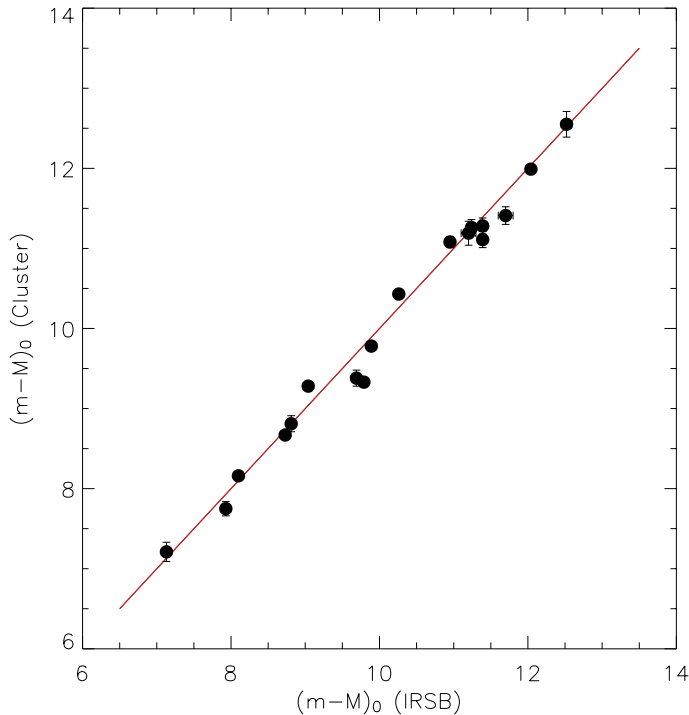


Figure 3. ZAMS-fitting distance moduli for 18 open cluster Cepheids versus their IRSB distance moduli calculated based on the prescription of Storm *et al.* (2011a). The agreement between the open cluster and IRSB distance scales is at the 3% level.

5. Discussion

The most important current systematic uncertainty affecting any version of the BW method is which p -factor law to adopt. Recently, Ngeow *et al.* (2012) used revised *Hipparcos* parallaxes (9 Cepheids) and ZAMS-fitting distances (16 cluster Cepheids) for a sample of 25 MW Cepheids in common with Storm *et al.* (2011a) to derive their individual p -factor values by requiring that the independent distances should agree with the IRSB distance determination. This work fully confirmed the steep p -factor law of Storm *et al.* A very recent study by Groenewegen (2013) using MW and LMC Cepheids also confirms the steep Storm *et al.* p -factor law, resulting in an even steeper dependence of p on the pulsation period. This makes it very likely that the conclusions about the universality of the Cepheid PL relation reached by Storm *et al.* are correct. How is it then possible that other BW-method implementations (perhaps except the latest implementation of the CORS method) using different p -factor laws quite frequently produce distances to individual Cepheids that are consistent with the IRSB determination? The answer seems to be, at least in part, that different implementations of the BW method require different p -factor laws. This, in turn, tells us that there is physics hidden in the p factor which is not yet fully understood or taken into account in the theoretical modeling of Cepheid atmospheres. This may be the reason why these models currently predict a relatively shallow dependence of p on period, in contrast to the IRSB results (Nardetto *et al.* 2009; also this volume). It is also possible (likely) that the p -factor relation for classical Cepheids exhibits an intrinsic dispersion. It seems to be independent, however, of the metallicity (Nardetto *et al.* 2011).

Future precision measurements of the p factors of Cepheids, particularly of short-period Cepheids, will be very important. There is hope that direct interferometric angular-diameter measurements (e.g., Mérand *et al.* 2005; Gallenne *et al.* 2012) will improve sufficiently to meet that goal. An interesting alternative is the analysis of Cepheids in eclipsing binaries, allowing an accurate distance determination based on application of the binary method (Pietrzyński *et al.* 2009, 2010, 2011), which promises to yield accurate p -factor measurements for these binary Cepheids.

Another possibly important source of systematic uncertainties in BW distances derived from infrared photometry is the recent detection of circumstellar shells around Cepheids (Kervella *et al.* 2006; Mérand *et al.* 2006, 2007; Gallenne *et al.* 2011). The effect on the flux in the K band is 1–4% for the (few) Cepheids which have been studied in this context so far, which may affect (reduce) the IRSB distances by up to 4%. It has yet to be seen how ubiquitous such shells are in order to assess more reliably their possible effect on BW distance determinations. If there are few Cepheids with strong flux contributions from circumstellar shells, these stars could be omitted from samples used for calibration or distance determination, similarly to binary Cepheids which are known members of systems hosting relatively bright companion stars.

Currently, BW distance determinations based on a variety of different implementations of the method reach statistical uncertainties of 1–2% for Cepheids using excellent existing data sets. The systematic uncertainties affecting these distances limit current BW distances to individual Cepheids to approximately 6% accuracy. There is room for improvement over the next few years along the lines discussed here. Theoretical models still seem to miss important physics and must be improved to produce predictions which can be reconciled with observational facts.

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