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Wesenheit function for Galactic Cepheids: Application to the projection factors

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Abstract. Galactic Cepheids are necessary tools for calibrating the period–luminosity relation, but distances to individual Galactic Cepheids are difficult to measure precisely and their application is limited to a small number of techniques, such as direct parallax measurements, main-sequence fitting to open clusters that host Cepheids, and Baade–Wesselink (BW)-type methods. Here, we re-examine the application of Wesenheit functions in determining distances to more than 300 Galactic Cepheids by taking advantage of the fact that the Wesenheit function is extinction-free by definition. Wesenheit distances are used to calibrate the projection (p) factor for Galactic Cepheids that also have BW distances. Based on ∼70 Cepheids, we find that the period–p-factor relation may exhibit a nonlinear trend with a considerable scatter. We found discrepant p factors for δ Cephei in the literature. This may be due to inconsistent measurements of its angular diameter using different empirical techniques. We discuss the reason for the inconsistency in angular-diameter measurements and offer a possible remedy.

Keywords. Cepheids, stars: distances, distance scale

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1. Introduction

Distance determinations to Galactic classical Cepheids (hereafter Cepheids) have important implications for modern distance-scale applications. In contrast to Cepheids in external galaxies for which the assumption of equidistance is met, Cepheids in our Galaxy range in distance from 100 pc to tens of kiloparsecs. Several methods exist to measure distances to individual Galactic Cepheids. These include (a) direct parallax measurements (for example, based on *Hipparcos*, the *Hubble Space Telescope (HST)*, and *Gaia* in the future), (b) Baade–Wesselink (BW)-type techniques (which come in several variants, including infrared surface-brightness methods, interferometric measurements of angular diameters, the CORS method of Caccin *et al.* [1981], and others), (c) main-sequence (MS) fitting to open clusters or associations that host Cepheids, and (d) the light-echo technique (RS Pup is currently the only Cepheid with a distance measured using this technique). These methods have only been applied to fewer than ∼ 200 Cepheids, and in some cases more than one method may be applicable to a given Cepheid. In contrast, more than ∼ 1000 Galactic Cepheids have been identified to date. In the absence of independent methods, applying a calibrated/theoretical period–luminosity (PL) relation, or a period–luminosity–color (PLC) relation, seems to be the only way to derive distances to Galactic Cepheids. However, applying a PL relation requires that the extinction to a given Cepheid be known *a priori*, and the error budget in the derived distances will have to include the intrinsic dispersion associated with the PL relation (which can be on the order of ∼ 0.2 mag at optical wavelengths). In addition, the metallicity dependence of the PL relation is still being debated. An alternative option is to use the Wesenheit function to derive distances to Galactic Cepheids (Opolski 1983; Ngeow 2012), when other independent methods cannot be applied.

2. Wesenheit distances and calibration of projection factors

The Wesenheit function adopted here is of the form $W = I - 1.55(V - I)$. In addition to being extinction-free by definition (Madore 1982), this form of the Wesenheit function also has the following advantages: (a) its intrinsic dispersion is reduced by $\sim$ 2–3$\times$ compared to optical PL relations (Madore & Freedman 2009; Ngeow *et al.* 2009); (b) it is linear (Ngeow *et al.* 2009); and (c) it is insensitive to metallicity (Bono *et al.* 2010; Majaess *et al.* 2011). The Wesenheit function used in this work is derived based on $\sim$ 1500 Cepheids in the Large Magellanic Cloud (LMC), using the superb observations from the OGLE-III project, and the intercept has been calibrated based on 10 Galactic Cepheids that have accurate *HST* parallaxes (see Ngeow 2012 for more details). Hence, the Wesenheit distance to a given Galactic Cepheid can be calculated using $\mu_W = I - 1.55(V - I) + 3.313\log(P) + 2.639$, where the period ($P$) and mean VI-band magnitudes are the only unknowns. Ngeow (2012) compared the Wesenheit distances to Cepheids that also have independent distance measurements (including *Hipparcos* parallaxes, MS-fitting, and BW-type distances), with mean differences in distance moduli ranging from -0.06 to 0.01 mag. These results suggested that the Wesenheit distance can indeed be used to derive distances to individual Galactic Cepheids. A large sample of Galactic Cepheids with derived Wesenheit distances can be used to study the metallicity gradient and kinematics of our Galaxy, as well as for deriving (multi-band) Galactic PL relations. A discussion of some of these applications can be found in Ngeow (2012) and will not be repeated here. In this work, we present the application of Wesenheit distances to the calibration of projection (p) factors.

The p factor converts the (observed) radial velocity to a pulsational velocity. It is an important parameter in BW-type analyses and/or distance-scale applications. Since

$$\theta(t) = \theta_0 - \frac{2p}{D}\int [V_r(t) - \gamma]\mathrm{d}t, \tag{2.1}$$

the p factor is degenerate with distance D for the same set of observables (the angular diameters θ, radial velocities V_r, and gamma velocity γ). The p factor can be calibrated if a given Cepheid has both a BW-based and an independent distance, i.e. $p_{\rm new} = p_{\rm BW} \times (D_{\rm indep}/D_{\rm BW})$. Fig. 1 shows the calibrated p factors for a sample of $\sim$70 Galactic Cepheids, where $D_{\rm BW}$ are adopted from Storm *et al.* (2011), and $D_{\rm indep}$ values were calculated based on their Wesenheit distances. This figure reveals that the period–p-factor (Pp) relation may not be linear, and may exhibit an intrinsic scatter. Note, however, that the p-factor relation presented in Fig. 1 includes also a quantity which is not related to the physics of the p factor: it also includes (by construction) the individual discrepancies in our (BW and Wesenheit-function) distance indicators, which might also be related to the intrinsic dispersion of the PL relation or any other bias in the implementation of the methods.

The p factor for δ Cephei caught our attention. The p factor given in Storm *et al.* (2011), or that calibrated here, does not agree with the empirical determination by Mérand *et al.* (2005). Ngeow *et al.* (2012) further investigated this problem and found that the derived angular diameters using the infrared surface-brightness (IRSB) method of Storm *et al.* (2011) and the angular diameters empirically determined using interferometric techniques (Mérand *et al.* 2005) do not agree (see fig. 4 in Ngeow *et al.* 2012). Since the

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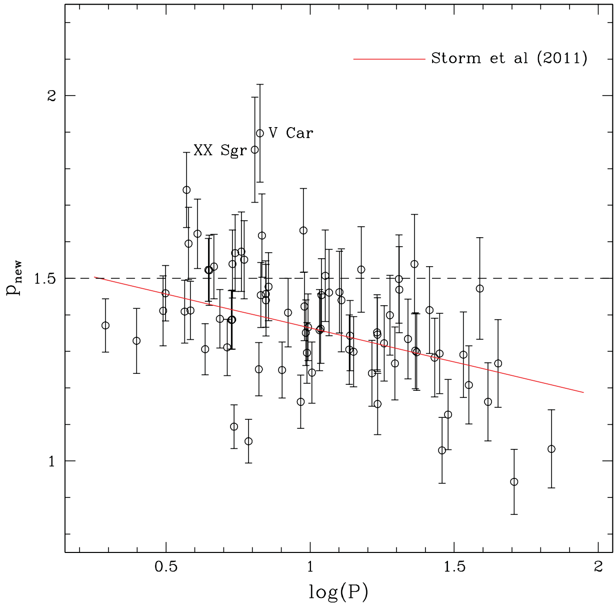

Figure 1. Calibrated p factors for Galactic Cepheids based on the Storm *et al.* (2011) sample. The error bars include the errors in both BW and Wesenheit distances. The horizontal dashed line represents the theoretical limit of the p factor (Nardetto *et al.* 2006; Storm *et al.* 2011). The Pp relation from Storm *et al.* (2011) is shown for comparison. A similar plot is shown in Ngeow *et al.* (2012), who calibrated the p factors using a smaller sample of Cepheids, with independent distances from either *Hipparcos* parallaxes or MS fitting to open clusters.

angular diameters are proportional to the p factor, as shown by Eq. (2.1)—at the same distance and using the same radial velocity curve—disagreement of angular diameters naturally leads to a corresponding disagreement in the p factors. Ngeow *et al.* (2012) postulate two possibilities to explain the disagreement in angular diameters:

(a) K-band flux excesses affecting the IRSB method. This flux excess is presumably due to the existence of a circumstellar envelope around δ Cephei, which could cause the angular diameters to be overestimated by $\sim 1\%$.

(b) Limb-darkening (LD) corrections associated with the interferometric technique. LD corrections, derived from plane-parallel atmospheres, need to be applied to interferometric measurements. Neilson *et al.* (2012) showed that the plane-parallel version of the LD corrections can underestimate the angular diameter by $\sim 2\%$ when a more appropriate LD correction based on spherically symmetric model atmospheres should be used.

To account for these 'biases,' angular diameters resulting from the IRSB method were reduced by 1% and those from interferometric measurements were increased by 2%. The adjusted angular diameters are compared in Fig. 2, showing good agreement. Using Eq. (2.1), adopting distances based on *HST* parallaxes, the combined angular diameters can be used to derive the p factor for δ Cephei, i.e. $p = 1.40 \pm 0.04$.

3. Conclusion

In the absence of independent methods and/or measurements, it is possible to derive the distances to individual Galactic Cepheids using the calibrated Wesenheit function. The derived Wesenheit distances are in good agreement with distances based on other

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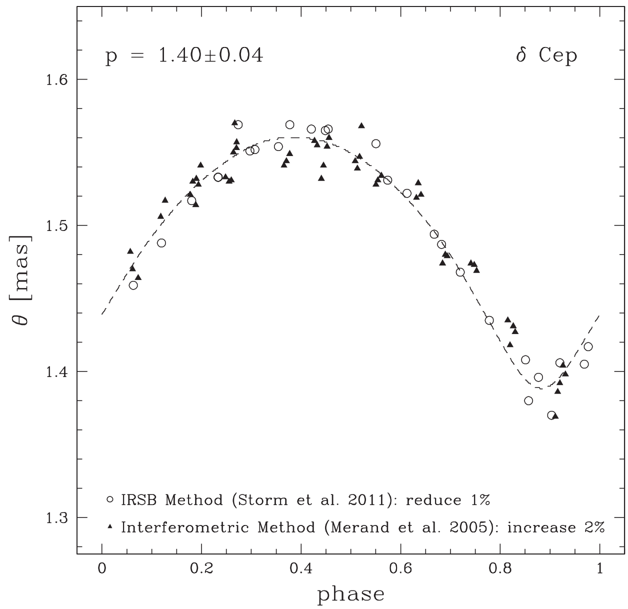

Figure 2. Comparison of the angular diameters resulting from the IRSB method (after reducing the original values by 1%) and from interferometric measurements (after increasing the original values by 2%). The curves are constructed using Eq. (2.1) by simultaneously fitting the angular diameters and p factor (for more details, see Ngeow *et al.* 2012). The fitted p factor is given in upper left-hand corner; it is still not consistent with the value by Mérand *et al.* (2005), who determined $p = 1.27$.

methods (such as *Hipparcos* parallaxes, BW-based distances, and distances from MS fitting), and can potentially be verified using *Gaia*'s parallaxes in the near future. Wesenheit distances can be applied to calibrate the p factors of Cepheids that also have BW distances. The calibrated p factors suggest that the Pp relation could be nonlinear and may exhibit an intrinsic scatter. For δ Cephei, the discrepant p factors found in literature, likely due to disagreements between angular diameters based on the IRSB and interferometric methods, can be remedied if the 'bias' in both methods can be corrected.

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