THE CEPHEID PERIOD-LUMINOSITY RELATION AND THE MASER DISTANCE TO NGC 4258

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ABSTRACT

In a recent paper describing Hubble Space Telescope observations of Cepheids in the spiral galaxy NGC 4258, Newman et al. report that the revised calibrations and methods for the Key Project on the Extragalactic Distance Scale yield that the true distance modulus of this galaxy is \( \mu_{0, 4258} = 29.40 \pm 0.09 \) mag, corresponding to a metric distance of \( 7.6 \pm 0.3 \) Mpc. This Cepheid distance, which holds for 18.50 mag as the true distance modulus of the Large Magellanic Cloud (LMC), is not significantly larger than 7.2 \pm 0.5 Mpc, the value determined by Herrnstein et al. from purely geometric considerations on the orbital motions of water maser sources. However, if the metallicity difference \( \Delta [O/H] \sim 0.35 \) between NGC 4258 and the LMC is taken into account, then the Key Project methods lead to a metallicity-corrected value of \( \mu_{0, 4258} = 29.47 \pm 0.09 \) mag, with \( \mu_{0, LMC} = 18.50 \) mag, namely, to a Cepheid distance of 7.8 \pm 0.3 Mpc, which is 1.2 \( \sigma \) from the maser determination. One might argue that these results are suggesting that a smaller distance to the LMC, \( \mu_{0, LMC} \sim 18.3 \) mag, should be used to calibrate the Cepheid brightness. However, even though the well-known controversy between short and long distance scale is far from being settled and current determinations of the LMC distance modulus span \( \sim 0.4 \) mag, it seems that the various empirical methods converge on the value adopted by the Key Project (see Carretta et al.). In this paper we show that the metallicity correction on Cepheid distance determinations, as suggested by pulsation models with three different chemical abundances \((Y = 0.25, Z = 0.004; Y = 0.25, Z = 0.008; Y = 0.28, Z = 0.02)\), might provide a natural way of reaching a close agreement between Cepheid and maser distances to NGC 4258 for a wide variety of LMC distance determinations. In fact, by adopting \( \mu_{0, LMC} = 18.50 \pm 0.10 \) mag we derive a Cepheid distance of 7.3 \( \pm 0.6 \) Mpc, which is only 0.2 \( \sigma \) from the maser determination, while using \( \mu_{0, LMC} = 18.60 \pm 0.10 \) or \( 18.40 \pm 0.10 \) mag, the Cepheid and maser distances are 0.8 \( \sigma \) and 0.4 \( \sigma \) apart, respectively.

Subject headings: Cepheids — galaxies: individual (NGC 4258) — Magellanic Clouds — stars: distances — stars: oscillations

1. INTRODUCTION

In recent papers, we have investigated in depth the pulsational properties of classical Cepheids on the basis of nonlinear, nonlocal, and time-dependent convective pulsating models where the coupling between pulsation and convection is properly taken into account. From computations with three different chemical abundances \((Y = 0.25, Z = 0.004; Y = 0.25, Z = 0.008; Y = 0.28, Z = 0.02)\) chosen to properly cover Cepheids observed both in the Magellanic Clouds and in the Galaxy, the pulsation amplitude and the average magnitudes of the pulsators are obtained and several predicted relations, e.g., period-luminosity (PL), period-color (PC), period-luminosity-color (PLC), and color-color (CC), in the \( B, V, R, I, J, K \) bands are provided. The discussion on the input physics and computing procedures and the whole set of predicted relations has already been presented (see Bono, Marconi, & Stellingwerf 1999a; Bono et al. 1999b; Bono, Castellani, & Marconi 2000a; Caputo, Marconi & Ripepi 1999; Caputo, Marconi, & Musella 2000a; Caputo et al. 2000b) and are not repeated here. We wish only to remark that both the slope and zero point of the predicted PL relations turn out to depend on metallicity, in the sense that metal-rich pulsators follow shallower PL relations and are on average fainter, for fixed period, than metal-poor ones.

On this basis, the metallicity correction to a true distance modulus \( \mu_0 \) determined from Cepheid PL relations at the Large Magellanic Cloud (LMC) has been evaluated (Caputo et al. 2000b) as given by \( \Delta \mu_0/\Delta \log Z \sim -0.27 \) mag dex\(^{-1}\), where \( \Delta \log Z \) is the difference between the metallicity of the Cepheids whose distance we are estimating and the LMC value \((Z \sim 0.008; \text{see Luck et al. } 1998)\). This result disagrees with earlier observational clues based on the analysis of Cepheids in different fields of M31 (Freedman & Madore 1990) and M101 (Kennicutt et al. 1998), which suggest an opposite metallicity effect on distance determinations (see also Kochanek 1997; Sasselov et al. 1997). Following Kennicutt et al. (1998), the metallicity correction is \( \Delta \mu_0/\Delta [O/H] \sim +0.24 \) mag dex\(^{-1}\), where \( \Delta [O/H] \) is the difference between the oxygen abundance of the Cepheid field and the LMC value \(([O/H] \sim -0.40; \text{see Pagel et al. } 1978)\). More recently, the revised procedures of the Hubble Space Telescope (HST) Key Project (Freedman et al. 2001) adopt a correction of \(+0.2 \pm 0.2 \) mag dex\(^{-1}\).

It should be noted that the empirical corrections have been estimated by forcing the slope of the Cepheid PL relations at different wavelengths to be that observed for the LMC. Since the pulsating models suggest also that the slope depends on the pulsator metallicity, we might suspect some systematic errors in the attempt to disentangle reddening from metallicity effects. We add that recent empirical studies on Galactic Cepheids seem to support the theoretical results. According to Groenewegen & Oudmaijer (2000), the \( V \) and \( I \) data of 236 Cepheids from the Hipparcos catalog do not exclude shallower PL relations than that...
observed for LMC Cepheids. Moreover, the V and K data of Cepheids in the Galactic open clusters with main-sequence fitted distances (Hoyle, Shanks, & Tanvir 2000) do suggest PLV and PLK slopes of $-2.1$ and $-2.82$, respectively, significantly flatter than the canonical LMC values of $-2.76$ (Freedman et al. 2001) and $-3.44$ (Lane & Stobie 1994).

In any case, even though the LMC distance is the benchmark of the Cepheid-calibrated distance scale, it would be reasonable to expect that the next most important role might be played by the metallicity of the observed Cepheids. We note that the oxygen abundance of distant galaxies with reasonable to expect that the next most important role mark of the Cepheid-calibrated distance scale, it would be great importance, since the distance to this galaxy has been obtained for LMC Cepheids. Moreover, the V834 CAPUTO, MARCONI, & MUSELLA Vol. 566 values of $Z$ respectively, significantly flatter than the canonical LMC abundance of distant galaxies with 2.55 $E(V - I)$, find that the Wesenheit-PL (hereafter N2001) relation of LMC Cepheids in the OGLE-II catalog is

$$W(VI) = 15.82(\pm 0.01) - 3.28(\pm 0.01) \log P$$

with a standard deviation of 0.08 mag.

Using this empirical WPL relation for the HST magnitudes of NGC 4258 Cepheids listed in N2001 and adopting $\mu_{0, \text{LMC}} = 18.50$ mag, we derive that the Cepheid distance to this galaxy is $\mu_{0,4258} = 29.42 \pm 0.09$ mag (random error) $\pm 0.08$ mag (standard deviation on WPL relation), in agreement with the Key Project result.

Let us now consider that the oxygen abundance adopted by N2001 for the HST fields in NGC 4258 is $[\text{O}/\text{H}] = -0.05 \pm 0.06$, which is 0.35 dex higher than that for the LMC Cepheids. In accordance with Freedman et al. (2001), the correction to the Cepheid distance modulus, as based upon current observational results, is 0.2 $\pm 0.2$ mag dex$^{-1}$. This yields that the distance modulus we have derived for the Cepheids in NGC 4258 must be increased by 0.07 $\pm 0.07$ mag.

In conclusion of this part of discussion, given the well-known debate on the LMC distance (see later), we can state that the Cepheid distance to NGC 4258, as inferred from LMC-based PL or WPL relations and empirical metallicity correction on the Cepheid distance scale, is given by

$$\mu_{0,4258} = \mu_{0, \text{LMC}} + 10.99 \pm 0.14 \text{ mag.}$$

2.2. Theoretical Models

Concerning the results of pulsating models, let us first compare the above empirical PL and WPL relations with the predicted ones for fundamental pulsators with $Z = 0.008$ and $Z = 0.02$.

In previous papers (e.g., Bono et al. 1999b; Caputo et al. 2000a), we have already shown that moving toward the shorter wavelengths the $M_j - \log P$ distribution of fundamental pulsators with mass larger than 5 $M_\odot$, i.e., period longer than $\sim 3$ days, is much better represented by a quadratic relation ($M_j = a + b \log P + c \log P^2$). However, if only periods shorter than $\log P = 1.5$ (as observed in the LMC) are considered in the final fit, then reliable linear solutions may be obtained. As for the $W(V, I)$ quantities, the predicted distributions with period are well represented by linear solutions over the whole range 0.5 $\leq \log P \leq 2.0$.

The values of the coefficients of the theoretical VI PL and WPL relations are given in Table 1. One finds that the slope of the predicted linear PLV and PLI relations with $Z = 0.008$ $(-2.75 \pm 0.02$ and $-2.98 \pm 0.01$, respectively) are in very good agreement with that provided by LMC Cepheids (see eqs. [1] and [2]). A fair agreement is also present between the empirical $(-3.28 \pm 0.01)$ and the predicted slope $(-3.17 \pm 0.04)$ of the WPL relation with $Z = 0.008$.

Concerning the zero points, one finds a very close agreement in the I band $(-1.95 \pm 0.01$ versus $-1.94 \pm 0.01$ in eq. [2]), whereas the predicted linear PLV relation with $Z = 0.008$ is fainter by $\sim 0.09$ mag than equation (1). Following the Key Project procedure, this yields that the theoretical PL relations would give a larger $\mu_0$ than 18.50 mag. This results also if the Wesenheit quantities are considered: at $\log P = 1$, the predicted WPL relation with $Z = 0.008$ gives a reddening-corrected magnitude of $-6.16 \pm 0.11$

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3 According to N2001, for NGC 4258, we consider DoPHOT photometry given the uncertainty on ALLFRAME.
In conclusion, both empirical LMC-based and theoretical WPL relations confirm that the true distance modulus of NGC 4258 is larger than the LMC value by 10.92 mag, on the condition that the Cepheids in NGC 4258 have the same metallicity as the LMC.

The pulsating models, however, suggest that for fixed period the metal-rich pulsators are generally fainter than metal-poor ones, with the difference in luminosity increasing toward the longer periods. As a consequence, if a higher metal content is adopted, then the true distance modulus inferred from the predicted relations should decrease, with the effect of metallicity increasing as the average period of the Cepheid sample moves toward longer periods. In fact, for the typical value of Galactic Cepheids, i.e., $Z = 0.02$, we determine $\mu_{0,\text{LMC}} = 18.65 \pm 0.14$ mag (total error) and $\mu_{0,4258} = 29.51 \pm 0.14$ mag.

Eventually, in accordance with the current oxygen abundance estimates for LMC ([O/H] $\sim -0.4$) and NGC 4258 ([O/H] $\sim -0.05 \pm 0.06$), adopting $\Delta \log Z = \Delta [O/H]$ and interpolating between the $Z = 0.008$ and $Z = 0.02$ results for NGC 4258, we derive that the predicted metallicity-corrected Cepheid distance modulus of NGC 4258 is given by

$$\mu_{0,4258} = \mu_{0,\text{LMC}} + 10.82 \pm 0.14 \text{ mag}, \quad (5)$$

which is 0.17 mag lower than the value determined with the empirical metallicity correction (see eq. [4]) for any adopted LMC distance.

### 3. Absolute Distances

According to Herrnstein et al. (1999), very long baseline interferometry observations of the NGC 4258 maser provide the way to determine a metric distance of $7.2 \pm 0.5$ Mpc, as inferred from simple geometric considerations of the speed and motions of the maser. This number, corresponding to a true distance modulus $\mu_{0,4258} = 29.28 \pm 0.15$ mag, appears to be the most accurate distance to faraway galaxies so far measured.

As for the Cepheid distance, its determination via equations (4) and (5) requires the knowledge of the absolute distance to the LMC. Given the well-known controversy between short and long distance scale, let us refer to the excellent reviews by Walker (1999) and Carretta et al. (2000), which provide a synthesis of LMC distance determinations.

As a whole (see also Fig. 1 in Clementini et al. 2000), the various distance indicators suggest a distance modulus in the range of $\sim 18.3 \sim 18.7$ mag and, according to the authors, they seem to converge on $18.54 \pm 0.07$ mag.
Concerning model atmospheres, the results presented in this paper rely on bolometric corrections and colors by Castelli, Gratton, & Kurucz (1997a, 1997b). The comparison of the adopted $V - I$ colors for solar metallicity with the more updated evaluations by Bessell, Castelli, & Plez (1998a, 1998b) shows that differences are negligible.

The remaining source of uncertainty in pulsation models deals with the treatment of convection and in particular the mixing length parameter ($\alpha$) adopted to close the nonlinear equation system (see Bono & Stellingwerf 1994 for details). The topology of the instability strip is affected by the $\alpha$ parameter in the sense that the strip narrows as $\alpha$ increases, with a larger effect on the red boundary (up to 300 K for an increase of 0.3 in the $\alpha$ parameter). Since the PL relations sensitively depend on the edges of the pulsation region (i.e., the distribution of pulsators within the instability strip), variations of the $\alpha$ parameter could in principle affect the PL relation coefficients, but with minor effects on the WPL relation (see Fig. 12 in Caputo et al. 2000a). The dependence of convective efficiency on metal abundance, however, might alter the metallicity effect on the Cepheid pulsation properties. Important clues on this critical issue are expected from the comparison between observed and modeled morphology of light and radial velocity curves (Bono et al. 2002; see also Bono, Castellani, & Marconi 2000c).

In conclusion, we cannot exclude that further refinements in pulsating models and more accurate parallaxes of Galactic Cepheids might lead to an LMC true distance modulus close to 18.50 ± 0.10 mag, the value suggested by empirical non-Cepheid methods.

One agrees that all the above discussion is based upon the assumption that the maser distance to NGC 4258 is correct. As presently we can rely on this unique maser distance, we hope that in the near future such a promising technique would increase the number of distance determinations to external galaxies with Cepheid observations. This seems fundamental for testing the whole pulsational scenario, as well as for setting the distance to LMC.

As for NGC 4258 itself, the number of observed Cepheids is rather small (15), so that new observations are needed to improve the statistics and reduce the uncertainties on PL distance determinations.

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