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THE DISTANCE TO THE LARGE MAGELLANIC CLOUD CLUSTER NGC 1866 FROM ITS CEPHEID MEMBERS

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ABSTRACT

We have derived distances to four Cepheid variables of similar periods (2.6–3.5 days) in the field of the young LMC cluster NGC 1866 using the visual surface brightness modification of the Baade-Wesselink method. For three of these variables, consistent distances are obtained which support their cluster membership and yield a true cluster distance modulus of 18.47 ± 0.20 mag. The distances have been corrected for the non-solar metallicity of −0.6 dex recently determined for NGC 1866 by Hilker et al. A fourth Cepheid, HV 12204, is shown to have a bright blue companion star which invalidates the Baade-Wesselink analysis; this Cepheid is likely to be a cluster member in a spectroscopic binary system.

We determine the radii of the variables and find consistent values in the narrow range between 26 and 31 $R_\odot$, which agree very well with the values expected from the galactic Cepheid period-radius relation.

Subject headings: Cepheids — galaxies: star clusters — Magellanic Clouds

1. INTRODUCTION

NGC 1866 is one of the richest young (~10^8 yr; Brocato et al. 1989) clusters in the LMC. This makes it an ideal object for studies of stellar evolution of intermediate-mass ($M \gtrsim 5\ M_\odot$) stars. The cluster is also outstanding for its richness in Cepheid variables; more than 20 have been discovered (Welch, Mateo, & Olszewski 1993) since the pioneering studies of Arp (1967), and Arp & Thackeray (1967), which is far more than in any other LMC cluster. This latter property offers the unique opportunity to derive an accurate distance to the cluster from its Cepheid variables, which is essential for cluster studies themselves (allowing to obtain accurate absolute magnitudes of the cluster stars), and for deriving an accurate distance to the LMC, which is still uncertain by at least several tenths of a magnitude (e.g., Walker 1993; Gieren 1993).

Côté et al. (1991) have derived Baade-Wesselink distances and radii of seven Cepheid variables in the field of NGC 1866, using the $(B-V)$ color indices as the surface brightness indicator. They found a very large scatter among the distances to the individual Cepheids, presumably due to the color index used in their analysis which is known to be a very imperfect surface brightness indicator for Cepheid variables (Coulson, Caldwell, & Gieren 1986; Laney & Stobie 1994). This resulted in a rather uncertain mean distance to the cluster which did not improve previous distance determinations to the LMC.

An improved technique which allows a direct, near reddening-independent determination of Cepheid distances and radii, and which is independent of the use of a Cepheid period-luminosity relation, is the visual surface brightness method (Barnes & Evans 1976). Recently Gieren, Barnes, & Moffett (1993) have determined the distances to 100 galactic Cepheids with this method and have derived a period-luminosity relation which essentially agrees with the open cluster-based Cepheid distance scale (Gieren & Fouqué 1993). The technique requires a $(V-R)_J$ color curve of a Cepheid variable which is used as a surface brightness indicator [which is superior to $(B-V)$ for Cepheid variables] and a radial velocity curve from which the linear displacement curve is obtained. Furthermore, a knowledge of the metallicity of the Cepheid is necessary to correct for the slight metallicity dependence of the surface brightness distance.

While no observations in the R band have so far been performed for Cepheids in NGC 1866, light curves on the BVI_C system have been published by Walker (1987) for seven variables in the cluster, which can be transformed to yield the $(V-R)$ color curves of the stars on the Johnson system (see § 3). Only very recently, the metallicity of NGC 1866, so far usually assumed to be solar (e.g., Brocato et al. 1989), has been measured for the first time by Hilker, Richtler, & Gieren (1994) using CCD photometry of the cluster on the Strömgren system, yielding a value of −0.6 dex. This result enables us to apply a proper metallicity correction to the surface brightness distance (§ 3) and to obtain an accurate distance to NGC 1866, and thus to the LMC, which is the principal aim of this *Letter*. On the basis of the individual distances to Cepheids in the field of the cluster, we can also address the question of cluster membership (§ 4).

We note that we are determining metallicities for other LMC and SMC clusters with Cepheid members in order to obtain metallicity-corrected distances to more clusters in the Magellanic Clouds.

In § 2, we proceed with a description of the available observations; in § 3 we present the distance and radius solutions and discuss their implications in § 4 of the *Letter*.

2. OBSERVATIONS

Walker (1987) has measured CCD light curves in the V, B, and I (Cousins) bands for seven Cepheid variables in NGC 1866. For all of these variables, CCD light curves in B and V have also been obtained by Welch et al. (1991). Welch et al. (1991) have compared their V and $B-V$ curves to Walker's observations and generally the agreement is good, but in a few cases (HV 12197, HV 12200) a systematic offset in V by a few hundredths of a mag is clearly visible. For all of the seven variables, Welch et al. (1991) have also measured radial velocity curves from Echelle spectra taken at the Las Campanas 2.5 m du Pont reflector. While the number of radial velocity observations per variable is low (~9 on average), their distribution in phase is excellent and the mean error of the observations is

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very small (~1 km s^{-1}). This has permitted Welch et al. to fit meaningful and relatively precise radial velocity curves to the data points of six of the seven Cepheid variables, the exception being HV 12200 for which only four observations were obtained which do not suffice to define a reliable velocity curve.

Côté et al. (1991) have analyzed the existing photometric observations of the seven NGC 1866 Cepheids observed by Welch et al., and Walker, in order to derive accurate periods, and to look for possible period variations. Only for one of the variables, HV 12198, there is some evidence for a very slight variability of the period ($\dot{P}/P = 0.8 \times 10^{-9}$ day^{-1}), while the periods of the other variables appear to be constant. This is important for the surface brightness analysis (next section) where we combine Walker's (1987) photometric observations with the radial velocity curves of Welch et al. (1991); the results of Côté et al. (1991) indicate that inaccurate values of the periods and/or variable periods will not be a significant source of error in our distance and radius calculations.

From the seven NGC 1866 Cepheids with existing I-band observations we have decided to exclude three from the present analysis, for different reasons. For HV 12200, the radial velocity curve is not well defined. Furthermore, there is a systematic ~0.1 mag shift in V between the data of Walker (1987) and Welch et al. (1991), which may be a consequence of the fact that the field close to HV 12200 is very crowded and accurate photometry is difficult. For HV 12197, there is a systematic 0.05 mag offset in V between Walker, and Welch et al. (although a revised period of 3.1439 days seems to produce better agreement between the two data sets; see Welch et al.) and the phase coverage in $(V-I_C)$ of the Walker data is rather poor, introducing the possibility of a considerable systematic error in the distance calculation. Finally, for HV 12202, Walker's (1987) $(V-I_C)$ curve is too sparse and noisy to permit a reliable distance and radius calculation with the surface brightness technique.

The remaining four Cepheids for which we consider the existing data as of sufficient quality to expect reasonable (~10% accuracy) distance and radius results, are given in Table 1. Their periods were taken from the study of Côté et al. (1991); in that paper, the reader will also find information on the parameters of the light, color, and radial velocity curves of the variables.

3. DISTANCE AND RADIUS CALCULATIONS

We have calculated the distances and radii of the variables listed in Table 1 using the precepts of Gieren, Barnes, & Moffett (1993). First, we transformed the $V-I_C$ observations of Walker (1987) to $(V-R)$ on the Johnson system using the relation

$$(V-R)_J = 0.005 + 0.711(V-I_C) \quad \sigma = 0.009 \qquad (1)$$

given by Laney (1993). This relation is based on 25 short-period Cepheids ($P < 10$ days) observed in both, the Cousins I band at SAAO, and in the Johnson R band at McDonald Observatory by Moffett and Barnes (1984), and should be valid for the present sample of NGC 1866 Cepheids which are in a similar period and color range as the Cepheids used to calibrate equation (1).

The photometric observations were dereddened adopting $E(B-V) = 0.06$ (Brocato et al. 1989) and $R = A_V/E(B-V) = 3.2$. Furthermore, we used $E(V-R) = 0.84E(B-V)$ (Gieren, Barnes, & Moffett 1993). As shown by Barnes et al. (1977), inaccuracies in the absorption corrections have a negligible influence on the distance and radius values derived from the surface brightness technique.

From the dereddened V and $(V-R)_J$ observations, we calculated the angular diameter curves of the Cepheid variables, which were then fitted to the variations of the linear diameters of the Cepheids which were obtained by integrating the radial velocity curves as given by Welch et al. (1991) (we adopted the fits to the radial velocity observations of each variable given by these authors). The projection factor used to convert radial into pulsational velocities was calculated for each Cepheid from formula (11) of Gieren et al. (1993), yielding values close to 1.37 for the present variables. Due to the constancy and relative accuracy of the period values in Table 1, no significant phase shifts between the angular diameter and linear displacement curves (whose underlying data were obtained at different epochs) were expected, and this is borne out in practice. One example is given in Figure 1 for the variable HV 12198. In Figure 2, we show the plot of the linear displacements versus the angular diameters throughout the pulsation cycle for the same Cepheid. The plotted straight line is the bisector fit to the data which assumes equal errors on both axes, an assumption which should be very nearly fulfilled in the case of the present sample of NGC 1866 Cepheids. The slope of the line yields the distance of the variable.

In Table 1, we present our adopted distance and radius solutions for the four Cepheids studied in this *Letter*. The distance values are corrected for their metallicity dependence in the way described by Gieren et al. (1993), using the mean metallicity value of −0.6 dex derived for NGC 1866 by Hilker, Richtler, & Gieren (1994) from CCD Strömgren photometry of the cluster. This metallicity value was obtained from the $(b-y)$, m_1 diagram for red giants and supergiants in NGC 1866, using the metallicity calibration of Grebel & Richtler (1992), and is tied to high-dispersion spectroscopic abundance determinations for supergiants in the SMC cluster NGC 330. The distance uncertainties given in column (4) include a contribution from a ±0.1 dex uncertainty in the metallicity of NGC 1866, as given by Hilker et al. (1994), in addition to the internal errors in the surface brightness solutions, which are dominant. Column (5) presents the corresponding true distance moduli. Column (6) gives the mean, absorption-corrected V magnitudes

TABLE 1

DISTANCES, ABSOLUTE MAGNITUDES, AND RADII OF NGC 1866 CEPHEIDS

Cepheid (1)	Period (days) (2)	d (kpc) (3)	σ (kpc) (4)	μ_0 (mag) (5)	$\langle V_0 \rangle$ (mag) (6)	$\langle M_V \rangle$ (mag) (7)	$\langle M_V \rangle_{pred}$ (mag) (8)	$\langle R \rangle$ ($R_\odot$) (9)	σ ($R_\odot$) (10)	$\langle R \rangle_{pred}$ ($R_\odot$) (11)
HV 12198......	3.52275	47.9	5.0	18.40	15.73	−2.67	−3.00	30.5	2.8	32.7
HV 12199......	2.63916	50.8	7.3	18.53	16.07	−2.46	−2.63	26.5	3.3	26.4
HV 12203......	2.95416	49.4	10.5	18.47	15.90	−2.57	−2.77	26.1	4.8	28.6
HV 12204......	3.43878	23.9	1.9	16.89	15.48	−1.41	−2.97	17.5	1.1	32.1

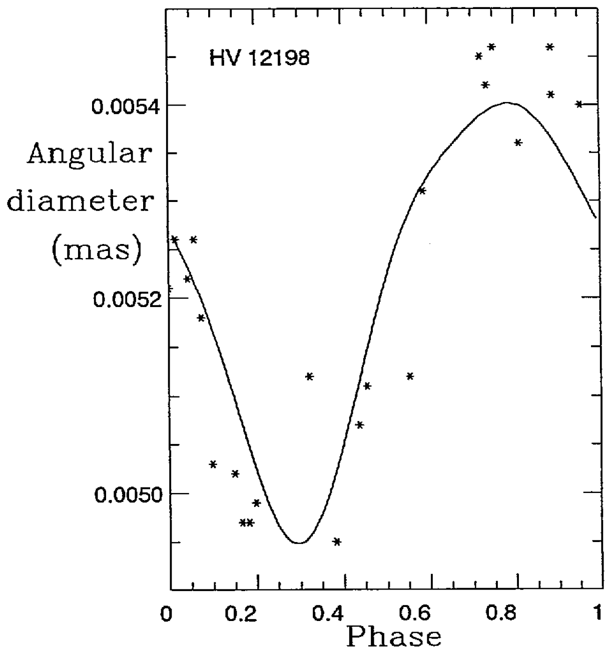

FIG. 1.—Linear displacement curve (*solid line*) and angular diameters (*asterisks*) at the same phases, for the NGC 1866 Cepheid HV 12198. No phase shifts between the two curves have been applied.

of the Cepheids (taken from Côté et al. 1991) which yield the absolute visual magnitudes for the variables given in column (7). Column (8) shows the $\langle M_V \rangle$ values predicted for the Cepheids from the period-luminosity relation of Gieren et al. (1993), assuming fundamental mode pulsation for all the variables. Column (9) presents the mean radii obtained from the present surface brightness solutions, column (10) their respective uncertainties. The present radius values are compared in column (11) to the values expected from the Cepheid period-radius relation of Gieren et al. (1989).

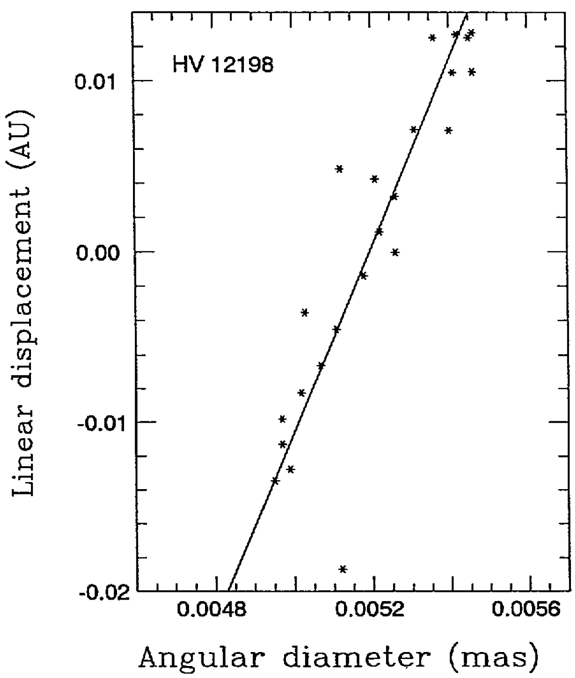

FIG. 2.—Linear displacements vs. angular diameters at the corresponding phases, for HV 12198. The line plotted is the bisector fit to the data which assumes equal errors on both axes.

4. DISCUSSION

The numerical values presented in Table 1 show that the individual distances to the three Cepheids HV 12198, HV 12199, and HV 12203 agree very well within the respective uncertainties. The distance to the fourth Cepheid of the sample, HV 12204, is clearly discrepant. This Cepheid has been suspected to be a nonmember of NGC 1866 by Côté et al. (1991) on the basis of its γ velocity which is slightly different from the values for the other Cepheids in the field of the cluster. We have looked into the photometric properties of HV 12204 and find clear indications for the presence of a relatively bright blue companion star to the Cepheid. The evidence comes from the mean intrinsic $(B-V)$ color which is $\sim$0.1 bluer than that of the other NGC 1866 Cepheids of similar period, and from the increased $(V-R)$ amplitude of the Cepheid (twice as large as for the other Cepheids of the present sample, whereas the $(B-V)$ amplitude is similar to that of the other Cepheids). These properties are characteristic for Cepheids with blue companion stars (e.g., Gieren 1982). The influence of a bright blue companion star on the distance and radius solutions is to decrease the corresponding values (e.g., Balona 1977), just what we see in the solutions of Table 1. We take this as further evidence for the reality of a blue companion to HV 12204. We might also note that Arp & Thackeray (1967), as well as Welch et al. (1991), have noted an "extended image of HV 12204" on their plates and CCD images, which may just be the nonresolved blue companion star to the Cepheid. The discrepant γ velocity of HV 12204 lends some support to the idea that the companion forms a physical pair with the Cepheid, but more radial velocity monitoring of HV 12204 is necessary to decide this question. HV 12204 may well be a NGC 1866 member in a spectroscopic binary system with a massive blue main-sequence companion.

From the discussion given above it is clear that we should not use the distance value of HV 12204 in calculating a mean distance to NGC 1866. Excluding HV 12204 and calculating the mean distance to the cluster from the remaining three Cepheids, we obtain

$$d(\text{NGC 1866}) = (49.4 \pm 5.0)\ \text{kpc}\ ,$$

where full weight has been given to HV 12198 and HV 12199, and half-weight to HV 12203, due to the inferior quality of the existing photometric observations for this Cepheid (giving the same weight to all three variables changes the mean cluster distance by a negligible amount of 0.1 kpc). This distance corresponds to a true distance modulus of NGC 1866, and thus of the LMC, of

$$\mu_0 = 18.47 \pm 0.20\ .$$

The uncertainty of this distance value can be significantly improved in the future by observing more complete light, color, and radial velocity curves of the Cepheid variables in NGC 1866. We also note that the metallicity correction to the surface brightness distances requires an extrapolation of the Hindsley & Bell (1989) models to lower metallicities, a step which may introduce a systematic error in the distance results. It would therefore be clearly worthwhile to extend the model atmosphere calculations to metallicities of ~ -1.0 dex, to cover the whole metallicity range observed in Magellanic

Cloud Cepheids which goes down to about this value (Luck & Lambert 1992). We also note that had we used the "normal" assumption that the stars in NGC 1866 have solar abundance, rather than the much lower metallicity found in the recent metallicity study of Hilker et al. (1994), the distance modulus to NGC 1866 would be ∼18.75 instead of the true, corrected value of 18.47. This shows that a metallicity determination of the cluster has been essential to obtain the correct distances to its Cepheids from the surface brightness technique.

The radii we find for the present Cepheids (Table 1, col. [9]) cluster in the narrow range of 26–31 $R_\odot$ (the exception being HV 12204 whose radius value cannot be trusted, for the reasons given above). The values are practically identical to the radii expected for these Cepheids from the period-radius relation for galactic Cepheids of Gieren et al. (1989) (given in col. [11] of Table 1). For HV 12198 and HV 12199, radii very discrepant (40 and 60 $R_\odot$, respectively) from our values have been derived by Côté et al. (1991); as mentioned before, this is probably a consequence of using the $(B-V)$ color curves of the Cepheids in their Baade-Wesselink analysis. We consider the present radius values for the NGC 1866 Cepheids as much more reliable than the values determined in the analysis of Côté et al., and they will strengthen the determination of the LMC Cepheid period-radius relation at the short-period end (Gieren, Barnes, & Moffett 1994). The excellent agreement of the present radii with the expected values, and the consistency among the determinations for three different variables of similar periods, increases our confidence in the accuracy of both, the radius values we derive in this study, and the present distance value to NGC 1866, which agrees very well with the recent determination of Bertelli et al. (1993) which was obtained from a completely different approach (requiring Cepheid evolutionary and pulsational masses to be equal).

We believe that the surface brightness technique applied to Cepheids in NGC 1866 has the potential to yield a cluster distance accurate to ∼0.1 mag if the observations are correspondingly improved and extended to more variables.

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