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Variable Stars in Clusters and the Distance Scale - Some Recent Results Concerning the LMC Cluster NGC 1866

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Abstract. After summarizing the importance of clusters and variable stars in the context of the distance scale, we focus on two new, and independent, programs to determine the distance to the Large Magellanic Cloud cluster NGC 1866.

1. Introduction

The establishment of a reliable distance scale over the 17 decades relevant to astronomy is an essential pre-requisite in order to allow the reliable physical interpretation of astronomical observations. In general, there has been great progress in recent years, as summarized in articles and papers contained in Heck & Caputo (1999), Chu et al. (1999), Pallavicini, Micela, & Sciortino (2000), and Szabados & Kurtz (2000). However, there is a vexing problem that is right on our doorstep. The Large Magellanic Cloud (LMC) has long been a site where distance indicators can be inter-compared, and yet the distance to the LMC is still controversial, with estimates thought reliable, at least by their advocates, covering a range 44 to 56 Kpc. The implications of this are succinctly summarized by Mould et al. (2000): *The uncertainty in the distance to the Large Magellanic Cloud is the dominant source of error in the determination of the Hubble constant.* Statements such as this are strong motivation to continue to work to improve the accuracy of the distance scale, particularly since Mould et al. (2000) assume that the error in the LMC distance is only ±3 Kpc.

The fact that we *can* recognize that there still is a problem is largely due to the identification of sites, such as the LMC, where critical inter-comparisons and consistency checks can be carried out. Clusters which contain RR Lyraes or Cepheids are another example where distance indicators can be compared, and carrying out such checks in a variety of environments is clearly necessary if we wish to build a reliable, consistent distance scale.

The few young open clusters in our galaxy that contain Cepheid variables can be used to calibrate the Cepheid P-L relation. Distances to the open clusters can be tied to parallaxes of nearby stars, and the P-L zeropoint so obtained can be compared to that derived in other ways (Feast 1999). In parallel manner, RR Lyrae variables in globular clusters provide similar constraints (Chaboyer 1999).

In general, clusters have the advantage of being simple stellar populations, and of course their contents are at the same distance, while field and cluster stars can in principle be segregated via radial velocity measurements. However, globular clusters are high density environments, and the evolution-environment interactions are not well understood. Galactic open clusters are generally rather sparse, and apart from those close to the Sun, are sited at low galactic latitude with consequent variable reddening and significant field star contamination.

In this paper we describe recent work on distance indicators in the populous cluster NGC 1866. Here we can compare distance indicators in an environment with fixed age and metallicity, and then relate the results to the LMC itself.

2. NGC 1866 and its Cepheids

NGC 1866 is an extremely rich cluster, with age about 150 Myr, and sufficiently massive that it will not fade or dissipate into oblivion; after another 12 Gyr of evolution it will look like a typical galactic globular cluster of today. It is a laboratory for tests of stellar evolution theory for $\sim 5M_{\odot}$ stars, the most recent investigation being that by Testa et al. (2000). It contains at least 21 Cepheids (Welch & Stetson 1993), more than are known in all Galactic open clusters combined. With a projected distance of 4 deg. from the LMC center, NGC 1866 is embedded in a rich LMC field population which consists of stars with a variety of ages (Walker 1995; Stappers et al. 1997), ranging from luminous main sequence (MS) stars younger than the cluster to the first generation of stars formed in the LMC, represented by a few RR Lyraes. Visual light-curves for Cepheids in NGC 1866 have been presented by Shapley & McKibben Nail (1951), Arp & Thackeray (1967), Walker (1987), Welch et al. (1991), Welch & Stetson (1993) and Gieren et al. (2000a). Due to crowding high-quality light curves are available for only one-third of the Cepheids. For these, preliminary comparisons with recent non-linear theoretical pulsation models calculated by Bono & Marconi (1997) appear to show relatively good agreement with the observations, although the distance modulus (DM) of 18.57 mag adopted from Welch et al. (1991) assumed that NGC 1866 has solar metallicity which is now known to be incorrect (see below). The LMC distance can be calculated for the NGC 1866 Cepheids, all of which have periods near 3 days, and compared with that obtained from other LMC Cepheids. The method has been described in detail by Walker (1987); use of the P-L relation is subject to uncertainties imposed by incomplete filling of the instability strip for the NGC 1866 variables, and perhaps some metallicity sensitivity: the P-L-C relation takes non-filling of the instability strip into account (Sandage 1972) but is strongly metal dependent. With improved metallicity measurements for many of the calibrating Cepheids now available, revisiting this method would no doubt give a more reliable result than earlier work. However the behavior of the P-L relation as a function of metallicity is controversial, and the question of the P-L zeropoint calibration via Galactic cluster Cepheids also would need attention.

The use of the Infrared Surface Brightness (ISB) technique circumvents most of these problems. The ISB technique is a variant of the Barnes & Evans (1976) version of the Baade-Wesselink geometric method for finding distances to pulsating variable stars. Here the physical displacement obtained by integrating the radial velocity curve is equated to the angular diameter obtained from a surface brightness-color relation, to hence derive the distance and mean radius. The zeropoint of the SB-color relation is tied to the Sun (BC, T_e, M_V, angular diameter), and the slope is found either from observations of stars with measured angular diameter, or from model atmospheres. The color index should be sensitive to temperature and insensitive to gravity. Welch (1994) suggested that a K, V–K variant was superior to visual colors, and would allow direct distance determinations to the Magellanic Clouds. Moving to the infrared lessens the effects of reddening, and the sensitivity to metallicity is also greatly reduced. Fouqué & Gieren (1997) calibrated V, V–K and J, J–K versions of the SB relation, and these calibrations were used in a study of the NGC 1866 Cepheid HV 12198 by Gieren et al. (2000b). Very high quality radial velocities and infrared photometry for this single star produce a DM = 18.42 ± 0.10 mag, where only a minority of the quoted error is said to be systematic in origin. With data for several other NGC 1866 Cepheids in hand, Gieren and co-workers are poised to provide a definitive distance to the LMC by this method.

3. NGC 1866 Color Magnitude Diagram

Calibration of distances to clusters is accomplished by fitting to local stars with parallaxes, by choosing stars with identical metallicity to the cluster, or by making a correction for metallicity, either established empirically or theoretically from models. The Hipparcos survey determined parallaxes for local clusters directly, but for clusters more distant than the Hyades these results are controversial. Unfortunately this includes the Pleiades, which in respect of age is a good match to NGC 1866. In order for the technique to work well, a very well-defined color magnitude diagram is needed. The V, V–I CMD is superior to the V, B–V diagram, as in the former the MS slope changes dramatically, constraining the fit in orthogonal directions corresponding to DM and reddening.

We (Walker et al. 2001) have produced a new CMD for NGC 1866, from HST WFPC2 observations in V (F555W) and I (F814W) filters. The data consist of three sets of exposures times at each of two different pointings, and was photometered using CCDCAP (Mighell et al. 1996) followed by application of calibrations listed by Holtzman et al. (1995). Comparison of these results with the extensive ground-based photometry by Walker (1995) allowed definitive tying into the Johnson-Cousins standard system. The CMD, shown in Figure 1, extends from V = 14 to 26 mag, with a narrowly defined main sequence together with a significant proportion of binary stars. The many evolved stars, including the Cepheids, are the stars brighter than V = 17 mag, and with V–I > 0.4 mag. There is a field star RGB visible, with turnoff at V $\sim$ 24 mag. Scaling from ground-based observations, field star contamination on the main sequence brighter than V = 24 mag is negligible.

Hill et al. (2000) provide a new and accurate metallicity measurement for NGC 1866, [Fe/H] = -0.49 ± 0.10 dex, [α/Fe] = 0.1 ± 0.1 dex, consistent with [Fe/H] = -0.43 ± 0.18 dex from Strömgren photometry by Hilker et al. (1995).

We then tie NGC 1866 to the Hyades, adopting the Hipparcos DM of 3.33 ± 0.01 mag (Perryman et al. 1997), E(B-V) = 0.00 mag, and [Fe/H] = 0.14 dex. The transfer is accomplished by use of evolutionary models, after checking that

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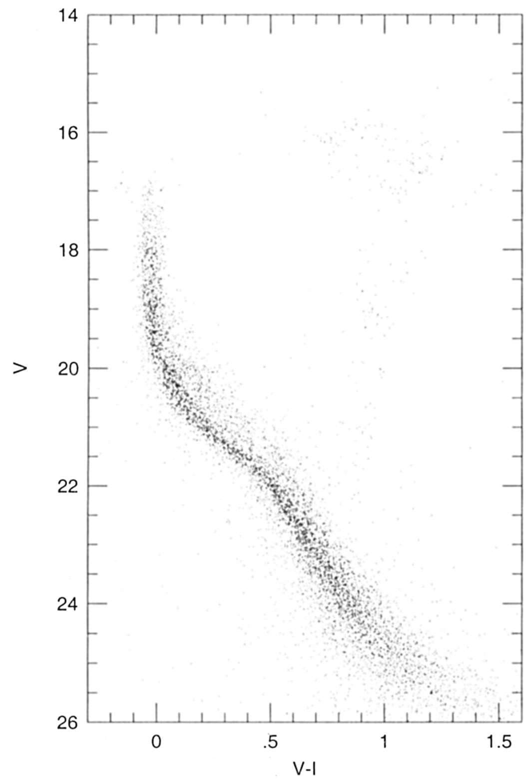

Figure 1. NGC 1866 – CMD from HST WFPC2

the models are a satisfactory fit to the Hyades MS with the above parameters. The model fit to the non-binary NGC 1866 MS stars is excellent, and the distance and reddening relative to the Hyades follow immediately, E(V–I) = 0.08 mag and DM = 18.35 mag. The reddening value derived is identical to that found in earlier studies, equivalent to E(B-V)=0.06 mag The systematic error of the method is dominated by the metallicity correction; discussion of this result and comparison of the full NGC 1866 CMD to evolutionary models can be found in Walker et al. (2001) and Brocato et al. (2001), respectively.

4. Conclusions

Two recent, and independent, determinations of the distance to NGC 1866 give a DM $\sim$ 18.4 mag. If NGC 1866 lies in the plane of the LMC, then the LMC distance is only 0.02 mag shorter, so it is likely that the NGC 1866 distance closely represents that of the LMC.

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Discussion

C. Cacciari: You quoted a distance modulus to the LMC of 18.42 from Cpheids and 18.45-18.53 from MS fitting. We obtain 18.48-18.50 from the HB luminosities of 19 globular clusters in M31 (assuming $DM_{M31} = 24.43$), and Clementini et al., from a large number of RR Lyraes in the LMC bar, obtain about 18.54. May we state with some confidence that the discrepancies in distance determinations from these methods are, or are about to be, resolved? See also SN 1987A.

A. Walker: There is certainly consistency between the cited investigations. The RR Lyrae distance scale itself, perhaps best based on Hipparcos subdwarf and subgiant parallaxes, is still somewhat controversial.

F. D'Antona: I'll show on Friday a population synthesis approach to the study of the clump stars distribution in NGC 1866. Did you try already this kind of modelling?

A. Walker: Not yet.