THE DISTANCE OF THE LARGE MAGELLANIC CLOUD CLUSTER NGC 1866

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ABSTRACT

Hubble Space Telescope V, I photometry of stars in the Large Magellanic Cloud cluster NGC 1866 shows a well-defined cluster main sequence (MS) down to V = 25 mag, with little contamination from field or foreground stars. We use the MS fitting procedure to link the distance of NGC 1866 to the *Hipparcos* determination of the distance for the Hyades MS stars, making use of evolutionary prescriptions to allow for differences in the chemical composition. On this basis, we find a true distance modulus for NGC 1866 of 18.35 \pm 0.05 mag. If the cluster is assumed to lie in the LMC plane, then the LMC modulus is 0.02 mag less.

Subject headings: galaxies: clusters: individual (NGC 1866) — galaxies: distances and redshifts — galaxies: individual (Large Magellanic Cloud) — Magellanic Clouds — stars: evolution

1. INTRODUCTION

The distance to the Large Magellanic Cloud (LMC) is a critical step in the establishment of the distance scale, since it allows us to compare and thus cross-calibrate a variety of methods, and on the basis of this evaluation the identification of reliable distance indicators should follow. Only then can extension to the more distant universe be confidently undertaken. However, the distance modulus (DM) of the LMC is still controversial since estimations from various indicators cover the range 18.2–18.7 mag (Walker 1999), and there is no definitive measurement available that could settle this dispute. We attempt here to improve this situation by providing an accurate DM for the Cepheid-rich LMC cluster NGC 1866 via the technique of main-sequence (MS) fitting.

NGC 1866 is a populous young cluster sighted some 4° north of center of the LMC. From the time of the pioneering work by Arp & Thackeray (1967), it has served as a laboratory for stellar evolution studies of intermediate mass (~5 M_{\odot}) stars, as the cluster is sufficiently rich that significant numbers of stars appear in rare stages of evolution; these include at least 20 Cepheids (Welch & Stetson 1993 and references therein). Although several efforts have been made to secure high-quality photometry for NGC 1866, most recently by Testa et al. (1999), ground-based efforts are hampered by crowding and by contamination from LMC field stars. Consequently, we have observed NGC 1866 with the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2), allowing accurate photometry several magnitudes down the main sequence together with greatly reduced sensitivity to crowding and contamination.

A detailed presentation of the observations and comparisons with evolutionary theory will be made elsewhere (E. Brocato et al. 2001, in preparation). In § 2, we describe the observations

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and the photometric calibration; in § 3, we test the correctness of our method of tying the NGC 1866 MS to *Hipparcos* parallaxes; in § 4, we fit to the NGC 1866 MS; and in § 5, we summarize the results of the analysis.

2. OBSERVATIONS AND PHOTOMETRIC CALIBRATION

The WFPC2 data set consists of two sets of pointings, one with NGC 1866 centered on WF3, and the other on PC1, through V (F555W) and I (F814W) filters. Three sets of different exposure times were taken, with multiple exposures for each. Photometry was performed using the program CCDCAP (Mighell et al. 1996), followed by conversion to the standard photometric system (Johnson V, Cousins I) via equations and zero points listed by Holtzman et al. (1995). Corrections for geometric distortion were also applied, together with charge transfer efficiency corrections according to prescriptions by Whitmore, Heyer, & Casertano (1999), with the exception that no long-short correction was applied, as our tests on this and other data sets using CCDCAP have found such a correction to be unnecessary (see also Dolphin 2000). The several data sets were matched and combined and brought to an internally consistent system.

As the WFPC2 photometric zero points are uncertain at the ~0.02 mag level (Holtzman et al. 1995; Dolphin 2000), we compared our photometry for the merged data set to the groundbased color-magnitude diagram (CMD) by Walker (1995), which is referenced to a sequence of local standards in the vicinity of NGC 1866, which are in turn tied in to the standard Johnson-Cousins system to ± 0.01 mag in both V magnitude and B-V and V-I colors. We based our comparison on all available overlap stars (~250) to find the differences between ground-based and HST observations, $\Delta V = 0.007 \pm 0.09$ (standard deviation [s.d.]), $\Delta(V-I) = -0.07 \pm 0.06$ (s.d.); trimming the sample to within ± 0.1 mag of the mean changed both differences to $\Delta = 0.01$ mag and reduced the s.d. by a factor of 2. No systematic differences as a function of color or magnitude were found, and given the small size of the corrections, we did not adjust the HST photometry.

3. FROM HYADES BY HIPPARCOS TO NGC 1866 BY HST

We wish to relate the NGC 1866 MS to the system of *Hipparcos* parallaxes (ESA 1997) with the minimum number of steps and assumptions. We chose to use the Hyades as our fundamental fiducial and calculated the absolute magnitudes



FIG. 1.— M_v , B-V (*left*) and M_v , V-I (*right*) diagrams of the subsample of the stars of the Hyades as provided with corrected parallaxes by Madsen et al. (2001). The solid lines represent the zero-age theoretical models computed by adopting [Fe/H] = 0.13. Three isochrones aged 500, 600, and 700 Myr are also plotted (*dotted lines*).

individually using the new kinematically improved parallaxes, where the error in the *Hipparcos* catalog has been diminished by combining its data with a kinematic modeling of the cluster dynamics (Madsen, Lindegren, & Dravins 2000; Madsen, Dravins, & Lindegren 2001). The binary systems identified by Perryman et al. (1998) are excluded; the sample totals 111 stars and has a well-determined mean DM of 3.33 ± 0.01 mag. The controversy over whether or not correlated errors systematically affect *Hipparcos* distances to nearby open clusters is irrelevant for the Hyades due to compensating effects (Pinsonneault, Terndrup, & Yuan 2000).

For our purposes, a complication is that many stars in the Hipparcos catalog, including most of the Hyades, do not have V-I colors actually measured on the Cousins system; instead, a variety of transformations are applied, depending on available photometry, to produce a quasi-Cousins V-I. Of our 111 Hyades stars, 83 are MS members with V-I < 1.0. For these 83 stars, 29 have photometry actually measured on the Johnson-Cousins system; the remainder have V-I colors calculated as described in the Hipparcos catalog (ESA 1997). The extreme tightness of the Hyades MS is evidence that the transformation procedure works well, as can be seen by comparing the M_{ν} , B-V and M_{ν} , V-I CMDs, plotted in Figure 1. In Figure 1 (right), we plot the transformed B-V colors according to the precepts of Cousins (1978; crosses) to demonstrate the concept developed in greater detail in the Hipparcos analysis. We differentiate, using different symbols, between the stars with measured V-I Cousins and those with transformed colors. This comparison shows no indication of significant systematic differences for the nonevolved stars over our color range of interest.

The critical step of comparing the MS of the Hyades with that for NGC 1866 requires a reliable comparison method and accurate metallicities for both clusters. Recent evaluations of the Hyades metallicity are all very consistent, with $[Fe/H] = 0.12 \pm 0.03$ (Cayrel, Cayrel de Strobel, & Campbell

1985), [Fe/H] = 0.13 ± 0.02 (Boesgaard & Friel 1990) [Fe/H] = 0.14 ± 0.05 (Perryman et al. 1998). We adopted [Fe/H] = 0.13 and combined the helium abundance with the metallicity according to the relation $\Delta Y/\Delta Z \sim 2$ with Y =0.27 and Z = 0.02 for the Sun. Thus, we will assume Y =0.282 and Z = 0.026 for the Hyades. We note that Perryman et al. (1998) and Castellani, Degl'Innocenti, & Prada Moroni (2001) used slightly lower metallicity (Z = 0.024) on the basis of a different assumption on the solar ratio (Z/H). However. such a difference in metallicity corresponds to a negligible shift in the location of the zero-age stellar models in the CMD due to the corresponding decrease of the helium content.

We accommodate the metallicity difference between the Hyades and NGC 1866 by computing a set of stellar models for the mass range 0.7–9 M_{\odot} , chemical composition (Y = 0.282and Z = 0.026), and a mixing length parameter $\alpha = 2.0$ using the evolutionary code FRANEC. The present version of the code uses the most recent physical inputs, in particular, the OPAL equation of state and opacity (Cassisi et al. 1998). Neither diffusion nor α -enhancement are adopted. Atmosphere models are from the Castelli, Gratton, & Kurucz (1997) compilation⁶ computed without any overshooting (see, for a discussion, Castelli et al. 1997).

Taylor (1980) found a negligible value of $E(B-V) = 0.003 \pm 0.002$ for the Hyades reddening, so we adopt zero reddening correction. The computed zero-age main-sequence (ZAMS) model is plotted in Figure 1 to show that there is excellent agreement over most of the range of the nonevolved stars ($M_V > 3$ mag). We also plot a sample of isochrones calculated at three different ages (for a discussion of the Hyades age, see Castellani et al. 2001 and references therein). The models are slightly bluer than the MS only for the very reddest stars. We conclude that our models correctly describe the Hyades MS, and in particular the ZAMS model is an excellent fit

⁶ See http://cfaku5.harvard.edu/grids.html.



FIG. 2.—Theoretical ZAMSs and isochrones calculated for the metallicity Z = 0.007 (*left*) and Z = 0.01 (*right*) superposed on the lower part of the NGC 1866 MS. The values of the uncorrected distance modulus and reddening for the best fit are also reported.

for 0.5 < V-I < 0.8. On the basis of this result, we can proceed with confidence to fit our ZAMS models to the NGC 1866 CMD. We note that shifting the Hyades MS to the NGC 1866 metallicity, i.e., using theory in a differential way, is exactly the same as directly comparing a new theoretical ZAMS, computed with the NGC 1866 chemical composition, to the NGC 1866 CMD. In addition, since the method makes use of ZAMS models, the differences between evolutionary tracks provided by different groups are only a minor source of indetermination.

4. THE NGC 1866 MAIN-SEQUENCE FITTING

The NGC 1866 MS plotted in Figure 2 shows a very clearly defined and well-populated sequence of single stars, with two significant changes in slope near V = 21 and V = 22, which will strongly constrain the model fit; in this respect the V, V-ICMD has a distinct advantage over the V, B-V CMD. The region V-I > 0.8, where our Hyades fit deviates slightly, has little power in the fit. There is clearly a significant population of binaries, as suggested previously by Testa et al. (1999). Contamination by the older field star population, visible as a red giant branch and red giant clump, with turnoff at $V \sim 23$, is minimal. We calculated the expected younger field star contamination to the NGC 1866 MS by scaling field star photometry from Walker (1995). In the range V = 19-20, V-I =-0.05 to 0.3, we expect 28 field stars on our HST frames. Since we find 1074 stars in this range on our HST CMD, the field star contamination in the vicinity of the NGC 1866 MS is very small and will have negligible effect on our fits.

Recent evaluations of metallicity of NGC 1866 via Strömgren photometry of a few stars found the value [Fe/H] = -0.43 ± 0.18 (Hilker, Richtler, & Gieren 1995), and from the integrated spectrum, Oliva & Origlia (1998) obtained [Fe/H] = -0.55 ± 0.4 . Using the ESO Very Large Telescope with the high-dispersion Ultraviolet/Visual Echelle Spectrograph, Hill et al. (2000) have measured abundances for three NGC 1866 red giant branch stars, finding [Fe/H] = -0.50 ± 0.1 and [α /Fe] = 0.1 ± 0.1 for O, Mg, Ti, and Ca elements. The internal scatter for the three [Fe/H]-values is only 0.05 dex.

With the same version of the stellar evolutionary code and prescriptions described above, we computed a new set of stellar models for two metallicities: Z = 0.007, which corresponds to [Fe/H] = -0.50, and a higher value of Z = 0.01 (around [Fe/H] = -0.30). The helium abundance is calculated by the above relation, $\Delta Y/\Delta Z \sim 2$ as recently confirmed for the Small Magellanic Cloud by Peimbert, Peimbert, & Ruiz (2000), so, respectively, Y = 0.24 and 0.25. The computed ZAMS models for these Z-values are very consistent with Castellani, Degl'Innocenti, & Marconi (1999) and with models computed for solar scaled abundances recently published by Salasnich et al. (2000) at the closest metallicity (Z = 0.008, Y = 0.25).

A set of models computed for a higher (Y = 0.27) and lower (Y = 0.23) original helium abundance at the metallicity Z = 0.007 disclose that the ZAMS becomes respectively fainter and brighter by about 0.05 mag in M_V in the relevant V-I color range.

To perform an accurate fit, we derived a fiducial line for the portion of the MS ranging from about V = 25 mag up to 20 mag. The last point is estimated by superposing a sample of suitable isochrones with different ages looking for the magnitude level where the isochrones turn away from the ZAMS. In this way, we are confident to avoid any contamination by stars evolved off the ZAMS. It is also important to note that the CMD is sufficiently deep and accurate such that the fit over the precise range of V-I colors where the Hyades ZAMS matches so well is identical (but with larger photometric error) to the fit using all the nonevolved NGC 1866 stars.

The points of the fiducial line have been derived with a running mean technique by taking the maximum value in the V-I histogram within each bin of magnitude. Then, we apply the MS fitting method comparing the theoretical ZAMSs with the observed fiducial line. By minimizing the χ^2 , we obtain $(m-M)_V = 18.50 \pm 0.05$ and $E(V-I) = 0.08 \pm 0.01$ with Z = 0.007 and $(m-M)_V = 18.53 \pm 0.05$ and $E(V-I) = 0.075 \pm 0.01$ for Z = 0.01. This procedure allows us to derive

separately both reddening and distance. The errors refer to the uncertainties due to the method adopted to built the fiducial line (i.e., the bin size in magnitude and color, the amplitude of the running mean, and the range in V considered for the fit).

By assuming $R_V = A_V / E_{B-V} = 3.1$, Bessell & Brett (1988) found the relation E(V-I) = 1.25E(B-V); thus, the reddening values E(V-I) = 0.08 and E(V-I) = 0.075 imply, respectively, E(B-V) = 0.064 and E(B-V) = 0.06, in agreement with the evaluations in the vicinity of NGC 1866 derived from *UBV* photometry, $E(B-V) = 0.060 \pm 0.005$ (Arp 1967; van den Bergh & Hagen 1968; Walker 1974). We note that the reanalysis of the ultraviolet extinction in the LMC by Misselt, Clayton, & Gordon (1999) suggests on average $R_v = 2.6$; if this value is used, then distances increase by only 0.03 mag. Taking into account the uncertainty due to the chemical composition, we suggest that the MS fitting method applied to the cluster NGC 1866 gives an absolute DM of $(m-M)_0 = 18.35 \pm$ 0.05 (1 σ). If NGC 1866 is assumed to lie in the plane of the LMC, then the correction to the LMC center is -0.02 mag; thus, we derive a DM for the LMC of $(m-M)_0^{\text{LMC}} =$ 18.33 ± 0.05 mag.

5. FINAL REMARKS

In this work, we have determined a distance to the LMC based on the well-defined *Hipparcos* distance to the Hyades, using theoretical models to account for the metallicity differ-

ence. With high-quality photometry and accurate abundances, the method appears robust. It would be very valuable to test the technique on equivalent data for other young LMC clusters, over a range of [Fe/H].

The result here is consistent with the infrared surface brightness DM of 18.42 ± 0.10 (Gieren et al. 2000) for a single NGC 1866 Cepheid (HV 12198); further results of this type for more NGC 1866 Cepheids are expected soon (W. Gieren 2001, private communication), which should allow a more critical comparison.

Since NGC 1866 contains a large number of Cepheids, the accurate study of their properties provides a unique opportunity to link stellar evolution theory and pulsational models and to evaluate both the distance of the LMC and the degree of confidence in the Cepheid period-luminosity and period-luminosity-color relations, which are fundamental steps in the building of the cosmological distance scale.

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REFERENCES

- Arp, H. 1967, ApJ, 149, 91
- Arp, H., & Thackeray, A. D. 1967, ApJ, 149, 73
- Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
- Boesgaard, A. M., & Friel, E. D. 1990, ApJ, 351, 467
- Cassisi, S., Castellani, V., Degl'Innocenti, S., & Weiss, A. 1998, A&AS, 129, 267
- Castellani, V., Degl'Innocenti, S., & Marconi, M. 1999, A&A, 349, 834
- Castellani, V., Degl'Innocenti, S., & Prada Moroni, P. G. 2001, MNRAS, 320, 66
- Castelli, F., Gratton, R., & Kurucz, L. R. 1997, A&A, 318, 841
- Cayrel, R., Cayrel de Strobel, G., & Campbell, B. 1985, A&A, 146, 249
- Cousins, A. W. J. 1978, Mon. Notes Astron. Soc. South Africa, 37, 62
- Dolphin, A. E. 2000, PASP, 112, 1397
- ESA. 1997, The *Hipparcos* and Tycho Catalogues, ed. M. A. C. Perryman (ESA SP-1200; Noordwijk: ESA)
- Gieren, W. P., Storm, J., Fouqué, P., Mennickent, R. E., & Gómez, M. 2000, ApJ, 533, L107
- Hilker, M., Richtler, T., & Gieren, W., 1995, A&A, 294, 648
- Hill, V., Francois, P., Spite, M., Primas, F., & Spite, F. 2000, A&A, 364, L19 Holtzman, J. A., et al. 1995, PASP, 107, 1065
- Madsen, S., Dravins, D., & Lindegren, L. 2001, A&A, submitted

- Madsen, S., Lindegren, L., & Dravins, D. 2000, in ASP Conf. Ser. 198, Stellar Clusters and Associations: Convection, Rotation, and Dynamos, ed. R. Pallavicini, G. Micela, & S. Sciortino (San Francisco: ASP), 137
- Mighell, K. J., Rich, R. M., Shara, M., & Fall, M. 1996, AJ, 111, 2314
- Misselt, K. A., Clayton, G. C., & Gordon, K. D. 1999, ApJ, 515, 128
- Oliva, E., & Origlia, L. 1998, A&A, 332, 46
- Peimbert, M., Peimbert, A., & Ruiz, M. T. 2000, ApJ, 541, 688
- Perryman, M. A. C., et al. 1998, A&A, 331, 81
- Pinsonneault, M. H., Terndrup, D. M., & Yuan, Y. 2000, in ASP Conf. Ser. 198, Stellar Clusters and Associations: Convection, Rotation, and Dynamos, ed. R. Pallavicini, G. Micela, & S. Sciortino (San Francisco: ASP), 95
- Salasnich, B., Girardi, L., Weiss, A., & Chiosi, C. 2000, A&A, 361, 1023
- Taylor, B. J. 1980, AJ, 85, 242
- Testa, V., Ferraro, F. R., Chieffi, A., Straniero, O., Limongi, M., & Fusi Pecci, F. 1999, AJ, 118, 2839
- van den Bergh, S., & Hagen, G. L. 1968, AJ, 73, 569
- Walker, A. R. 1995, AJ, 110, 638
- ———. 1999, in Post-*Hipparcos* Cosmic Candles, ed. A. Heck & F. Caputo (Dordrecht: Kluwer), 125
- Walker, M. F. 1974, MNRAS, 169, 199
- Welch, D. L., & Stetson, P. B. 1993, AJ, 105, 1813
- Whitmore, B., Heyer, I., & Casertano, S. 1999, PASP, 111, 1559