Near Infrared Survey of Populous Clusters in the LMC: Preliminary Results

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Abstract.

We report preliminary results from our near-infrared JHK survey of star clusters in the LMC. The primary goals of the survey are to study the three-dimensional structure and distance of the LMC. In 2003 and 2004 we used the Infrared Side Port Imager (ISPI) on the CTIO 4m to obtain near infrared photometry for a sample of populous LMC clusters. We utilize the K-band luminosity of core helium burning red clump (RC) stars to obtain individual cluster distances and present a preliminary assessment of the structure and geometry of the LMC based on a subset of our data.

1. Introduction

The Large Magellanic Cloud (LMC) is an attractive astronomical target for a variety of reasons. Owing to its relative proximity, stellar populations in the LMC can be easily resolved. These populations exhibit an array of star formation processes and episodes in a dynamic environment making the LMC well suited for studying the formation and evolution of a satellite galaxy. Traditionally, the LMC has been thought of as an approximately planar galaxy that, in spite of its proximity, can be assumed to lie at a single distance from us. In contrast, Caldwell & Coulson (1986) have shown that the LMC disk is tilted with respect to the plane of the sky. More recent work has not only confirmed that the LMC is tilted, but it also indicates that the LMC disk is considerably thicker than previously assumed.

van der Marel & Cioni (2001) determined, through the use of red giant branch and asymptotic giant branch stars as relative distance indicators, that the LMC is tilted $34^\circ.7 \pm 6^\circ.2$ with respect to the line of sight (0° is face-on) such that the Northeast portion of the LMC is closer to us than the Southwest. Olsen & Salyk (2002) confirmed this result, finding $i = 35^\circ.8 \pm 2^\circ.4$ by utilizing core He burning red clump (RC) stars as their relative distance indicator. Additionally,
by studying carbon star kinematics in the LMC disk, van der Marel et al. (2002) have determined that $v/\sigma = 2.9 \pm 0.9$, implying that the LMC disk is thicker than the Milky Way thick disk ($v/\sigma \approx 3.9$). Lastly, the Magellanic Stream (e.g. Putman et al. 2003), flaring (Alves & Nelson, 2000) and elongation of the LMC disk (van der Marel & Cioni 2001) and the possibility that the LMC disk is warped (Olsen & Salyk 2002, Nikolaev et al. 2004) all indicate that the LMC has not escaped unharmed from its tidal interactions with the Milky Way and Small Magellanic Cloud.

The distance to the LMC has been a topic of considerable discussion in recent years and a variety of methods have been employed to calculate this distance; e.g. variable stars (Cepheids, RR Lyraes, Miras), color-magnitude diagram (CMD) features (main sequence turn off, tip of the red giant branch, RC stars), and SN 1987a. There has been, until recently, little agreement between the different methods and sometimes even amongst distances calculated using a single method. This lead to a “long” and “short” distance scale for the LMC with a “short” distance modulus, $(m - M)_0$, of $\sim 18.2-18.3$ mag and a “long” distance of $\sim 18.5-18.7$ mag. Clementini et al. (2003) demonstrate this distance problem (top panel, their Fig. 8), and find that the long and short distance scale can be reconciled, at least to within the errors, with improved photometry and/or reddening estimates (bottom panel, their Fig. 8) for some of the previous works.

A primary reason for interest in the LMC distance is its use as the extragalactic distance scale zeropoint. The Hubble Space Telescope Key Project to determine $H_0$ (Freedman et al. 2001) utilized a sample of LMC Cepheid variables to define the fiducial period-luminosity relation. Cepheid distances were then used to calibrate secondary standard candles which lie further along the extragalactic distance ladder. Thus, the accuracy of their determination of $H_0$ ($72 \pm 8$ km s$^{-1}$ Mpc$^{-1}$) hinges on the accuracy of their zeropoint, $(m - M)_{0,\text{LMC}} = 18.5 \pm 0.10$. It turns out the error in their calculation is dominated by the uncertainty in $(m - M)_{0,\text{LMC}}$; it takes up 6.5% of their 9% error budget (Mould et al. 2000).

In this paper we will present preliminary results from our near-infrared survey of populous clusters in the LMC. Section 2 presents our observations of LMC cluster and field stars. In the next two sections we discuss our application of the $K$-band luminosity of the RC as a standard candle for calculating absolute cluster distances (§3) and for determining relative distances to the LMC fields (§4). Finally, in §5 we talk about our future work on this project.

2. Data

2.1. Observations

We have obtained near infrared images for a sample of intermediate age LMC clusters over the course of two, three night observing runs (20-22 January 2003 and 06-08 February 2004) at the CTIO 4m. Our observations were made with the Infrared Side Port Imager (ISPI) which utilizes a $2048 \times 2048$ pixel HAWAII 2 HgCdTe array. In the f/8 configuration, ISPI yields an $11' \times 11'$ field of view and a plate scale of $\sim 0.33$ pixel$^{-1}$. For our observations we used a nine-point dither pattern, centered on each cluster, and total integration times as follows: $J = 540s$, $H = 846s$, $K' = 846s$. Average seeing for all six nights was $\sim 1.2''$. Table
lists two of our 18 program clusters along with right ascension and declination (J2000) and passbands in which the clusters were observed.

| Cluster   | Alternate name | RA (J2000) | Dec (J2000) | Filters |
|-----------|----------------|------------|-------------|---------|
| NGC 1651  |                | 04^h37^m32^s67 | -70^o35’07’’7 | JHK’    |
| Hodge 4   | SL 556         | 05 32 25.00 | -64 44 12.0 | JHK’    |

2.2. Reduction

All data was processed using standard data reduction steps, which we will now summarize. Images were dark subtracted, sky subtracted and then flat fielded using on-off dome flats. Due to the combination of ISPI's wide field of view and the relatively large steps in our dither pattern (≥ 30’), these images suffer from geometric distortions, caused mostly by the curvature of the focal plane. To correct for this, we apply a high order distortion correction to each image using the IRAF task GEOTRAN. The corrected images are then aligned, shifted and averaged to create a final science frame for each cluster and filter.

Science frames were photometered using a combination of DAOPHOT and ALLSTAR (Stetson 1987) as follows. A rough PSF was constructed using the brightest ~ 200 stars in each image. The rough PSF was then used to remove neighbors from around the PSF stars, allowing the creation of a more robust PSF from the cleaned image. ALLSTAR was utilized to fit this improved PSF to all stars in the science frame. In an effort to detect and photometer faint stars and/or companions, we used a single iteration of subtracting all stars detected and fit in the first ALLSTAR pass, then searching for previously undetected stars in our fields. All new detections were run through ALLSTAR using the same PSF as in the first ALLSTAR pass and these stars were added to the photometry list. At this point, aperture corrections, calculated for each frame, were applied to the PSF photometry. Finally, aperture corrected photometry lists from each filter were combined with the requirement that a star be detected in all filters for it to be kept in the final combined list of instrumental magnitudes. Zero points and color transformations appropriate for our data were calculated by comparing our instrumental magnitudes with photometry from the 2MASS All-Sky Data Release¹ for each field in our program.

3. Preliminary Distances

Figure 1 presents (K, J − K) CMDs for NGC 1651 and Hodge 4, where all stars within ~ 1’ of the cluster centers are shown. Both CMDs show a prominent RC at K ~ 16.9 and a well populated RGB extending up to K ~ 12.5.

We follow the method of Grocholski & Sarajedini (2002) in using a box that extends 0.8 mag in K and 0.2 mag in J − K (shown in Fig. 1), centered by eye, ¹http://www.ipac.caltech.edu/2mass/releases/allsky
to select the RC stars. $K_{RC}$ is calculated by taking the median value of all stars within this box. For NGC 1651, $K_{RC} = 16.93 \pm 0.02$ and $K_{RC} = 16.81 \pm 0.02$ for Hodge 4.

With regards to the reddening of each cluster, we utilize the dust maps of Burstein & Heiles (1982) and Schlegel, Finkbeiner, & Davis (1998). Since the values determined from both dust maps, for each cluster, are in good agreement, we adopt the average value from the two maps as our cluster redenings. For NGC 1651 we find $E(B-V) = 0.12 \pm 0.02$ and for Hodge 4, $E(B-V) = 0.05 \pm 0.01$. Using the relations from Cardelli, Clayton, & Mathis (1989), $A_V = 3.1E(B-V)$ and $A_K = 0.11A_V$, these redenings translate to $A_K = 0.041 \pm 0.003$ and $A_K = 0.017 \pm 0.007$.

Previous authors have shown that the absolute RC magnitude varies as a function of age and metallicity for visible and near-infrared bands, with this variation seen in both theoretical (e.g. Salaris & Girardi 2002) and observational data (e.g. Sarajedini 1999, Cole 1998). An in-depth comparison of the absolute $K$-band RC magnitude with age and metallicity for a sample of simple stellar populations was performed by Grocholski & Sarajedini (2002). These authors advocate using an interpolation over either their observational data or the theoretical models of Girardi & Salaris (2001) to create an $M_{K}(RC)$ “plane” which, given a cluster’s age and metallicity, can be used to predict $M_{K}(RC)$ for that cluster.

In many cases, however, age and metallicity values for LMC clusters are not readily available or not reliable. For example, Olszewski et al. (1991) have presented the only large scale determination of metallicities for LMC clusters, based on the Ca II triplet. However, many of their cluster [Fe/H] values, in-
cluding NGC 1651 and Hodge 4, are based on observations of a single star. Sarajedini et al. (2002) calculated [Fe/H] values for both of these clusters using the slope of the RGB. While their value for Hodge 4 is consistent with that of Olszewski et al. (1991), their value for NGC 1651 is 0.3 dex more metal rich. As such, in the current work we choose not to apply the full calibration of $M_K(\text{RC})$ as discussed above, but rather we adopt the value of $M_K(\text{RC}) = -1.61 \pm 0.04$ given in Grocholski & Sarajedini (2002). We note that Sarajedini et al. (2002), utilizing the full RC treatment from Grocholski & Sarajedini (2002), find $M_K(\text{RC}) = -1.56 \pm 0.12$ for NGC 1651 and $M_K(\text{RC}) = -1.64 \pm 0.17$. This implies that error in the value we have chosen to use for $M_K(\text{RC})$ is likely larger than that quoted.

Using the values listed above for $K(\text{RC})$, $M_K(\text{RC})$, and $A_K$ for each cluster, we find for NGC 1651, $(m-M)_0 = 18.50 \pm 0.06$ and $(m-M)_0 = 18.40 \pm 0.05$ for Hodge 4. The errors quoted are the random errors added in quadrature. These numbers are consistent with the LMC distance, $(m-M)_0 = 18.50 \pm 0.10$ used in the HST Key Project to determine an accurate value of $H_0$ (see Freedman et al. 2001 for more information). Additionally, these distances agree with the LMC geometry determined by van der Marel & Cioni (2001) and Olsen & Salyk (2002) in that Hodge 4 should be closer to us than NGC 1651, based on the tilt of the LMC’s disk and the location of the clusters in the LMC. Lastly, Sarajedini et al. (2002) find, for NGC 1651 and Hodge 4, $(m-M)_0 = 18.55 \pm 0.12$ and $18.52 \pm 0.17$. These distances are in agreement, within the errors, with our results.

4. Field Stars

In Figure 2 we show $(K, J-K)$ CMDs for the field stars surrounding our clusters and, as with the clusters, the RC and RGB for the two fields are easily visible. The major difference between the cluster and field CMDs is the wider field RGB (spread in color) and larger field RC (spread in both color and luminosity) caused by the intrinsic distribution in age and metallicity of the field population. Although this situation is a bit more complicated for the RC (see Salaris & Girardi 2002; Grocholski & Sarajedini 2002), in general, older and/or more metal rich populations have redder RGBs and redder and fainter RCs than younger and/or metal poor populations. Due to the mixed population in the LMC field, dealing with the field RC luminosity as a standard candle becomes a much more formidable task than dealing with a simple stellar population RC.

However, if we can make the assumption that each observed field within the LMC has a similar mix of stars in terms of age and metallicity, then the field RC can be easily applied as a relative distance indicator since $M_K(\text{RC})$ should be the same for all fields. This assumption is reasonable given that the bulk of the LMC RC stars are $\sim 4$ Gyr old (Girardi & Salaris 2001) and differential rotation should destroy any record of the initial local age and metallicity distribution on timescales much shorter than this (Olsen and Salyk 2002). Additionally, if this assumption holds true, the variation in RC colors amongst our fields is indicative of the relative reddenings of these fields.

Similar to §3, we determine the magnitude and color values of the field RC by taking the median value of all stars within a predefined box, centered on the
RC. Since the field RC is more extended than the cluster RCs, we have doubled the size of our box to 1.6 mag in $K$ and 0.4 mag in $(J-K)$, as shown in Fig. 2. For our NGC 1651 and Hodge 4 fields, respectively, we find $K_{RC} = 17.01 \pm 0.01$, $(J-K)_{RC} = 0.630 \pm 0.002$ and $K_{RC} = 16.85 \pm 0.01$, $(J-K)_{RC} = 0.662 \pm 0.002$.

Applying the reddening corrections we derived from the dust maps (section 3), we find $K_0(RC) = 16.97 \pm 0.01$ and $K_0(RC) = 16.83 \pm 0.01$ for the NGC 1651 and Hodge 4 fields. This result implies that the field around NGC 1651 is 0.14 mag farther from us than the Hodge 4 field, consistent with the results from §3. However, assuming the difference in color is solely due to a change in the reddening between these two fields, the Hodge 4 field suffers from $E(B-V) = 0.061$ more extinction than the NGC 1651 field, in the opposite sense of what is predicted by both dust maps discussed in §3. This could indicate that the field populations are in fact not composed of the same stellar mixture (the Hodge 4 field may be older and/or more metal rich), which would render this relative distance method invalid for our data. It is also possible that there exists a problem in our photometric calibration, leading to the discrepancy between our results and the reddening maps of Schlegel et al. (1998) and Burstein & Heiles (1982). We are currently exploring the cause of this disagreement.

5. Future Work

As mentioned previously, the two clusters presented here are only a sample of our entire data set. We plan to use these data to address two problems. First, we will utilize $K(RC)$ values for each cluster, along with the full method of
determining $M_K(RC)$, to calculate the individual cluster distances. (We note that we are in the process of measuring homogeneous ages and metallicities for each of our clusters, which will be used in properly calculating $M_K(RC)$.) This will allow us to determine an accurate distance for the LMC. Additionally, with the areal coverage of our clusters, we will be in a position to compare the distribution of our program clusters with the LMC geometry derived by van der Marel and Cioni (2001). Second, the plethora of field stars surrounding each of our clusters provides an opportunity to study the field populations in the LMC. If the assumption that RC stars are evenly mixed throughout the LMC is confirmed, then we will be able to determine the relative distance to each of these fields, thereby studying the three dimensional distribution of the LMC disk. This information will provide insight into the reality of the “warp” found in the southwest portion of the LMC disk (Olsen and Salyk 2002). We will also be in a position to compare the relative distributions of our LMC clusters with their surrounding fields and explore whether or not the LMC clusters occupy the same plane as the LMC disk.

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