HUBBLE SPACE TELESCOPE STUDIES OF THE WLM GALAXY. I. THE AGE AND METALLICITY OF THE GLOBULAR CLUSTER1

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Received 1999 February 5; accepted 1999 March 31

ABSTRACT

We have obtained V and I images of the lone globular cluster that belongs to the dwarf Local Group irregular galaxy known as WLM. The color-magnitude diagram of the cluster shows that it is a normal old globular cluster with a well-defined giant branch reaching to \( M_V = -2.5 \), a horizontal branch at \( M_V = +0.5 \), and a subgiant branch extending to our photometry limit of \( M_V = +2.0 \). A best fit to theoretical isochrones indicates that this cluster has a metallicity of \( [\text{Fe/H}] = -1.52 \pm 0.08 \) and an age of 14.8 \( \pm \) 0.6 Gyr, thus indicating that it is similar to normal old halo globulars in our Galaxy. From the fit we also find that the distance modulus of the cluster is 24.73 \( \pm \) 0.07 and the extinction is \( A_V = 0.07 \pm 0.06 \), both values that agree within the errors with data obtained for the galaxy itself by others. We conclude that this normal massive cluster was able to form during the formation of WLM, despite the parent galaxy's very small intrinsic mass and size.

Subject headings: galaxies: individual (WLM) — galaxies: star clusters — Local Group

1. INTRODUCTION

The galaxy known as WLM is a low-luminosity, dwarf irregular galaxy in the Local Group. A history of its discovery and early study was given by Sandage & Carlson (1985). Photographic surface photometry of the galaxy was published by Ables & Ables (1977). Its stellar population has been investigated from ground-based observations by Ferraro et al. (1989) and by Minniti & Zijlstra (1997). The former showed that the main body of the galaxy consists of a young population, which dominates the light, while the latter added the fact that there appears to be a very old population in its faint outer regions. Cepheid variables were detected by Sandage & Carlson (1985), who derived its distance, and were reanalyzed by Feast & Walker (1987) and by Lee, Freedman, & Madore (1993). The latter paper used I photometry of the Cepheids and the RGB (red giant branch) distance criterion to conclude that the distance modulus for WLM is 24.87 \( \pm \) 0.08. The extinction determined by Feast & Walker (1987) is \( A_V = 0.1 \).

Humphreys, Mayall, & Sandage (1956), when measuring the radial velocity of WLM, noticed a bright object next to it that had the appearance of a globular cluster. Its radial velocity was the same as that of WLM, indicating membership. Ables & Ables (1977) found that the cluster's colors were like those of a globular cluster, and Sandage & Carlson (1985) confirmed this. Its total luminosity is unusual for its being the sole globular of a galaxy. Sandage & Carlson (1985) quote a magnitude of \( V = 16.06 \), indicating an absolute magnitude of \( M_V = -8.8 \). This can be compared to the mean absolute magnitude of globulars in galaxies, which is \( M_V = -7.1 \pm 0.43 \) (Harris 1991). The cluster, though unusually bright, has only a small fraction of the \( V \) luminosity of the galaxy, which is 5.2 mag brighter in \( V \).

One could ask the question of whether there are other massive clusters in the galaxy, such as luminous blue clusters similar to those in the Magellanic Clouds. Minniti & Zijlstra (1997), using the NTT and thus having a wider field than ours, searched for other globular clusters and found none. However, the central area of the galaxy has one very young, luminous cluster, designated C3 in Hodge, Skelton, & Ashizawa (1999). This object is the nuclear cluster of one of the brightest Hβ regions (Hodge & Miller 1995). There do not appear to be any large intermediate age clusters, such as those in the Magellanic Clouds or that recently identified spectroscopically in the irregular galaxy NGC 6822 by Cohen & Blakeslee (1998).

No other Local Group irregular galaxy fainter than \( M_V = -16 \) contains a globular cluster. The elliptical dwarf galaxies NGC 147 and NGC 185 (0.8 and 1.3 absolute magnitudes brighter than WLM, respectively) do have a few globular clusters each and Fornax (1.7 absolute magnitudes fainter) has five, which makes it quite anomalous, even for an elliptical galaxy (see Harris 1991 for references).

Another comparison can be made using the specific frequency parameter, as defined and discussed by Harris (1991). The value of the specific frequency calculated for WLM is 7.4, which can be compared to Harris's value calculated for late-type galaxies, which is 0.5 \( \pm \) 0.2. The highest average specific frequency is found for nucleated dwarf elliptical galaxies by Miller et al. (1998), which is 6.5 \( \pm \) 1.2, while non-nucleated dwarf elliptical galaxies have an average of 3.1 \( \pm \) 0.5. These values are similar to those found by Durrell et al. (1996), implying that the specific frequency for WLM is comparable to that for dwarf elliptical galaxies but possibly higher than that for other late-type galaxies.

Because the WLM cluster as a globular in an irregular dwarf galaxy is unique, it may represent an unusual

1 Based on observations with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
opportunity to investigate the question of whether Local Group dwarf irregulars share the early history of our Galaxy and other more luminous Group members, which formed their massive clusters some 15 Gyr ago, or whether they formed later, as the early ideas about the globular clusters of the Magellanic Clouds seemed to indicate. Of course, we now know that the LMC has several true globular clusters that are essentially identical in age to the old halo globulars of our Galaxy (Olsen et al. 1998; Johnson et al. 1998), so the evidence suggesting a delayed formation now seems to come only from the SMC. In any case, WLM gives us a rare opportunity to find the oldest cluster (and probably the oldest stars) in a more distant and intrinsically much less luminous star-forming galaxy in the Local Group.

2. DATA AND REDUCTION

2.1. Observations

As part of a Cycle 6 HST GO program, we obtained four images of the WLM globular cluster on 1998 September 26. There were two exposures taken with the F814W filter of 2700 s and two with the F555W filter, one each of 2700 and 2600 s. The globular cluster was centered on the PC chip and the orientation of the camera was such that the WF chips lay approximately along the galaxy's minor axis, providing a representative sample of the WLM field stars to allow us to separate cluster stars reliably.

2.2. Reductions

With two images of equal time per filter, cosmic rays were cleaned with an algorithm nearly identical to that used by the IRAF task CRREJ. The two images were compared at each pixel, with the higher value thrown out if it exceeded 2.5 sigma of the average. The cleaned, combined F555W image is shown in Figure 1.

Photometry was then carried out using a program specifically designed to reduce undersampled WFPC2 data. The first step was to build a library of synthetic point spread functions (PSFs), for which Tiny Tim 4.0 (Krist 1995) was used. PSFs were calculated at 49 positions on each chip in F555W and F814W, subsampled at 20 per pixel in the WF chips and 10 in the PC chip. The subsampled PSFs were adjusted for charge diffusion and estimated subpixel QE variations, and combined for various locations of a star's center within a pixel. For example, the library would contain a PSF for the case of a star centered in the middle of a pixel, as well as for a star centered on the edge of a pixel. In all, a $10 \times 10$ grid of possible centerings was made for the WF chips and a $5 \times 5$ grid for the PC chip. This served as the PSF library for the photometry.

Fig. 1.—Combined $V$ image of the WLM globular cluster after cosmic-ray cleaning.
The photometry was run with an iterative fit that located stars and then found the best combinations of stellar profiles to match the image. Rather than using a centroid to determine which PSF to use for a star, a fit was attempted with each PSF centered near the star's position and the best-fitting PSF was chosen. This method helped avoid the problem of centering on an undersampled image. Residual cosmic rays and other nonstellar images were removed through a chi-squared cut over the final photometry list.

The PSF fit was normalized to give the total number of counts from the star falling within a 0.5 radius of the center. This count rate was then converted into magnitudes as described in Holtzman et al. (1995), using the CTE correction, geometric corrections, and transformation. For the color-magnitude diagram (CMD) and luminosity function analyses below, roughly the central 20% of the image was analyzed to maximize the signal from the globular while minimizing the background star contamination. In that region, the effect of background stars is negligible. The CMD from this method, showing all stars observed, is shown in Figure 2a, with the same data reduced with DAOPHOT shown in Figure 2b. Error bars are shown corresponding to the artificial star results (which account for crowding in addition to photon statistics), rather than the standard errors from the PSF fits and transformations. The photometry list is given in Table 1, which will appear in its entirety only in the electronic edition. The table contains X and Y positions of each star, with V and I magnitudes and uncertainties. Uncertainties given are from the PSF fitting and from the transformations.

Artificial star tests were made, with each star added and analyzed one at a time to minimize additional crowding often caused by the addition of the artificial stars. The artificial stars were added to both the combined V and I images, so that a library of artificial star results for a given position, V magnitude, and color could be built. In addition to completeness corrections, these data were employed in the generation of synthetic CMDs for the determination of the star formation history of the cluster.

3. ANALYSIS

3.1. Luminosity Function

The luminosity functions (LFs) of the globular cluster in V and I are shown in Figures 3a and 3b, respectively, binned into 0.5 mag bins. Theoretical luminosity functions are given as well, from interpolated Padova isochrones (Girardi et al. 1996; Fagotto et al. 1994) using the star formation parameters and distance obtained in the CMD analysis below.

The observed and theoretical LFs are in excellent agreement. The bump in the observed V LF between magnitudes 25 and 26, and the bump in the observed I LF starting at 24.5 mag are due to the horizontal branch stars, which cannot be separated from the rest of the CMD cleanly. The only other significant deviation, the bump in the V LF between magnitudes 22.5 and 23, is the clump of stars at the tip of the RGB, which is also observed in the CMD. This seems to be a statistical fluke, a result of the relatively small number of stars in that part of the RGB, and is similar to statistical flukes seen in Monte Carlo simulations. Thus, as far as can be determined, the observed LF agrees with the theoretical expectations.

3.2. Color-Magnitude Diagram

For the CMD analysis, a cleaner CMD was achieved by omitting all stars with PSF fits worse than a chi-squared value of 3. The observed V, V − I CMD is shown in Figure 4a and was analyzed as described in Dolphin (1997). Interpolated Padova isochrones (Girardi et al. 1996; Fagotto et al. 1994) were used to generate the synthetic CMDs, with

![Fig. 2.—The V, V − I color-magnitude diagram of the cluster is shown in (a); (b) shows the same data, reduced with the IRAF task DAOPHOT.](image)

| TABLE 1 |
| --- |
| PHOTOMETRY |
| X | Y | V | δV | I | δI | V − I | δ(V − I) |
| 282.1 | 428.0 | 25.203 | 0.008 | 24.352 | 0.009 | 0.851 | 0.012 |
| 282.8 | 276.0 | 24.657 | 0.006 | 23.596 | 0.007 | 1.061 | 0.009 |
| 282.8 | 415.2 | 27.938 | 0.073 | 27.341 | 0.101 | 0.597 | 0.125 |
| 283.5 | 341.0 | 26.902 | 0.028 | 27.015 | 0.073 | 0.113 | 0.078 |
| 285.2 | 254.0 | 28.455 | 0.087 | 27.905 | 0.071 | 1.251 | 0.112 |
| 284.1 | 347.8 | 27.706 | 0.009 | 28.120 | 0.154 | 2.414 | 0.154 |
| 285.2 | 453.9 | 25.548 | 0.010 | 24.832 | 0.012 | 0.715 | 0.016 |
| 285.2 | 504.0 | 28.353 | 0.105 | 27.266 | 0.096 | 1.087 | 0.142 |
| 286.6 | 474.1 | 27.947 | 0.073 | 27.231 | 0.092 | 0.715 | 0.117 |
| 287.5 | 355.8 | 26.865 | 0.028 | 25.976 | 0.030 | 0.889 | 0.041 |
| 288.5 | 522.8 | 27.649 | 0.056 | 27.043 | 0.077 | 0.607 | 0.095 |
| 289.6 | 483.5 | 26.758 | 0.026 | 26.329 | 0.042 | 0.429 | 0.049 |
| 289.9 | 308.0 | 24.657 | 0.006 | 23.596 | 0.007 | 1.061 | 0.009 |
| 289.9 | 435.9 | 28.157 | 0.088 | 26.990 | 0.075 | 1.167 | 0.116 |

Note.—Table 1 is published in its entirety in the electronic edition of The Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
photometric errors and incompleteness simulated by application of artificial star results to the isochrones. No assumptions were made regarding the star formation history, metallicity, distance, or extinction to the cluster, and a fit was attempted with all of these parameters free. The best fits that returned single-population star formation histories were then combined with a weighted average to determine the best parameters of star formation. Uncertainties were derived by taking a standard deviation of the parameters from the fits and thus include the fitting errors and uncertainties resulting from an age-metallicity-distance “degeneracy.” Systematic errors due to the particular choice of evolutionary models are naturally present but are not accounted for in the uncertainties. The following parameters were obtained:

1. Age: $14.8 \pm 0.6$ Gyr.
2. Fe/H: $-1.52 \pm 0.08$.
3. Distance modulus: $24.73 \pm 0.07$.
4. Av: $0.07 \pm 0.06$.

Profiles were calculated in bins of 10 pixels (0.45") in both the $V$ and $I$ images and are shown in Figure 5, corrected for incompleteness (both as a function of magnitude and position). The cutoff magnitudes of 27 in $V$ and 26 in $I$ were chosen to minimize the corrections required due to incompleteness. Additionally, the central bin (0–10 pixels) was omitted because of extreme crowding problems. The remaining bins were fit to King models with a least-squares fit. The best parameters for the King models (assuming a distance modulus of 24.73) are as follows (shown by the solid lines in Fig. 5):

1. Core radius: $1.09 \pm 0.14$ (4.6 \pm 0.6 pc).
2. Tidal radius: $31" \pm 15"$ (130 \pm 60 pc).
3. Core density: $59 \pm 8$ stars arcsec$^{-2}$ (3.2 \pm 0.4 stars pc$^{-2}$) $V$, $44 \pm 6$ stars arcsec$^{-2}$ (2.4 \pm 0.3 stars pc$^{-2}$) $I$.
4. Background density: $0.07 \pm 0.012$ stars arcsec$^{-2}$ (0.042 \pm 0.007 stars pc$^{-2}$) $V$, $0.77 \pm 0.12$ stars arcsec$^{-2}$ (0.042 \pm 0.007 stars pc$^{-2}$) $I$.

For a distance modulus of 24.87 (Lee et al. 1993), the corresponding sizes would be 7% larger. For comparison, Trager, Djorgovski, & King (1993) find that 2/3 of Milky Way clusters have core radii between approximately 5 and 60 pc.

4. CONCLUSIONS

Our analysis shows that the WLM globular cluster is virtually indistinguishable from a halo globular in our Galaxy. We find that a formal fit to theoretical isochrones
indicates an age of $14.8 \pm 0.6$ Gyr, which agrees with ages currently being measured for Galactic globulars (e.g., van-denBerg 1998) and a metallicity of $[\text{Fe}/\text{H}] = -1.52 \pm 0.08$, a typical globular cluster value that is similar to that obtained for the outer field giant stars along the minor axis of WLM by Minniti & Zijlstra (1997) and by us (Dolphin 1999). The distance modulus for the cluster, derived independently from the parent galaxy, is $24.73 \pm 0.07$, which agrees within the errors with that derived from Cepheids and the RGB (Lee et al. 1993) of the galaxy.

In structure the globular is elongated in outline, with a mean radial profile that fits a King (1962) model within the observational uncertainties. We derive a core radius of $1.09 \pm 0.14$ and a tidal radius of $31' \pm 15'$, which translate to $4.6 \pm 0.6$ pc and $130 \pm 60$ pc, respectively. The core radius is very similar to that found for massive globulars in our Galaxy (Trager et al. 1993), while the tidal radius, though quite uncertain, is rather large by comparison. The former result indicates that formation conditions in this galaxy near its conception were such that a massive, highly concentrated star cluster could form, despite the very small amount of the total mass of material available. The latter result is probably an indication that the tidal force of the galaxy on the cluster is small.

The presence of a normal, massive globular cluster in this dwarf irregular galaxy may be an useful piece of evidence regarding the early history of star, cluster and galaxy formation. Recent progress in the field of globular cluster formation has resulted from both observational and theoretical studies (Searle & Zinn 1978; Harris & Pudritz 1994; McLaughlin & Pudritz 1994; Durrell et al. 1996; Miller et al. 1998; McLaughlin 1999). Although the uncertainties from a single data point are sufficiently large to discourage quantitative analysis, the presence of a globular cluster in WLM would constrain formation models that predict $\leq 1$ cluster in such a galaxy.

We are indebted to the excellent staff of the Space Telescope Science Institute for obtaining these data and to NASA for support of the analysis through grant GO-06813.

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