WLM-1: AN OLD, NONROTATING, GRAVITATIONALLY UNPERTURBED, HIGHLY ELLIPTICAL EXTRAGALACTIC GLOBULAR CLUSTER

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ABSTRACT

Globular clusters have long been known for presenting (at times) significant deviations from spherical symmetry. While rotation has been the main proposed explanation, other complicating factors such as their constant interaction with the strong gravitational potential of their host galaxy have made it difficult for a consensus to be reached. To address this question we have obtained high-resolution spectra of WLM-1, the lone, old globular cluster associated with the isolated, low-mass dwarf irregular galaxy WLM. Using archival HST WFPC2 data, we measure the radial ellipticity profile of WLM-1, finding it to be highly elliptical, with a mean value of 0.17 in the region 0"5–5", which is comparable to what is found in our Galaxy for the most elliptical globular clusters. There is no evidence of isophote twisting, except for the innermost regions of the cluster (r < 0"5). To investigate whether the observed flattening can be ascribed to rotation, we have obtained long-slit high-resolution Very Large Telescope UVES spectra of this cluster along and perpendicular to the axis of flattening. Using cross-correlation we find that the velocity profile of the cluster is consistent with zero rotation along either axis. Thus, neither cluster rotation nor galactic tides can be responsible for the flattened morphology of WLM-1. We argue that the required velocity dispersion anisotropy between the semimajor and semiminor axes that would be required to account for the observed flattening is relatively small, of order 1 km s\(^{-1}\). Even though our errors preclude us from conclusively establishing that such a difference indeed exists, velocity anisotropy remains at present the most plausible explanation for the shape of this cluster.

Key words: galaxies: star clusters — stars: kinematics

1. INTRODUCTION

Globular clusters have long been noted to deviate, sometimes substantially, from perfect spherical symmetry (Shapley 1917; Pease & Shapley 1917). What is the reason why many globular clusters are nonspherical? A conclusive answer to such an important question in the study of globular cluster dynamics, with potentially important ramifications in the study of the evolution of globular cluster stars (Norris 1983, 1987), has so far not been conclusively established (see Meylan & Heggie [1997] for an extensive review and references).

Several possible causes of deviations of globular cluster shapes from sphericity have been suggested, including tidal stresses due to the presence of strong galactic tidal fields (Longaretti & Lagoute 1997; Combes et al. 1999), gravothermal shocks during the passage of a cluster through the disk (Kontizas et al. 1989), velocity anisotropies, and internal rotation (which may also be acquired by interaction with a massive galaxy; Lee et al. 2004 and references therein). In particular, the former two phenomena are now well documented, with a particularly impressive example being given by Palomar 5 (Odenkirchen et al. 2001). The possibility that rotation may be the main driver of cluster ellipticities (Ryden 1996) is supported by the Meylan & Mayor (1986) and Merritt et al. (1997) studies of ω Centauri (NGC 5139), which are based on a detailed analysis of its structural and dynamical profiles. Yet, it still remains unclear, from both an empirical and a theoretical perspective, whether rotation can be the main cause of flattening of globular star clusters.

On the observational side, we currently lack detailed velocity profiles for most globular clusters; and even though we do have detailed rotational information for a few clusters, such as 47 Tucanae (NGC 104), ω Cen, M4 (NGC 6121), and M15 (NGC 7078) (Mayor et al. 1984; Gebhardt et al. 1995; Peterson et al. 1995; Gerssen et al. 2002; M. Zoccali 2004, private communication), the lack of a wider sample, as well as of reliable measurements of the variation in flattening as a function of radius for clusters encompassing the full range of observed ellipticities, has hindered further progress in establishing the general correspondence, or lack thereof, between flattening and cluster rotation. Indeed, the latest catalogs of globular cluster ellipticities, published by Frenk & Fall (1982) and White & Shawl (1987), are entirely based on photographic data, consider exclusively the outermost cluster regions, and, relying on visual data, can be severely affected by differential reddening (van den Bergh 1982). Our group is currently building a new, detailed catalog of globular cluster...
ellipticities based on Two Micron All Sky Survey (2MASS) near-infrared data, which will greatly improve on the current situation (C. Navarro et al. 2006, in preparation).

Theoretically, too, the case for rotation as one of the main drivers of globular cluster ellipticity is far from being settled. In particular, Meza (2002) has recently argued that globular clusters can rotate at very fast rates without deviating substantially from sphericity. This result is in contrast with those from Alimi & Perez (1999), who instead were unable to produce models of fast-rotating globular cluster–like structures without an accompanying deviation from sphericity, in the sense that their modeled structures became lengthened along one or two axes, depending on the initial anisotropy of the velocity distributions.

An ideal test, from an empirical viewpoint, of the impact on rotation on the shapes of globular star clusters is to measure the rotation velocity of a highly flattened, isolated extragalactic globular cluster, where there is little possibility that tidal effects and/or gravothermal shocks may be responsible for its flattening. The closest possible approximation to such an isolated, flattened system is represented by the single, old globular cluster in the Wolf-Lundmark-Melotte (WLM) dwarf irregular galaxy (DDO 221). While distant (885 kpc; Hodge et al. 1999), the mass of the WLM galaxy is much smaller than even the LMC or SMC, with $M_V$ of $-14.4$, $-18.5$, and $-17.1$, respectively (van den Bergh 2000), thus effectively ruling out the possibility that the nonspherical shape of the WLM cluster (WLM-1) can be due to tidal effects or gravothermal shocks. Note, in this sense, that this is not necessarily the case even in the Magellanic Clouds (Goodwin 1997), where nonspherical globular clusters of all ages can be found (van den Bergh 1991 and references therein).

In this paper we begin by reanalyzing archival Hubble Space Telescope (HST) WFPC2 data in § 2, in which we measure the ellipticity and surface brightness profiles of WLM-1. We then discuss our new Very Large Telescope (VLT) UVES observations in § 3, and attempt to measure the rotation (§ 5) and velocity dispersion (§ 6) of WLM-1. We conclude with a discussion of the possibility of velocity anisotropy in WLM-1 as a possible explanation for its observed morphology, and give some final remarks in § 9.

2. HST WFPC2 OBSERVATIONS

In order to measure accurate ellipticity and surface brightness profiles of WLM-1, we have downloaded calibrated HST WFPC2 F814W and F555W images from the HST archive (program GO 6813, principal investigator P. W. Hodge). In these images WLM-1 is centered on the PC chip. The only processing required was to combine the two images in each filter to reject cosmic rays. We also combined the images from different filters to reject the remaining few cosmic rays. This final image, rotated to put north at the top, is shown in Figure 1.

2.1. Cluster Ellipticity

The ellipticity and position angle as a function of semimajor axis distance are measured with the Image Reduction and Analysis Facility (IRAF\(^2\)) routine ellipse, where $\epsilon = 1 - b/a$, and $a$ and $b$ are the semimajor and semiminor axis lengths, respectively. The position angle is the angle $(-90^\circ < \alpha < 90^\circ)$ made by the major axis measured degrees east of north. The results are illustrated in Figure 2. The mean ellipticities and position angles for our spectral extraction regions are listed in Table 1.

Note that since there are many resolved stars in the HST image, there are many irregularities in the measurement of the ellipticity and position angle, especially at larger radii where these stars contribute a significant fraction of the total flux (see discussion in C. Navarro et al. 2006, in preparation). Also, when the ellipticity gets close to zero (nearly circular), the position angle becomes poorly constrained and shows large fluctuations.

The mean ellipticity of WLM-1 in the region $0.5 < r < 5''$ is $0.172 \pm 0.039$. This ranks among the highest values among Galactic globular clusters according to the lists tabulated by Frenk & Fall (1982) and White & Shawl (1987), and only ~10 Galactic globular clusters have ellipticities greater than this according to the recent analysis of 2MASS data by C. Navarro et al. (2006, in preparation). It has previously been noted that LMC and SMC globular clusters of all ages also have significant ellipticities, and in fact tend to be more elliptical than either Galactic or M31 clusters (van den Bergh 1991; Goodwin 1997 and references therein), suggesting an inverse relationship between galaxy mass and globular cluster ellipticity, which would appear to be broadly consistent with the case of WLM-1. However, Harris et al. (2002) have recently shown that the giant elliptical galaxy NGC 5128, with $M_V = -20.1$ mag (de Vaucouleurs 1980), also contains a sizable population of flattened clusters.

It is also interesting to note that Han & Ryden (1994) have suggested that, while Galactic and M31 globular cluster shapes are broadly consistent with oblate spheroids, LMC and SMC clusters are instead more consistent with triaxial ellipsoids. As is well known, triaxiality is often accompanied by isophote twisting (Williams & Schwarzschild 1979). In the case of WLM-1, we do find some interesting evidence that isophote twisting may indeed be present, but this is clearly restricted to the innermost $0.5'$ of the cluster (Fig. 2).
2.2. Surface Brightness Profile

We have independently measured the surface brightness profile on HST WFPC2 F555W ($\sim V$) and F814W ($\sim I$) images obtained from the HST archive. Using the IRAF ellipse task with the ellipticity and position angle fixed at the mean values of 0.17 and 7.1, respectively, we measured the average flux in each elliptical annulus, which was then converted to surface brightness using the photometric zero points (ZPs) from the HST manual \([\text{ZP}(555) = 22.545, \text{ZP}(814) = 21.639]\). The data from the F555W filter are shown as circles in Figure 3.

Finally, we fitted the surface brightness measurements with King (1962) profiles using a $\chi^2$ minimization algorithm and the rms scatter in each annulus as an estimate of the measurement errors (although this is actually a measure of the true range of flux values at any particular semimajor axis distance rather than a measure of how accurately one can measure the surface brightness). Pixels within $\sim 0'15$ of the center of the cluster are saturated, and were therefore excluded from the fit. These excluded points are indicated by open circles in Figure 3. The resulting fits for each filter were then averaged together to give the final values. We find a best-fit core radius of $r_c = 0'0126 \pm 0'021$ and a tidal radius of $r_t = 16'3 \pm 10'4$, where the magnitude of the errors is driven by the large scatter of fluxes in each annulus (due to the resolved nature of the cluster population). The fitting also takes into account the background surface brightness; the best-fit values are $22.37 \pm 0.13$ mag arcsec$^{-2}$ in F555W and $21.45 \pm 0.13$ mag arcsec$^{-2}$ in F814W filter. Note that we have not taken into account the finite size of the HST point-spread function (PSF), which has a nominal value of less than $0'1$ in both filters.

Assuming $(m - M)_V = 24.73$ (Hodge et al. 1999), $1''$ corresponds to 4.28 pc at the distance of WLM-1, and our measurements of the core and tidal radii convert to $r_c = 0.54 \pm 0.09$ pc and $r_t = 70 \pm 44$ pc. Both of these values fall squarely in the range of parameters exhibited by Galactic globular clusters: $0.03 < r_c (\text{pc}) < 21.9$ and $1.6 < r_t (\text{pc}) < 214$, with median values of $r_c = 1.06$ pc and $r_t = 35.4$ pc (Harris 1996). This implies a very compact globular cluster, with $\epsilon \simeq 2.1 \pm 0.3$. We cannot discard the possibility of a collapsed core. Note that our measured half-light radius for the WLM-1 cluster, along with its $M_V = -8.74$ ($\S$ 6.1), are not inconsistent with the trend between $r_h$ and $M_V$ for globular clusters in dwarf galaxies and the outer Galactic halo suggested by van den Bergh & Mackey (2004, their Fig. 7).

The structural parameters of WLM-1 have been derived previously using star counts by Hodge et al. (1999), who found a core radius of $1'09 \pm 0'14$ (4.6 \pm 0.6 pc) and a tidal radius of $31'7 \pm 15'1$ (130 \pm 60 pc). A comparison of the background-subtracted star-count profile and background-subtracted surface brightness profile (Fig. 3) yields a very good match down to $\sim 2''$, where the star counts start to become incomplete. At $\sim 1''$ the two profiles diverge; the star counts turn over, while the surface brightness profile continues to rise down to $\sim 0',1$, at which point the CCD becomes saturated. We speculate that this incompleteness in the star counts is the source of Hodge’s large parameter values.

Other quantities that are of use in the following sections include the half-light radius $r_h$, the central $V$-band surface brightness $\mu_V(0)$, and the mean surface brightness inside the half-light radius $\langle \mu_V \rangle_h$. We estimate these parameters from the best-fit

\begin{table}[h]
\centering
\caption{Ellipticity}
\begin{tabular}{lcc}
\hline
$\alpha$ & $\epsilon$ & P.A. \\
(arsec) & & (deg) \\
\hline
0.1–0.5 & 0.074 \pm 0.042 & 4.7 \pm 44.1 \\
0.5–1.0 & 0.153 \pm 0.025 & 7.0 \pm 9.8 \\
1.0–1.5 & 0.150 \pm 0.021 & 9.4 \pm 6.5 \\
1.5–5.0 & 0.180 \pm 0.038 & 7.7 \pm 6.6 \\
\hline
\end{tabular}
\end{table}
King model to the F555W (V) band HST data. We find $v_\pi = 0.75^{+0.27}_{-0.31}$ (3.2$^{+1.2}_{-1.3}$ pc), $\mu_r(0) = 14.83^{+0.32}_{-0.46}$ mag arcsec$^{-2}$, and $\langle \mu_r \rangle_1 = 17.31^{+0.25}_{-0.58}$ mag arcsec$^{-2}$.

3. VLT UVES OBSERVATIONS

The new data analyzed in this paper were obtained with the UVES on the 8.2 m VLT UT2 (Kueyen) telescope. UVES is a two-arm cross-dispersed echelle spectrograph with a dichroic splitting the red and blue components of the light. The blue light is recorded on a single 2K×4K EEV CCD, and the red light on a mosaic of an EEV CCD and an MIT Lincoln Laboratory CCD for the reddest orders.

In order to obtain the highest spatial resolution we used a 0.5 wide slit, which allows us to obtain velocity information on a similar scale. While slightly undersampling the spectral information, we chose to bin the CCDs 2×2 to improve the signal-to-noise ratio in the faint outer parts of the cluster. This binning yields a plate scale of 0.492 pixel$^{-1}$ in the blue and 0.364 pixel$^{-1}$ in the red. The blue slit has a length of 8′′ (~16 pixels) and the red slit 11′′ (~30 pixels). The wavelength coverage and resolution of this configuration are listed in Table 2.

WLM-1 (R.A. = 00h01m49, decl. = −15°27′30″, J2000.0) was observed for 3060 s in each of two slit positions, one aligned with the major axis (position angle P.A. = 68°) and another aligned along the minor axis (P.A. = 96°). An HST image of the cluster (Hodge et al. 1999) with the slit orientations indicated is shown in Figure 1.

4. UVES DATA REDUCTION

The data reduction was carried out with IRAF. Each of the three UVES CCDs (BLUE, REDL, and REDU; see Table 2 for wavelength coverages) was reduced independently, beginning with overscan, bias subtraction, and removal of the scattered interorder light. Before dividing by the flat field, any variations with scales larger than a few pixels were removed from the illuminated regions by fitting and dividing by a high-order spline3 fit using the apflatten task. The resulting “flattened” field flat was then normalized to unity and divided into the science frames. Finally, we located and interpolated over cosmic rays and bad pixels in the science frames using the IRAF median filtering task crmedian.

The center of the cluster was traced in all orders and then extracted using the apertures discussed in §4.1. The calibration lamp spectrum and flat field were extracted using traces and extraction apertures identical to those for the cluster to ensure the most accurate wavelength calibration. The extracted science spectra were then divided by the normalized extracted flat field to remove the blaze function and any wiggles due to absorption or emission features in the flat field. Finally, we removed any large-scale problems from the extracted spectra, such as bad columns or cosmic-ray strikes, using linear interpolation from 100 pixels on either side of the blemish.

The wavelength solution was derived from a thorium-argon calibration lamp spectrum. The solutions have an rms scatter of ~0.003 Å and use ~1150, ~750, and ~450 lines in each of the BLUE, REDL, and REDU wavelength regions, respectively. Note that we redrew the wavelength solution for each extraction. We performed one last cleaning of any remaining cosmic rays in the spectra by fitting by a cubic spline of high enough order to fit the absorption features, and iteratively replacing +4σ and −6σ outliers with the fit. Finally, we trimmed the noise-dominated ends of each order and combined the orders into a single spectrum.

4.1. Extractions

The key to measuring a rotation velocity in data such as these, for which a highly concentrated object is barely resolved, is the careful analysis of the light coming from the edges of the cluster. While the center of the cluster contains most of the light, and hence has the highest signal-to-noise ratio, the slit of the spectrograph is 0.5 wide; thus, we can obtain no velocity information in the central 0.5. The seeing, which ranged from 0.53 to 0.56, and the coarseness of our binned pixels (0.0492 pixel$^{-1}$ in the blue and 0.364 pixel$^{-1}$ in the red) also blur the spatial resolution.

We must therefore concentrate on the outer regions of the cluster. However, the cluster is very compact, with a core radius of 0.126 ± 0.021 (‡ 2.2), and the light profile plummets as one moves away from the center; the cluster light fades into the background only −3′′ from the center.

We have extracted five different regions of various sizes and radii in hopes of obtaining the best measure of the cluster rotation profile. Since the cluster is fairly elliptical (e ≈ 0.16 in this region), we scale the minor-axis extraction apertures to ensure that we consistently measure the same physical radius of the cluster. The extraction regions are listed in Table 3. The first region includes the entire half of the cluster and is meant to give a luminosity-weighted rotation estimate. However, as mentioned before, due to the width of the spectrograph slit, the innermost regions include an equal mix of approaching and receding stars, so the second extraction region excludes the inner 0.5. The final three extraction regions are very narrow and are used to try to estimate the rotation profile of the cluster.

When possible, the extractions use background subtraction, where the background is calculated as the median in two regions on either side of the cluster. These background regions are scaled according to the ellipticity for the minor axis extractions. Note that the slit is too narrow for background subtraction on the blue chip; however, as there are no significant sky lines in the blue, this should not affect the results.

One should note that the WLM-1 cluster is relatively large. The tidal radius is 16″ ± 10″ (‡ 2.2), while the slits used in this paper to obtain the spectra are only 8″ and 11″ long. Thus, the entire slit has contributions from cluster stars, and any attempt at background subtraction will also subtract cluster light.

| Extraction Regions | MAJOR REGIONS | MINOR REGIONS |
|--------------------|---------------|---------------|
| A                  | BLUE          | RED           | BLUE          | RED           |
| 0.00−1.50.......... | 0.00−3.05     | 0.00−4.12     | 0.00−2.56     | 0.00−3.46     |
| 0.50−1.50.......... | 1.02−3.05     | 1.37−4.12     | 0.85−2.56     | 1.15−3.46     |
| 0.00−0.50.......... | 0.00−1.02     | 0.00−1.37     | 0.00−0.85     | 0.00−1.15     |
| 0.50−1.00.......... | 1.02−2.03     | 1.37−2.75     | 0.85−1.71     | 1.15−2.31     |
| 1.00−1.50.......... | 2.03−3.05     | 2.75−4.12     | 1.71−2.56     | 2.31−3.46     |
| Background.......... | None          | 7.20−13.19    | None          | 6.04−11.10    |

Note.—Extraction regions in pixels.
We plot the three narrow spectral extractions along the major axis in Figure 4. This very small piece of the total spectrum illustrates the variation in signal-to-noise ratio with each extraction and the abundance of absorption features available for measuring velocities.

4.2. Atmospheric Absorption

Terrestrial atmospheric absorption lines are noticeable in our REDU spectra. Two bands are especially strong: H$_2$O at 5880–6020 Å and O$_2$ at 6200–6360 Å. We did not observe atmospheric standards, and therefore, we have no way to accurately correct for this absorption. However, if not removed these absorption lines would bias our REDU derived rotation velocity toward zero, since they are at exactly the same wavelengths on both sides of the cluster.

To remove the telluric absorption lines we simply set any such absorption to the continuum value. We start with a high-resolution atmospheric transmission atlas,$^3$ smooth it to our resolution, and create a “telluric mask” for our spectra. This mask has regions of high transmission set to 1, and absorption regions, where the transmission is less than 95%, set to a very large number. Before cross-correlating the spectra, but after continuum subtraction, we divide by this telluric mask and effectively set all significant regions of atmospheric absorption to the continuum level. We thus lose any velocity information about WLM-1 that may have been contained in these masked regions, but the cross-correlation is no longer biased by these strong atmospheric features. A region of telluric absorption is shown in Figure 5 before and after masking.

5. CLUSTER ROTATION

The goal of these observations is to unambiguously measure the rotation velocity of WLM-1. One method of getting an estimate of the magnitude of this rotation would be to follow the original theoretical calculations of King (1961) for the ellipticity of a rotating cluster, which is equivalent to assuming that the cluster is a rotating fluid body. Assuming a distance modulus of $(m - M)_0 = 24.73$ (Hodge et al. 1999), which corresponds to 4.28 pc arcsec$^{-1}$, we find that the rotation velocity of WLM-1 should be of order

$$v_{\text{rot}} = 6.50 \text{ km s}^{-1} \left( \frac{r}{177} \right) \left( \frac{\rho'}{10^{-5} M_\odot \text{ pc}^{-3}} \right)^{1/2} \left( \frac{e}{0.16} \right)^{1/2},$$

where $\rho'$ is the effective density calculated for nonhomogeneous clusters (van Wijk 1949). Thus, if this cluster is indeed elliptical as a result of rotation, we might expect to measure a difference of $\sim 13 \text{ km s}^{-1}$ along the major axis and zero along the minor axis (see § 6 for a more detailed estimate of the expected rotation).

While our spectra are not of high signal-to-noise ratio, especially in the very narrow extractions, we do have a reasonably large wavelength coverage. Thus, while measuring the position of a single line yields a relatively large error, combining the results for the hundreds of lines present across the spectra increases the precision greatly. One way to simultaneously compare the positions of all features in two spectra is cross-correlation.

We use the Fourier cross-correlation technique of Tonry & Davis (1979), which has been implemented in the IRAF $\text{fxcor}$ task. This routine computes the height, width, and location of the cross-correlation peak of two spectra. For each axis we correlate the north-south (major) and east-west (minor) extractions that lie at equal radii. The results of these correlations for the narrow extractions along both the major and minor axes are shown in Figure 6. The center of the peak is determined by fitting the top five points with Gaussian functions. This yields a direct measure of the velocity shift between the two, which is equal to twice the cluster rotation velocity at that distance.

We start with the reduced, extracted spectra from each chip. In preparation for the cross-correlation we subtract the continuum by fitting with a cubic spline. The telluric absorption is removed

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$^3$ Available at ftp://ftp.noao.edu/catalogs/atmospheric_transmission.
from the REDU spectra following the procedure outlined in § 4.2. We then cross-correlate the spectra from each chip (BLUE, REDL, and REDU). Since the reductions, extractions, and wavelength calibrations are completely separate for each chip, this should give three independent, although weaker, measures of the cross-correlation velocity for each extraction. The results of this piecewise cross-correlation are listed in Table 4 for all symmetric extractions and allow one to compare the quality of the correlation for each chip. We then combine the spectra from all the chips and cross-correlate the result, excluding the ~100 Å gaps between the chips. The results of correlating the combined spectra are listed in Table 5 and shown in Figure 7.

Rather than make only one cross-correlation measurement to obtain the velocity at each radius, we can also cross-correlate all possible permutations and find the velocities that are most consistent with all correlations. In other words, cross-correlating the spectrum extracted from \( r_i \) and \(-r_i\) will give a measure of \( 2v_i \).

### Table 4: Piecewise Cross-Correlation Velocities

| Region         | 0.0–0.5 (arcsec) | 0.5–1.0 (arcsec) | 1.0–1.5 (arcsec) |
|----------------|------------------|------------------|------------------|
| **Major Axis** |                  |                  |                  |
| BLUE           | 0.09 ± 0.16      | 1.77 ± 0.55      | 0.39 ± 1.58      |
| REDL           | −0.20 ± 0.15     | −0.28 ± 0.78     | 0.38 ± 0.57      |
| REDU           | 0.02 ± 0.11      | −0.23 ± 0.73     | 0.20 ± 0.40      |
| Combined       | −0.09 ± 0.08     | −0.17 ± 0.41     | −0.17 ± 0.27     |
| **Minor Axis** |                  |                  |                  |
| BLUE           | −0.02 ± 0.15     | −0.38 ± 0.52     | −1.48 ± 0.79     |
| REDL           | 0.05 ± 0.16      | 0.02 ± 0.65      | 0.06 ± 0.54      |
| REDU           | 0.03 ± 0.11      | 0.96 ± 0.65      | 0.45 ± 0.49      |
| Combined       | −0.03 ± 0.08     | −0.56 ± 0.32     | −0.39 ± 0.31     |

*Note.*—Velocities in \( \text{km s}^{-1} \).

### Table 5: Combined-Spectrum Cross-Correlation

| Region   | Major Axis | Minor Axis |
|----------|------------|------------|
|          | Height (1) | Velocity\(a\) (2) | Height (4) | Velocity\(a\) (5) |
|          |            |            |            |            |
| 0.00–1.50 | 0.68 | +0.01 ± 0.08 | 0.67 | −0.01 ± 0.08 |
| 0.50–1.50 | 0.26 | −0.29 ± 0.33 | 0.28 | −0.42 ± 0.28 |
| 0.00–0.50 | 0.70 | −0.09 ± 0.08 | 0.69 | −0.03 ± 0.08 |
| 0.50–1.00 | 0.23 | −0.17 ± 0.41 | 0.27 | −0.56 ± 0.32 |
| 1.00–1.50 | 0.16 | −0.17 ± 0.27 | 0.16 | −0.39 ± 0.31 |

* Velocities in \( \text{km s}^{-1} \).

However, one can also correlate spectra from different radii, \( r_i \) and \( r_j \), to obtain the relative velocity difference \( \Delta v_{ij} \).

Using all six narrow extractions yields 15 correlation permutations. Thus, we have 15 measurements that depend on only three quantities, assuming that we should find equal but opposite velocities at the same radius on either side of the cluster. We solve for the most probable velocities by minimizing the sum of the squares of the deviation of each correlation.

Thus, instead of basing a rotation velocity on only one measurement of the cross-correlation of two spectra at equal distances from the cluster center, we measure 15 correlations between all six spectral extractions and find the three velocities that are in best agreement with all measurements. These “best-fit” rotation velocities are given as a function of semimajor axis distance in Table 6. We find no statistically significant rotation along the line of sight at any distance along either axis of WLM-1.

#### 5.1. Rotation Errors

In order to estimate the robustness of our results we have performed various cross-correlation simulations. All of these tests...
start out with a base spectrum that is the average of the major- and minor-axis integrated spectra of WLM-1.

To test the dependence of the cross-correlation velocity on the signal-to-noise ratio of the spectra we create pairs of spectra at various signal levels by adding random noise to two copies of the base spectrum, treating them as opposite sides of the cluster. We then remove the telluric absorption and shift one of the spectra by 5 km s\(^{-1}\). The pair of spectra are then cross-correlated as described in \S\ 5 to obtain their relative velocity. The results of these tests are illustrated in Figure 8, along with the height and FWHM of the cross-correlation peak. This figure shows no systematic trends with signal-to-noise ratio and verifies that the velocity errors returned by IRAF are indeed valid. From this analysis we estimate that the errors associated with the measurement of the cross-correlation FWHM are approximately 3 times the reported velocity errors and have plotted them as such in Figure 8.

To estimate the errors of the \(\chi^2\)-minimization technique used to determine the "best" rotation velocity, we ran 50 simulations consisting of six copies of the integrated spectrum of WLM-1 to mimic the six 0.5\(^\circ\) extractions. Each of the six spectra is shifted such that the simulated cluster has a monotonically increasing rotation velocity with radius and equal but opposite rotation velocities on opposite sides of the cluster. Specifically, the spectra were shifted by \(-3, -2, -1, +1, +2, +3\) km s\(^{-1}\) each. Noise was added to each spectrum so that the cross-correlation height measured in the simulation (Fig. 8) matched that measured in the real data (cols. [2] and [4] in Table 5).

The velocity error distributions (recovered — input) resulting from the 50 simulations have widths of 0.02, 0.05, and 0.06 km s\(^{-1}\) for the central, middle, and outer velocities, respectively. For each simulation we also record the average error of each measurement that results from making all cross-correlation measurements consistent (the square of this quantity is actually what is minimized when solving for the best set of rotation velocities). The mean of this error over all simulations is 0.031 km s\(^{-1}\). However, in the real data the error is 0.056 km s\(^{-1}\) along the major axis and 0.074 km s\(^{-1}\) along the minor axis. This discrepancy indicates that the simulation was too idealistic, and we have therefore scaled the estimated velocity errors by 1.8 for the major axis and 2.4 for the minor axis, yielding our formal error estimates of 0.04, 0.09, and 0.11 km s\(^{-1}\) for the central, middle, and outer extractions along the major axis and 0.05, 0.12, and 0.14 km s\(^{-1}\) along the minor axis.

6. CLUSTER VELOCITY DISPERSION

The velocity dispersion can be derived from the width of the cross-correlation peak, which is the sum of the line widths of the two spectra being correlated added in quadrature. In the case of the globular cluster WLM-1, the line width is a combination of the intrinsic stellar line width, the instrumental profile, and the velocity dispersion of the cluster. Unfortunately, no template star was measured at the time of our observations.

In order to estimate the velocity dispersion of WLM-1, we used two high-resolution stellar spectra obtained from the UVES Paranal Observatory Project (Bagnulo et al. 2003) as templates. We chose HD 30562 and HD 45067 (both F8 V stars) because of their similarities in line strengths to the WLM-1 spectrum. It is important to note that the template spectra were obtained using the 0.5\(^\circ\) slit and no binning, while the WLM-1 spectra used 2 \(\times\) 2 binning. We therefore rebinned the template stars to the same resolution as our observations.

In order to increase the signal-to-noise ratio of the WLM-1 spectra, we averaged together the spectra extracted from opposite sides of the cluster (since we only want to compare the velocity dispersions along the major and minor axes). We then analyzed the spectra measured on each chip separately to allow optimal Fourier filtering and rejection of undesirable lines. For example, we rejected the blue end of the blue chip, which was contaminated by broad hydrogen lines and Ca \(\text{II}\) H and K lines, the region around H\(\beta\) on the REDL chip, and H\(\alpha\) on the REDU chip.

We then cross-correlated each WLM-1 spectrum with each of the two template spectra. This gives cross-correlation widths for each template, which are then averaged. The resulting cross-correlation widths derived for the integrated cluster spectra are 28.7 and 29.0 km s\(^{-1}\) for the major and minor axes, respectively. This width is the quadratic sum of the WLM-1 and template line widths. In order to estimate the line widths of the templates, we cross-correlate the two templates with one another, and averaging the values from each chip, we find a width of 16.4 km s\(^{-1}\).

If we make the (generous) assumption that the WLM-1 and template spectra have the same instrumental width and intrinsic stellar line widths, it is now possible to subtract these components to find the stellar velocity dispersion. Subtracting in quadrature yields velocity dispersions of 23.5 and 23.9 km s\(^{-1}\) along the major and minor axes, respectively. Following the same procedure for each of the various spectral extractions of WLM-1 yields the velocity dispersion profile shown in Figure 9, where the errors are 3 times the velocity errors, as estimated in \S\ 5.1. Here the extraction semimajor axis distances are shown using flux-weighted centers.
For comparison we have overplotted the velocity dispersion profiles predicted by the isotropic Maxwellian distribution of the King model. These curves show the velocity dispersions computed according to equation (31) in King (1966) with a concentration $c = 2.00, 2.25$, and $2.50$, scaled to match the observed central velocity dispersion (but see §6.1), where the $c = 2.5$ profile is the flattest and, of these three curves, the best fit to the data. The discrepancy between the model and the measured data points (given that the light profile indicates $c = 2.1 \pm 0.3$) suggests either that the mass distribution is more extended than predicted by a King profile or that there is a systematic problem in our measurement of the velocity dispersion.

In order to verify that any observed differences (or lack thereof) in line widths are inherent in the source spectra and not due to changes in the instrumental/atmospheric contribution, we have also compared the widths of unresolved telluric absorption lines in each spectrum using the atmospheric transmission spectrum described in §4.2 as the template. We first excise a region of each WLM-1 spectrum in the range 6270–6320 Å, which is dominated by absorption lines due to atmospheric O$_2$. We remove the continuum and broad features by fitting with a high-order cubic spline and estimate the instrumental width of each via cross-correlation with the atmospheric spectrum. The widths of the telluric lines present in the major- and minor-axis spectra differ by less than 0.05 km s$^{-1}$, confirming the stability of the conditions during the observations.

Our absolute measurement of the velocity dispersion profiles is uncertain due to the low signal-to-noise ratio of our spectra and the imperfect match with the templates, which were obtained at a different time using a different instrument configuration. However, the relative velocity dispersion between the major and minor axes should be much more reliable. Figure 9 (bottom) shows the difference between the velocity dispersions measured along the major and minor axes. All spectral extraction regions are consistent with zero difference, and comparing the integrated cluster spectra measured along the major and minor axes yields a difference of only $-0.4 \pm 2.6$ km s$^{-1}$ (major − minor).

### 6.1. Central Velocity Dispersion Estimate

We can obtain an estimate of the central velocity dispersion of WLM-1 as a reality check of our measurement of the velocity dispersion profile. The simplest way to obtain a rough estimate of the velocity dispersion is to use the correlation between the central velocity dispersion and the cluster absolute magnitude, which was found by Djorgovski et al. (2003) to be followed by globular clusters in several different galaxies. On the basis of Figure 3 (top) in Djorgovski et al., we find

$$\log \sigma = -1.01 - 0.229M_V,$$

where $\sigma$ is in km s$^{-1}$. We use the apparent magnitude of the cluster from Table I in Sandage & Carlson (1985), $V = 16.06$ mag, and the extinction and distance moduli estimated by Hodge et al. (1999), $A_V = 0.07$ mag and $(m - M)_0 = 24.73$ mag, respectively, to find $M_V = -8.74$ mag for WLM-1. The above relation then gives a central velocity dispersion $\sigma \approx 9.8$ km s$^{-1}$.

A perhaps more accurate estimate for the central velocity dispersion of the cluster can be obtained from the “fundamental plane” correlation for globular clusters, as provided by Djorgovski (1995). In particular, Djorgovski has shown that (Galactic) globular clusters follow tight relations between the central velocity dispersion $\sigma$, the central surface brightness $\mu_V(0)$, and the core radius $r_c$, on the one hand, and between $\sigma$, the half-light radius $r_h$, and the mean surface brightness within $r_h$, $\langle \mu_V \rangle_h$ on the other. Based on his equations (3) and (6), we find that

$$\log \sigma = 4.173(\pm 0.175) + 0.45 \log r_c - 0.204(\pm 0.008)\mu_V(0),$$

$$\log \sigma = 4.829(\pm 0.237) + 0.70 \log r_h - 0.244(\pm 0.012)\langle \mu_V \rangle_h,$$

where $r_c$ and $r_h$ are in parsecs and $\sigma$ is in km s$^{-1}$.

Using equation (2) with the structural parameters derived in §2.2, core radius $r_c = 0.56$ pc and central $V$-band surface brightness $\mu_V(0) = 14.83$ mag arcsec$^{-2}$, we estimate the velocity dispersion to be $10.8^{+0.3}_{-0.3}$ km s$^{-1}$. Equation (3) with the half-light radius $r_h = 3.21$ pc and the mean surface brightness inside the half-light radius $\langle \mu_V \rangle_h = 17.31$ mag arcsec$^{-2}$ gives a central velocity dispersion of $9.1^{+0.3}_{-0.3}$ km s$^{-1}$. These estimates of the central velocity dispersion are lower than our measurements in Figure 9, but the uncertainties do not exclude our value. The larger velocity dispersion implies that the mass of WLM-1 lies on the high side of the relation derived for Galactic clusters.

### 7. Cluster Velocity

Extracting an integrated spectrum from the entire cluster using a 3″ ($\pm 1.5$”) aperture yields a relatively high signal-to-noise ratio spectrum relative to the partial extractions used to measure cluster rotation. These integrated spectra have many strong lines from which we can measure the net radial velocity of the cluster. In order to make this measurement, we first calculated and corrected for terrestrial motion based on the observation times of 2003 October 3 at 3:23 and 4:23 UT for the minor and major axis, respectively. We obtained an atomic line list from Reader & Corlies (1980) and used the IRAF task *reidlines* to calculate the radial velocity. Centroiding ~70 lines in each of the major- and minor-axis spectra yields heliocentric radial velocities of...
\[ -105.77 \pm 0.50 \text{ and } -105.84 \pm 0.50 \text{ km s}^{-1}, \text{respectively. } \]

Averaging the results, we estimate that the heliocentric radial velocity of WLM-1 is \(-105.8 \pm 0.4 \text{ km s}^{-1}. \) The radial velocity of the WLM galaxy is \(-116 \pm 2 \text{ km s}^{-1} \) (Huchra et al. 1993); thus, the cluster has a velocity of 10 km s\(^{-1}\) with respect to its host.

8. VELOCITY ANISOTROPY

It appears that the ellipticity of WLM-1 cannot be due to rotation, so perhaps WLM-1 is (in a sense) more like elliptical galaxies, in which anisotropies in the velocity dispersion play an important role in the observed morphology. To address this hypothesis we employ the tensor virial theorem, as described in Binney & Tremaine (1987), to obtain information about the relation between the ratio of the rotation velocity and velocity dispersion \(v_{\text{rot}}/\sigma\) on the one hand and ellipticity on the other.

We start by assuming that a globular cluster is an oblate spheroid, rotating around the \(z\)-axis, and is seen edge-on. We assume, moreover, that the system’s isodensity surfaces are concentric ellipsoids. Defining \(v_{\text{rot}}^2/\sigma^2\) as the mass-weighted mean-square rotation speed and \(\sigma_0^2\) as the mass-weighted mean-square random velocity along the line of sight, we arrive at the following relation:

\[
\frac{v_{\text{rot}}^2}{\sigma_0^2} = \frac{1 - \delta}{\sqrt{1 - e^2}} \arcsin(e) - e\sqrt{1 - e^2} - 2, \quad (4)
\]

where \(\delta < 1\) is a parameter that measures the anisotropy of the velocity dispersion tensor and \(e\) is the eccentricity, which is related to the ellipticity \(\epsilon\) as

\[
e = \sqrt{1 - (1 - \epsilon)^2}. \quad (5)
\]

Using these equations, we can build a family of curves giving \(v_{\text{rot}}^2/\sigma_0^2\) as a function of ellipticity for different values of \(\delta\). The result is shown in Figure 10. Binney & Tremaine (1987) argue that the representative points in the \((v_{\text{rot}}/\sigma, \epsilon)\)-plane of systems that are flattened by rotation lie close to the curve \(\delta = 0\), independent of the inclination angle \(i\).

The mean ellipticity of WLM-1, as measured in \(\S\, 2.1\), is \(\epsilon = 0.17\), which is indicated in Figure 10 by the vertical dashed line. As the low mass of the WLM galaxy effectively rules out the possibility that WLM-1 owes its ellipticity to tidal effects or gravothermal shocks, this figure very nicely illustrates the kinematical combinations available to explain the ellipticity of WLM-1.

At one extreme, the ellipticity of WLM-1 could be produced entirely by rotation. In this scenario there is no velocity anisotropy (\(\delta = 0\)), and reading from the plot we see that \(v_{\text{rot}}/\sigma \approx 0.57\). Taking a conservative estimate of 10 km s\(^{-1}\) for the central velocity dispersion of the cluster (\(\S\, 6\) ), the required rotation would be 5.7 km s\(^{-1}\). However, as we find no measurable rotation (\(v_{\text{rot}} \lesssim 0.1 \text{ km s}^{-1}\)), we exclude this possibility.

At the other extreme, the ellipticity of WLM-1 is due entirely to velocity anisotropy. The quantity \((1 - \delta)\), defined as the ratio between the diagonal terms of the velocity dispersion tensor along the rotation (“\(z\)”)-axis and elongation (“\(x\)”)-axis, should scale as

\[
1 - \delta \approx \sigma_z^2/\sigma_x^2. \quad (6)
\]

From Figure 10 one sees that if there is zero rotation (\(v_{\text{rot}}/\sigma = 0\)), it is possible to produce the observed ellipticity with a velocity dispersion parameter of \(\delta = 0.14\). Therefore, WLM-1’s flattening could be accounted for if the velocity dispersion along the rotation axis were smaller than along the elongation axis by

\[
\sigma_z \approx 0.93\sigma_x. \quad (7)
\]

Again taking the nominal velocity dispersion to be \(\sim 10\) km s\(^{-1}\), this velocity anisotropy would only produce a difference of 0.7 km s\(^{-1}\) in velocity dispersion between the major and minor axes. Such a difference would be too small to be detected on the basis of our data. Therefore, while we cannot prove that velocity anisotropy is responsible for the observed shape of WLM-1, it certainly appears to be the only option that is consistent with our observations.

9. CONCLUSIONS

We have analyzed VLT UVES long-slit spectra and HST WFPC2 images of the old extragalactic globular cluster WLM-1 in an attempt to understand the cause of its elliptical morphology. Unlike the situation for Galactic globular clusters whose detailed shapes may be influenced by their massive host galaxy, WLM is a low-mass dwarf irregular galaxy, eliminating the possibilities that the nonsphericity of WLM-1 could be caused by either tidal stresses or gravothermal shocks. This leaves two explanations for the flattening of this cluster: internal rotation and/or velocity dispersion anisotropy.

Cluster rotation seemed to be a prime candidate for the origin of WLM-1’s ellipticity, since two-body relaxation, which erases any primordial anisotropy, is relatively efficient in star clusters. In addition, rotation has been measured for several Galactic globular clusters using both proper motion and radial velocity techniques (the review by Meylan & Heggie [1997] lists the rotation velocities of 11 clusters). The most notable case is that of \(\omega\) Cen, which exhibits correlated rotation and flattening profiles, strongly suggesting that its ellipticity is due to rotation.
We therefore obtained high-resolution long-slit echelle spectra along the major and minor axes of the cluster. We used cross-correlation to look for velocity shifts on opposite sides of the cluster, dividing the cluster into annuli in an attempt to obtain a rotation velocity profile. However, we found no evidence for rotation \( (v_{\text{rot}} < 0.1 \text{ km s}^{-1}) \) along either the major or minor axes of the cluster. As the cluster would require a rotation of >6 km s\(^{-1}\) to sustain its shape, we conclude that rotation is definitely not the main driver of WLM-1’s ellipticity.

The only remaining plausible source of flattening in the WLM cluster is velocity dispersion anisotropy, the main reason elliptical galaxies are elliptical. We attempted to measure the stellar velocity dispersion in WLM-1 based on the width of the cross-correlation peak; however, due to our large errors, we could see no statistically significant difference between the velocity dispersions measured along the major and minor axes. Calculations reveal that the magnitude of the velocity anisotropy required to produce the observed ellipticity is relatively small: a 7% difference in velocity dispersion, or less than 1 km s\(^{-1}\), which is smaller than our velocity dispersion measurement errors. In summary, we conclude that the ellipticity of the globular cluster WLM-1 is most likely due to anisotropy in the stellar velocity dispersion.

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