The velocity dispersion and mass-to-light ratio of the remote halo globular cluster NGC 2419

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ABSTRACT
Precise radial velocity measurements from HIRES on the Keck I telescope are presented for 40 stars in the outer halo globular cluster NGC 2419. These data are used to probe the cluster’s stellar mass function and search for the presence of dark matter in this cluster. NGC 2419 is one of the best Galactic globular clusters for such a study due to its long relaxation time ($T_{\text{rel}} \approx 10^{11}$ yr) and large Galactocentric distance ($R_{\text{GC}} \approx 90$ kpc) — properties that make significant evolutionary changes in the low-mass end of the cluster mass function unlikely. We find a mean cluster velocity of $<v_r> = -20.3 \pm 0.7$ km/sec and an internal velocity dispersion of $\sigma = 4.14 \pm 0.48$ km/sec, leading to a total mass of $(9.0 \pm 2.2) \cdot 10^3$ $M_\odot$ and a global mass-to-light ratio of $M/L_V = 2.05 \pm 0.50$ in solar units. This mass-to-light ratio is in good agreement with what one would expect for a pure stellar system following a standard mass function at the metallicity of NGC 2419. In addition, the mass-to-light ratio does not appear to rise towards the outer parts of the cluster. Our measurements therefore rule out the presence of a dark matter halo with mass larger than $\sim 10^7$ $M_\odot$ inside the central 500 pc, which is lower than what is found for the central dark matter densities of dSph galaxies. We also discuss the relevance of our measurements for alternative gravitational theories such as MOND, and for possible formation scenarios of ultra-compact dwarf galaxies.

Key words: stellar dynamics, methods: N-body simulations, galaxies: star clusters, dwarf galaxies.

1 INTRODUCTION
An important unanswered question in modern astrophysics concerns the mechanism(s) by which stars and star clusters form. This is especially true in the case of globular clusters, which, due to their large ages, are probes of the evolution and assembly history of galaxies in the early universe. Various theories have been proposed concerning the formation process of globular clusters. A number of authors proposed that globular clusters formed at the centers of dark matter halos (e.g. Peebles 1984, West 1993, Cen 2001, Kravtsov & Gnedin 2005). Such a cosmologically-motivated formation scenario for globular clusters is indicated by the extreme age of most clusters, their low metallicities, and their characteristic masses (which are close to the Jeans mass at recombination). The fact that most clusters in the Milky Way contain no measurable amount of dark matter is not in contradiction to these theories, since, over the course of a Hubble time, dark matter would get depleted from the central regions of globular clusters due to the dynamical friction of stars against the much lighter dark matter particles (Baumgardt & Mieske 2008). As a result, dark matter tends to get pushed towards the outer cluster parts, where it is much more difficult to detect and can be more easily stripped away by the tidal field of the Milky Way (e.g., Mashchenko & Sills 2005).

A significant dark matter content might also be the explanation for the high mass-to-light ratios of ultra-compact dwarf galaxies (UCDs), which have been discovered in spectroscopic surveys of nearby galaxy clusters since the late 1990s (Hilker et al. 1999; Drinkwater et al. 2000). UCDs are bright ($-11 \leq M_V \leq -13.5$ mag) and compact ($7 \leq r_h \leq 100$ pc) stellar systems that: (1) appear to obey a set of structural scaling relations distinct from those of globular clusters; and (2) have mass-to-light ratios that are, on average, about twice as large than those of globular clusters of comparable metallicity, and somewhat larger than what one would expect based on simple stellar evolution models assuming a standard stellar initial mass function (Haşegan et
al. 2005; Dabringhausen, Hilker & Kroupa 2008; Mieske et al. 2008). One possible formation scenario for UCDs could be adiabatic gas infall into the center of a dwarf galaxy, which also funnels dark matter into the center (Goerdt et al. 2008). Later tidal disruption of these galaxies would leave only the central star cluster behind. Since some of the most massive Galactic globular clusters have masses and sizes only slightly smaller than UCDs (e.g. Rejkuba et al. 2007), it is conceivable that some of them may have formed in a similar way.

On the other hand, observations of interacting and starburst galaxies have shown that star clusters with masses comparable to globular clusters also form during major mergers between galaxies (Whitmore & Schweizer 1995; Whitmore et al. 1999; Goud稠roij et al. 2001) in the local universe, which makes it possible that globular clusters formed by similar processes in the early universe (e.g. Searle & Zinn 1978, Ashman & Zepf 1992). In such a scenario, globular cluster formation is driven mainly by gas-dynamical processes and the globular clusters should not contain significant amounts of dark matter.

Globular clusters in the outer halo of the Milky Way are ideal objects to test for the presence of dark matter and therefore examine the formation mechanism of globular clusters. Because the tidal field is weak in the remote halo, tidal stripping of the outer cluster regions will be much less important than for globular clusters orbiting close to the Galactic center. Baumgardt & Mieske (2008) have shown that, due to dynamical friction, dark matter gets depleted from the central regions of a star cluster on a timescale

$$T_{\text{Fric}} = 5.86 \left( \frac{M_{\text{tot}}}{10^5 M_\odot} \right)^{1/2} \left( \frac{r_h}{5 \text{pc}} \right)^{3/2} \left( \frac{m}{M_\odot} \right)^{-1} \text{Gyr} , \quad (1)$$

where $M_{\text{tot}}$ is the total cluster mass, $r_h$ is the half-mass radius and $m$ is the average stellar mass in the cluster. For clusters with $T_{\text{Fric}} < T_{\text{Hubble}}$, dark matter will be removed from the central parts within a Hubble time.

Fig. 1 shows the dynamical friction timescales of Galactic globular clusters. Here the cluster masses and half-mass radii, $r_h$, were calculated from the absolute magnitudes, projected half-mass radii $r_{hp}$ and distances given by Harris (1996), assuming $M/L = 2.5$, which is appropriate for most metal-poor clusters with $[Fe/H] < -1.2$ and $r_h = 1.33 r_{hp}$, which is approximately correct for most King models. It can be seen that the majority of galactic globular clusters have friction timescales much less than a Hubble time. According to the results of Baumgardt & Mieske (2008), dark matter would exist in such clusters only in the outer parts, where it is difficult to detect due to low stellar densities and the influence of the Galactic tidal field on the stellar velocities. Only a few clusters have friction timescales significantly longer than a Hubble time and are therefore good candidates to look for primordial dark matter. Among the clusters with long dynamical friction timescales are Pal 3, Pal 4 and Pal 14, which are currently being investigated by Jordi et al. (2009) in an effort to test alternative gravity theories like MOND (Milgrom 1983a,b).

The Galactic globular cluster with the longest dynamical friction time, and therefore the smallest amount of dark matter depletion, is NGC 2419. With a Galactocentric distance of $R_{\text{GC}} \approx 90$ kpc, NGC 2419 is also one of the most remote Galactic globular clusters, meaning that tidal stripping was likely to be least effective in this cluster. Finally, NGC 2419, as one of the most massive Galactic globular clusters (see Fig.1), represents a possible Local Group analogue to a UCD. Its half-light radius of $r_{hp} = 47.5'' \approx 19$ pc$^1$ (see §3.1) is also $\sim 6\times$ larger than is typical for globular clusters in the Milky Way and external galaxies (Jordán et al. 2005), although still a factor of $\sim 2$ smaller than the most extreme UCDs (see, e.g., Table 5 of Mieske et al. 2008). For all of these reasons, NGC 2419 is an excellent place to search for the presence of dark matter and thereby test different formation scenarios of globular clusters and, possibly, UCDs.

The only published velocity dispersion for NGC 2419 is that of Olszewski, Pryor & Schommer (1993) who, based on MMT radial velocity measurements with a median precision of 1.6 km/sec for 12 stars, found a mean radial velocity of $v_c = -20.0 \pm 0.9$ km/sec and an intrinsic velocity dispersion of $\sigma_c = 2.7 \pm 0.8$ km/sec. Fitting single-mass, isotropic

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Dynamical friction time, $T_{\text{Fric}}$, of stars against lighter dark matter particles for Galactic globular clusters. Most globular clusters have friction timescales of less than a Hubble time, meaning that dark matter would have been depleted from their centers if they formed as a mix of dark matter and stars. Only a few extended clusters have friction times longer than a Hubble time and should therefore still retain dark matter in their centers. With the longest friction timescale of all Galactic globular clusters, NGC 2419 is a promising target for a search for dark matter.}
\end{figure}

\begin{equation}
1 \text{ At our adopted distance for NGC 2419, (}m-M)_{0} = 19.60 \text{ mag (Ripepi et al. 2007), }1''\text{ corresponds to 0.40 pc.}
\end{equation}
amplifier was used (gain = 2.4 ADU$^{-1}$) — one of the smallest values measured for a Galactic globular cluster and much lower than the M/L$^V$S found for some UCDs.

In this paper, we report on radial velocity measurements for 44 candidate red giant branch (RGB) stars in the direction of NGC 2419 taken with the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the Keck I telescope. The paper is organized as follows: In § 2 we describe the details of the observations and data reduction. In § 3 we determine the total cluster luminosity, velocity dispersion and mass-to-light ratio of NGC 2419, and in § 4 we draw our conclusions.

2 OBSERVATIONS AND DATA REDUCTION

Candidate RGB stars in NGC 2419 were selected for observation with HIRES from the photographic study of Racine & Harris (1975), as well as from unpublished CCD photometry of Peter Stetson. Fig. 2 presents a finding chart for the candidate RGB stars that were observed for this program. HIRES spectra were obtained on four separate nights during two observing runs on the Keck I telescope. The dates of the two runs were February [10-11] and March [9-11] 1999 (i.e., five nights in total). During each run, we limited the entrance aperture using the C1 decker (0.866 × 7.0′′) and binned the detector 1 × 2 (i.e., in the spatial direction) to reduce the read noise. The spectral resolution for this instrumental configuration is $R = 45000$. A single readout amplifier was used (gain = 2.4 ADU$^{-1}$) with the red collimator and a cross-disperser in first order. Thorium-Argon comparison lamp spectra were acquired frequently during each night. In all, spectra were acquired for 44 different RGB candidates during the two runs, with exposure times ranging from 180 to 600 sec. Approximately two dozen high-S/N candidates during the two runs, with exposure times ranging from 180 to 600 sec. Approximately two dozen high-S/N candidates during the two runs, with exposure times ranging from 180 to 600 sec. Approximately two dozen high-S/N candidates during the two runs, with exposure times ranging from 180 to 600 sec. Approximately two dozen high-S/N candidates during the two runs, with exposure times ranging from 180 to 600 sec. Approximately two dozen high-S/N candidates during the two runs, with exposure times ranging from 180 to 600 sec. Approximately two dozen high-S/N candidates during the two runs, with exposure times ranging from 180 to 600 sec. Approximately two dozen high-S/N candidates during the two runs, with exposure times ranging from 180 to 600 sec.

Spectra for program objects and standard stars were reduced in an identical manner following the general procedures described in Côté et al. (1999, 2002). Briefly, the radial velocity of each RGB candidate was measured by cross-correlating its spectrum against that of a master template correlator and a cross-disperser in first order. Thorium-Argon and matching the chemical abundances of the cluster: e.g., [Fe/H] = -2.32 dex and [α/Fe] = +0.2 dex (e.g., Shetrone, Côté & Sargent 2001). In making this comparison, we have adopted a reddening of E(B - V) = 0.10 mag — intermediate between the values of 0.11 mag and 0.08 mag reported by Harris et al. (1997) and Ripepi et al. (2007) — and a de-reddened distance modulus of (m - M)$_0$ = 19.60 mag (Ripepi et al. 2007). Note that all of our program stars, and those from the previous MMT program, are located within ~2 mag of the RGB tip. The right panel of Fig. 3 shows a magnified view of this part of the CMD. The dashed lines show a region of ±0.15 mag width centered on the isochrone — an interval chosen to roughly match the observed width of the RGB sequence and encompass all of the probable radial velocity members.

Since NGC 2419 is located at a Galactic latitude of $b \approx 25^\circ$, it is important to consider the possibility of contamination by foreground disk stars. To gauge the extent of such contamination, we show in the right panel of Fig. 3 the results of one simulation using the Besançon Galaxy model (Robin et al. 2003), for field stars in the range 0-100 kpc and located within a 500′′ × 500′′ region in the direction of NGC 2419. This simulation yields a total of 10 stars having magnitudes and colours that would place them within the region bounded by the dashed lines in the right panel of Fig. 3. However, as we shall see in §3.2, only two stars in this simulation have radial velocities within ±3σ of the cluster mean. Since our radial velocity survey is by no means complete within this simulated region, we conclude that our final sample should have minimal foreground contamination with 1 interloper, at most, expected within ±3σ of the cluster’s systemic velocity. The final column of Table 1 gives our division of the sample into cluster members and foreground stars. In most cases, the assignments are unambiguous, al-
though three stars (S17, S22 and S38) are more problematical. We shall return to this issue in §3.

3 RESULTS

3.1 Surface density profile

The surface brightness profile of NGC 2419 has most recently been determined by Bellazzini (2007) using surface photometry and star counts from HST/ACS and SDSS. In this paper we use his data for our analysis. Fig. 4 shows the V-band surface brightness profile of NGC 2419 as determined by Bellazzini (2007) and compares it with several different model profiles. Bellazzini (2007) found that the best-fitting King (1962) profile has a central core radius of \( r_c = 19.2 ^\circ \) and a concentration index of \( c = \log(\frac{r_e}{r_c}) = 1.35 \). We show this profile by the blue dashed curve in Fig. 4. As can be seen, a King profile provides a satisfactory fit to the observed surface density profile out to \( \approx 300 \). Beyond this point, however, the observed brightness profile declines more slowly than the fitted King profile. Such an excess could be the signature of extra-tidal stars (e.g., Leon et al. 2000). However, at the distance of NGC 2419, \( 300 \) corresponds to a physical distance of about 120 pc. The expected tidal radius of NGC 2419 at its current distance is \( r_t \sim 750 \) pc: i.e., more than 5 times as large, if we assume a circular cluster orbit and a logarithmic potential with circular velocity \( v_c = 200 \).
Velocity dispersion and M/L ratio of NGC 2419

km/sec for the Milky Way and a cluster mass of $10^6 M_\odot$. In addition, tidal radii often correspond to breaks in the surface density distribution but no such break is visible in Fig. 4. Hence, unless the cluster orbit is highly eccentric ($\epsilon > 0.9$), the outermost stars are most likely bound to NGC 2419 so that the tidal radius has not yet been reached by the observations, something which was also noted by Ripepi et al. (2007).

We have therefore also tried to fit the surface brightness profile with Sérsic (1968) profiles, which are known to provide accurate representations of the surface brightness profiles of most early-type galaxies, including UCDs, over nearly their entire profiles (e.g., Graham & Guzmán 2003, Ferrarese et al. 2006, Côté et al. 2007, Evstigneeva et al. 2007, Hilker et al. 2007). We find that Sérsic models that best fit the data over the whole range (red dotted curve) and those fitted to the data for $r > 20''$ both give good fits in the outer profiles but significantly overpredict the central surface brightness. In order to obtain a model that fits the surface brightness profile over the whole radial range, we add a constant density core to the Sérsic profile fitted to the data for $r > 20''$:

$$\Sigma(r) = \Sigma_0 \exp(-(1.9992n - 0.3271) \cdot \left(\frac{r'}{r_c}\right)^{1/n} - 1.0)$$  \hspace{1cm} \text{(2)}$$

where $r' = \sqrt{r^2 + r_c^2}$. A $\chi^2$ minimization gives 14'' as best fitting value for $r_c$. The solid red curve in Fig.4 shows the surface brightness profile of the outer Sérsic profile once a constant density core with $r_c = 14''$ has been added. With this model we obtain a very good fit to the overall surface brightness profile. The lower panel shows the residuals between our fitted model and the observed data. At most radii, the differences between the observed surface density and our model are within the observational uncertainties.

Table 2 summarises our results. For a King model fit, we find that the best-fitting profile has $r_c = 19''$ and $c = 1.39$, which agrees reasonably well with Bellazzini (2007). The other rows list the parameters of our best-fitting Sérsic profiles. The integrated V magnitudes are calculated separately for each surface density profile. They are, in general, some-
what smaller than the values by Bellazzini (2007), who found $V=10.47 \pm 0.07$ mag. Because the King profile underpredicts the light in the outer parts while the two Sérsic profiles significantly overpredict the light in the inner parts, we consider the values from the cored Sérsic profile to be most reliable and we will use them in the remainder of this paper. For the cored Sérsic profile, we obtain a total luminosity of $V=10.57$ mag and a projected half-light radius of $r_{hp} = 47.5''$. The latter value agrees quite well with the half-light radius found by Trager, King & Djorgovski (1995), $r_{hp} = 45.7''$. With a distance modulus of $(m-M)_0 = 19.60 \pm 0.05$ mag and a reddening of $E(B-V)=0.08$ mag (Ripepi et al. 2007), these values lead to a total absolute magnitude and projected half-mass radius of NGC 2419 of $M_V = -9.28$ mag and $r_{hp} = 19.2$ pc respectively.

### 3.2 Velocity dispersion of NGC 2419

Table 1 lists 44 stars in the direction of NGC 2419 with radial velocities measured in the course of this study. Rejecting the four stars with the most discrepant velocities and consequently identified as non-members in Table 1 (e.g., S3, I93, 11 and I43) leaves us with a sample of 40 stars having radial velocities in the range $-35 \leq v_r \leq -5$ km/sec. Although this sample shows a clear peak at $\sim -20$ km/sec corresponding to the cluster systemic velocity, there are three stars that differ by $\sim 10$ km/sec or more from the apparent cluster mean. The upper panel of Fig. 5, which plots radial velocity against distance from the cluster center, reveals all three to be among the centrally concentrated stars (i.e., with radii of $r \lesssim 15''$) and thus unlikely to be interlopers. Nevertheless, we now pause to consider the extent to which our sample could be contaminated by foreground disk stars.

As noted in §2, one simulation of the expected Galactic foreground using the Besançon model (Robin et al. 2003) suggests we might expect a total of $\sim 10$ interloping field stars: (1) within a $500'' \times 500''$ region along this line of sight; and (2) falling along the cluster RGB shown in the right panel of Fig. 3. In the lower panel of Fig. 5 we compare the observed velocity distribution of radial velocities (open blue histogram) with that from the simulation (filled red histogram). The foreground stars plotted here represent all stars in this velocity range with magnitudes and colours that place them within the RGB locus shown in Fig. 3. Because our sample of 44 RGB candidates constitutes only a small fraction ($\approx 13\%$) of the full sample of stars in this region of the CMD and lying within $\sim 250''$ of the cluster core, we conclude that we would expect, at most, 1 interloper in our final sample of 40 cluster members.

We now proceed by calculating the average radial velocity and velocity dispersion of NGC 2419 using the method of Pryor & Meylan (1993). We first assume that each velocity, $v_i$, is drawn from a normal distribution,

$$f(v_i) = \frac{1}{\sqrt{2\pi (\sigma^2 + \sigma^2_{\epsilon,i})}} \exp \left( -\frac{(v_i - v_c)^2}{2(\sigma^2 + \sigma^2_{\epsilon,i})} \right),$$

where $v_c$ and $\sigma$ are the cluster’s average radial velocity and intrinsic velocity dispersion, and $\sigma_{\epsilon,i}$ is the individual velocity error for each star. Calculating the likelihood function, $L$, for all stars and taking the partial derivatives of its logarithm $l = \log L$ with respect to $v_c$ and $\sigma_c$ leads to the following set of equations:

$$\sum_{i=1}^{N} \frac{v_i}{\sigma^2 + \sigma^2_{\epsilon,i}} - v_c \sum_{i=1}^{N} \frac{1}{\sigma^2 + \sigma^2_{\epsilon,i}} = 0$$

- $V_{tot}$: $10.65$ mag.

### Table 2. Photometric parameters of best-fitting surface density profiles for NGC 2419

| Model Type       | $c$  | $r_c$ | $r_{hp}$ | $\mu_0$  | $V_{tot}$ |
|------------------|------|-------|----------|----------|-----------|
| King (1962)      | 1.39 | 19.0  | 47.5     | 19.61    | 10.65     |
| Sérsic (all r)   | 2.15 | 49.8  | 49.8     | 22.32    | 10.77     |
| Sérsic ($r > 20''$) | 3.01 | 43.2  | 32.2     | 21.31    | 10.48     |
| Sérsic-core      | 3.01 | 43.2  | 47.5     | 21.23    | 10.57     |

![Figure 4](image-url) Figure 4. Upper panel: V-band surface brightness profile of NGC 2419 as determined by Bellazzini (2007). The blue, short-dashed curve shows the best fitting single-mass, isotropic King (1962) model. This model cannot fit the “excess” light at large radii. The dotted and long-dashed red curves are fits of two Sérsic profiles that fit the outer parts of the cluster well but not the central region. The solid curve is a Sérsic profile with an added core of size $r_c = 14''$. It provides a good match to the density profile and is within the reported observational uncertainties at most radii (bottom panel).
The above equations can be solved analytically to obtain a first guess value for \( v_i \) and \( \sigma_c \), if zero measurement errors \( \sigma_{c,i} \), for all stars are assumed. The full solution can then be obtained iteratively, starting with the solution for zero measurement errors as first estimate. The errors of \( v_i \) and \( \sigma_c \) are obtained from the information matrix, \( \mathbf{I} \), by

\[
\sigma_v = \frac{I_{22}/(I_{11}I_{22} - I_{12}^2)}{11} (6)
\]

\[
\sigma_\sigma = \frac{I_{11}/(I_{11}I_{22} - I_{12}^2)}{20} (7)
\]

where the components \( I_{ij} \) of the information matrix are calculated as given in Pryor & Meylan (1993).

Using the 40 probable members from Table 1, we obtain a mean cluster velocity of \( v_c = -20.63 \pm 0.74 \text{ km/sec} \) and an intrinsic velocity dispersion of \( \sigma_c = 4.61 \pm 0.53 \text{ km/sec} \). This mean velocity agrees very well with the one obtained by Olszewski, Pryor & Schommer (1993). Our velocity dispersion is, however, significantly higher than the value of \( 2.7 \pm 0.8 \text{ km/sec} \) determined by Olszewski, Pryor & Schommer (1993) and agrees with their value only at the \( 2\sigma \) level. The explanation for this difference appears to lie in the radial distribution of the stars in the two samples: Fig 5 reveals the Olszewski, Pryor & Schommer (1993) sample to contain only three stars in the central \( r \sim 1' \), whereas we observe a significant rise in the cluster velocity dispersion based on a larger sample of 17 stars in this region. In the outer parts of the cluster, our measured velocity dispersion (see below) is in very good agreement with the previous estimate.

The lower panel of Fig. 5 shows the distribution of radial velocities of the 40 candidate members in the velocity range \(-36 \) to \(-4 \text{ km/sec} \) (open histogram). The dotted curve shows a gaussian fit to this distribution using the above values for \( v_c \) and \( \sigma_c \). As can be seen, the observed radial velocity distribution is well approximated by this Gaussian except, as noted above, that the number of outliers in the wings of the distribution is somewhat higher than predicted: i.e., stars S17 and S38 are more than \( 2.2\sigma \) away from the mean while star S22 is almost \( 3\sigma \) away from the mean. For a Gaussian distribution and a sample of 40 stars, one would expect to find a star that is more than \( 3\sigma \) away from the mean in only 10% of all cases. Also, the chance to have three or more stars more than \( 2.2\sigma \) away from the mean is only 10%, while the chance to have two such stars is twice as high. This makes it possible that at least one star, most likely star S22, is either a cluster nonmember or a radial velocity variable.

Since star S22 is located in the cluster center and has a photometry that places it squarely on the RGB (see the right panel of Fig. 3), it could be a binary system, in which case it should be excluded from the analysis. The absolute radial velocity difference between star S22 and the cluster mean (~15 km/sec) is also so large that star S22 would be nearly unbound if the radial velocity difference is due to a different orbital velocity. Star S22 is also one of the five stars in common with Olszewski, Pryor & Schommer (1993), and has the most discrepant velocity in both samples. Moreover, two independent measurements differ by 5.1 km/sec, or three times the quadrature sum of the individual uncertainties. These facts suggest that star S22 may be a cluster binary or, perhaps more likely, an RGB star that shows a velocity “jitter” that has previously been found for some globular cluster stars on the upper RGB (e.g., Gunn & Griffin 1979, Mayor et al. 1984). If we omit star S22, we obtain a mean cluster velocity and an intrinsic velocity dispersion of:

\[
\begin{align*}
    v_c &= -20.28 \pm 0.68 \text{ km/sec} \\
    \sigma_c &= 4.14 \pm 0.48 \text{ km/sec}.
\end{align*}
\] (8)

These values are within the errorbars of the values that we obtain when using all stars and we will use them throughout the rest of this paper.

We note that the three stars with the most discrepant radial velocities are also among the four most central stars. While this could simply be a statistical effect, it could also point to either a high binary fraction in the core or the broadening of the velocity distribution due to additional un-
3.3 Cluster Rotation

Our sample of 40 member stars also allows us to check for a possible rotation of NGC 2419. Fig. 6 shows the radial velocities of stars as a function of position angle (PA). Here the position angle is measured from north (PA=0°) towards east (PA=+90°). There is a clear dependence of the average velocity from the position angle visible in the data. This is confirmed by fitting a sinusoidal curve to the radial velocity data. Allowing for a variable rotation angle, we obtain a rotation amplitude of 3.26 ± 0.85 km/sec around an axis with position angle of PA = 40.9 ± 17.8 degree. Our data therefore implies cluster rotation at more than the 3σ level. The root mean square scatter around the rotation curve is 4.00 km/sec. NGC 2419 is therefore partly rotationally supported and partly supported by random stellar motions. Bellazzini (2007) found that NGC 2419 is slightly elliptical with average ellipticity of ε = 0.19 ± 0.15 and position angle of PA = +105° ± 28°. Both the relatively small amount of ellipticity and the average angle of ellipticity, which is within the errorbars 90° away from the rotation axis that we find, supports our finding that NGC 2419 is rotating.

3.4 Mass modeling and mass-to-light ratio

The global mass-to-light ratio is calculated from the velocity dispersion and the total cluster luminosity under the assumption that mass follows light. Unless there is primordial mass segregation, this is probably a valid assumption since the relaxation time of NGC 2419 is larger than a Hubble time; i.e., the central and half-mass relaxation times are \( T_{\text{ch}} \approx 10.5 \text{ Gyr} \) and \( T_{\text{ch}} \approx 19 \text{ Gyr} \), respectively (Djorgovski 1993). In addition, Dalessandro et al. (2008) found no evidence for mass segregation among the blue straggler stars in NGC 2419, which supports the assumption that mass follows light. We also neglect the cluster rotation and assume that the cluster has an isotropic velocity dispersion. In such a case, we can use the method described in Hilker et al. (2007) to calculate the mass-to-light ratio. Their method first decomposes the surface density profile into the three-dimensional spatial density distribution, \( \rho(r) \). The spatial density is then used to calculate the potential, \( \Phi(r) \), of NGC 2419 and from \( \rho \) and \( \Phi \), the distribution function, \( f(E) \), is calculated by assuming spherical symmetry and using eq. 4-140a of Binney & Tremaine (1987). This distribution function is then used to create an N-body representation (i.e., particle positions and velocities) of NGC 2419 with a given first guess of \( M' \) for the cluster mass. We then draw a number of \( N' \) stars located at the same projected radius of each observed star from this N-body model and measure the projected velocity dispersion, \( \sigma'_{\text{Mod}} \), of the sample stars. The total mass of NGC 2419 can then be calculated by comparing this velocity dispersion with the observed velocity dispersion according to:

\[
M_C = M' \cdot \frac{\sigma_{\text{Mod}}^2}{\sigma^2}.
\]

This method has the advantage that it can work for any given observed surface density profile and for any given radial distribution of stars. This set it apart from parameterized formulas which work only for certain density distributions and usually need the core or global velocity dispersion to calculate the cluster mass. If the stars with radial velocity measurements are neither concentrated in the cluster core, nor spread out over the cluster in the same way as the cluster stars, using such formulae can lead to a bias in the derived cluster mass.

We calculate an N-body model with \( N = 5 \cdot 10^5 \) stars in total and extract for each observed star \( N' = 200 \) stars from this model. Calculating the velocity dispersion for the theoretical model and comparing it with NGC 2419, we find a total mass of \( M_C = (9.02 \pm 2.22) \cdot 10^5 \, M_\odot \) for NGC 2419 and a mass-to-light ratio of \( M/L_V = 2.05 \pm 0.50 \) in solar units, using all stars except star S22. If we were to include star S22, the total mass would rise to \( M_C = (1.09 \pm 0.26) \cdot 10^6 \, M_\odot \) and the mass-to-light ratio would be \( M/L_V = 2.48 \pm 0.60 \) in solar units. These values are significantly higher than the M/L ratio derived by Olszewski et al. (1993), \( M/L_V \approx 0.7 \pm 0.4 \, M_\odot/L_\odot \). Since our method gives a very similar M/L than what they found if we use their stars as input, the main reason for the discrepant M/L values seems to be the different input stars.

We finally tested our modeling method by randomly drawing 40 stars from the N-body model and then measuring their velocity dispersion and fitting the model against them in the same way as was done for the NGC 2419 data.

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Figure 6. Radial velocities as a function of position angle (PA) measured from north (PA=0°) towards east. The solid curve shows our best-fitting rotation curve for NGC 2419. It has an amplitude of 3.26 ± 0.85 km/sec, implying significant rotation of the cluster. The direction of rotation, PA=40.9° ± 17.8° is, within the errorbars 90° away from the semi-major axis found in the surface density profile by Bellazzini (2007), PA=+105° ± 28°, supporting the fact that NGC 2419 is rotating.
In order to compare the observed mass-to-light ratio with the predictions of population synthesis models, we need to know the cluster age and metallicity. Based on an analysis of a high-resolution Echelle spectrum for a single RGB star (10), Shetrone, Côté & Sargent (2001) measured a metallicity of [Fe/H] = -2.32 for NGC 2419, which is one of the lowest abundances among all Galactic globular clusters. Salaris & Weiss (2002) have used horizontal branch and turn off star brightenings to determine ages of Galactic globular clusters. Salaris & Weiss (2002) have used horizontal branch and turn off star brightenings to determine ages of Galactic globular clusters. Salaris & Weiss (2002) have used horizontal branch and turn off star brightenings to determine ages of Galactic globular clusters. Salaris & Weiss (2002) have used horizontal branch and turn off star brightenings to determine ages of Galactic globular clusters. Salaris & Weiss (2002) have used horizontal branch and turn off star brightenings to determine ages of Galactic globular clusters.

We also added different DM halos to our N-body model in order to see the effect of these halos on the velocity dispersion. The DM halos follow NFW profiles with scale radii $R_S = 500$ pc, which agrees with measured scale radii of Galactic dSph galaxies which are generally larger than a few hundred pc (Wu 2007), and had various ratios of dark halo mass inside $R_S$ to the stellar mass of NGC 2419. We then calculated a new velocity dispersion profile for NGC 2419 and fitted it to the data in the same way as described above. From our fit procedure, we derive a best-fitting (stellar) $M/L$ ratio and the total stellar and dark mass of NGC 2419. As can be seen in Fig. 7, significant amounts of dark matter are basically ruled out by our observations since they overpredict the velocity dispersion in the outer cluster parts, at least for models with isotropic stellar velocity dispersions. A DM halo with total mass of $M_{DM} = 1.65 \cdot M_{stars}$ overpredicts the velocity dispersion by more than $2\sigma$ at a radius of $R=140^\prime$. This model also has a best-fitting stellar $M/L$ ratio of only $M/L = 1.40 \pm 0.34$, which is $2\sigma$ below the predictions of the stellar evolution models. Our observations therefore rule out a DM halo of more than $M \approx 1 \cdot 10^7 M_\odot$ inside 500 pc around NGC 2419, corresponding to a density of $0.02 M_\odot/pc^3$. This is significantly lower than the dark matter content of Galactic dSph galaxies inside a similar radius as derived by Walker et al. (2007) and Strigari et al. (2008). It is also a factor 5 lower than central dark matter densities of dwarf galaxies as determined by Gilmore et al. (2007). Our observations therefore argue strongly against the formation of NGC 2419 within a sizeable dark matter halo. More radial velocities would help to strengthen our conclusions and test the validity of several assumptions that we made for our data analysis, in particular that the stellar orbits are isotropic and that the cluster is not mass segregated.

Finally, we note that the low observed velocity dispersion in the outer parts of NGC 2419 might also be a problem for MOND. According to MOND, the orbits of stars show a difference with respect to standard Newtonian behavior once their acceleration falls below a critical acceleration $a_0 \approx 1.2 \cdot 10^{-8}$ cm/sec$^2$ (Sanders & McGaugh 2002). While the acceleration of stars near the half-mass radius of NGC 2419 is still higher than $a_0$, it falls significantly below $a_0$ in the outer parts of NGC 2419. At the radius of our out-

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**Figure 7.** Observed velocity dispersion as a function of radius. The solid line shows our prediction based on the best-fitting cored Sérsic model. Dotted and dashed lines show the predicted velocity dispersion if we add NFW halos with a scale radius of $R_S = 500$ pc and masses of $M_{DM} = 4 \cdot 10^6 M_\odot$ and $M_{DM} = 10^7 M_\odot$ inside $R_S$ to this model. Models with additional dark matter halos significantly overpredict the velocity dispersion in the outer parts, showing that NGC 2419 does not possess a dSph-like DM halo.

Doing this 100 times, each time with a different random realisation of stars, we obtained an average ratio of derived mass-to-light ratio to true mass-to-light ratio of 1.00 ± 0.01, i.e. our modeling method gives an unbiased estimate of the true mass-to-light ratio.

In order to test the presence of a significant amount of dark matter in the cluster. In order to test if a possible DM halo could exist at least in the outer cluster parts, we have divided the sample into three equally large groups according to their radial distance and calculated velocity dispersions separately for each group. Fig. 7 compares velocity dispersions at different radii with the predicted velocity dispersion profile from our N-body model. It can be seen that the velocity dispersion of the cored Sérsic model is in reasonable agreement with the data. If at all, additional mass is required only in the inner parts of the cluster, where the predicted velocity dispersion is smaller than the observed one by about 1σ, not in the outer parts as might be expected for a dark matter halo.

The “normal” mass-to-light ratio of NGC 2419 also argues against the presence of a significant amount of dark matter in the cluster. In order to test if a possible DM halo could exist at least in the outer cluster parts, we have divided the sample into three equally large groups according to their radial distance and calculated velocity dispersions separately for each group. Fig. 7 compares velocity dispersions at different radii with the predicted velocity dispersion profile from our N-body model. It can be seen that the velocity dispersion of the cored Sérsic model is in reasonable agreement with the data. If at all, additional mass is required only in the inner parts of the cluster, where the predicted velocity dispersion is smaller than the observed one by about 1σ, not in the outer parts as might be expected for a dark matter halo.

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ermost datapoint in Fig. 7, the internal acceleration is only one third of $a_0$, while the external acceleration is only one tenth of $a_0$, so one would expect that the observed velocities start to deviate significantly from the prediction of our $N$-body model which was created based on Newtonian dynamics. This is not seen in our data. In fact, as shown by Milgrom (1994), if one neglects the external field of the Milky Way, MOND predicts that the line-of-sight velocity dispersion should level off at a value $\sigma_{\text{min}} = 0.471 \sqrt{GM/c^2}/a_0$ at large distances. If we use the above calculated cluster mass, we find $\sigma_{\text{min}} = 2.6$ km/sec for NGC 2419. Our outermost datapoint is already probing this value, so acquiring additional data at even larger radii might prove a powerful way to test the validity of MOND.

4 CONCLUSIONS

We have measured precise radial velocities for $\approx 40$ stars in the outer halo globular cluster NGC 2419 using the Keck telescope High Resolution Echelle Spectrometer. We find a mean cluster velocity of $\langle v_r \rangle = -20.3 \pm 0.7$ km/sec and an internal velocity dispersion of $\sigma = 4.14 \pm 0.48$ km/sec. Our observations also reveal a slight cluster rotation with amplitude $3.26 \pm 0.85$ km/sec around a position angle of $40.9 \pm 17.8$ degrees. From a comparison of the measured velocity dispersion to the velocity dispersion of a spherically symmetric model for NGC 2419, we find a total mass of $M_C = (9.01 \pm 2.22) \cdot 10^6 M_\odot$ and a mass-to-light ratio of $M/L_V = 2.05 \pm 0.50$ in solar units. This value is entirely compatible with the one expected for a stellar system at the metallicity of NGC 2419 following a standard mass function like Kroupa (2001) or Chabrier (2003).

NGC 2419 therefore does not show any dynamical evidence of a significant depletion of low-mass stars, which is consistent with expectations given the large relaxation and dissolution time for this cluster. Similar $M/L$ ratios which are in agreement with standard mass functions have been found for other galactic globular clusters with large relaxation and dissolution times like Omega Cen ($M/L_V = 2.5$ van de Ven et al. (2006)). This sets Milky Way globular clusters apart from UCDs for which standard mass functions on average seem to underpredict mass-to-light ratios (Mieske et al. 2008). If real, this points to a significant change in the star formation process occurring at a characteristic mass of $M_C \approx 2 \cdot 10^6 M_\odot$ (e.g., Hagegan et al. 2005; Mieske et al. 2008, Dabringhausen et al. 2009). Such a transition might arise, for example, if more massive clusters become optically thick to far infrared radiation and are born with top heavy initial mass functions (Murray 2008).

We do not find any evidence for the presence of substantial amounts of dark matter in NGC 2419. Since both the depletion of dark matter from the cluster center due to two-body relaxation and dynamical friction (Baumgardt & Mieske 2008), as well as tidal stripping of dark matter from the cluster halo are unlikely, this indicates that NGC 2419 did not contain substantial amounts of dark matter at the time of formation. NGC 2419 is, however, one of the most likely candidates for a globular cluster to have formed with an associated dark matter halo given its quite low metallicity. Our non-detection of dark matter in this cluster therefore supports the hypothesis that globular clusters, as a rule, did not form at the centers of dark matter halos. Instead, an origin driven by gas dynamical processes during mergers between galaxies (Bournaud, Duc & Emsellem 2008) or proto-galactic fragments seems to be the more likely explanation for the formation of even the lowest metallicity globular clusters.

We also find a slightly larger than expected velocity dispersion in the central regions of the cluster, which might point to a significant binary fraction or additional unseen matter in the core. At the same time, the rather low velocity dispersion in the outer regions of the cluster could pose a problem for alternative gravitational theories like MOND. These conclusions rely on several assumptions that we had to make for our modeling, in particular that stellar orbits are isotropic throughout the cluster and that the stellar mass-to-light ratio is constant with radius. Acquiring additional radial velocities would help test the validity of these assumptions and strengthen our conclusions.

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REFERENCES

Ashman, K.M., Zepf, S.E., 1992, ApJ, 384, 50
Baumgardt, H., Makino, J., Hut, P., 2005, ApJ, 620, 238
Baumgardt, H., Mieske, S., 2008, MNRAS, 391, 942
Bellazzini, M., 2007, A&A, 473, 171
Binney, J., Tremaine, S., 1987, Galactic Dynamics, Princeton Univ. Press, Princeton, p. 425
Bournaud, F., Duc, P.A., Emsellem, E., 2008, MNRAS, 389, 8
Bruzual, A.G., Charlot, S., 2003, MNRAS, 344, 1000
Cen, R., 2001, ApJ, 560, 592
Chabrier, G., 2003, PASP, 115, 763
Côté, P., Mateo, M., Olszewski, E. W., & Cook, K. H. 1999, ApJ, 526, 147
Côté, P., Djorgovski, S. G., Meylan, G., Castro, S., & McCarthy, J. K. 2002, ApJ, 574, 783
Côté, P., et al. 2007, ApJ, 671, 1456
Dabringhausen, J., Kroupa, P. & Baumgardt, H., 2009, MNRAS in press, arXiv:0901.0915
Dabringhausen, J., Hilker, M. & Kroupa, P., 2008, MNRAS, 386, 864
Dalessandro, E., Lanzoni, B., Ferraro, F. R., Vespe, F., Bellazzini, M., Rood, R.T., 2008, ApJ, 681, 311
Djorgovski, S. 1993, Structure and Dynamics of Globular Clusters, 50, 373
Dotter, A., Chaboyer, B., Jevremović, D., Kostov, V., Baron, E., & Ferguson, J. W. 2008, ApJS, 178, 89
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Drinkwater, M.J., Jones, J.B., Gregg, M.D. & Phillipps, S., 2000, PASA, 17, 227

Evstigneeva, E.A., Gregg, M.D., Drinkwater, M.J. & Hilker, M., 2007, AJ, 133, 1722

Ferrarese, L., et al. 2006, ApJS, 164, 334

Gilmore, G., Wilkinson, M.I., Wyse, R.F.G., Kley, J.T., Koch, A., Evans, N.W., Grebel, E.K., 2007, ApJ, 663, 948

Goerdt, T. et al., 2008, MNRAS, 385, 2136

Goudfrooij, P. et al., 2001, MNRAS, 322, 643

Graham, A. W., & Guzmán, R. 2003, AJ, 125, 2936

Gunn, J. E., & Griffin, R. F. 1979, AJ, 84, 752

Harris, W.E., 1996, AJ, 112, 487

Harris, W.E., et al. 1997, AJ, 114, 1030

Haşegan, M. et al., 2005, ApJ, 627, 203

Hilker, M., Infante, L., Viera, G., Kissler-Patig, M. & Richtler, T., 1999, A&AS, 134, 75

Hilker, M., et al., 2007, A&A, 463, 119

Jordán, A., et al. 2005, ApJ, 634, 1002

Jordi, K., et al., 2009, MNRAS, in press, arXiv:0903.4448

King, I., 1962, AJ, 67, 471

Kravtsov, A.V., Gnedin, O.Y., 2005, ApJ 650, 665

Kroupa, P., 2001, MNRAS 322, 231

Leon, S., Meylan, G., Combes, F., 2000, A&A 359, 907

Maraston, C., 2005, MNRAS, 362, 799

Mashchenko, S., & Sills, A. 2005, ApJ, 619, 258

Mayor, M., et al. 1984, A&A, 134, 118

Mieske, S., et al. 2008, A&A, 487, 921

Milgrom, M., 1983a, ApJ, 270, 365

Milgrom, M., 1983b, ApJ, 270, 371

Milgrom, M. 1994, ApJ, 429, 540

Murray, N.W., 2008, ApJ in press, arXiv:0809.4320

Olszewski, E.W., Pryor, C., Schommer, R.B., 1993, in The globular clusters-galaxy connection, eds. G.H. Smith and J.P. Brodie, ASP Conf. Ser. 48, p.99

Peebles, P.J.E., 1984, ApJ, 277, 470

Pryor C., Meylan G., 1993, in Structure and Dynamics of Globular Clusters, eds. S. Djorgovski, G. Meylan, ASP Conference Series 50, p. 357

Racine, R., & Harris, W.E. 1975, ApJ, 196, 413

Rejkuba, M., Dubath, P., Minnit, D., & Meylan, G., 2007, A&A, 469, 147

Ripepi, V., et al., 2007, ApJ, 667, L61

Robin, A.C., et al., 2003, A&A, 409, 523

Salaris, M., & Weiss, A., 2002, A&A, 388, 492

Sanders, R.H., McGaugh, S.S., 2002, ARA&A, 40, 263

Searle, L., Zinn, R., 1978, ApJ, 225, 357

Sérsic, J. L. 1968, Cordoba, Argentina: Observatorio Astronomico, 1968

Shetrone, M. D., Côté, P., & Sargent, W. L. W. 2001, ApJ, 548, 592

Strigari, L.E., Bullock, J.S., Kaplinghat, M., Diemand, J., Kuhlen, M., Madau, P., 2008, AJ 669, 676

Tonry, J., & Davis, M. 1979, AJ, 84, 1511

Trager, S.C., King, I.R., & Djorgovski, S. 1995, AJ, 109, 218

van de Ven, G., van den Bosch, R.C.E., Verolme, E.K., de Zeeuw, P.T., 2006, A&A, 445, 513

Vogt, S. S., Allen, S. L., Bigelow, B. C., et al., 1994, SPIE, 2198, 362

Vogt, S. S., Mateo, M., Olszewski, E. W., & Keane, M. J. 1995, AJ, 109, 151