CANADA-FRANCE-HAWAII TELESCOPE ADAPTIVE OPTICS OBSERVATIONS OF THE CENTRAL KINEMATICS IN M15

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ABSTRACT

We have used an Imaging Fabry-Perot Spectrophotometer with the Adaptive Optics Bonnette on the Canada-France-Hawaii Telescope to measure stellar radial velocities in the globular cluster M15 (NGC 7078). An average seeing of 0.15 FWHM, with the best-seeing image having 0.09, allowed us to measure accurately the velocities for five stars within 1° of the center of M15. Our estimate of the second moment of the velocity distribution (i.e., the dispersion, ignoring rotation) inside a radius of 2° is 11.5 km s\(^{-1}\), the same value we find out to a radius of about 6°. However, the projected net rotation does increase dramatically at small radii, as our previous observations led us to suspect. The rotation amplitude inside a radius of 3.4° is \(v = 10.4 \pm 2.7 \) km s\(^{-1}\) and the dispersion after removing the rotation is \(\sigma = 10.3 \pm 1.4\) km s\(^{-1}\), so \(v/\sigma \approx 1\) in this region. In addition, the position angle of the projected rotation axis differs by 100° from that of the net cluster rotation at larger radii. Current theoretical models do not predict either this large an increase in the rotation amplitude or such a change in the position angle. However, a central mass concentration, such as a black hole, could possibly sustain such a configuration. The rotation increase is consistent with the existence of a central dark mass concentration equal to 2500 \(M_\odot\). The Strehl ratio is 1% in our worst images and 6% in our best. Despite these low values, the images allow us to resolve the brighter stars with an angular resolution close to the diffraction limit and to perform photometry on these stars accurate to a few percent. Thus, these adaptive optics observations provide us with crucial information on the central kinematics of M15.

Key words: celestial mechanics, stellar dynamics — globular clusters: individual (M15) — galaxies: distances and redshifts — instrumentation: adaptive optics

1. INTRODUCTION

M15 (NGC 7078) was one of the first globular clusters known to have a steep central stellar density profile, inconsistent with isothermal models (King 1975; Djorgovski & King 1986). Its central structure is usually interpreted to be a product of "core collapse" (e.g., Grabhorn et al. 1992)—a gravothermal instability that leads to a very small and dense core surrounded by a power-law cusp. Core collapse predicts a specific density profile, about \(r^{-2.2}\), and velocity dispersion profile, about \(r^{-0.1}\) or nearly constant, in the cusp for the stellar component that contributes most of the mass (Cohn 1980; Spitzer 1987). However, the observed luminous component may have different profiles because of mass segregation. Thus, both photometric and kinematic observations are needed to estimate the profile of the gravitational potential and to test the models.

The stellar density profile near the center has been measured by many authors; the best study comes from the Hubble Space Telescope (HST) analysis of Guhathakurta et al. (1996), who show that M15 contains a central cusp with a logarithmic slope around ~1.8. This estimate is based on the deprojection of individual positions of the central stars. Although M15 has one of the highest surface brightnesses among the centrally concentrated clusters, at the radii of interest these measurements still suffer from poor statistics because of the small number of stars. Thus, the uncertainty of the slope within a radius of 1° is around 50%. Even more uncertain is the two-dimensional distribution of stars; i.e., whether the central isophotes are spherical or flattened.

Unfortunately, kinematic profiles are more difficult to measure than the light distribution and suffer from larger uncertainties. The central kinematics of M15 have been the subject of numerous studies (Newell, Da Costa, & Norris 1976; Peterson, Seitzer, & Cudworth 1989, hereafter PSC; Dubath, Meylan, & Mayor 1994; Zaggia, Capacciolo, & Piotto 1993; Gebhardt et al. 1994, 1995, 1997; Dull et al. 1997; Drukier et al. 1998, hereafter D98). Measuring the central dispersion has been the primary goal in most of these studies. However, the central stellar density is so high that severe blending of the stellar images limits the number of stars that can be measured individually from the ground, while the large range of stellar luminosities on the giant
branch limits the number of stars making significant contributions to the integrated light.

The improvements in our understanding of the central region have come from data taken under extremely good conditions (i.e., Guhathakurta et al.’s 1996 study of the stellar distribution using HST) or from the use of instruments designed to optimize the seeing profiles (i.e., Gebhardt et al.’s 1997 study using the fast-guiding Sub-arcsecond Imaging Spectrograph [SIS] on the Canada-France-Hawaii Telescope [CFHT]). However, we have not yet achieved the optimal situation of equal angular resolution for the spatial and kinematic observations, primarily because the relatively small aperture of the HST makes spectroscopy very expensive. Combining adaptive optics (AO) observations, which yield the highest spatial resolution possible from the ground, with the twodimensional velocity reconstruction enabled by Fabry-Perot (FP) observations should provide the most accurate measurements for the central kinematics.

Adaptive optics is one of the most powerful tools available to astronomers today, potentially allowing imaging at the diffraction limit of a ground-based telescope. AO is presently most efficient at near-infrared wavelengths. However, high-resolution spectrographs are only beginning to be used there, so most kinematic studies must still rely on optical wavelengths. Fortunately, in an overlap region near 9000 Å, spectrographs and CCDs are efficient, while AO systems still yield significant corrections. However, in this region the Strehl ratio—the ratio of the central intensity in the real stellar profile to that of a diffraction-limited profile—generally lies below 20%. This ratio is one of the most important numbers characterizing the quality of the corrected images. Values that low mean that careful measurements of the stellar point-spread function (PSF) are required to interpret the results.

Globular clusters provide an ideal target for AO observations because the field is filled with stars that yield the PSF. Slit or aperture spectrographs do not lend themselves to AO kinematic studies because they do not generally allow an accurate measurement of the spatial PSF and because it can be hard to determine exactly where the slit was placed. Fabry-Perot imaging, in contrast, does provide both accurate spectral and accurate spatial information. In this paper, we describe results from using the Adaptive Optics Bonnette (AOB) on the CFHT with an imaging Fabry-Perot.

The results from these data provide crucial information for the region within 3’” of the center of M15. They confirm the earlier results of Gebhardt et al. (1997) that the observed velocity dispersion profile remains flat inside a radius of a few arcseconds and that the net projected rotation profile rises in that region. The increase in the rotation is difficult to understand but might be explained by the existence of a central massive dark object.

The rest of this paper is organized as follows. Section 2 describes how the Fabry-Perot AO data were taken and reduced, including a discussion of the impact that the small and variable Strehl ratio had on the accuracy of our photometry. Section 3 presents the profiles of the projected velocity dispersion and net projected rotation that result from these data, while § 4 briefly revisits the mass density profiles derived with the techniques of Gebhardt et al. (1997). Finally, § 5 summarizes the results and discusses how the large rotation at small radii in M15 might be understood in the context of the dynamical models of globular cluster evolution.

2. DATA

2.1. Instrumentation

In normal use, a Fabry-Perot etalon is placed in a collimated beam to avoid degradation of the spectral resolution. With the AO system on the CFHT at the time of our observations (see the description by Rigaut et al. 1998), this placement was not possible. In consultation with the CFHT staff, we chose to place our etalon in the f/40 converging beam behind the AOB focal expander. The STIS 2 CCD then yielded 0’0305 pixels and a 63’’ field of view. However, the AOB optics are not telecentric—the optical axes of the converging beams were not perpendicular to the etalon away from the center of the field—and this caused additional loss of wavelength resolution. The converging beam caused a negligible degradation of the 2.0 Å intrinsic resolution of the etalon at the center of the field, but by a radius of about 6’’, the resolution was worse by a factor of 1.4. Because our primary targets were the centers of clusters, this limitation of the usable field did not significantly compromise our scientific goals.

Our usual observing procedure is to scan across the Hβ line, since it is a deep line that is not very sensitive to metallicity. With AO, we cannot obtain adequate correction at wavelengths that short. Fortunately, the coatings of the Rutgers etalon allowed us to work with the 8542 Å Ca II triplet line. We employed our own filter to isolate the correct etalon order. It had a passband with a 30 Å FWHM, centered on 8542 Å. A dichroic in the AO system sent the I-band light to the etalon and the CCD, and all other wavelengths to the wave-front sensor.

2.2. Observations and Data Reduction

We took data on 1998 June 15–19, observing M15 on three of the nights and obtaining a total of 26 usable 15 minute exposures for this cluster stepped across 8536–8543 Å. We observed three other clusters (M13, M30, and M80) as well, which we will present in a later paper.

Because of the converging and nontelecentric beam, we could not use our standard wavelength calibration procedures and the result was increased uncertainty in the solution. Normally, a single exposure of a screen illuminated by an emission-line lamp produces a bright ring in the image because of the simple quadratic dependence of transmitted wavelength on distance from the optical axis. We measure the radii of these rings to calibrate the relation between etalon spacing and wavelength. However, in the present case, measurable rings did not exist because of a complicated dependence of both the mean wavelength and the spectral resolution on the distance from the optical axis. We were thus forced to take a sequence of images that scanned the etalon across the calibration line to measure the etalon spacing corresponding to the peak of the line. This procedure produced an adequate wavelength calibration (uncertainties less than 0.1 Å) but required more time than usual. We corrected for pixel-to-pixel sensitivity variations and the change in the transmission of the order-separating filter with wavelength using images of an internal incandescent flat field.

The CFHT AO system requires a natural guide star in the field to correct the wave front. For the globular clusters
studied, the choice was governed by a trade-off between brightness and distance from the center. The central brightness cusps of M15 and M30 had too much structure to act as good guide stars. For M15, we used the star AC 3 (Aurière & Cordoni 1981), which has $V = 13.3$ and is 6.7 away from the center. The $V$-band magnitudes of the guide stars ranged from 13.3 to 15.5, with the best correction coming from the brighter stars.

2.3. Photometry with Adaptive Optics

The high stellar density near the center of M15 produces crowded frames that force us to use profile-fitting photometry as opposed to aperture photometry. Thus, errors in estimating the PSF directly affect the photometry and accurate photometry depends on understanding the PSF both as a function of position on the chip and as a function of time throughout the observations. AO in the optical complicates both of these matters; the small isoplanatic patch causes the PSF to vary significantly over the field and, since the AO correction is highly dependent on the native seeing, sudden changes in the seeing cause large temporal variability in the PSF. Some published reports suggest that these problems will limit the accuracy of stellar photometry in crowded fields with AO to be no better than 10% (Roberts, ten Brummelaar, & Mason 1997; Esslinger & Edmunds 1998).

Estimating the PSF is a hard problem because the profile for a stellar source observed with the AO system is approximately a combination of an unguided profile—the natural site seeing—and the diffraction-limited profile, so the low Strehl ratios in the optical imply that most of the stellar light resides in the uncorrected PSF and very little in the diffraction-limited core. The fraction of the flux in the diffraction-limited core is approximately equal to the Strehl ratio. Therefore, we need to use very large PSFs to accurately measure all of the light at large radii, but at the same time, we must finely sample the PSF to maintain the high spatial resolution information provided in the diffraction-limited core. Getting enough signal-to-noise to measure accurately the wings of the PSF is difficult.

Figure 1 shows Strehl ratios for the guide star in each M15 frame plotted as a function of FWHM of the star. The Strehl ratios range from 0.01 to 0.06; for our typical exposure, over 90% of the light is in the broad component of the PSF. Although these Strehl ratios are low, accurate photometry depends solely on the ability to measure the PSF. Fortunately, the centers of globular clusters have bright stars scattered throughout the field and so are well suited to measuring the PSF well into its wings with high spatial resolution.

Because with FP observations we are building a spectrum from data that were taken over several days, the accuracy with which we measure the PSF in each individual frame is one of the most crucial aspects of the whole reduction. Previously, in these crowded fields, we have obtained photometry errors of roughly 2%–3%; the errors are distributed among the following sources: crowding, the wings of the PSF, frame-to-frame normalizations for changing transparency, and wavelength calibration. With adaptive optics, we have to pay special attention to the PSF measurement. Photometry errors greater than 10% would render the data useless, since such errors would result in velocity uncertainties larger than 10 km s$^{-1}$, an unusable uncertainty for most globular clusters. We discuss below in turn the spatial extent of the PSF, the spatial variability of the PSF within a frame, and the temporal variability between frames.

2.3.1. PSF Extent

We determined the PSF for each frame with the normal DAOPHOT routines (Stetson 1994) and obtained the final photometry using ALLFRAME (Stetson et al. 1998). A quadratic variation with position on the chip provided an excellent fit for the PSF across the frame. We paid particular attention to the extent to which the PSF was both fitted and subtracted. For our observations, the diffraction limited core of the PSF is about 0′′05 across and the broader component is about 0′′5. This means that we must use a PSF that goes out beyond 1″ to contain most of the light. Given the pixel scale, we used a PSF radius of 50 pixels and a fitting radius of 20 pixels. The large PSF radius mandates using a large number of stars to overcome the low signal-to-noise ratio in the wings of the PSF. Figure 2 demonstrates the PSF’s extent by plotting the flux of the guide star in each M15 frame versus radius. We truncate the logarithmic plot at a radius of 60 pixels (1′″), but light is still present at these radii; our ALLFRAME photometry thus requires aperture corrections.

We can verify this extent for the PSF from data for an isolated standard star. Four consecutive 10 s exposures of HD 107328 (HR 4695, $V = 4.96$) were taken in twilight on the fourth night. Conditions were mildly nonphotometric; the Strehl ratios were about 0.03. The circles in Figure 3 show the rms scatter around the average aperture magnitude for apertures with radii between 3 and 150 pixels. The triangles are the uncertainties in the magnitudes expected from photon statistics. The rms scatter in the magnitudes decreases with increasing aperture size until a radius of 50 pixels, after which it slowly increases. This scatter suggests that changes in the PSF caused by variations in the seeing and wave-front correction have become small at an aper-
PSF Variability

We show the spatial dependence of the PSF in Figures 5 and 6. Figure 5 overplots radial profiles of four PSFs at distances of 0", 10", 20", and 30" from the guide star. The PSFs are normalized to have identical volumes. For each profile, the broad component—the uncorrected profile—is essentially unchanged, as we expect. What does change is the amount of light in the diffraction-limited core, as stars at the largest radii have almost no light in the core because of the AO correction. To demonstrate this effect with the FWHM, each line in the top panel of Figure 6 shows the ratio of the FWHM of the PSF to the FWHM of the guide star as a function of CCD column number for the central row of an M15 frame. The ratio changes by a factor of two from the middle of the image to its edges. In addition, the change is similar for each frame. There is a slight dependence on the base FWHM; the bottom panel of Figure 6 presents the FWHM ratio at the edge of each image as a function of the base FWHM. The smallest FWHM image has the largest variation across the field.

Photometric Accuracy

The ideal situation for determining the photometric accuracy of the observations would be to expose frame after frame using an identical setup. We obviously cannot employ this ideal method since we must scan across the absorption line in order to measure stellar velocities, but we can use our measured absorption-line profile to estimate photometric accuracy. Figure 8 plots the line profiles for four bright stars in our field. The line is a fitted Voigt profile (see Gebhardt et al. 1994 for details). The deviation of the points from the fitted line result from the photometric errors; the error bars for each point come from the standard DAOPHOT uncertainties. If the actual deviations divided by the expected uncertainties do not have a Gaussian distribution with unit standard deviation, the additional uncertainty is probably caused by our lack of understand-

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3 In this regard, our AO images are more like pre-COSTAR HST images.
ing of the PSF. The points to which we fit Voigt profiles, such as those in Figure 8, are already corrected on a frame-by-frame basis for the combined effects of transparency variations and the truncation of the PSF. As discussed in the beginning of § 2.3, this last effect arises because our measured PSF does not include all of the light. Since we have many stars at different radial and spectral (i.e., different velocities) positions, these frame normalizations are unique and well measured (see Gebhardt et al. 1994 for more discussion).

We average the fractional deviations from the fitted line profile for every star in each frame in order to estimate the true photometric uncertainties for each of the frames. Each point in Figure 9 is the rms dispersion of the fractional differences between the fitted profiles and the data points in a frame as a function of the FWHM of the guide star in the
frame. We estimate the dispersion from the biweight estimate of scale (Beers, Flynn, & Gebhardt 1990) using all stars with a velocity measurement and breaking the sample of stars into three groups according to brightness.

The photometric uncertainties indicated in Figure 9 result from both photon statistics and any uncertainties due to particulars of the analysis—i.e., difficulties in measuring the PSF and the wavelength calibration. DAOPHOT provides an estimate of the photon noise through its reported uncertainty. For the brightest stars (Fig. 9, filled circles), the typical DAOPHOT uncertainty is around 0.5%, and for the faintest stars, it varies from 6% to 10% (depending on the PSF FWHM). These typical uncertainties are smaller than the actual photometric scatter shown in Figure 9 for both the faint and the bright stars. This difference does not suggest an additive uncertainty independent of brightness, such as that expected from PSF errors, but rather a multiplicative error in the DAOPHOT uncertainties—they are about a factor of 1.5 too small. Making such a correction brings the observed and predicted uncertainties of the faint and medium stars into reasonable agreement. However, the dispersion around the profiles of the bright stars shown in Figure 9 is still larger than expected. This trend suggests the presence of an additive uncertainty of about 2%. We take this value as the upper limit to errors in our photometry caused by the difficulty of estimating the AO-corrected PSF.

2.4. Velocity Zero Point and Uncertainties

In all of our Fabry-Perot runs, we correct the zero point of our velocities since it is difficult to get an accurate absolute wavelength calibration—we build up the spectrum over the course of a few nights and each frame has to be accurately calibrated. As discussed in § 2.2, our current wavelength calibration is less accurate than for previous observations, and for this reason, we have an increased velocity zero-point uncertainty. However, we do not believe that we have systematic errors in our velocities as a function of velocity because we did not observe adjacent wavelength points at adjacent times.
To determine the velocity zero point, we compare our velocities with the many previous data sets for M15: Gebhardt et al. (1994, 1997), PSC, Dull et al. (1997), D98, and Dubath & Meylan (1994, hereafter DM94). The present data have been compared with each of these individually and to a combined data set. All of the comparisons yield the same result: the required velocity offset is 5.7 km s\(^{-1}\). In addition, one must increase the uncertainty for each AO velocity by adding 3.0 km s\(^{-1}\) in quadrature with the estimated uncertainty. Previous FP studies added 0.5–1.0 km s\(^{-1}\) in quadrature, which is consistent with the intrinsic velocity jitter of the giant stars (Gunn & Griffin 1979; Mayor et al. 1983). We attribute the larger errors in the present study to the difficulty of the wavelength calibration.

Figure 10 plots the difference between the 1995 CFHT SIS and the shifted AO velocities as a function of the 1995

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**Figure 8.** Line profiles for four bright stars for which we were able to obtain a reliable velocity measurement. The values and their error bars come from ALLFRAME and include the frame normalizations. The solid line is the fitted Voigt profile.

**Figure 9.** Dispersion in the fractional difference between the fitted line profile and the actual spectral data for stars in each M15 image, plotted vs. the FWHM of the guide star in the image. Different symbols denote the dispersion for stars with different brightnesses: filled circles are the brightest third, open circles are the intermediate third, and triangles are the faintest third.

**Figure 10.** Comparison of our velocities taken at CFHT in 1995 and the velocities derived from the AO data.
velocities. The two sets of data agree within their uncertainties and give a reduced $\chi^2 = 1.2$ for 67 degrees of freedom.

We list the mean radial velocities in Table 1. For each star, we give the ID (col. [1]), the offsets east-west and north-south from the center (as defined by Guhathakurta et al. 1996) in arcminutes (cols. [2] and [3]), the velocity and its uncertainty (col. [4] and [5]), the $V$-band magnitude from either HST or ground-based photometry (col. [6]), the probability of the $\chi^2$ from the multiple measurements exceeding the observed value by chance (ellipsoid if there is only a single measurement; col. [7]), and the ID from Aurière & Cordoni (1981; col. [8]). The ID in column (1) is that of the HST Wide Field Planetary Camera 2 (WFPC2) photometry of Guhathakurta et al. (2000). When those did not exist, we generated our own sequence numbers starting with 40001. The reported velocity is the classical mean of all of the measurements for that star, each

| ID  | $V_{FP95}$ | $V_{FP94}$ | $V_{FP92}$ | $V_{FP91}$ | $V_{PSIC}$ | $V_{FP94}$ | $V_{FS9}$ | $V_{DS9}$ |
|-----|------------|------------|------------|------------|------------|------------|-----------|-----------|
| 30  | -114.1 ± 0.9 | ...        | -126.7 ± 1.5 | ...        | ...        | ...        | ...       | ...       |
| 36  | -122.1 ± 0.9 | -122.4 ± 1.4 | ...        | ...        | ...        | ...        | ...       | ...       |
| 332 | -110.5 ± 0.7 | -112.3 ± 1.6 | -108.3 ± 2.3 | -109.3 ± 0.6 | ...        | -109.1 ± 0.8 | ...       | ...       |
| 405 | -117.3 ± 1.2 | ...          | -111.6 ± 3.3 | -117.1 ± 4.6 | ...        | ...        | ...       | ...       |
| 716 | -118.6 ± 1.3 | -122.7 ± 2.1 | ...        | ...        | ...        | ...        | ...       | ...       |
| 1084| -107.5 ± 0.8 | -108.5 ± 1.5 | -108.0 ± 2.7 | -107.0 ± 2.1 | ...        | ...        | ...       | ...       |
| 1222| -126.5 ± 1.1 | ...          | -118.4 ± 2.3 | -125.9 ± 2.9 | ...        | ...        | ...       | ...       |
| 1254| ...          | ...          | -115.9 ± 1.2 | -95.5 ± 1.4 | ...        | ...        | ...       | ...       |
| 1422| -109.9 ± 0.7 | -100.0 ± 1.1 | -101.9 ± 1.7 | -104.1 ± 3.4 | -100.1 ± 0.7 | ...        | ...       | ...       |
| 1685| -124.4 ± 0.9 | ...          | -122.5 ± 2.1 | -120.6 ± 3.6 | -124.2 ± 2.5 | ...        | ...       | ...       |
| 1740| -99.6 ± 1.3  | ...          | ...          | -125.9 ± 2.9 | ...        | ...        | ...       | ...       |
| 1761| -114.6 ± 0.9 | ...          | -116.5 ± 2.0 | -113.4 ± 2.8 | -114.2 ± 0.9 | ...        | ...       | ...       |
| 2073| -92.8 ± 4.2  | ...          | ...          | ...          | ...        | -130.2 ± 14.3 | ...       | ...       |
| 2103| -121.6 ± 2.2 | -120.2 ± 1.5 | -119.3 ± 3.3 | -115.6 ± 3.4 | ...        | ...        | ...       | ...       |
| 2357| -102.5 ± 1.5 | -102.2 ± 2.1 | ...          | -104.8 ± 4.8 | ...        | ...        | ...       | ...       |
| 2515| -116.8 ± 0.8 | -126.2 ± 1.8 | -115.4 ± 2.4 | -116.0 ± 4.9 | -115.3 ± 1.7 | ...        | ...       | ...       |
| 2560| -121.7 ± 1.9 | ...          | -108.6 ± 4.8 | ...          | ...        | ...        | ...       | ...       |
| 2687| -92.9 ± 0.9  | ...          | ...          | ...          | ...        | -85.9 ± 6.7 | ...       | ...       |
| 2703| -87.4 ± 0.9  | ...          | -95.8 ± 2.2  | -89.0 ± 3.1  | -92.3 ± 1.0 | -86.8 ± 2.2 | ...       | ...       |
| 2883| -105.0 ± 1.5 | ...          | ...          | ...          | ...        | -100.1 ± 6.0 | ...       | ...       |

Note—Table 2 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.
weighted by the inverse of the square of the measurement uncertainty. The uncertainty in the mean is derived classically as well and will not be a good estimate of the true uncertainty when the χ² probability is low. Table 2 lists the individual velocity measurements from the eight epochs of data. The zero-point correction discussed above has been applied to the AO velocities, so all of the sets are consistent with the zero point of PSC (we note that the Fabry-Perot velocities from 1991 to 1994 are the same as by Gebhardt et al. 1997; however, the 1995 FP velocities are 0.6 km s⁻¹ larger because of a better estimate of the zero point). There was no zero-point correction for either the D98 or the DM94 data. In contrast, the additional uncertainties that we have adopted—3 km s⁻¹ for the present data set, 1.5 km s⁻¹ for FP95, 2.0 km s⁻¹ for FP94, 1.5 km s⁻¹ for FP92, 1.5 km s⁻¹ for FP91, 0.7 km s⁻¹ for PSC, 0.7 km s⁻¹ for D98, and 0.7 km s⁻¹ for DM94—have not been included in the listed uncertainties. These additional uncertainties were used to calculate the velocity uncertainties and the χ² probabilities given in Table 1.

In the paper of Gebhardt et al. (1997), there is an inconsistency between the IDs of the stars in their Table 1 compared with those in their Table 2. For this reason, we do not repeat those IDs in Table 1 here; instead, we introduce new IDs that are consistent between the two tables presented in this paper. Since all of the velocity data are provided in Table 2, there is no need for a cross-reference with previous papers.

### 3. RESULTS

The total velocity sample for M15 yields 1773 stars with a mean cluster velocity of \([-107.5 \pm 0.2 \text{ km s}^{-1}\). Only the sampling uncertainty is included in the standard deviation. The AO data set contains 104 stars with velocity uncertainties smaller than 10 km s⁻¹. Keeping only the best data based on visual inspection of the profiles provides a sample of 82 stars but does not significantly alter the results; we thus use the full data set in the following dynamical analysis. Given a total sample of 1773 stellar velocities, the 104 stars measured here only provide very modest gains in the total sample size. However, we stress that these measurements are in the central regions where it is crucial to determine the kinematics accurately, as these regions are of the most importance for measuring the current dynamical state of the cluster.

In the central 1.5 radius, there are five stars (the first five listed in Table 1) with velocities that the present data set measured more accurately than previous data sets. The line profiles from the AO data set for four of the five stars are shown in Figure 11. One of these five stars, AC 215 (No. 5933 in Table 1 and Fig. 11), is a potential binary based on three epochs of observations; however, a detailed binary analysis will be the subject of a future paper. Another, AC 214 (No. 5831 in Table 1 and Fig. 11), is at least three stars (HST IDs 5831, 5846, and 5872) according to the photometry of Yanny et al. (1994) and Guhathakurta et al. (1996). These authors point out that this clump of stars is a candidate for the center of the cluster and note that the velocities of the stars should differ by \(\gtrsim 40 \text{ km s}^{-1}\) if the center contains \(\gtrsim 10^3 \, M_\odot\) concentrated within the approximately 1000 AU projected extent of the clump. Since we have not separated AC 214 into three components, we could only measure these velocity differences by a broadening of the average line profile. Our fitted profile for this object is not larger than what we measure for the other stars in the sample. However, one of the three stars, No. 5831, is 0.8 and 2.0 mag brighter in the I band than the other two. It is also the reddest, hence the most strong-lined, of the three (which lie on the horizontal branch or its transition to the asymptotic giant branch; Guhathakurta et al. 1996), so it is likely that our measured profile mostly reflects that of this star. In any case, the signal-to-noise ratio of the spectrum is very
With only a small number of new velocity measurements compared with the previous study by Gebhardt et al. (1997), we do not present a complete dynamical analysis of M15. Since, however, all of the velocities in this study are in the central 20', we present the kinematic state of the central regions of M15. The previous data set for M15 contained 15 stars inside a radius of 2.5'. The present data add eight new stars and confirm the velocity dispersion for most of the original 15 stars. With such small samples, it is important to have multiple measurements to secure the velocities. Two competing explanations explain why we were not able to measure velocities for all of the stars in the previous samples: crowding and stellar flux. The AO system does allow for better separation of crowded stars; however, it requires more light because of the greater number of pixels over which a star is spread. Thus, our previous non-AO observations achieved fainter flux limits, whereas the AO system provided better separation in the most crowded regions. In total, there are 34 new velocity measurements from the AO system, all for stars at radii less than 17'.

3.1. Kinematics inside 20' 

Our goal here is to measure the moments of the velocity distribution as functions of radius to constrain the dynamical state of M15. The second moment about the mean cluster velocity represents a straightforward quantity that can be directly compared with dynamical models. A more difficult measurement is determining the amplitude of the projected net rotation (v) and the projected velocity dispersion (σ) separately; it is especially difficult for systems such as globular clusters, where v/σ is small. We estimate each of these quantities in turn below.

Figure 12 plots the radial profile for the second moment of the velocity distribution for M15. The solid and dashed lines represent an estimate and its associated 90% confidence band obtained using the LOWESS technique described by Gebhardt et al. (1994). At around 2', the density of points decreases drastically as we shift from Fabry-Perot data to other data sets. Because of the change in density, our LOWESS technique artificially biases the second moment in the lower density regions toward that in the higher density regions. This bias results from our windowing function, which includes a set number of data points rather than a specified radial range. For that reason, we do not use the LOWESS estimate at these radii and instead rely on radially binned values taken from D98 (col. [2] of Table 4). A bias may occur at small radii as well, if both the density of data and the value of the second moment change dramatically over a small radial range. We thus also estimate the second moment in a central bin containing the inner 10 stars. The circles in Figure 12 and their 68% error bars are these binned values.

The value of the second moment for the central 10 stars, with an average radius of 1', is 11.7 ± 2.8 km s⁻¹. The second moment remains approximately constant out to a radius of 30', a value and trend identical to those found previously (Gebhardt et al. 1997).

Gebhardt et al. (1997) suggest that the projected rotation increases within 3' of the center of M15 and that the position angle (P.A.) of the projected rotation axis there differs by 100° from that at larger radii. This estimate came from the integrated cluster light, as there were too few individual stellar velocity measurements to constrain the rotation.

With the additional velocity information from the AO data set, we can measure the rotation from the stars alone. We are interested in looking for significant changes in the rotation over a small radial range. Smoothing techniques, such as the LOWESS technique, tend to wash out small-scale features. Although techniques based on binning do not suffer from this particular effect, they are sensitive to the subjective choice of bin width and bin location. We have tried to preserve the better features of both techniques by using a hybrid approach: a variable-width data window in radius with lower weights for the points near the window edges. The variable-width window allows for recovery of sharp radial variations, and the weighting scheme is designed to lessen possible large variations due to discrepant data points.

We apply the data window to the velocities sorted into radial order. The window contains 251 points, except that it shrinks to a minimum of 25 points at the inner and the outer boundaries of the data. At each position of the window, a maximum likelihood estimator determines the rotation amplitude, rotation position angle, and dispersion about the rotation. Within each bin, the weight of a point varies as the cube of its distance from the bin center—i.e., \( w_i = 1 - (|1 - n/2|)^3/(n/2)^3 \), where \( n \) represents the number of points in the subsample and \( i \) is that point's rank in the sorted data set. This weight multiplies that point's contribution to the likelihood function. The likelihood function minimizes the deviations of the velocities minus the cluster systemic velocity from a mean velocity that varies sinusoidally as a function of position angle. A sinusoidal variation is expected for solid-body rotation. However, for other rotation profiles, a sine function may not be optimal for measuring the rotation amplitude. The radius corresponding to each position of the window is the average of the linear radii of the included points.

Figure 13 plots the results from the hybrid technique for the following four quantities, each with their 68% confidence bands: the projected rotation amplitude, the dispersion about the rotation, \( v/\sigma \), and the P.A. of the projected...
rotation axis. Significant rotation exists at most radii in the cluster; only at 0.3 is the net rotation near zero, causing the position angle estimate to fluctuate rapidly near that radius. Most surprising is the rotation seen at small radii. Inside of 0.05, the rotation amplitude rises significantly, and at 0.04, the rotational support equals the pressure support (i.e., $v/p = 1$). Figure 14 displays this rotation directly by plotting the offset from the mean cluster velocity for the 40 stars in the central 3′4 versus azimuth. The rotation amplitude for these stars is $v = 10.4 \pm 2.7$ km s$^{-1}$ and the dispersion after removing the rotation is $\sigma = 10.3 \pm 1.4$ km s$^{-1}$, so $v/\sigma \approx 1$ in this region. The probability of measuring a rotation this high by chance when none is present is much less than 1%. Figure 13 suggests that the rotation amplitude remains high into the center. Even for the five stars inside of 1′, the rotation has the same position angle and an amplitude equal to $15.3 \pm 6.2$ km s$^{-1}$. For these five stars, a rotation amplitude this large is expected by chance only 5% of the time.

The confidence bands in Figure 13 result from a Monte Carlo analysis. We create 100 realizations of the velocity sample by drawing points from the initial fit to the rotation as a function of radius. To each point we add random uncertainties that come from the data uncertainty distribution, determined by the velocity difference of the individual measurements relative to the rotation profile; this procedure includes both the velocity dispersion and the individual velocity uncertainties. To mimic the radial variation of dispersion and uncertainty in the data (the velocities at large radii primarily come from D98, which are on average more precise than the FP velocities), we have drawn the additive uncertainties from radial bins. For each realization, we estimate the radial variation of the kinematics as we did for the observed data. The scatter in the distribution of the kinematic properties at each radius provides the 68% confidence bands.

4. MASS MODELING

Since our data set is not dramatically larger than in our previous analysis, we have not recomputed the mass density profile and the stellar mass function. Instead, we concentrate on the central dynamics and, in particular, the black hole models, since the most important changes in the data set are at small radii.

Figure 15 plots both the actual second moment profile of the data from Figure 12 and the expected second moment profile for a black hole model with a mass of 7 $M_\odot$ and a position angle of 226° ± 14°. The dispersion around this line is $11.9$ km s$^{-1}$.
profiles for models with no rotation, an isotropic velocity dispersion tensor, a constant stellar $M/L$, and black holes of various masses. We construct the models from the surface brightness profile used by Gebhardt et al. (1997). The deprojection of that profile determines the potential, assuming a constant $(M/L)_v = 1.7$. We add black holes of various masses to this potential and calculate the projected second moments using the isotropic Jeans equation. The model that best matches the data, given these assumptions, contains a $2000 M_\odot$ black hole. The full range of acceptable black hole masses is $0$–$4000 M_\odot$. Alternatively, the data are consistent with models with no black hole that have a stellar $(M/L)_v$ that increases toward the center to a value of 5, possibly because of a central concentration of white dwarfs or neutron stars.

An additional, and probably more interesting, constraint to the dynamical models comes from our observed rotation profile. The AO data argue that net rotation exists inside of $3''4$ (1.7 pc) with greater than 99% confidence and the best estimate of the rotation amplitude yields $v/\sigma = 1.0$. The innermost 40 stars have an average radius of $2''1$ and a projected rotation amplitude of 10.4 km s$^{-1}$. Assuming pure rotational support, this amplitude implies a central mass concentration equal to $2500 M_\odot$. Net rotation this large at these small radii is surprising but might be easier to explain with the presence of a few thousand solar mass black hole.

5. SUMMARY AND DISCUSSION

Two of the most obvious and interesting features of the M15 kinematics are the increase in the rotation amplitude at small radii, where $v/\sigma \approx 1$, and the difference in the rotation axis P.A. at those same radii compared with the rotation of the rest of the cluster. The cluster 47 Tuc also shows more rotation than expected at small radii (Gebhardt et al. 1994), though less dramatically than M15. These two clusters have the largest velocity data sets presently available, suggesting that large central rotation may be a common feature among centrally concentrated globular clusters. Can these features be understood in the context of dynamical evolution producing a collapsed core? Or does the rapid increase in net rotation suggest the presence of a central massive black hole? Unfortunately, few theoretical studies of cluster dynamical evolution include net rotation. Studies of the effects produced by central black holes in rotating systems are also rare.

5.1. Rotation and Core Collapse

The exchange of stellar energies and momenta caused by two-body relaxation acts to eliminate gradients in the mean velocity and, thus, to create solid-body rotation in a cluster with a net angular momentum (e.g., Ogorodnikov 1965). However, this equilibrium may not be stable, so the real evolution of a cluster can be more complex. Hachisu (1979) was one of the first to point out the gravo-gyro instability, where the central regions shrink and then spin up to maintain virial equilibrium as relaxation transports angular momentum outward. This requires that the rotation supplies significant support against gravity. $N$-body simulations of clusters with equal-mass stars by Akiyama & Sugimoto (1989) suggest that the random velocities eventually increase more rapidly than the net rotation, so that $v/\sigma$ decreases and the cluster again tends toward solid-body rotation. Similar $N$-body simulations by Aronsson & Richstone (1998a) found that the flattening (and, presumably, the $v/\sigma$) of the central regions decreased more slowly when a spectrum of stellar masses was present. But it still decreased or, at best, remained constant.

The $N$-body simulations were unable to follow the collapse of the core very far because they only had $N = 1000$ and 3000, respectively. Einsel & Spurzem (1999) studied the dynamical evolution of a rotating globular cluster by numerically solving the Fokker-Planck equation to follow the change in the stellar distribution function. The clusters are tidally limited and contain stars of only a single mass. These simulations have much less noise than $N$-body models, though they are also too simple for confident comparison with real clusters. In their simulations, the net rotation velocity in the core increases rapidly at first, probably driven by the gravo-gyro instability, and then more slowly, at the same rate that the central velocity dispersion increases as the core collapses. However, there is only a small increase in $v/\sigma$ in the core and certainly no steep gradient in this quantity near the center. The amount of rotation at large radii decreases, but the maximum mean rotation velocity always occurs at about the half-mass radius. This result is consistent with our data outside of the central few arcseconds, for which the maximum rotation velocity occurs at 0.9—approximately the half-mass radius for M15.

Preliminary multimass Fokker-Planck simulations (Einsel 2000) do show a larger increase in the net rotation for the most massive stars in the cluster center, perhaps similar to the results of Aronsson & Richstone (1998a). These models need further testing, however, and are also being checked with additional $N$-body simulations (R. Spurzem 1999, private communication). If the giants whose radial velocities we measure are the heaviest stars in the cluster and have been concentrated in the core by mass segregation, then we would expect the central mass-to-light ratio to be lower than that of the rest of the cluster. Figure 7 of Gebhardt et al. (1997) suggests that the mass-to-light ratio increases at small radii, though the uncertainties are large enough that a decrease cannot be ruled out.
An argument against core collapse being the explanation for the rotation at small radii in M15 is the large change in the position angle of the apparent rotation axis. None of the simulations discussed above have any torque that could produce what is nearly counter-rotation. Tidal forces from our Galaxy can exert torques and will act differently on the inner and outer regions of the cluster. We would naively expect any resulting change in the rotation axis to occur at much larger radii. Perhaps gravitational coupling such as that in warped disks could align the rotation over most of the cluster, but the nearly spherical shape of M15 must make that weak and we see no reason that small radii would be exempted. Two-body relaxation also acts to align rotation throughout the cluster and should be most effective at small radii, where the relaxation time is short.

In summary, models of globular cluster dynamical evolution do not seem to produce the changing rotation axis P.A. and the $v/\sigma$ profile with a sharp central upturn that we observe in M15. The models might be more successful in explaining the more moderate departure from solid-body rotation in 47 Tuc. More simulations, particularly with models containing a range of stellar masses are needed, but we now turn to whether models with central black holes can explain the M15 data.

5.2. Rotation and a Central Black Hole

Whether M15 contains a massive black hole remains a central question for black hole demographics and has been the subject of much debate, starting with the discovery of a central X-ray source (Giacconi et al. 1974; Bahcall & Ostriker 1975) and revived more recently by the velocity dispersion measurements of PSC. From dynamical studies of galaxies, Kormendy & Richstone (1995) and Magorrian et al. (1998) find a relation between the mass of the black hole and the mass of the host galaxy. This relation is based on massive stellar systems (M32 being the smallest), and we have not yet explored its extrapolation to smaller systems. Possibly all hot stellar systems harbor a central massive black hole; this situation would have significant consequences in modeling these systems and may even suggest that black holes act as a seed for hot stellar systems. Globular clusters are the natural targets to answer such a hypothesis because of their low mass. M15 is particularly well suited for these studies because of its proximity (9 kpc) and the high surface brightness of its cusp.

Bahcall & Wolf (1976) calculated the mass density and velocity dispersion profiles for the region of a nonrotating globular cluster influenced by a central black hole. The dispersion profile in Figure 12 is consistent with their prediction, but we still do not have the spatial resolution necessary to choose between the models presented there. Detailed analysis by Sosin & King (1997) of the central stellar cusp in M15 found that neither the black hole model of Bahcall & Wolf (1976) nor pure core-collapse models are a good match to the light profile. More sophisticated dynamical models, perhaps combining a black hole with core collapse, are necessary.

Lee & Goodman (1989) demonstrated that the adiabatic growth of a central black hole in a rotating stellar system increased the projected $v/\sigma$ within the region of gravitational influence of the black hole (where the mass of the stars approximately equals the final mass of the black hole). However, this study did not include the effects of two-body relaxation. The presence of the black hole reduces the mass density of stars that would otherwise be deduced from the velocity dispersion, and this increases the relaxation time at small radii, perhaps helping to maintain a larger rotation. However, this time remains much shorter than the age of M15 at small radii.

Arabadjis & Richstone (1998b) followed the dynamical evolution due to two-body relaxation of a system that initially had solid-body rotation and stars of a single mass (the collisional coalescence of stars was allowed) and contained a central black hole. The rotation amplitude and dispersion both increased near the center as the system evolved; however, $v/\sigma$ was essentially constant in time. The radial profile of $v/\sigma$ at late times was flat. These conclusions are somewhat weakened by the noise in these $N$-body simulations ($N = 3000$), which makes it hard to determine kinematic quantities over a large range of radii.

Thus, while the models of Lee & Goodman (1989) are suggestive, Fokker-Planck simulations including a black hole and net rotation are probably needed to reach any definite conclusions. A central black hole with a mass of about 2500 $M_\odot$ is consistent with all of the dynamical data (we note that this mass is consistent with that from Phinney's 1993 estimate of the enclosed mass from pulsar timing measurements near the center of M15). However, this model also provides no clear explanation for the changing rotation axis position angle. Becoming (even) more speculative, stars formed in a disk of gas, accreted from outside of the cluster, might explain the rotation with or without a central black hole. The color-magnitude diagram for the inner region provides, at most, only a little evidence for a younger stellar population at small radii (Guhathakurta et al. 1996; De Marchi & Paresce 1995; Sosin & King 1997).

5.3. Potential of Adaptive Optics

The high angular resolution provided by the Adaptive Optics Bonnette on the CFHT has strengthened some of the most surprising results in our previous M15 velocity samples. While the increase in the sample size was modest, the AO data provided crucial confirmation and, hence, better velocity uncertainties for many of the stars closest to the cluster center. Even more importantly, the AO observations increased the size of the velocity sample in this critical region. As adaptive optics systems become better understood and available on larger telescopes, and as the data-analysis tools become better tailored to these observations (i.e., larger and better sampled PSFs), we will be able to greatly improve our measurements of the kinematics near the center of M15 and other core-collapse globular clusters.

Our AO observations have Strehl ratios of 2%–6%. Even under these poor conditions for AO corrections, we were able to obtain photometry with errors less than 2%. Of course, our observations were the best of all worlds for photometry since we had bright stars everywhere in our field. The ability to extend this detailed understanding of the spatial and temporal variation of the PSF to observations where only a handful of calibration stars is present is not clear. Surely, present and future AO studies will deal with this concern.

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