THE MASS DISTRIBUTION IN THE ELLIPTICAL GALAXY NGC 3377: EVIDENCE FOR A $2 \times 10^8 M_\odot$ BLACK HOLE

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ABSTRACT

This paper is part of a search for supermassive black holes (BHs) in galaxy nuclei (see Kormendy 1992a,b, 1993; Kormendy & Richstone 1995, hereafter KR95; for reviews). There is a growing body of dynamical evidence for central dark objects of mass $10^4 - 10^7 M_\odot$ in galaxies. The simplest interpretation is that these are BHs that once were engines for nuclear activity. Most stellar-dynamical searches have found BHs in six dwarf galaxies (M 31: Dressler 1984; Kormendy 1987a, 1988a,b; Dressler & Richstone 1988; Bacon et al. 1994, 1995; Kormendy & Richstone 1992; Kormendy et al. 1996a, and NGC 4594: Kormendy 1988c; Elsner et al. 1994; Kormendy et al. 1996b). In contrast, nuclear activity is strongest in giant ellipticals. The only ellipticals with stellar-dynamical evidence for BHs are the inactive dwarfs M 32 (Tonry 1984, 1987; Dressler & Richstone 1988; van der Marel et al. 1995; Bender, Kormendy, & Dehnen 1996; van der Marel et al. 1997a,b) and NGC 4486B (Kormendy et al. 1997). However, failure to detect BHs is not evidence against them. Gas-dynamical searches have found BHs in six galaxies, three of which are active giant ellipticals (Harms et al. 1994; Ferrarese et al. 1996; Bower et al. 1998). In fact, any giant elliptical could hide a $10^8 M_\odot$ BH from past stellar-dynamical searches.

The BH search is becoming dominated by the Hubble Space Telescope (HST); with it, BH detection is possible in most giant galaxies out to the distance of the Virgo cluster. But for ground-based searches, BH detection is difficult. There are two main reasons. First, giant ellipticals do not rotate, so mass measurements are maximally sensitive to velocity anisotropies. Second (e.g., Lauer et al. 1995), they have cuspy cores with large break radii; inside $r_b$, the brightness profile is relatively shallow, so projected spectra are dominated by light from large radii where a BH has no effect. Kormendy (1992b) illustrates this effect for the HST profile of M 87.

The BH in M 32 was found because the galaxy is nearby and rapidly rotating. Similarly, M 31, NGC 3115, and NGC 4594 contain rapidly rotating nuclear disks. They are nearly edge-on; this ensures that spatially unresolved rotation contributes to the apparent velocity dispersion. Finally, a detection was possible in NGC 4486B because the BH is unusually massive compared to the rest of the galaxy. Ground-based BH detection is still only possible in galaxies like these where circumstances are favorable.

NGC 3377 is such a galaxy. It is a prototypical E5 galaxy illustrated in the Hubble Atlas (Sandage 1961). At $M_B = -18.8$, it is just fainter than the transition between ellipticals that rotate and those that do not: it rotates rapidly enough to be nearly isotropic (Davies et al. 1983). Also, it has a coreless, power-law profile (Lauer et al. 1995), so small radii have large luminosity weight in projection. The axial ratio is 0.5; since no

1. INTRODUCTION

This paper is part of a search for a supermassive black hole (MDO) in the elliptical galaxy NGC 3377. Stellar rotation velocity and velocity dispersion profiles (seeing $\sigma_* = 0''20 - 0''26$) and $V$-band surface photometry ($\sigma_* = 0''20 - 0''26$) have been obtained with the Canada-France-Hawaii Telescope. NGC 3377 is kinematically similar to M 32: the central kinematic gradients are steep. There is an unresolved central rise in rotation velocity to $V = 110 \pm 3$ km s$^{-1}$ (internal error) at $r = 1''0$. The apparent velocity dispersion rises from $95 \pm 2$ km s$^{-1}$ at $1''0 \leq r < 4''0$ to $178 \pm 10$ km s$^{-1}$ at the center.

To search for a central black hole, we derive three-dimensional velocity and velocity dispersion fields that fit the above observations and Hubble Space Telescope surface photometry after projection and seeing convolution. Isotropic models imply that the mass-to-light ratio rises by a factor of $\sim 4$ at $r < 2''0$ to $M/L_V \gtrsim 10$. If the mass-to-light ratio of the stars, $M/L_V = 2.4 \pm 0.2$, is constant with radius, then NGC 3377 contains a central massive dark object (MDO), probably a black hole, of mass $M_r \sim (1.8 \pm 0.8) \times 10^8 M_\odot$. Several arguments suggest that NGC 3377 is likely to be nearly isotropic. However, flattened, anisotropic maximum entropy models can fit the present data without an MDO. Therefore the MDO detection in NGC 3377 is weaker than those in M 31, M 32, and NGC 3115.

The above masses are corrected for the E5 shape of the galaxy and for the difference between velocity moments and velocities given by Gaussian fits to the line profiles. We show that the latter correction does not affect the strength of the MDO detection, but it slightly reduces $M_r$ and $M/L_V$.

At $3'' \leq r \leq 35''$, $M/L_V$ is constant at $\sim 2.4$. Therefore the inner parts of NGC 3377 are dominated by a normal old stellar population. In this elliptical, as in the bulge-dominated galaxies NGC 3115 and NGC 4594, halo dark matter is unimportant over a significant range in radius near the center.
elliptical is much flatter (Sandage, Freeman, & Stokes 1970; Binney & de Vaucouleurs 1981; Franx, Illingworth, & de Zeeuw 1991; Tremblay & Merritt 1995), NGC 3377 must have a high inclination. We assume that it is edge-on. Finally, NGC 3377 is one of the nearest ellipticals. It is therefore an excellent target for a BH search. This paper presents high-resolution surface photometry and stellar-kinematic measurements and uses them to calculate the mass-to-light ratio \( M/L \) as a function of radius. NGC 3377 turns out to be kinematically similar to M32. Isotropic models imply that it contains a BH of mass \( M_* \approx 1.8 \times 10^8 \, M_\odot \).

We also discuss the mass distribution at \( 3'' \lesssim r \lesssim 35'' \). Mass distributions have been measured in only a few bulges and ellipticals. At radii well outside the de Vaucouleurs (1948) effective radius \( r_e \), a variety of techniques show that halo dark matter dominates the mass distribution (see Kent 1990 for a review). Mass-to-light ratios \( M/L \sim 10^2 \) are large compared to values \( M/L \lesssim 10 \) for old stellar populations and not by halo dark matter. Here \( M/L \) need to be more accurate. Variations in \( M/L \) due to metallicity gradients, halo dark matter and all but the most spectacular BHs are likely to be smaller than a factor of 2 to 4. Measurements intended to be this precise are vulnerable to velocity anisotropies. Only a few well-studied galaxies are likely to be isotropic or else contain embedded, edge-on disks that simplify the measurements without contributing much to being anisotropic or else contain embedded, edge-on disks.

2. KINEMATICS

2.1. Observations and Data Reduction

The kinematic measurements were made during four observing runs with the Canada-France-Hawaii Telescope. For the first two runs, the Herzberg Spectrograph (Salmon 1985) was used at f/4 with an RCA CCD (316 × 498, 30 \( \mu \)m pixels; read noise \( \sim 71 \) e\(^{-}-\)pixel\(^{-1}\); Walker et al. 1984). Spectra were taken at position angles PA = 50° and 44°. Leach (1981) measured these as the PAs of the major axis at small and moderate radii. Subsequently, we found that our photometry shows no twist near the center. Present and published CCD photometry (§3) imply that the major axis is at PA = 41° ± 1° (external error). We neglect the small difference between the correct major-axis PA and that of the spectra.

For subsequent runs, we used the Subarcsecond Imaging Spectrograph (SIS). Tip-tilt guiding is incorporated: by offsetting the guide probe, we can center the object on the slit to one-pixel accuracy. An observing sequence consists of a series of direct images to center the object at the slit, an exposure with the slit in place but with no grism, the object spectrum, another image through the slit but without the grism and one with neither slit nor grism to verify that the object is still centered, and a comparison spectrum. The seeing was measured on the bracketing direct images. The brightness profile of the galaxy is the same in these images and in the spectrum, so the PSF in the images is correct for the spectrum.

Parameters of the spectra are given in Table 1. Integration times, position angles, and seeing estimates are given in Table 2. Atmospheric dispersion was negligible. The centering exposures were taken with an \( I \) filter and the same CCD that was used for the spectroscopy, so the effective wavelength was close to that of the Ca triplet. Also, the mean zenith distances were 24°3 for spectrum 77f07, 6°7 for spectrum 78f873, and 7°5 for spectrum 80f027. The BH models were fitted to spectrum 80f027.

| Parameter                  | Run 1         | Run 2         | Run 3         | Run 4         |
|----------------------------|---------------|---------------|---------------|---------------|
| Dates of observations      | 1986 Dec. 25–28 | 1987 Mar. 20–25 | 1994 Apr. 18–21 | 1996 Apr. 25–27 |
| Spectrograph               | Herzberg     | Herzberg     | SIS           | SIS           |
| Spectra (Table 2)          | 29f56        | 33f56        | 74f770        | 77f707, 78f873, 80f027 |
| Slt length                 | 20           | 20           | 25            | 28            |
| Scale along slit           | 0'44 pixel\(^{-1}\) | 0'44 pixel\(^{-1}\) | 0'0864 pixel\(^{-1}\) | 0'15 pixel\(^{-1}\) |
| Slt width                  | 0'5          | 0'5          | 0'26          | 0'37          |
| Wavelength range           | 5067–5067 Å  | 5064–5068 Å  | 7975–8975 Å  | 7580–9405 Å  |
| Reciprocal dispersion      | 1.17 Å pixel\(^{-1}\) | 1.22 Å pixel\(^{-1}\) | 0.977 Å pixel\(^{-1}\) | 1.781 Å pixel\(^{-1}\) |
| Reciprocal dispersion      | 66 km s\(^{-1}\) pixel\(^{-1}\) | 68 km s\(^{-1}\) pixel\(^{-1}\) | 34.6 km s\(^{-1}\) pixel\(^{-1}\) | 63.3 km s\(^{-1}\) pixel\(^{-1}\) |
| Comparison line FWHM       | 1.7 pixel    | 1.8 pixel    | 2.54 pixel    | 2.19 pixel    |
| Instrumental velocity dispersion | 45 km s\(^{-1}\) | 51 km s\(^{-1}\) | 37 km s\(^{-1}\) | 59 km s\(^{-1}\) |
| Standard star              | \( \gamma \) Tau | \( \eta \) Cyg | \( \eta \) Cyg, \( \kappa \) Oph, \( \mu \) Leo, \( \gamma \) Dra | \( \eta \) Cyg, \( \kappa \) Oph, \( \gamma \) Dra |
| Standard star spectral type | K0 III       | K0 III       | K0 III, K2III | K2III, K5III  |

**NOTE.** – The spatial resolution of the Herzberg Spectrograph is limited approximately equally by the spectrograph camera and by seeing.
Instrumental reduction of RCA CCD data is routine. The spectra were corrected for geometric distortion and rewritten on a \( \ln \lambda \) scale using the “longslit” package in the National Optical Astronomy Observatories’ Image Reduction and Analysis Facility (Tody et al. 1986).

Spectra of MK standard stars chosen from Morgan & Keenan (1973) were observed and reduced similarly. Since their images were smaller than the slit, stars were trailed along the slit at position angles slightly different from 0° or 90°. After rectification, intensities were averaged along the slit to produce one-dimensional spectra with the proper instrumental dispersion. In the Fourier analysis, different K0–5 III stars gave almost identical results. The adopted star(s) (Table 1) gave marginally the best internal and external consistency.

Velocities \( V \) and velocity dispersions \( \sigma \) were calculated using a Fourier quotient program (Sargent et al. 1977; Schechter & Gunn 1979) as discussed in Kormendy & Illingworth (1982) and in Kormendy & Richstone (1992). Results are listed in Table 2. The adopted center is determined with an accuracy of \( \sim 0.1 \) pixel by comparing the brightness profile along the slit with the surface photometry discussed in §3. The rotation curves measured from the Run 4 spectra are slightly asymmetric; the results in Table 2 contain a shift of \( \Delta r = 0.15'' \) applied to all radii. It is not clear whether this is real (as in M31) or not. It is difficult to believe that it could be due to an undiagnosed problem with centering or guiding, because the brightness profile along the slit provides a check on both. We will not attempt to interpret the asymmetry; it is small enough that it does not affect our conclusions.

2.2. A First Look at the Kinematics

Figure 1 illustrates the kinematics. The rotation and dispersion profiles closely resemble those of M32 (Tonry 1984, 1987; Kormendy 1987a; Dressler & Richstone 1988; Carter & Jenkins 1993; van der Marel et al. 1994a; Bender, Kormendy, & Dehnen 1996; van der Marel, de Zeeuw, & Rix 1997). The kinematic gradients near the center are unresolved. The maximum rotation velocity \( V = 110 \pm 3 \) km s\(^{-1}\) (internal error) has already been reached 170 from the center. The velocity dispersion increases by 87 % from \( 95 \pm 2 \) km s\(^{-1}\) at 1'0 \( \leq r < 4' \) to \( 178 \pm 10 \) km s\(^{-1}\) at the center. As in M32, \( V \) and \( \sigma \) continue to decrease slowly at large radii.

Our value of the central dispersion is somewhat larger than \( \sigma = 160 \) km s\(^{-1}\) adopted by Whitmore, McElroy, & Tonry (1985) based on three published measurements. We also find a larger maximum rotation velocity than the value \( 80 \pm 6 \) km s\(^{-1}\) quoted by Davies et al. (1983) based on measurements in Illingworth (1977). The difference is due to the lower resolution of the photographic spectra available in 1977. Figure 1 shows that the maximum rotation velocity, the apparent central velocity dispersion, and the central gradients in \( V \) and \( \sigma \) all get larger as resolution improves.

![Figure 1](image-url)
### TABLE 2

**ROTATION AND VELOCITY DISPERSION DATA**

| NGC 3377 Spectrum 29566  |
|--------------------------|
| Exp. = 1800 s PA = 44° σ* = 0′′.49 |

| r  | V  | ε(V) | σ  | ε(σ) |
|----|----|------|----|------|
| −5.8 | 108 | 11   | 77 | 15   |
| −2.1 | 100 | 9    | 90 | 12   |
| −1.3 | 97  | 9    | 101| 13   |
| −0.9 | 70  | 10   | 121| 12   |
| −0.4 | 41  | 8    | 144| 11   |
| 0.0  | 0   | 9    | 158| 11   |
| 0.4  | −48 | 8    | 143| 11   |
| 0.9  | −79 | 10   | 131| 13   |
| 1.5  | −103| 8    | 95 | 11   |
| 2.7  | −103| 12   | 109| 16   |
| 6.2  | −97 | 10   | 83 | 14   |

| NGC 3377 Spectrum 33266  |
|--------------------------|
| Exp. = 1800 s PA = 50° σ* = 0′′.47 |

| r  | V  | ε(V) | σ  | ε(σ) |
|----|----|------|----|------|
| −2.6 | 96  | 11   | 103| 14   |
| −1.5 | 105 | 12   | 105| 17   |
| −1.1 | 96  | 11   | 121| 14   |
| −0.6 | 71  | 8    | 147| 10   |
| −0.2 | 24  | 7    | 145| 9    |
| 0.2  | −41 | 7    | 152| 9    |
| 0.7  | −72 | 8    | 132| 10   |
| 1.1  | −84 | 8    | 108| 11   |
| 1.9  | −100| 10   | 110| 14   |
| 5.8  | −91 | 11   | 102| 14   |

| NGC 3377 Major Axis 74770  |
|--------------------------|
| Exp. = 3600 s P.A. = 41° σ* = 0′′.56 |

| r  | V  | ε(V) | σ  | ε(σ) |
|----|----|------|----|------|
| −15.02 | 90  | 10   | 82 | 14   |
| −5.73  | 105 | 8    | 86 | 10   |
| −3.89  | 104 | 10   | 86 | 12   |
| −2.87  | 93  | 7    | 101| 9    |
| −1.61  | 91  | 6    | 112| 7    |
| −0.93  | 80  | 7    | 132| 8    |
| −0.59  | 60  | 8    | 139| 8    |
| −0.34  | 30  | 7    | 138| 8    |
| −0.12  | 3   | 9    | 149| 9    |
| 0.04   | −30 | 9    | 155| 9    |
| 0.27   | −28 | 8    | 149| 8    |
| 0.54   | −61 | 8    | 138| 8    |
| 0.92   | −79 | 7    | 133| 7    |
| 1.47   | −89 | 8    | 107| 9    |
| 2.09   | −101| 6    | 100| 7    |
| 4.36   | −102| 6    | 91 | 7    |
| 9.25   | −87 | 10   | 69 | 13   |

| NGC 3377 Spectrum 80627  |
|--------------------------|
| Exp. = 1800 s PA = 40° σ* = 0′′.20 |

| r  | V  | ε(V) | σ  | ε(σ) |
|----|----|------|----|------|
| −2.06 | 109 | 6    | 79 | 9    |
| −1.80 | 110 | 6    | 101| 12   |
| −1.57 | 107 | 6    | 92 | 8    |
| −1.27 | 110 | 6    | 99 | 7    |
| −1.05 | 108 | 8    | 109| 9    |
| −0.90 | 109 | 8    | 106| 10   |
| −0.75 | 101 | 7    | 105| 8    |
| −0.60 | 87  | 8    | 122| 8    |
| −0.45 | 83  | 8    | 131| 8    |
| −0.30 | 60  | 8    | 139| 8    |
| −0.15 | 48  | 9    | 171| 9    |
| 0.00  | 20  | 10   | 178| 10   |
| 0.15  | 5   | 9    | 161| 9    |
| 0.30  | −48 | 9    | 148| 9    |
| 0.45  | −82 | 9    | 140| 9    |
| 0.60  | −90 | 8    | 122| 9    |
| 0.75  | −100| 8    | 122| 9    |
| 0.90  | −119| 8    | 94 | 9    |
| 1.12  | −104| 6    | 100| 7    |
| 1.41  | −107| 6    | 96 | 7    |
| 1.85  | −99 | 5    | 92 | 7    |

| NGC 3377 Spectrum 80627  |
|--------------------------|
| Exp. = 5400 s PA = 40° σ* = 0′′.25 |

| r  | V  | ε(V) | σ  | ε(σ) |
|----|----|------|----|------|
| −20.99 | 92  | 7    | 66 | 12   |
| −11.75 | 88  | 6    | 72 | 8    |
| −7.20  | 89  | 5    | 80 | 7    |
| −4.62  | 98  | 4    | 75 | 6    |
| −3.29  | 102 | 6    | 85 | 8    |
| −2.61  | 104 | 6    | 90 | 8    |
| −2.17  | 105 | 7    | 104| 7    |
| −1.71  | 102 | 4    | 92 | 5    |
| −1.35  | 111 | 7    | 100| 8    |
| −1.20  | 112 | 7    | 99 | 8    |
| −1.05  | 108 | 7    | 102| 8    |
| −0.90  | 110 | 6    | 101| 8    |
| −0.75  | 111 | 6    | 104| 7    |
| −0.60  | 92  | 6    | 122| 7    |
| 0.60   | −89 | 7    | 122| 7    |
| 0.75   | −102| 7    | 121| 7    |
| 0.90   | −110| 6    | 99 | 8    |
| 1.05   | −113| 7    | 104| 8    |
| 1.20   | −100| 6    | 101| 7    |
| 1.35   | −111| 6    | 100| 8    |
| 1.50   | −101| 7    | 101| 8    |
| 1.87   | −104| 5    | 98 | 6    |
| 2.60   | −104| 4    | 92 | 5    |
| 3.77   | −105| 5    | 90 | 7    |
| 5.28   | −94 | 6    | 82 | 8    |
| 6.79   | −100| 7    | 85 | 9    |
| 9.98   | −90 | 5    | 73 | 7    |
| 22.65  | −86 | 11   | 83 | 14   |

**NOTE.** The photometric major axis is at PA = 41° ± 1°.
FIG. 2.—Unsharp-masked, $V$-band image of NGC 3377. This is image 5f57 in Table 3, i.e., a 180 s exposure with seeing $\sigma_* = 0''26$. Inside the outermost contour for which the brightness profile was calculated, the image was divided by a reconstruction that has exactly elliptical isophotes and the galaxy's measured brightness, ellipticity, and PA profiles. Outside this contour, the image is set equal to 1. The grayscale is linear between 0.8 (black) and 1.1 (white). Most dust patches are a few percent deep; the strongest absorption is 8%. Note that the appearance of diskiness is enhanced by the geometry of the dust distribution. The area shown is $1.13'$ high and $0.83'$ wide. North is $16^\circ$ clockwise from upward, and east is $16^\circ$ clockwise from left.
3. Photometry

Four \( V \)-band images of NGC 3377 were obtained at the CFHT Cassegrain focus with the RCA CCD (scale = 0′′/215 pixel\(^{-1}\)). Results are listed in Table 3. For images 5f54 – 5f57, the quoted seeing is an average for 0, 1, 3, and 9 stars, respectively, scattered around the galaxy on the frames. No star is bright enough for the shortest exposure, 5f54. However, Figure 4 (below) clearly shows that the seeing was better than for 5f55, which has a well measured \( \sigma_0 \approx 0′′/22 \). Also, at the time of the observations (1984 March), the best images ever obtained with the CFHT had \( \sigma_0 \approx 0′′/19 \) (FWHM \( \approx 0′/45 \)). Therefore we adopt \( \sigma_0 = 0′′/20 \pm 0′′/01 \).

CCD photometry of large galaxies is usually limited by the accuracy of sky subtraction. Here, too, the galaxy image is larger than the chip. For all four images, we adopt the median sky brightness in a 900 s exposure on a blank field taken immediately after image 5f57. We also measured median brightnesses at the corners of the galaxy exposures (in each case, NGC 3377 is close to the center). The ratios of these brightnesses to the adopted sky value for an elliptical galaxy that rotates rapidly (Bender 1988; Nieto & Bender 1989; Peletier 1987; Michard & Simien 1988; Bender, Döbereiner, & Möllenhoff 1988; Nieto et al. 1990; Pierce (1991), 0.85 – 2.26; and for Michard & Simien, Pierce used an 800 pixel TI CCD at the University of Hawaii 2.2 m telescope; the scale was 0′′/6 pixel\(^{-1}\) and the unvignetted field was 5′ × 5′. The sky was determined at the corners of the images; sky subtraction should be more accurate than for the other CCD photometry. Michard and Simien took photographic plates at the 1.2 m telescope of the Observatoire de Haute-Provence. The CCD data are preferred at small radii, but the photographic profile is probably the most accurate at large radii.

For each measurement, synthetic aperture photometry on image 5f57 gave an instrumental magnitude. The difference between this and the published magnitude is the zeropoint. Zeropoints were found to be independent of aperture radius. Results from different papers are remarkably consistent: the mean of ten zeropoint determinations has an accuracy of \( ±0.004 \) mag. We applied the zeropoint from image 5f57 to the other images by shifting the profiles in \( \mu \) to minimize the scatter. We also checked that zeropoints calculated from the individual images are consistent. For images 5f54 – 5f56, they differ from the adopted zeropoint by 0.002, 0.025, and 0.002 mag arcsec\(^{-2}\), respectively. Table 3 lists the brightness profiles with 5f57 zeropoints applied. Major-axis radius \( r \) is in arcsec, \( \mu_0 \) is in \( V \) mag arcsec\(^{-2}\), \( \epsilon \) is ellipticity, and PA is position angle in degrees east of north.

We verified that, except for resolution differences, the galaxy brightness profile is the same on the spectra and on the images.

Figure 3 shows the results. Also shown is photometry by Jedrzejewski (1987), Michaud & Simien (1988), Peletier et al. (1990), and Pierce (1991). \( HST \) WFPC1 photometry from Lauer et al. (1995) provides the profile near the center. Figure 3 is the most accurate composite profile we can derive from available data; the published profiles are truncated at small radii where they “peel off” because of low resolution. The profiles by Jedrzejewski (1987) and by Peletier et al. (1990) are also truncated at large radii because of deviations due to inaccurate sky subtraction. The best data at large radii are those by Pierce and by Michard and Simien. Pierce used an 800 × 800 pixel TI CCD at the University of Hawaii 2.2 m telescope; the scale was 0′′/6 pixel\(^{-1}\) and the unvignetted field was 5′ × 5′. The sky was determined at the corners of the images; sky subtraction should be more accurate than for the other CCD photometry. Michard and Simien took photographic plates at the 1.2 m telescope of the Observatoire de Haute-Provence. The CCD data are preferred at small radii, but the photographic profile is probably the most accurate at large radii.

![Figure 3](https://example.com/figure3.png)

**FIG. 3.—** Major-axis brightness profile of NGC 3377. Sources of the published photometry are given in the key; “\( B, R \)” means that \( B \) and \( R \)-band profiles have been intensity-averaged to approximate \( V \). Since points are not distinguishable at \( \log r < 1.6 \), we note that the log radius range of the plotted data is: for Jedrzejewski (1987), 0.81 – 2.06; for Peletier et al. (1990), 0.51 – 1.40; for Pierce (1991), 0.85 – 2.26; and for Michard & Simien (1988), 1.00 – 2.40. Points omitted because of poor seeing or sky subtraction are included in Figure 4.

For each measurement, synthetic aperture photometry on image 5f57 gave an instrumental magnitude. The difference between this and the published magnitude is the zeropoint. Zeropoints were found to be independent of aperture radius. Results from different papers are remarkably consistent: the mean of ten zeropoint determinations has an accuracy of \( ±0.004 \) mag. We applied the zeropoint from image 5f57 to the other images by shifting the profiles in \( \mu \) to minimize the scatter. We also checked that zeropoints calculated from the individual images are consistent. For images 5f54 – 5f56, they differ from the adopted zeropoint by 0.002, 0.025, and 0.002 mag arcsec\(^{-2}\), respectively. Table 3 lists the brightness profiles with 5f57 zeropoints applied. Major-axis radius \( r \) is in arcsec, \( \mu_0 \) is in \( V \) mag arcsec\(^{-2}\), \( \epsilon \) is ellipticity, and PA is position angle in degrees east of north.

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The profiles were calculated using a slightly modified form of the PROFILE program in the Lick Observatory image processing system VISTA (Stover 1988). PROFILE was written by T. Lauer (1985). It uses sinc interpolation optimized for high spatial resolution and is remarkably accurate. Even test profiles observed with 2 – 3 pixels per FWHM are well measured.

PROFILE fits elliptical isophotes to the image. Since real isophotes in many elliptical galaxies show disky or boxy distortions, we checked that the above procedure adequately measures the major-axis profile. Figure 2 shows the “unsharp-masked” version of image 5f57. A synthetic image was constructed with exactly elliptical isophotes and the measured brightness, ellipticity, and PA profiles. Image 5f57 was divided by this synthetic image to produce Figure 2. The cross-shaped pattern is the signature of a disky distortion (Carter 1987; Jedrzejewski 1987; Michaud & Simien 1988; Bender, Döbereiner, & Möllenhoff 1988; Nieto & Bender 1989; Peletier et al. 1990; Nieto et al. 1991; Scorza & Bender 1995); this is normal for an elliptical galaxy that rotates rapidly (Bender 1988; Nieto, Capaccioli, & Held 1988; Nieto & Bender 1989; Bender et al. 1989; Kormendy & Bender 1996). Most of the light in the disky distortion is included in the profile; the residuals are too small to affect our analysis. Figure 2 also shows an irregular distribution of dust, but the amount of absorption is too small to be important here.

The zeropoint of the \( V \) magnitude scale is based on published aperture photometry by Webb (1964); Strom et al. (1976); Sandage & Visvanathan (1978); Persson, Frogel, & Aaronson (1979); Caldwell (1983), and Poulan (1988). Ten measurements with aperture radii of 11′′ to 30′′/5 were used. One measurement by Webb through a 12′′ aperture was discarded; it appears imperfectly centered.
### Table 3

**NGC 3377 Brightness Profile**

| $r$  | $\mu_V$  | $\epsilon$ | PA  |
|------|-----------|-------------|-----|
| 0.00 | 13.997    | 0.097       | 44.50 |
| 0.22 | 14.237    | 0.097       | 44.50 |
| 0.43 | 14.716    | 0.173       | 44.50 |
| 0.64 | 15.121    | 0.251       | 44.50 |
| 0.86 | 15.449    | 0.313       | 45.42 |
| 1.07 | 15.719    | 0.363       | 44.23 |
| 1.29 | 15.927    | 0.409       | 43.83 |
| 1.50 | 16.145    | 0.427       | 43.70 |
| 1.72 | 16.317    | 0.442       | 43.42 |
| 1.94 | 16.468    | 0.452       | 43.16 |
| 2.15 | 16.606    | 0.461       | 43.01 |
| 2.37 | 16.726    | 0.471       | 42.12 |
| 2.58 | 16.847    | 0.474       | 42.05 |
| 2.80 | 16.941    | 0.483       | 41.53 |
| 3.01 | 17.040    | 0.487       | 41.48 |
| 3.23 | 17.114    | 0.501       | 41.45 |
| 3.44 | 17.199    | 0.505       | 41.35 |
| 3.65 | 17.281    | 0.514       | 41.35 |
| 3.87 | 17.357    | 0.515       | 41.35 |
| 4.19 | 17.453    | 0.524       | 41.31 |
| 4.62 | 17.585    | 0.528       | 41.23 |
| 5.05 | 17.700    | 0.532       | 41.27 |
| 5.48 | 17.836    | 0.529       | 41.93 |
| 6.02 | 17.977    | 0.521       | 42.31 |
| 6.67 | 18.123    | 0.510       | 42.32 |
| 7.42 | 18.302    | 0.495       | 42.22 |
| 8.38 | 18.471    | 0.499       | 41.77 |
| 9.46 | 18.661    | 0.489       | 41.31 |
| 10.64| 18.830    | 0.498       | 40.87 |
| 13.29| 19.145    | 0.496       | 40.16 |
| 15.49| 19.384    | 0.491       | 40.53 |
| 16.76| 19.483    | 0.496       | 40.57 |
| 18.81| 19.643    | 0.499       | 37.39 |
| 20.74| 19.780    | 0.499       | 34.70 |

| $r$  | $\mu_V$  | $\epsilon$ | PA  |
|------|-----------|-------------|-----|
| 0.00 | 14.104    | 0.174       | 44.18 |
| 0.22 | 14.297    | 0.174       | 44.18 |
| 0.43 | 14.721    | 0.200       | 44.18 |
| 0.64 | 15.119    | 0.255       | 44.18 |
| 0.86 | 15.438    | 0.316       | 45.18 |
| 1.08 | 15.700    | 0.364       | 43.98 |
| 1.29 | 15.927    | 0.399       | 43.39 |
| 1.50 | 16.142    | 0.419       | 43.33 |
| 1.72 | 16.315    | 0.436       | 43.25 |
| 1.94 | 16.472    | 0.442       | 43.22 |
| 2.15 | 16.603    | 0.454       | 42.70 |
| 2.37 | 16.735    | 0.460       | 42.62 |
| 2.58 | 16.850    | 0.468       | 41.85 |
| 2.80 | 16.943    | 0.481       | 41.56 |
| 3.01 | 17.033    | 0.490       | 41.30 |
| 3.23 | 17.127    | 0.495       | 41.27 |
| 3.44 | 17.194    | 0.509       | 41.18 |
| 3.65 | 17.285    | 0.516       | 41.18 |
| 3.87 | 17.345    | 0.519       | 41.18 |
| 4.09 | 17.418    | 0.522       | 41.18 |
| 4.30 | 17.489    | 0.523       | 41.12 |
| 4.51 | 17.557    | 0.524       | 41.23 |
| 4.73 | 17.623    | 0.526       | 41.23 |
| 4.95 | 17.686    | 0.524       | 41.29 |
| 5.16 | 17.743    | 0.524       | 41.44 |
| 5.48 | 17.831    | 0.524       | 41.38 |
| 6.02 | 17.977    | 0.517       | 42.02 |
| 6.67 | 18.142    | 0.503       | 42.34 |
| 7.31 | 18.285    | 0.494       | 42.24 |
| 7.96 | 18.415    | 0.492       | 41.86 |
| 8.60 | 18.533    | 0.490       | 41.42 |
| 9.46 | 18.678    | 0.487       | 41.08 |
| 10.53| 18.816    | 0.496       | 40.44 |
| 14.08| 19.253    | 0.491       | 40.60 |
| 15.05| 19.334    | 0.497       | 40.46 |
| 22.79| 19.900    | 0.512       | 40.63 |
| 24.62| 20.016    | 0.512       | 40.34 |
### TABLE 3 — Continued

NGC 3377 BRIGHTNESS PROFILE

| $r$   | $\mu_V$ | $\epsilon$ | PA   |
|-------|---------|-------------|------|
| 0.00  | 14.151  | 0.154       | 44.29|
| 0.22  | 14.334  | 0.154       | 44.29|
| 0.43  | 14.744  | 0.176       | 44.29|
| 0.64  | 15.134  | 0.233       | 44.29|
| 0.86  | 15.452  | 0.300       | 45.27|
| 1.08  | 15.710  | 0.354       | 43.98|
| 1.29  | 15.939  | 0.387       | 43.63|
| 1.50  | 16.144  | 0.409       | 43.56|
| 1.72  | 16.317  | 0.426       | 43.54|
| 1.94  | 16.461  | 0.441       | 43.53|
| 2.15  | 16.600  | 0.449       | 43.42|
| 2.37  | 16.729  | 0.455       | 42.71|
| 2.58  | 16.847  | 0.464       | 42.02|
| 2.80  | 16.940  | 0.478       | 41.59|
| 3.01  | 17.032  | 0.488       | 41.54|
| 3.23  | 17.118  | 0.497       | 41.53|
| 3.44  | 17.194  | 0.506       | 41.30|
| 3.65  | 17.271  | 0.512       | 41.15|
| 3.87  | 17.351  | 0.513       | 41.14|
| 4.09  | 17.415  | 0.518       | 41.14|
| 4.41  | 17.520  | 0.521       | 41.22|
| 4.84  | 17.651  | 0.524       | 41.35|
| 5.27  | 17.772  | 0.524       | 41.58|
| 5.70  | 17.886  | 0.523       | 41.95|
| 6.13  | 18.009  | 0.510       | 42.21|
| 6.56  | 18.109  | 0.505       | 42.44|
| 6.99  | 18.214  | 0.497       | 42.39|
| 7.63  | 18.354  | 0.490       | 42.16|
| 8.38  | 18.497  | 0.486       | 41.83|
| 9.03  | 18.595  | 0.491       | 41.60|
| 9.68  | 18.692  | 0.494       | 41.26|
| 10.43 | 18.803  | 0.494       | 40.84|
| 11.28 | 18.919  | 0.494       | 40.46|
| 12.15 | 19.033  | 0.494       | 40.32|
| 13.01 | 19.132  | 0.493       | 40.43|
| 13.87 | 19.226  | 0.492       | 40.54|
| 14.73 | 19.306  | 0.493       | 40.62|
TABLE 3 — Continued

NGC 3377 BRIGHTNESS PROFILE

| r    | $\mu_V$ | $\epsilon$ | PA |
|------|---------|------------|----|
| 0.00 | 14.263  | 0.148      | 45.04 |
| 0.22 | 14.420  | 0.148      | 45.04 |
| 0.43 | 14.782  | 0.174      | 45.04 |
| 0.64 | 15.152  | 0.225      | 45.04 |
| 0.86 | 15.462  | 0.285      | 46.39 |
| 1.08 | 15.724  | 0.330      | 44.88 |
| 1.29 | 15.947  | 0.368      | 43.84 |
| 1.50 | 16.150  | 0.393      | 43.59 |
| 1.72 | 16.321  | 0.413      | 43.38 |
| 1.94 | 16.473  | 0.427      | 43.18 |
| 2.15 | 16.607  | 0.437      | 43.05 |
| 2.37 | 16.730  | 0.447      | 43.04 |
| 2.58 | 16.841  | 0.457      | 42.28 |
| 2.80 | 16.943  | 0.468      | 41.74 |
| 3.01 | 17.030  | 0.480      | 41.38 |
| 3.23 | 17.118  | 0.488      | 41.22 |
| 3.44 | 17.198  | 0.496      | 41.20 |
| 3.65 | 17.276  | 0.502      | 41.20 |
| 3.87 | 17.352  | 0.506      | 41.20 |
| 4.09 | 17.426  | 0.509      | 41.22 |
| 4.30 | 17.492  | 0.513      | 41.31 |
| 4.51 | 17.555  | 0.516      | 41.42 |
| 4.73 | 17.620  | 0.518      | 41.42 |
| 4.95 | 17.681  | 0.520      | 41.44 |
| 5.16 | 17.742  | 0.520      | 41.48 |
| 5.38 | 17.801  | 0.520      | 41.66 |
| 5.59 | 17.876  | 0.518      | 41.97 |
| 5.81 | 17.923  | 0.513      | 42.08 |
| 6.02 | 17.976  | 0.512      | 42.15 |
| 6.35 | 18.059  | 0.505      | 42.32 |
| 6.78 | 18.164  | 0.497      | 42.32 |
| 7.20 | 18.256  | 0.493      | 42.27 |
| 7.64 | 18.348  | 0.489      | 42.15 |
| 8.17 | 18.452  | 0.487      | 42.05 |
| 8.81 | 18.560  | 0.485      | 41.85 |
| 9.46 | 18.660  | 0.488      | 41.32 |
| 10.11| 18.760  | 0.488      | 41.17 |
Finally, Figure 5 shows the ellipticity profile. Because of the disky distortion, the apparent ellipticity gets larger as the resolution improves. The VISTA isophote fitting program is especially sensitive to an edge-on embedded disk, so the CFHT and HST data show it very strongly. As found already by Scorza & Bender (1995), Figure 5 shows that the embedded disk contributes most at $r \gtrsim 5''$. Our modeling results are insensitive to the adopted flattening, so we assume that $\epsilon = 0.5$ at all radii.

![Graph of ellipticity profile](image)

**FIG. 5.—**Isophote ellipticity $\epsilon = 1 - b/a$ as a function of major-axis radius in NGC 3377 ($b/a$ is isophote axial ratio).

### 4. Analysis Technique

To derive masses and mass-to-light ratios as a function of radius, we need seeing-corrected and unprojected brightnesses, rotation velocities, and velocity dispersions. As in previous papers, we do not try to invent a deconvolution and deprojection technique that is powerful enough to produce unique results. Instead, we convolve models with seeing and compare them to the data. Also, we do not try to prove uniqueness. Rather, we construct fits that bracket the observations in $V(r)$, and $\sigma(r)$. In particular, we find low-mass "error bar" models in which the calculated $V(r)$ and $\sigma(r)$ are too small near the center.

One more piece of machinery is needed. Fourier quotient measurements respond nonlinearly to mixtures of stellar populations with different dispersions. Also, the observed dispersion comes partly from rotational line broadening. Model calculations therefore mimic the construction by seeing and projection of the observed spectra. The first step is to make a library of input spectra suitable for NGC 3377. It consists of the spectrum of the standard star broadened to $\sigma = 60$ – 240 km s$^{-1}$ in steps of 20 km s$^{-1}$; for each $\sigma$ there are entries at $V = -1000$ to 1000 km s$^{-1}$ in steps of 20 km s$^{-1}$. The library is used to construct synthetic "observed" spectra, as follows. We begin with a trial unprojected rotation curve $V(r)$ and dispersion profile $\sigma(r)$, both assumed to be independent of distance from the equatorial plane. Then for each radius $r$ along the major axis, consider all other pixels at radius $r'$ and depth $z'$ along the line of sight. We calculate the luminosity-weighted projected spectrum at $r'$. This scatters light into the model pixel by an amount proportional to $I_\star(r_\star)$, where $I_\star$ is a star profile with $\sigma_\star = 0''20$ and $r_\star = |r' - r'|$.
Here \( I_r \) was measured for stars in the bracketing direct images that were taken to check the galaxy centering for spectrum 80f027; they were fitted with a modified Moffat (1969) function to give the PSF used in the analysis,

\[
I_r (r) = \frac{1}{1 + \left( \frac{r}{0''29701} \right)^{2.68487} 1.54730}.
\]

The output spectrum is the sum over all scattering pixels weighted by the product of the projected brightness and the star profile. The pixels used in the calculation are smaller by a factor of 3.5 than the ones in spectrum 80f027 (1 pixel = 0''043). The integration is carried out to \( r = 5\sigma \) to include the non-Gaussian wings in the star profile. Finally, the model spectrum is analyzed with the Fourier program. The parameters of the model are then varied until the results fit the kinematics. Uncertainties are estimated by exploring the range of \( V(r) \) and \( \sigma(r) \) allowed by the data. This technique was developed independently by Kormendy (1988a, b) and by Dressler & Richstone (1988).

The calculations are routine but time-consuming. To keep them manageable, seeing effects are calculated only \(|z| = 5''1\) deep along the line of sight. A separate model run with \( \sigma_r = 0''0 \) does the projection integral for \( 5''1 \leq |z| \leq 166''\). We checked that seeing is not important for \(|z| > 5''1\). At each radius in the output image, the two synthetic spectra are sums of 116,040 and 3,740 spectra, respectively. Their sum is the required model spectrum.

Finally, the mass inside \( r \) is given by the first velocity moment of the collisionless Boltzmann equation,

\[
M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G} \left[ \frac{d \ln \rho}{d \ln r} - \frac{d \ln \sigma_r^2}{d \ln r} \right] + \left( 1 - \frac{\sigma_r^2}{\sigma_t^2} \right) - \left( 1 - \frac{\sigma_\theta^2}{\sigma_t^2} \right).
\]

Here \( \sigma_r \), \( \sigma_\theta \), and \( \sigma_t \) are the radial and two tangential components of the unprojected velocity dispersion. Also, \( \rho \) is the unprojected density of the stars that contribute to the spectra. We assume that \( M/L_V \) for these stars is independent of radius; then \( d \ln \rho/d \ln r = d \ln I/d \ln r \).

Equation (2) is based on the approximations that the mean rotation is circular and that the mass distribution is spherical. We will correct the results for the flattening of the galaxy in §8.

If \( M/L_V \) is nearly constant at large radii and if it rises rapidly toward the center at \( r < 1'' \), then there is evidence for a central dark object.

5. VOLUME LUMINOSITY PROFILE

Previous BH papers were based on ground-based measurements of brightness profiles. Consequently it was necessary to model the effects of seeing on \( I(r) \) in the same way that we model its effects of \( V \) and \( \sigma \); we constructed a series of analytic approximations to \( I(r) \) near the center that bracketed the observed profile after projection and seeing-convolution. This is not necessary for NGC 3377, because Hubble Space Telescope (HST) measurements of its projected profile (Lauer et al. 1995, 1997) have essentially infinite resolution compared to the spectroscopic resolution. We have therefore constructed a composite projected brightness profile from 0''022 to 182'' by using the HST profile at \( r < 4'' \) and the best ground-based measurements in Figure 3 at \( r > 4'' \). This profile was deprojected and the result was used as the luminosity model in all calculations discussed below. Preliminary results reported earlier (e.g., Kormendy 1992b) were based on analytic luminosity models such as those discussed above; the results did not change significantly when the HST profile was adopted because it is almost identical to one of the analytic models.

The mean projected and unprojected major-axis brightness profiles of NGC 3377 are illustrated in Fig. 6.

6. ISOTROPIC KINEMATIC MODELS

We used the machinery of §4 to find the best-fitting isotropic model and several that bracket the observations. The unprojected model rotation and dispersion profiles are shown in Figure 7, fits to the kinematic data are shown in Figure 8, and the mass-to-light ratio profiles are shown in Figure 9. Figure 10 shows residual mass-to-light ratios after various MDO masses are subtracted. Table 4 lists the model parameters.

Unprojected rotation and dispersion profiles were chosen as in previous papers. Each rotation curve is the sum in quadrature of a Keplerian and three rotation curves for exponential disks (Freeman 1970). This sounds complicated, but we emphasize that these are no more than convenient fitting functions. The total unprojected rotation curves (Fig. 7) are simple: they rise very slowly from large radii toward the center and then either drop to zero, stay constant, or rise steeply inside 1''. The Keplerian and the central exponential rotation curve are varied to bracket the observed amount of rotation at \( r < 1'' \) and hence to see how much central mass is implied by the observations. Two more exponential disk rotation curves are needed to fit the outer rotation curve; the reason is that these are not particularly suitable "basis functions" to fit an almost-flat rotation curve. The present models are slightly more complicated than the ones used in earlier papers because we need to model an almost-flat rotation curve over a larger range in radius. Similarly, the unprojected velocity dispersion is assumed to be the sum in quadrature of a "Keplerian" \( \sigma = \sigma_K/r^{1/2} \) in arcsec, and a constant \( \sigma_c \). The total \( V \) and \( \sigma \) are restricted to be \( \geq 111 \text{ km s}^{-1} \) and \( \geq 70 \text{ km s}^{-1} \), respectively.

![Figure 6](image_url)
The best-fitting model, number 3, is a good fit to both the rotation and the dispersion profiles (Fig. 8). Its dispersion gradient is not quite steep enough to be a perfect fit to the low observed $\sigma \approx 100$ km s$^{-1}$ at 1$''$, and similarly, the rotation curve rises to a slightly sharper peak at 0$'$9. These features in the data are probably due to the embedded disk structure (Scorza & Bender 1995). But the slope of the inner rotation curve is fitted essentially perfectly. If we slightly underestimate the slope in $\sigma(r)$, we only underestimate $M_\bullet$. Compared to model 3, models 2 and 1 have progressively more rotation and steeper dispersion gradients near the center. Model 2 is a reasonable “error bar”, while model 1 is clearly excluded by the data. Similarly, models 4 and 5 have too little rotation and dispersion gradient near the center; model 4 is a reasonable “error bar”, while model 5 is clearly excluded.

Figure 9 shows the corresponding mass-to-light ratios. It is interesting and reassuring that all models imply constant mass-to-light ratios $M/L_V \approx 2.6$ to 3 between $r \approx 2''$ and $35''$. This means that the inner part of the galaxy is dominated by an old stellar population, with no significant contribution from halo dark matter. The same is true in NGC 3115 (Kormendy & Richstone 1992) and in NGC 4594 (Kormendy & Westpfahl 1989). In all three galaxies, the $M/L$ profile at large radii is simple and requires no unseen mass other than that normally associated with stars. This is a useful result in its own right. Since the volume brightness changes by a factor of $\sim 630$ over this radius range, and since the modeling machinery allows $M/L_V$ to vary as much as it likes, the constancy of $M/L_V$ is a good sign that the machinery is working correctly.

In contrast, $M/L_V$ increases at $r < 2''$ by a factor of at least 4. The absolute values to which $M/L_V$ rises are not larger than we see in more luminous ellipticals. Also, the rise is important only at small radii. Finally, it is possible to make anisotropic, three-integral maximum entropy models (Richstone et al. 1998a) that fit the data without an MDO. Therefore this is a weaker MDO detection than those in the Galaxy, M31, M32, and NGC 3115 (KR95).

As in previous papers, we derive two estimates of the mass of the central dark object (Table 4). First, $M_\bullet^{M/L}$ is the total mass interior to $r = 0''1$. Unlike estimates that depend on the mass distribution at $r \gtrsim 0''5$, this value is not corrected for the flattening of the galaxy, because the potential near the center is almost spherical. If the stellar mass-to-light ratio is nearly constant with radius as suggested by the lack of strong line-strength gradients, then Fig. 9 implies that essentially all of the mass inside 0''1 radius is dark. However, $M_\bullet^{M/L}$ is very sensitive to the effects of projection and seeing. Also, when it is subtracted from the mass distribution, a mass-to-light ratio gradient remains. A second estimate is therefore derived by requiring that the residual $M/L_V(r)$ be as nearly constant as possible after a central point mass $M_\bullet^{M/L}$ is subtracted. Figure 10 shows the residual $M/L_V(r)$. It varies slightly with radius; the MDO mass is therefore uncertain by about $\pm 0.4 \times 10^8 M_\odot$ (slightly more for model 1 and less for model 5). The adopted mass for model 3 is $M_\bullet^{M/L} = 2.4 \times 10^8 M_\odot$. The “error bar” models 2 and 4 imply that the uncertainty is about $\pm 0.7 \times 10^8 M_\odot$. 

### Table 4

| Model | $V_K$ (km s$^{-1}$) | $V_E$ (km s$^{-1}$) | $r_0$ (arcsec) | $V_E$ (km s$^{-1}$) | $r_0$ (arcsec) | $V_E$ (km s$^{-1}$) | $r_0$ (arcsec) | $\sigma_K$ | $\sigma_c$ | $M_\bullet^{M/L}$ | $M_\bullet^{M/L}$ | $<M/L_V>$ |
|-------|---------------------|---------------------|-----------------|---------------------|-----------------|---------------------|-----------------|------------|------------|-----------------|-----------------|-----------------|
| 1     | 122                 | 103                 | 0.30            | 112                 | 1.1             | 103                 | 7.0             | 102        | 45         | 3.0             | 3.6             | 2.3             |
| 2     | 122                 | 103                 | 0.30            | 112                 | 1.1             | 103                 | 7.0             | 99         | 45         | 1.7             | 2.8             | 2.4             |
| 3     | 0                   | 172                 | 0.30            | 99                  | 1.2             | 105                 | 7.0             | 96         | 45         | 1.4             | 2.4             | 2.5             |
| 4     | 0                   | 156                 | 0.45            | 86                  | 1.2             | 105                 | 7.0             | 90         | 45         | 1.3             | 1.8             | 2.5             |
| 5     | 0                   | 144                 | 0.60            | 80                  | 1.2             | 105                 | 7.0             | 85         | 45         | 1.3             | 1.2             | 2.6             |
| 6     | 45                  | 175                 | 0.25            | 102                 | 1.2             | 105                 | 7.0             | 96         | 45         | 1.6             | 2.7             | 2.5             |
| 7     | 55                  | 159                 | 0.35            | 93                  | 1.2             | 105                 | 7.0             | 96         | 45         | 1.7             | 2.6             | 2.5             |
| 8     | 63                  | 155                 | 0.47            | 74                  | 1.5             | 104                 | 7.0             | 96         | 45         | 1.8             | 2.4             | 2.5             |
| 9     | 71                  | 154                 | 0.60            | 54                  | 1.8             | 103                 | 7.0             | 96         | 45         | 1.9             | 2.3             | 2.5             |
| 1m    | 112                 | 95                  | 0.30            | 103                 | 1.1             | 95                  | 7.0             | 105        | 45         | 2.7             | 3.3             | 2.3             |
| 2m    | 112                 | 95                  | 0.30            | 103                 | 1.1             | 95                  | 7.0             | 104        | 45         | 1.6             | 2.7             | 2.4             |
| 3m    | 0                   | 158                 | 0.30            | 91                  | 1.2             | 97                  | 7.0             | 98         | 45         | 1.4             | 2.3             | 2.4             |
| 4m    | 0                   | 144                 | 0.45            | 79                  | 1.2             | 97                  | 7.0             | 92         | 45         | 1.3             | 1.7             | 2.4             |
| 5m    | 0                   | 133                 | 0.60            | 74                  | 1.2             | 97                  | 7.0             | 87         | 45         | 1.3             | 1.1             | 2.5             |

NOTES. - Column (1), model number (Fig. 7 - 15). Columns (2) - (8), rotation curve parameters. A rotation curve consists of the sum in quadrature of a Keplerian with velocity $V_K$ at 1$''$ (Column 2) and three exponential disk rotation curves, each with a maximum velocity $V_E$ and a scale length $r_0$ (Columns 3 - 8). Similarly, the total velocity dispersion $\sigma$ is the sum in quadrature of a “Keplerian” with dispersion $\sigma_K$ at 1$''$ (Column 9) and a constant $\sigma_c$ (Column 10). The minimum total velocity and velocity dispersion allowed are 111 km s$^{-1}$ and 70 km s$^{-1}$, respectively. In models 2 and 2m, $V < 184$ km s$^{-1}$ and $V < 169$ km s$^{-1}$, respectively. Column (11), total mass inside 0$''$1. Column (12), central dark mass estimated by requiring that the MDO-subtracted mass-to-light ratio at $r \lesssim 25''$ (Column 13) be as nearly constant as possible. Except for $M_\bullet^{M/L}$, masses and mass-to-light ratios are corrected for the E5 shape of the galaxy (see §8). The distance to NGC 3377 is assumed to be 9.9 Mpc.
FIG. 7.—Intrinsic (i.e., not projected or seeing-convolved) rotation and dispersion profiles for kinematic models 1 – 5 in Table 4.

FIG. 8.—Models 1 – 5 (top to bottom at 0.4″) fitted to the major-axis kinematic data. Here the models have been projected and convolved with seeing as discussed in §4. Only the high-resolution data are plotted inside $r = 2"$. 
Averaging this result with $M_\odot^{0,1}$, we arrive at our final estimate for the MDO mass given by models 1 – 5, $M_\bullet = (1.9 \pm 0.8) \times 10^8 M_\odot$. The errors are not Gaussian: a range of $M_\bullet$ values is allowed because of parameter coupling in the models, but outside the above range, masses become rapidly excluded by the present machinery.

Model 3 fits the data and implies that NGC 3377 contains an MDO, but it has a shortcoming. The rotation velocity decreases to zero at the center. This is not impossible in principle – the BH detection comes mostly from the dispersion gradient – but it is not the natural expectation. It is important to note that we are just measuring masses, like when we use an embedded H I disk to measure the mass of a galaxy, but with the added complication of a non-zero velocity dispersion. We are not making self-consistent dynamical models. So we may be allowing some freedom in the tradeoff between $V$ and $\sigma$ that the galaxy does not have. The results of such models have proved to be very reliable in the past (see, e.g., Kormendy et al. 1996a,b and van der Marel et al. 1997a,b, which compare HST results on NGC 3115, NGC 4594, and M32 with BH results from papers using techniques like ours). Nevertheless, the tradeoff between $V$ and $\sigma$ deserves further exploration.

We have therefore constructed a more closely spaced series of models that have various small amounts of Keplerian rotation curve near the center. These are models 6 – 9 in Table 4; they are illustrated in Figures 11 – 13. Models 7 and 8 are good fits to the data. In fact, they are better fits than model 3, because the extra rotational line broadening allows a better fit of the central velocity dispersion. Models 6 and 9 are error bars to $V(r)$, although they are not excluded by the data. Their rotation curves are slightly more complicated than those of models 1 – 5 (see Fig. 11). Other, similar models are possible. But these, too, have steeply rising mass-to-light ratio profiles near the center (Fig. 13), and in these cases, the central dark mass is implied by both $V$ and $\sigma$.

Together, models 1 – 9 show that the detection of a central dark object in NGC 3377 is very robust, within the assumption that the velocity distribution is isotropic. The implied mass is $M_\bullet = (1.9 \pm 0.8) \times 10^8 M_\odot$. It requires two small corrections. It already contains a correction for the flattening of the galaxy; this is discussed in §8. Also, in §7, we correct for the fact that we fit Gaussians to the line-of-sight velocity distributions instead of measuring moments as required by Equation (2).
Fig. 10.—Mass-to-light ratio $M/L_V$ as a function of radius for models 1–5 before (heavy solid lines) and after (light lines) subtraction of the MDO masses listed in the keys. At $r < 0.2''$, the curves get very noisy and so are not plotted. For each model, residuals are shown for four values of $M^{M/L}_\star$; the second-smallest, which corresponds to the light solid line, is the adopted value. The others (dashed lines) illustrate the uncertainty that results from the fact that $M/L_V$ is not exactly constant with radius. The horizontal straight line in each panel is the adopted mean stellar mass-to-light ratio. All mass-to-light ratios are corrected for the E5 shape of the galaxy.
7. LINE-OF-SIGHT VELOCITY DISTRIBUTIONS

The quantities $V$ and $\sigma$ in Equation (2) are moments of the line-of-sight velocity distribution (LOSVD). In real life, moments cannot be measured, because they are sensitive to small numbers of stars that are far from the mean velocity and hence out in the (unknown) continuum. In §2, we derived velocities and velocity dispersions by fitting Gaussians to the line profiles. Several authors have pointed out that the derivation of $M(r)$ can suffer systematic errors if such measurements are substituted for moments (van der Marel & Franx 1993; van der Marel et al. 1994a, b; Bender et al. 1994). However, KR95 (see p. 598 – 599) point out that the moment $V(r)$ is proportional to the Gaussian fit $V(r)$, so the main effect is to lower the global (i.e., bulge) mass-to-light ratio slightly; the strength of the BH case is almost unchanged. Since many BH papers are based on Gaussian fit $V$ and $\sigma$ values, it is useful to illustrate this point for at least one galaxy. Therefore we investigate here how LOSVD asymmetries affect the conclusions of §6.

We measured non-parametric LOSVDs using the Fourier Correlation Quotient method (FCQ, Bender 1990). To extract higher-order information on the LOSVD shapes, we fitted them with a Gaussian plus third- and fourth-order Gauss-Hermite polynomials $H_3$ and $H_4$ (van der Marel & Franx 1993, Gerhard 1993):

$$\text{LOSVD}(v) = \frac{\gamma}{\sqrt{2\pi\sigma^2}} e^{-\frac{(v-V)^2}{2\sigma^2}} \cdot \left[ 1 + h_3H_3\left(\frac{v-V}{\sigma}\right) + h_4H_4\left(\frac{v-V}{\sigma}\right) \right]. \quad (3)$$

The coefficients $h_3$ and $h_4$ parametrize the lowest-order asymmetric and symmetric deviations from Gaussian line profiles. Positive $h_4$ implies that the line profile is more triangular than Gaussian; i.e., it is more strongly peaked and has more extended wings than the best-fitting Gaussian. Negative $h_4$ parametrizes deviations toward rectangular line profiles. The $h_4$ amplitudes are generally small in ellipticals, with values less than a few percent (Bender et al. 1994). This is also the case in NGC 3377: $h_4 \simeq 0$ at $r \leq 6''$. The FCQ results are shown in Fig. 14.

The $h_3$ amplitude can reach values of $\pm 0.15$; it couples with rotation as $h_3 \simeq -0.1V/\sigma$ (Bender et al. 1994). In NGC 3377, $h_3 \simeq -0.09V/\sigma$ with no significant deviations (Fig. 14). Therefore there are more stars on the retrograde (systemic-velocity) side of the LOSVD than on the prograde side. Such behavior is natural for rotating stellar systems (see the above references); it is especially expected when there is a disky, rapidly-rotating structure embedded in a more nearly spherical and slowly-rotating body (Scorza & Bender 1995).

Having measured $h_3$ and $h_4$ profiles, we can derive more realistic estimates of the velocity moments than we got from Gaussian fits alone. For the case $h_4 \simeq 0$ and $-0.15 < h_3 < 0$, Bender et al. (1994, see Fig. 3) find that

$$\frac{V_{\text{mom}} - V_{\text{fit}}}{\sigma_{\text{fit}}} = -1.0|h_3|^{0.83}; \quad (4)$$

$$\frac{\sigma_{\text{mom}} - \sigma_{\text{fit}}}{\sigma_{\text{fit}}} = 4.7|h_3|^{2.4}. \quad (5)$$

Here $V_{\text{mom}}$ and $\sigma_{\text{mom}}$ are the approximate true moments, and $V_{\text{fit}}$ and $\sigma_{\text{fit}}$ are derived by fitting Equation (3) to
the LOSVDs. Moments derived in this way are illustrated in Figure 14, together with the velocities and velocity dispersions given by the Fourier Quotient and Fourier Correlation Quotient methods. The velocity dispersions are virtually identical for all three procedures, but the velocities differ by up to 15%. As expected for negative $h_3$, the velocity moments are smaller than both the FQ and FCQ fitted values. However, the FQ values are between the FCQ and moment velocities. Therefore Gaussian fits give velocities that are closer to the true moments than higher-order fits incorporating $h_3$ and $h_4$.

How do these results affect the mass measurements in this and previous BH papers? Figure 14 confirms the remark in KR95 that the velocity moments are smaller than the FQ velocities by a scale factor that is almost independent of radius. Models 1m – 5m (Table 4) are models 1 – 5 recalculated with velocities scaled down by a factor of 0.92. They fit the moment data in Figure 14 in the same way that models 1 – 5 fit the FQ data in Figure 8. Model 3m is a good fit; model 4m provides a low-$M_\bullet$ error bar, and model 5m clearly does not fit the data. Models 1m and 2m similarly provide high-$M_\bullet$ error bars.

Figure 15.—Comparison of Fourier Quotient measurements, Fourier Correlation Quotient measurements, and approximate velocity moments calculated from the FCQ measurements using Equations 4 and 5. The lines show models 1m – 5m, i.e., models 1 – 5 with velocities scaled down by a factor of 0.92.

Figure 16 shows the mass-to-light ratio profiles for models 1m – 5m. As expected, they are similar in shape to those in Fig. 9; i.e., $M/L_V$ still climbs quickly at $r \lesssim 2''$. This means that the strength of the BH case is essentially unchanged. But the overall mass scale is slightly smaller. The factor is not as extreme as 0.92$^2$, because $\sigma(r)$ must be made steeper to preserve a good fit to the data now that rotational line broadening is reduced. The BH masses and mass-to-light ratios are given for models 1m – 5m in Table 4. We find that $M_\bullet = (1.8 \pm 0.8) \times 10^8 M_\odot$.

Note that models 1m – 5m are not attempts to fit the full LOSVDs of NGC 3377, i.e., they are not intended to model the complete dynamical behavior of the galaxy. They have essentially Gaussian LOSVDs; this is why they do not themselves require a correction from Gaussian fit to moment $V$ and $\sigma$ values. We emphasize that the purpose of this paper is only to measure the mass distribution well enough to search for a BH. With models 1m – 5m, we have corrected our measurements of $M(r)$ and $M_\bullet$ for the most important effects of LOSVD asymmetries. As expected, the corrections are small. Similar conclusions apply to past BH papers based on FQ measurements: the errors made by neglecting $h_3$ and $h_4$ are small compared to other uncertainties in the analysis. This is especially true
when bulge-subtracted spectra were analyzed (Kormendy 1988b, c), since bulge subtraction removes most of the LOSVD asymmetries (Kormendy 1994).

### 8. DISCUSSION

Isotropic models imply that NGC 3377 contains a central dark object, probably a BH, of mass $M_\bullet \sim 2 \times 10^8 M_\odot$. The BH mass and stellar mass-to-light ratio require one more correction. While the fits of the kinematic models to the observations were correctly based on an E5 light distribution, the $M(r)$ and $L(r)$ calculations were based on the approximation that the galaxy is spherical. For any test particle at radius $r$ along the major axis, the observed velocities imply less mass in a flattened galaxy because stars are on average closer to the test particle than we assumed. Binney & Tremaine (1987) gave the required correction in their Fig. 2-12. This is for a modified Hubble density distribution, which is not a bad approximation here. The E0 and E5 rotation curves are proportional to each other; the flattening correction to $M(r)$ is a factor of 0.80. This is approximate, because we assume that the mass distribution is E5 everywhere, whereas in reality, it gets rounder as $r \to 0$ because of the BH. Nevertheless, the correction should be accurate enough so that other uncertainties dominate. Similarly, the correction to $L(r)$ is a factor of 0.5. Therefore we correct $M_\bullet$ by a factor of 0.80 and $M/L(r)$ by a factor of $0.80/0.5 = 1.61$. Table 4 and Figures 9, 13, and 16 include these corrections.

We conclude that isotropic kinematic models imply that NGC 3377 contains a central dark object of mass $M_\bullet = (1.8 \pm 0.8) \times 10^8 M_\odot$. The stellar mass-to-light ratio $M/L_V = 2.4 \pm 0.2$ is smaller than normal for an elliptical of absolute magnitude $M_B = -18.8$ (e.g., Kormendy 1987b, Fig. 3; note that this is based on a Hubble constant of 50 km s$^{-1}$ Mpc$^{-1}$). The BH mass supports the emerging correlation between bulge luminosity and $M_\bullet$ (Fig. 17; Kormendy et al. 1997; KR95; Kormendy 1993).

Our detection of an MDO in NGC 3377 is not quite definitive, because anisotropic, three-integral maximum entropy models (Richstone et al. 1998a) can fit our data without a BH (Richstone et al. 1998b). However, several arguments suggest that NGC 3377 is not likely to be very radially anisotropic. To explain the data without a BH requires that $\sigma_r \gg \sigma_\phi$ and $\sigma_r$. But NGC 3377 contains an embedded nuclear disk (Scorzla & Bender 1995). Our understanding of how these form – gas dissipation and star formation – would not tend to make $\sigma_r$ very large compared to $\sigma_\phi$ and $\sigma_r$. In fact, van der Marel et al. (1997b) conclude that valid models of M32, whose kinematics are similar to those of NGC 3377, “are all dominated by azimuthal motion at most radii” (their Fig. 10). Also, NGC 3377 rotates rapidly enough to be near the “oblate line” in the well known $V/\sigma - \epsilon$ diagram (Illingworth 1977; Binney 1978, 1980, 1981, 1982; Binney & Tremaine 1987: $\epsilon = $ ellipticity and $V/\sigma = $ ratio of the maximum rotation velocity to a mean velocity dispersion near the center). The oblate line, $V/\sigma \approx [\epsilon/(1 - \epsilon)]^{1/2}$ (Kormendy 1982), describes oblate spheroids that are isotropic and flattened only by rotation. This is a direct constraint only on $\sigma_z/([\sigma_x^2 + \sigma_y^2]^{1/2})$, but rapidly rotating ellipticals have generally turned out to be less anisotropic than slowly rotating ellipticals. Finally, isotropic model measurements of $M_\bullet$ have turned out to be close to correct when anisotropic models were constructed (see KR95 for a review). So it is likely that our measurement of $M_\bullet$ is reasonably accurate. Nevertheless, it will be important to see whether higher-resolution observations confirm our MDO detection.

This work is in progress: Richstone et al. (1998b) have obtained HST FOS spectroscopy of NGC 3377. Their three-integral maximum entropy models of NGC 3377 show conclusively that it contains a central dark object of mass $M_\bullet \sim 10^8 M_\odot$. 

**Fig. 16.**—Mass-to-light ratio $M/L_V$ (solar units) as a function of radius for models 1m – 5m, corrected for the E5 flattening of NGC 3377 as discussed in § 8.

**Fig. 17.**—BH mass as a function of bulge absolute magnitude, from Kormendy et al. (1997) but with $M_B$ (Bower et al. 1998; Green 1997) and NGC 4342 (van den Bosch & Jaffe 1997; Cretton & van den Bosch 1998) added and with NGC 3377 updated. Circles, diamonds, and squares show objects with stellar-dynamical, ionized gas dynamical, and maser evidence for BHs, respectively. Upper limits on $M_\bullet$ are plotted as crosses. The correlation may be only the upper envelope of a distribution that extends to smaller $M_\bullet$. 

-0.5ex}
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