THE ASTROPHYSICAL JOURNAL, 324:701–713, 1988 January 15

STELLAR DYNAMICS IN THE NUCLEI OF M31 AND M32: EVIDENCE FOR MASSIVE BLACK HOLES[1]

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Received 1987 February 24; accepted 1987 July 9

ABSTRACT

We present new kinematic data based on the calcium IR triplet lines that define rotation and velocity dispersion profiles for the nuclei of M31 and M32 with high accuracy. These data confirm earlier work by Dressler, Kormendy, and Tonry which indicated rapid rotation and high-velocity dispersions in the central few parsecs of both systems.

Stellar dynamical models which allow for anisotropic velocity dispersions have been constructed using the maximum entropy technique. These three-dimensional models have been projected in the plane of the sky and convolved with the seeing profile and finite slit width using a new technique that constructs synthetic spectra. These spectra are then analyzed in exactly the same manner as the real data, thus guaranteeing that the response of the Fourier program to multiple-temperature components and steep rotation gradients has been properly taken into account.

We conclude that constant M/L models are ruled out for both systems, regardless of the degree of anisotropy of the velocity dispersions. The most straightforward interpretation is that M31 and M32 harbor central black holes of ~ 3–7×10^7 and $\sim 8 \times 10^6$ solar masses, respectively. The case of M31 is somewhat complicated by a curious separation of the kinematic center from the luminosity peak, but none of our explanations for this phenomenon weaken the interpretation that a central black hole is present. The presence of black holes in these two neighboring galaxies with spheroidal stellar components suggests that black holes of up to $10^9\ M_\odot$, favored in many quasar models, may be present in galaxies with the largest spheroidal components.

Subject headings: black holes — galaxies: individual (M32, M32) — galaxies: nuclei

I. INTRODUCTION

M31 (NGC 224) and M32 (NGC 221) are the closest galaxies with dense spheroidal stellar components. They show no sign of nuclear activity as is found in NGC 1068, M87 (NGC 4886), and (weakly) M81 (NGC 3031), but the proximity of M31 and M32 to our Galaxy makes it possible to map the mass distribution on scales of a few parsecs using optical tracers. This high spatial resolution, together with the small velocity dispersions of the spheroidal components, affords much greater sensitivity to mass concentrations in the range 10^7–$10^8\ M_\odot$ than in more distant objects (Richstone 1987). Black holes in the $10^8\ M_\odot$ range are implicated as the underlying power sources for quasars, but the observational evidence supporting that view is weak.

Pioneering observations of M31 by Walker, Lallemand, Duchesne (1960) and M32 by Walker (1962) found rapid rotation of the stellar systems in both nuclei. Later studies of M32 by Tonry (1984) and Dressler (1984) and of M31 by Dressler (1984) and Kormendy (1987) confirmed abrupt rises in the stellar rotation rates as well as sharp increases in the apparent velocity dispersions of both these systems. These authors argued that black holes of $\sim 10^6$–$10^8\ M_\odot$ are present in the nuclei of both galaxies. However, a major ambiguity in interpretation of such data has been the possibility that the rise in apparent central velocity dispersion is the result of the smearing of an extremely steep rotation curve, as opposed to a genuine rise in dispersion. Another critical problem has been a lack of dynamical models that could test the ability of *anisotropic* velocity fields to produce rising dispersion profiles without a substantial rise in M/L. We consider a demonstration of the failure of constant M/L models to be a crucial step that has been missing in attempts to establish the presence of central black holes.

This paper presents new data on both M31 and M32 that in signal-to-noise ratio and spatial resolution are superior to the data of the earlier studies and the equal of any now available. Using new dynamical models, we determine the mass distribution of the centers of these galaxies with much greater reliability than in the past. There is no question that the nuclei have very large mass-to-light ratios, recalling, in the case of M31, model A of Ostriker and Tremaine (1982). Our results strongly suggest the presence of massive black holes in the nuclei of both galaxies.

Section II presents the data and discusses their reduction and analysis. Section III discusses dynamical models that were fitted to these data and the conversion of these models to simulated optical observations. In § IV we present our conclusions regarding the case for massive black holes in these two galaxies.

[1] Observations were made at the Palomar Observatory as part of a collaborative agreement between the California Institute of Technology and the Carnegie Institution of Washington.

II. DATA AND ANALYSIS

a) *The Data*

As discussed in detail in Dressler (1984, hereafter D84), the absorption lines of the Ca II triplet at 8498, 8542, and 8662 Å provide a strong, uncontaminated signal well suited to the measurement of stellar kinematics in the integrated light of external galaxies. These lines are strong in all old stellar populations, and contamination by young stars is small in the infrared. The most serious problem is the accurate subtraction of the night-sky spectrum, but this is easily done in the case of nearby galaxy nuclei like M31 and M32 since in both cases the central surface brightness is well above that of the night sky.

Observations of M31 and M32 were made by Dressler on 1985 August 22 using the double spectrograph on the 5 m Hale telescope at Palomar Observatory. The instrument was configured to sample the 4800–5700 and 8300–9000 Å regions with two Texas Instruments 800 × 800 CCDs. The sampling was ~1.1 Å per pixel in the blue and ~0.8 Å per pixel in the infrared. The observations were made with a 1″0 slit which resulted in instrumental FWHM widths of 2.2 and 1.6 Å, which correspond to velocity widths $\sigma = 57$ km s^{-1} and 25 km s^{-1}, respectively. Two consecutive exposures of M32 and three consecutive exposures of M31 of 500 s duration were made, each aligned along the major axis. The galaxies were bisected by the slit, and guiding was done manually using an isophotal display on the viewing television. Because of the strong intensity gradients in the cores of both systems, it was quite easy to guide to a fraction of 1″ on this night of extremely good seeing. The air mass during the exposures varied between 1.02 and 1.08. A K0 III star, HD 253, was trailed along the slit for ~20 s to provide a template spectrum, and a guided 50 s exposure of a star within 3′ of M32 was taken to provide a measure of the seeing through the instrument. Reduction of this frame showed that the seeing was 1″04 FWHM, or a Gaussian width of $\sigma = 0\farcs45$. This is marginally better than Kormendy's (1987) seeing, but this difference is compensated by his use of a narrower (0″5) slit.

The data were processed with the standard techniques of bias subtraction and flat fielding, and rows of spectra were binned together when necessary to achieve a good signal-to-noise ratio throughout. The central nine columns of pixels of M32 and central seven columns of M31 had sufficiently strong signals that they each could be analyzed separately, with the central column defined as the one of maximum intensity. The resulting 19 spectra for M32 cover a width of 52 pixels on the array or 30″4. The 17 spectra of M31 cover 50 pixels. These were compared to the trailed spectrum of HD 253 using a Fourier analysis program to determine systemic velocity and velocity dispersion. The results are shown for M32 in Figure 1*a* (velocity) and Figure 1*b* (dispersion) and for M31 in Figures 2*a* and 2*b*. As discussed in Dressler (1984), the excellent agreement of models and data for calcium triplet measurements implies typical errors of only 1–3 km s^{-1} in systemic velocity and velocity dispersion. Figures 1 and 2 show discrepancies between repeat observations that are clearly larger than these errors associated with goodness of fit, which suggests that other systematic errors such as variations in positioning and seeing are dominant.

b) *M32*

Figure 1 confirms the results of Tonry (1984) and D84 of a sudden rise in the velocity dispersion and a correspondingly steep rotation gradient. The spatial resolution is a factor of 2 better than in these earlier studies, yet the kinematic features still appear to be unresolved. As can be seen from the intercomparison of the two frames, which were reduced separately, the errors in systemic velocity v_r and σ are very small, so there can be no doubt as to the reality of the apparent rise of the velocity dispersion to ~84 km s^{-1} and a rotation gradient of at least 40 km s^{-1} arcsec^{-1} (1 arc second = 3.35 pc). The spectra taken in the blue confirm these results but with less precision. This rapid nuclear rotation, also seen in M31, is of interest in its own right, as noted in § IV.

c) *M31*

The results for M31 are even more striking, as revealed in Figure 2. As one looks further toward the nucleus, the gently falling rotation curve for the outer bulge of M31 is suddenly reversed by what is clearly a discrete kinematical structure with an semiamplitude of ~100 km s^{-1}. The velocity dispersion appears to increase from ~140 km s^{-1} to over 220 km s^{-1}. Again, the agreement of the three separate frames is excellent, and the kinematic features seem to be spatially unresolved for the innermost points.

The M31 data reveal yet another surprise. The discrete kinematic features are *not centered on the light*, as shown in Figure 2. There is a displacement of slightly more than one pixel or 0″62 from the peak of the velocity dispersion curve to the column of maximum light. The zero crossing of the rotation curve is also displaced from the column of maximum light, by 0″37. We will assume that these displacements are the same within the errors and conclude that the kinematic center is displaced from the luminosity peak by 0″50. It is tempting to blame this decentering on the presence of dust in the nucleus, but as we shall argue later, it is not obvious that this is only possible interpretation.

III. DYNAMICAL MODELS AND COMPARISON WITH THE DATA

a) *Dynamical Models*

The construction of dynamical models for comparison with the observed velocities uses a new "maximum entropy" (ME) technique to be described elsewhere (Richstone and Tremaine 1987). The basic principles have been thoroughly covered already, and the essential new properties of the ME technique are also published (Richstone 1986). As in the earlier work on M87 (Richstone and Tremaine 1985), the observed surface brightness of the galaxy is used to recover the volume emissivity, under the assumption of spherical symmetry. The mass distribution is assumed to be the same shape as the light distribution (constant M/L) except for a central mass point of specified mass in units of the scaled mass distribution (the mass may be zero). A complete set of bound orbits (all possible energies and angular momenta) is assembled in the scaled mass distribution. The orbits are assembled, using a hill climbing technique, to maximize a linear combination of the classical entropy, the chi-squared statistic measuring the goodness of fit of the model dispersions to the observed dispersions, and the rotation speed within some region, while always maintaining the exact light distribution. The adjustable multipliers on the entropy, chi-squared term, and rotation speed permit considerable investigation of the model space. We have used this program to construct dynamical models which approximate kinematic models of the data, with a resolution of 0″1. We then blurred and observed them, as described below. The successes and failures led to iterative refinements.

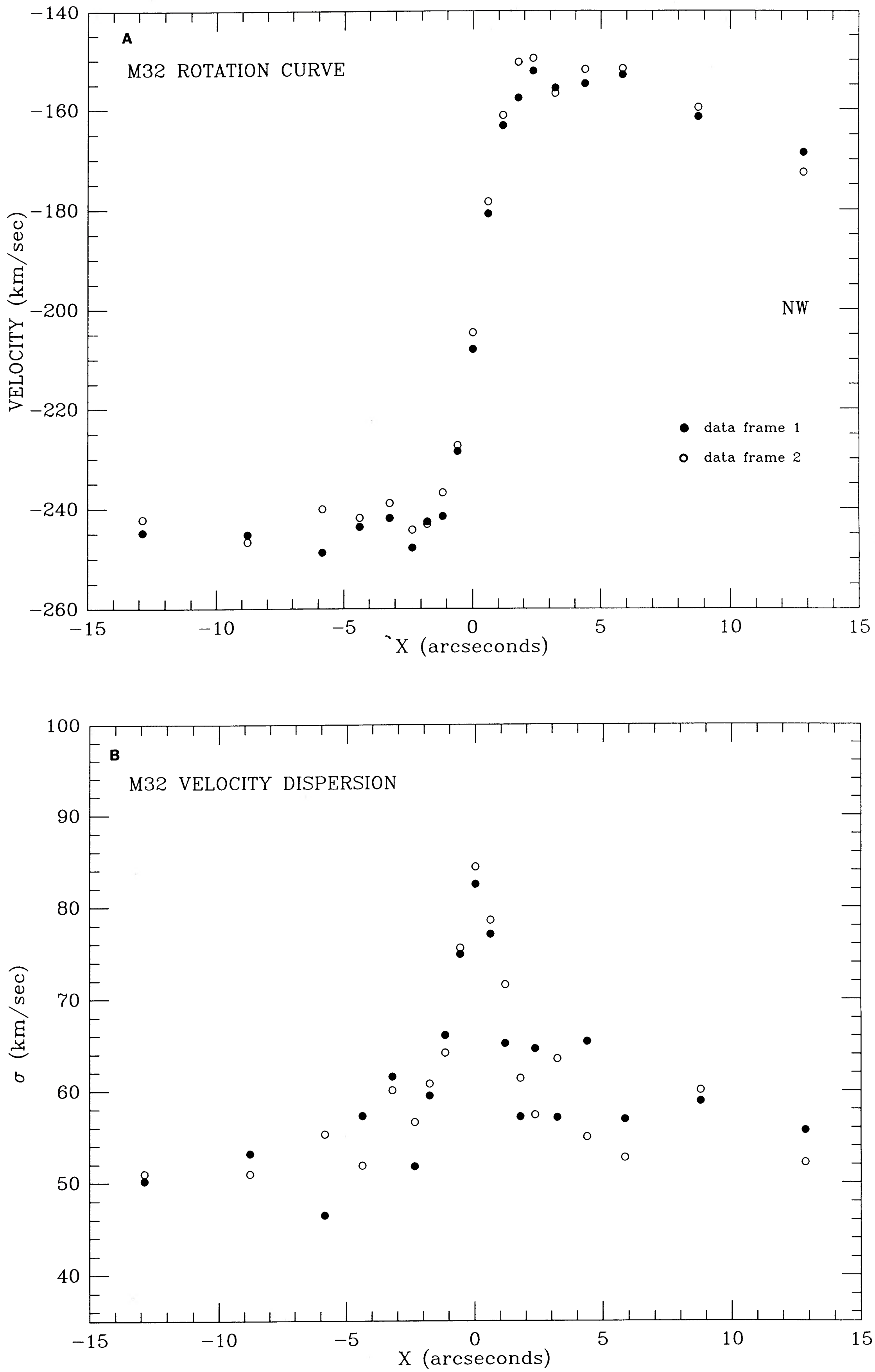

FIG. 1.—Rotation curve and velocity dispersion profile as determined with the Fourier program using spectra in the calcium triplet region. Data are shown for two separate exposures. One arc second is ∼3.3 pc.

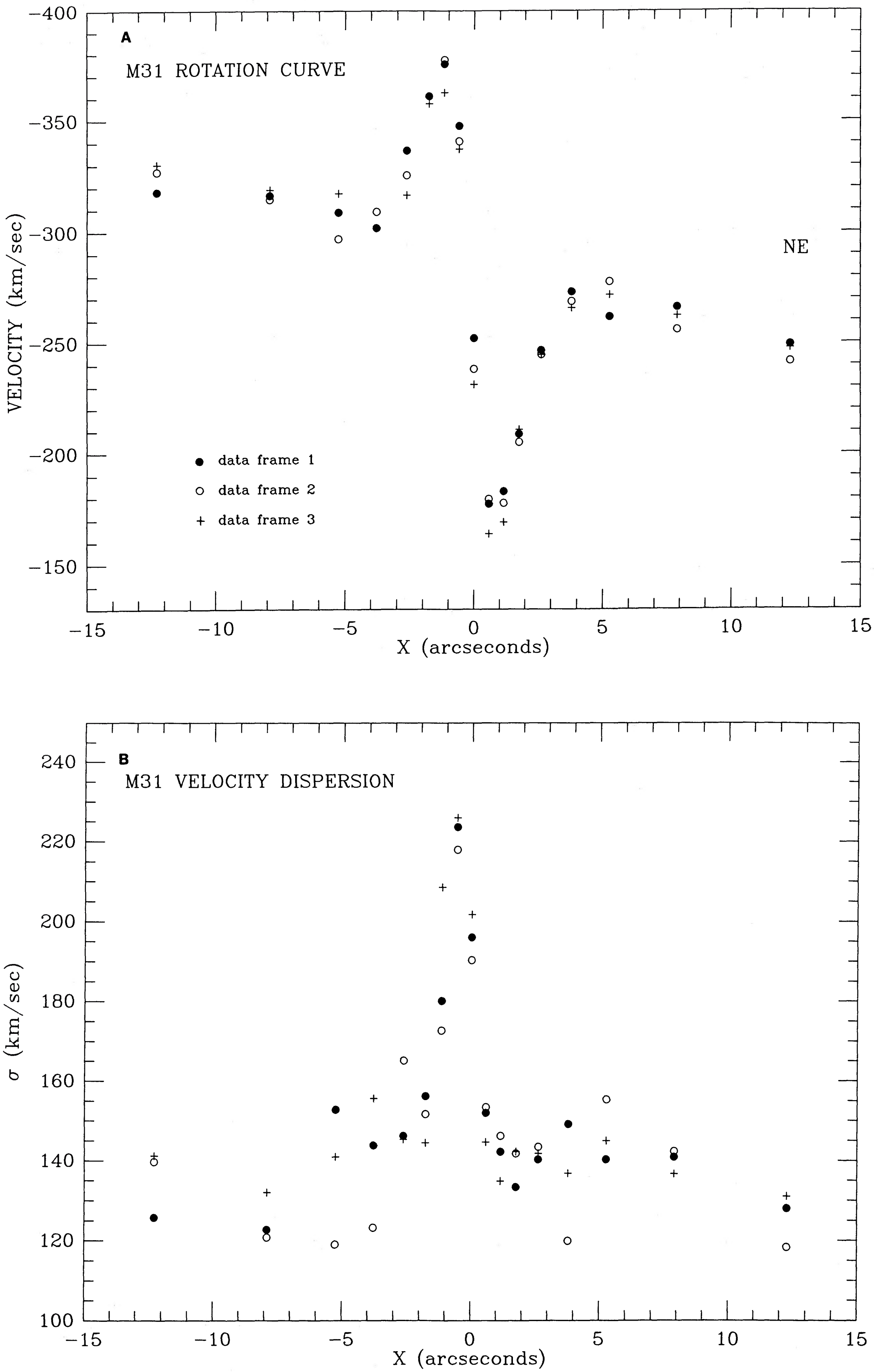

FIG. 2.—Same as Fig. 1, but for M31. Data are shown for three separate exposures.

b) *Simulating Data*

It is clear from Figures 1 and 2 that M31 and M32 present an unusual problem to the modeler because the steep gradients in velocity dispersion and systemic velocity result in substantial blending of line profiles *over a single resolution element*. This is apparent, for example, in the points immediately straddling the nucleus whose spectra show very asymmetrical line profiles due to the rapid rotation gradient. Any given analysis program, like the Fourier technique used here, will have certain sensitivities to the moments of the line profile, thus a blend of different velocities and dispersions are sampled in a rather nonlinear way. For example, Whitmore (1980) has shown that the Fourier technique inherently gives a higher weight to lower velocity dispersion components of composite spectra. This also raises the question: what exactly is being measured as the rotation velocity in a highly asymmetrical profile? Also how is the smoothing due to the seeing profile and the finite slit width to be modeled?

We have developed a new approach to circumvent these problems. We use dynamical models to predict the projected intensity, systemic velocity, and velocity dispersion at each point in the central region of the galaxy. A computer program then synthesizes spectra for the inner seven data pixels, each of which is subdivided into a 5×10 grid with spacing 0$''$.12 along the major axis and 0$''$.10 along the minor axis. A spectrum is synthesized for each of the 7×50 grid locations in the following manner. The program contains a set of template spectra with velocity dispersions 0–380 km s^{-1} (as measured by the Fourier program) in 20 km s^{-1} increments. For each grid location the program samples all points within the 2 σ limits of the seeing profile ($\sim$250 points), chooses the spectrum of appropriate dispersion, and shifts in wavelength to match the rotation curve, as specified by the model. The amplitude is the product of the intensity profile times exp $(-d^2/\sigma^2)$, where d is the distance from the grid location to the point sampled in the galaxy. A synthesized spectrum is built up by repeating the procedure for all 50 points for each of the seven pixels. These synthesized spectra are then analyzed with the Fourier program *in exactly the same way as the real data were treated*. Although this brute force technique is intensive of computer time, the synthetic data generated this way are subject to the same biases and nonlinearities of the Fourier program as are the real data. Even the intensity profile measured through the slit can be used to compare the model intensity profile to the data. In principle, we can further improve on this procedure by using the actual orbits in the model to compute the entire projected velocity distribution (not just the first two moments) at all points in the galaxy, prior to synthesizing the spectrum and convolving with seeing. We have not yet gone this far. In summary, *the observation* of a galaxy has been modeled, as well as the galaxy itself.

c) *The Model for M32*

M32 has a rotation curve that rises steeply from the nucleus to a maximum of $\sim$45 km s^{-1}. As Tonry (1984) points out, this alone is a strong indication that M/L is rising in toward the nucleus, regardless of whether the rise in velocity dispersion is genuine or simply the artifact of a rapidly spinning core which is unresolved in the central spectrum. However, it is not a proof: it is possible to construct constant M/L models rapid nuclear rotation which satisfy the equation of hydrostatic equilibrium, although such models may be nonphysical (Richstone and Tremaine 1985).

For the models of M32 we adopted a radial intensity profile of $I \propto r^{-1.0}$ for $r < 3''$. This is consistent with published data (e.g., Tonry 1984) and the intensity measurements from the spectra themselves, when convolved with the seeing.

We attempted to make models of M32 with a constant M/L that have a rising velocity dispersion in the center. This is accomplished by preferentially selecting radial orbits for stars near the center, with orbits on the outside that are more circular than isotropic. We found that we could, in fact, produce the observed rise in velocity dispersion to $\sim$82 km s^{-1} for the central spectrum. However, the amplitude of the rotation curve would be only 20 km s^{-1}, less than half that which is observed, as shown in Figure 3. It is easy to see why this is the case, since a strong favoring of radial orbits necessarily limits the angular momentum that can be present in the system. Thus, it is straightforward to rule out the possibility that the rise in velocity dispersion is due to a constant M/L core with increasing anisotropy.

Parameters of the best fitting model, both true and projected, are shown in Figure 4. For this model $v/\sigma \sim 0.5$ at radii of a few arc seconds, appropriate for a rotationally flattened spheroid with an ellipticity like that typical for M32. A comparison of this model with the data, accomplished as described in § III*a*, is shown in Figure 5. The model, which includes a central, nonluminous point mass of $8 \times 10^6\ M_\odot$ in a constant M/L core, reproduces both the rise in velocity dispersion and the rotation curve.

The nonluminous mass dominates the luminous mass for $r < 1''$, which includes a volume of less than 100 cubic parsecs. An obvious interpretation is that this mass is contained in a central black hole. Alternatively, could this dark matter be distributed over the entire volume? Such a density of more than 10^5 solar masses per cubic parsec is one or two orders of magnitude larger than the densest "normal" systems like globular star clusters as measured within their half-mass radius. Indeed, if this is a globular-like cluster, its half-mass radius must be of order 1 pc, implying a density within the half-mass radius of greater than $10^6\ M_\odot$ pc^{-3}. This density implies rapid dynamical evolution, as discussed below. Furthermore, the mass must be in objects with high M/L since the light does not increase as rapidly as the mass. Infrared colors seem to rule out a rapid change in the luminosity function (as suggested for M31 by Faber and French 1980 and tested by Persson *et al.* 1980), so the only remaining candidates are collapsed objects: black dwarfs, neutron stars, or black holes. Even if a reasonable model could be found for the progenitors of such a population of 10^5 remnants in the core it seems likely that a great number of these collapsed stars would capture companions and result in a large population of binary X-ray sources, which is not observed (a calculation based on this argument is beyond the scope of this paper).

In summary, a massive black hole seems the most reasonable hypothesis to explain the unusual kinematics in M32. In our opinion this is a very clean case, and it appears that spectra and photometry observations with the Hubble Space Telescope at a distance of a few tenths of an arc second from the nucleus are likely to be conclusive.

d) *The Model for M31*

The kinematic features of the nucleus of M31 are perhaps even more remarkable than those of M32 but, as we shall see, their interpretation is somewhat more complex. Although the Stratoscope observations (Light, Danielson and Schwarzschild

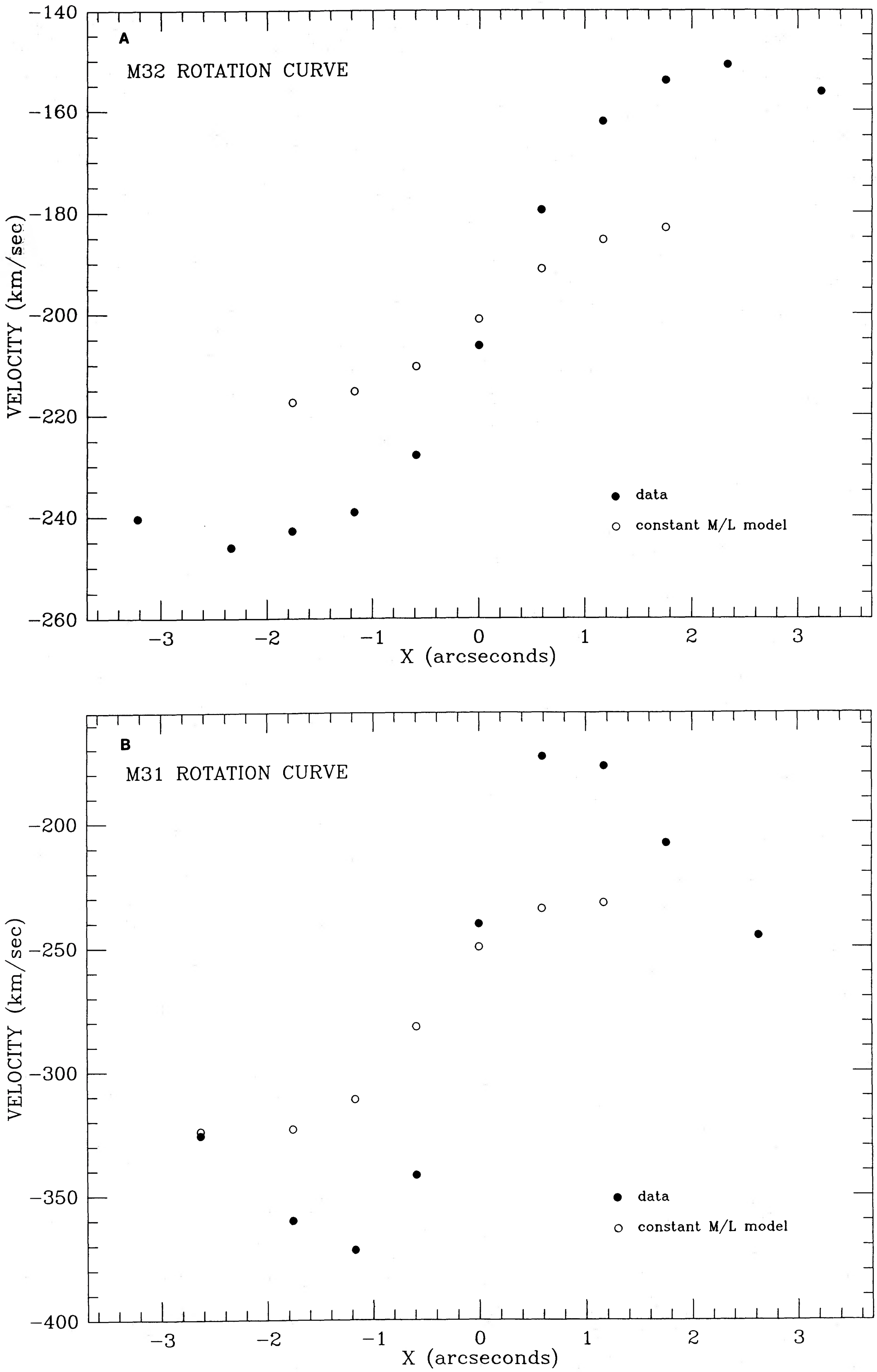

FIG. 3.—Comparison of the data for both M32 and M31 to constant M/L models that roughly fit the dispersion profile and have the maximum possible angular momentum within 1″. The procedure for simulating the "observed" properties of the model is described in the text. It is impossible to model either galaxy at constant M/L and match both the dispersion profile and the nuclear rotation curve.

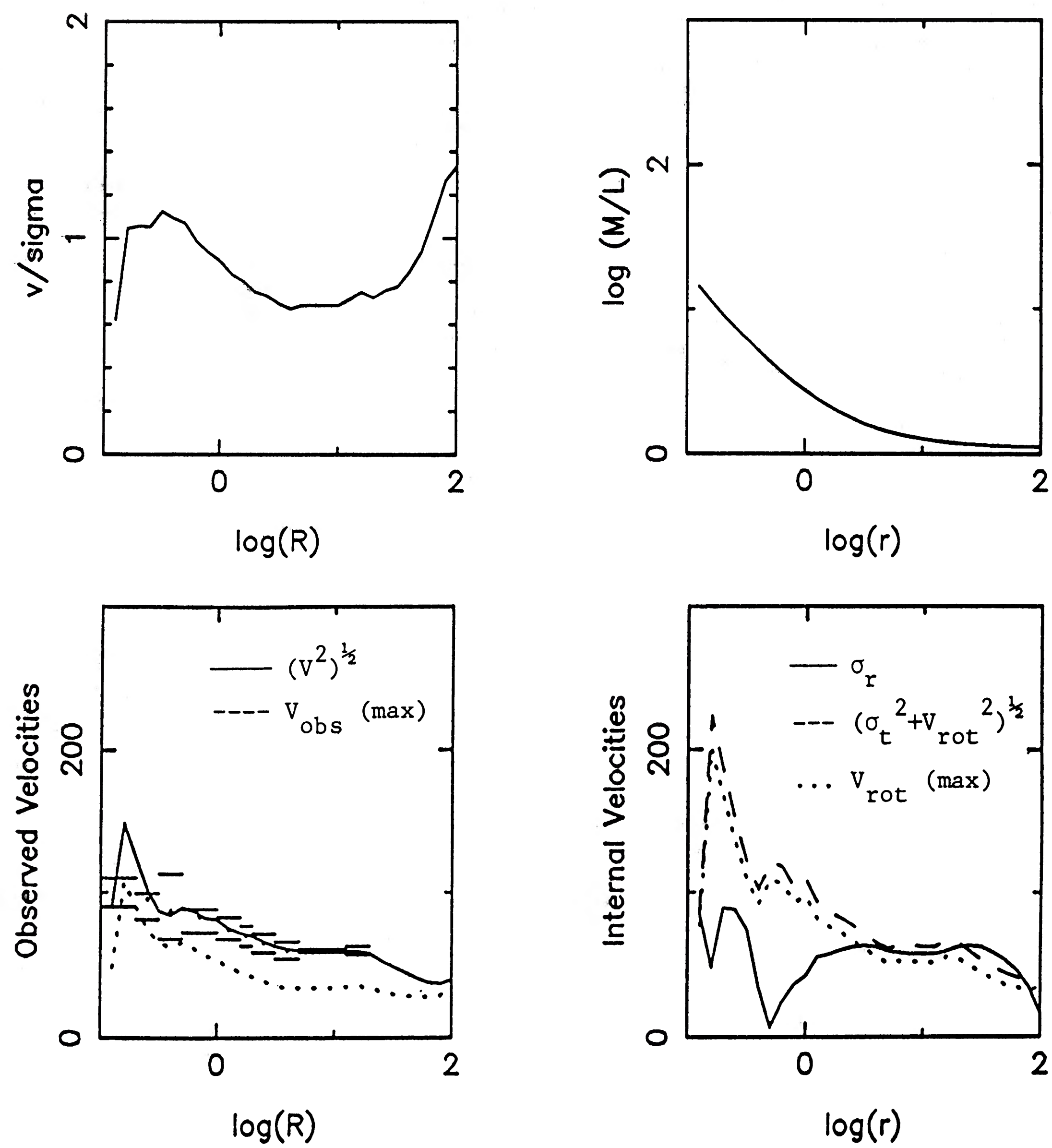

FIG. 4.—Run of parameters for the best fitting model for M32, described in § IIIc. The radial and tangential components of the velocity dispersion are indicated as σ_r and σ_t. The use of the term (max) for the predicted rotational velocities refers to the fact that these are the maximum values allowed. The observed values can always be lower than this if the direction of some fraction of the orbits is reversed. In the upper frames displaying v/σ, v is the rotation velocity that would be observed within finite spatial resolution, while σ is the velocity dispersion that would be observed with infinite resolution. Abscissa in all plots are either projected central distance (R) or true distance to the center (r), in either case the units are arc seconds.

1974) clearly indicate a well-defined separate nucleus, it is not centered with respect to the bulge. In the following analysis, we have adopted a more shallow power law for the radial intensity gradient, $I \propto r^{-0.6}$. This is most appropriate if the nucleus is indeed off-center. We have also performed these calculations with a sharply spiked nucleus centered on the light. The results are qualitatively robust—a large nuclear M/L is required in either case. As in the case of M32, we first tried to match the data with a constant M/L model that achieves a rising σ through an anisotropic velocity field. As with M32, however, we were unable to match the large amplitude of the rotation curve within a few arc seconds (the failure of our constant M/L efforts is documented in Fig. 3). Our best fitting model, whose internal and projected properties are shown in Figure 6, contains a central point mass of $7 \times 10^7 M_\odot$. It is compared to the observational data for M31 in Figure 7.

There is an added complication, however. As mentioned earlier, in each of the M31 data frames the peak of the light distribution and the peak of the velocity dispersion are *separated by one pixel.* There seems little doubt that this is real since signs of it are seen in the D84 data, in Kormendy's (1987) data, and in the companion blue spectra obtained here. The displacement of the kinematic center from the light centroid is shown graphically in Figure 7*c*. We advance four possible explanations for this phenomenon: (1) the true center of the galaxy is marked by the pixel of maximum light, but the kinematics appear to be offset due to a sheet of absorbing material that cuts across the nucleus; (2) the true nucleus is marked by

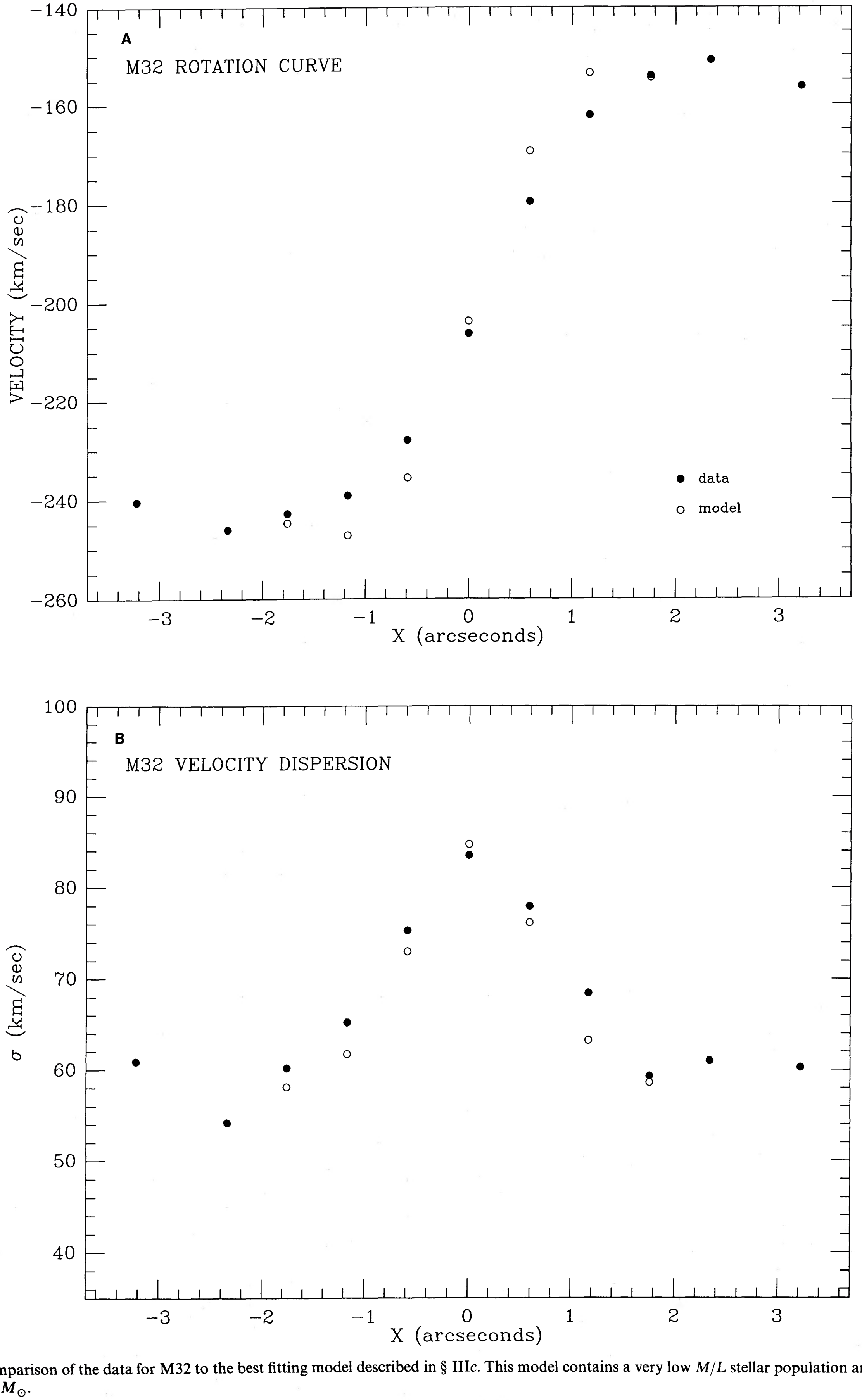

FIG. 5.—Comparison of the data for M32 to the best fitting model described in § IIIc. This model contains a very low M/L stellar population and a central point mass of $8 \times 10^6\ M_\odot$.

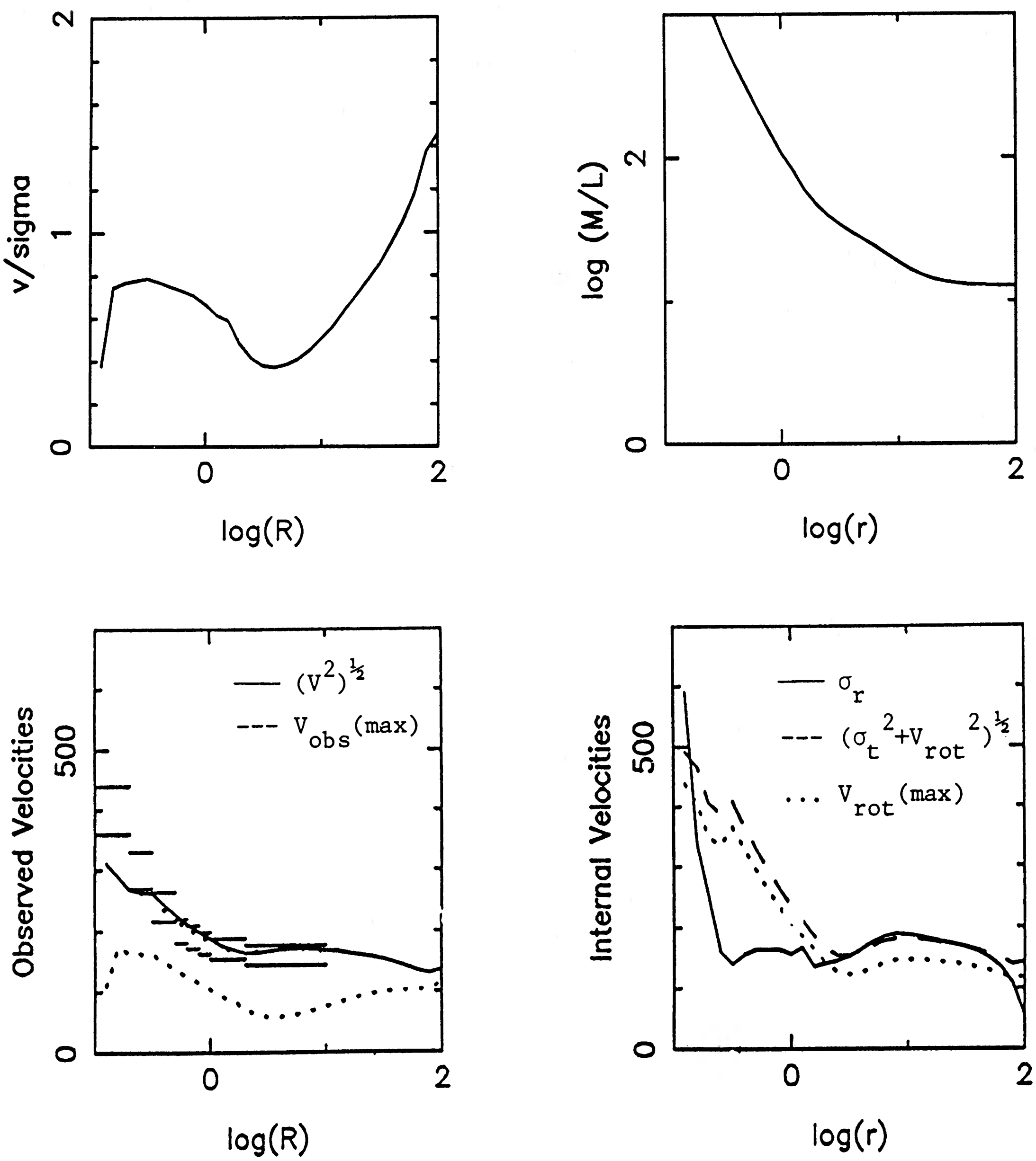

FIG. 6.—Same as Fig. 4 for the best fitting M31 model, described in § III*d*. This model contains a $7 \times 10^7\ M_\odot$ point mass.

the kinematical center, but its light is severely attenuated by a dust cloud covering the nucleus; (3) there is little obscuring dust (at most a few tenths of a magnitude), the kinematical center marks the true center, and a low M/L substructure (like the nucleus of a dwarf galaxy) orbiting the center is responsible for the asymmetry; (4) the asymmetry represents a true dynamical oscillation of the stellar population around the mass center.

To evaluate these possible models we need to cite a few relevant facts. First, the Stratoscope image (in blue light) of the nucleus, which has a resolution of a few tenths of an arc second (Light, Danielson, and Schwarzchild 1974), clearly shows that the nucleus of the galaxy is not centered on isophotes of a few arcseconds radius. Nieto *et al.* (1986) have reached the same conclusion based on new imaging data from a ground-based telescope. This asymmetry in the core of M31 is in the same sense as we have found here, i.e., the kinematics are symmetrical on the centroid of the outer isophotes, but there is additional light ~0".5 to the southeast along the major axis. Second, the color subtraction pictures by Kent (1983) indicate absorbing material at the level of a few tenths of a magnitude in the green. Third, our observations are made at 8500 Å where effects of absorption are less than in the blue, yet we see no difference in the kinematics as a function of wavelength. Fourth, assuming that much of the rise in apparent velocity dispersion is due to a rapid rotation gradient, as it is in M32, the position of the maximum of the velocity dispersion is a sensitive measure of the kinematical center of the galaxy.

The last point seems to rule out possibility (1). While it might be possible to move the apparent center of the rotation curve by a sheet of obscuring material with a steep gradient, this is not effective when the rotation curve itself has a very

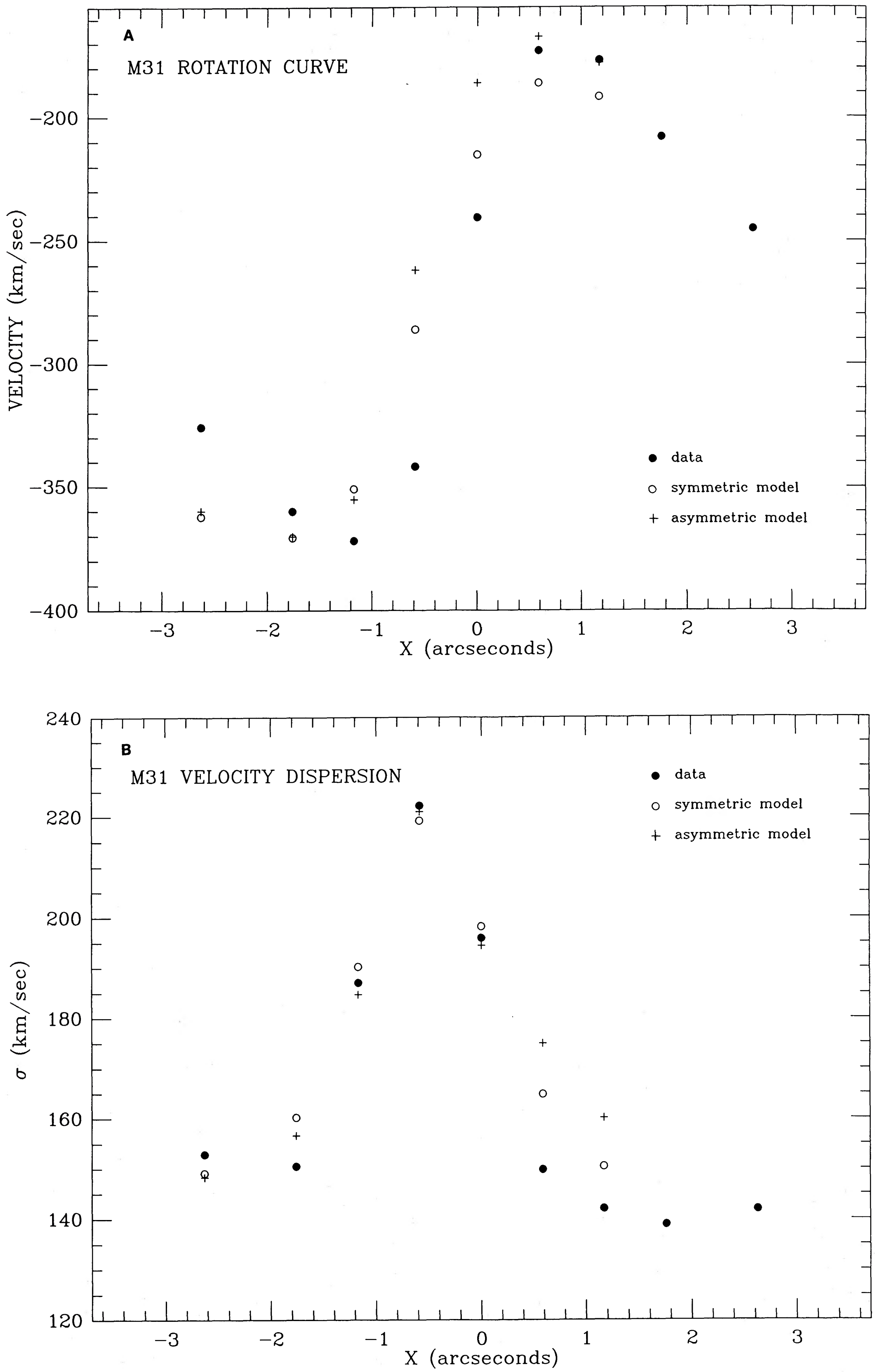

FIG. 7.—Comparison of the data for M31 to the model described in § III*d*. Both the symmetric and asymmetric models are good fits to the rotation curve (7*a*) and velocity dispersion (*b*), but only the asymmetric model fits the intensity profile (*c*). The zero crossing of the rotation curve, marked by the line "V" in (*c*), and maximum of the velocity dispersion, σ, are displaced from the peak intensity, indicated by the line marked "I".

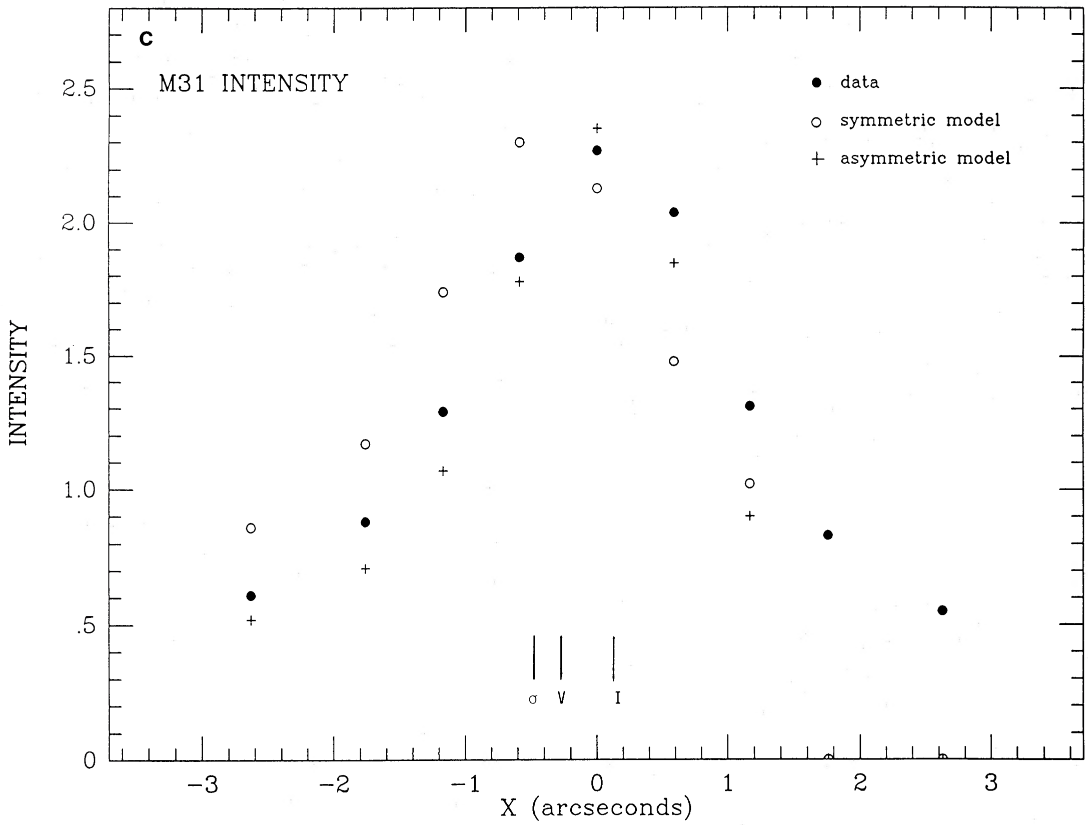

FIG. 7—*Continued*

sharp gradient, as it must in order to give the apparent rise in velocity dispersion. In other words, when convolved with a steep function the centroid of a narrow distribution like a δ-function does not shift as much as would a broad distribution function.

Explanation (2) seems the most straightforward. We have been able to make a model in which the nucleus is half-covered with an absorbing cloud that will displace the apparent light center from the kinematical center by roughly one-half of the seeing profile σ, or 0.″25. By introducing two clouds judiciously placed, the displacement can be brought up to ~0.″5. However, it is not obvious from the data that this is what is going on. The Stratoscope image shows a sharp, apparently unresolved spike. If this were only a shoulder of the light distribution indicative a rise in intensity that is obscured by a central dust cloud, this would imply that the obscured region must have a true intensity ~50% greater than is observed. The implied obscuration would have to be considerable (recall that our observations were made at 8500 Å where the effects of dust are greatly abated), which may be inconsistent with the Kent color data. Nieto *et al.* have similarly concluded that the decentering of the nucleus is not due to dust, which they have mapped in detail. On the other hand, if this occulting dust cloud was very small, it might not have been resolved in these studies. Furthermore, although the Stratoscope image shows smooth symmetrical profiles that suggest dust is not the cause, these images were apparently heavily smoothed due to the low signal-to-noise ratio of the data. It would seem that these three imaging studies constrain models with strongly absorbing dust clouds, but they cannot be considered decisive in ruling them out.

Explanation (3) is also able to account for most the observations. To test this we used the same model of M31 with a central point mass but with a low M/L (one that adds negligibly to the mass of the system compared to the black hole, as would be the case for a typical stellar system) point source added 0.″5 from the kinematical center. This component was assumed to be in corotation with the M31 stellar population, but velocity differences of $\lesssim 50$ km s^{-1} would have little effect. As shown in Figure 7, this model is still able to reproduce the kinematics and can also account for the displacement of the luminosity center from the kinematical center. Although this model is successful, it has two disturbing features. One is that it is not obvious that any garden-variety stellar system would have the required high surface brightness and high luminosity. The only candidate seems to be the nucleus of a galaxy somewhat less luminous than M32, for example. The other problem is that a system of $10^7\ M_\odot$ orbiting at 1.5 pc should have a lifetime of $\lesssim 10^7$ yr before dynamical friction drags it into the nucleus. Thus the likelihood of catching such an event seems rather small. Furthermore, the velocity dispersion of this patch is not lower as one would expect if this were an orbiting galaxy core with the mass of M32 or less.

In explanation (4) we raise the possibility that an event like the accretion of a small galaxy might perturb the system in such a way as to overpopulate an area of phase space available to the stellar orbits. Even if such a process is possible, it would likely be damped in a dynamical time, thus this explanation encounters the same objection as explanation (3). On the other hand, in this case one would not necessarily expect a lower velocity dispersion, so this problem of (3) may not be an issue.

If dust does indeed lower the luminosity of the true center, as suggested in explanation (2), then our modeling of the light profile has been two conservative in the sense that there is roughly a factor of 2 more light associated with the central mass. This would lower our estimate of the mass of the putative black hole accordingly. We thus adopt a range of 3–7 $\times 10^8$ solar masses for the central point mass in M31. The lower figure is the appropriate one to compare with Kormendy's value of 1×10^7 solar masses. His model assumes a disk geometry and thus is expected to give a point mass a factor of 2 smaller.

Perhaps this unique separation of kinematic and luminous centers is not critical to the issue of whether there is a central, massive black hole, as the dynamics alone seem to support. It seems likely that high-resolution HST images will be decisive. In this case, however, we already have the advantage of the Stratascope image which shows a clear miscentering of the nucleus with respect to the outer isophotes.

Finally, we note that Kormendy's model for M31, also supportive of the massive black hole interpretation, identifies the central structure as a disk. Although we cannot specifically argue against this model, we see no data that compel it. We followed Kormendy's procedure of subtracting the outer bulge light in order to isolate the light of the inner structure. However, in our analysis we did not find that the velocity dispersion of the inner structure ($\lesssim 2''$) falls significantly below that of the M31 bulge, as did Kormendy. Whether it falls further beyond 2″ is, we believe, difficult to prove, and in any event offers little support to the idea that the inner structure is really disklike. We note that Kormendy's data, like ours, have $v/\sigma \sim 1$ in the inner region. This is perhaps a slightly higher value than one would expect for a rotationally flattened spheroid of ellipticity E4, but is clearly much lower than the value expected for a disk. Furthermore, we point out that the Stratoscope images give no indication that the isophotes are becoming more elliptical as one approaches the center. Although rotational support is important in our models of the nuclei of both M31 and M32, these are a long way from disk models. We conclude that the data are not conclusive on this point and that, again, this issue is probably not crucial to the interpretation that massive black holes reside in both M31 and M32. As in the case of M32, the unseen mass in M31 could be distributed over a volume of ~ 100 pc^3. But the total mass is nearly 10^8 solar masses, so the density would be nearly 10 times larger.

IV. DISCUSSION

The data and analysis presented above have yielded two key results for both M31 and M32: unlike large elliptical galaxies (or these objects on larger scales) the nuclei rotate very rapidly, and there is strong evidence for a large central mass concentration is each galaxy. Although the universality of these results cannot be demonstrated from our small sample, it is worth noting that these two somewhat unexpected results are now known for all (both) of the objects that can be studied in this way.

Rapid nuclear rotation presents a serious constraint for models of formation of galactic nuclei. For example, the model of nucleus formation by globular cluster accretion (Tremaine, Ostriker, and Spitzer 1975) would be expected to produce rapidly rotating nuclei only if the globular clusters were accreted from a rotating disk population, or if more than one but only a few clusters were accreted. In the second case there is no particular reason that the orientation of the angular momentum of the nucleus should correspond to the system on a larger scale. If nucleus formation proceeds via accretion of reprocessed gas, then we would expect star formation to occur in a gas disk formed when the accreting gas reaches the radius at which it achieves the circular velocity.

Regardless of their detailed geometry and stellar dynamics, the nuclei of these galaxies possess very large mass-to-light ratios. The lack of abrupt color changes in these systems suggests that the object or objects responsible must have a very large M/L, pointing to either an aggregate of collapsed objects or a single massive black hole. In order to discuss a cluster of high M/L objects, we note that we are unable to reproduce the observed dynamics of the nuclei unless these mass concentrations are smaller than $r = 2$ pc. To illustrate, we adopt a total mass of 10^8 solar masses and a median (half-mass) radius $r_h = 1$ pc. For such a system, the mean density inside r_h is $\rho_h = 1.2 \times 10^7\ M_\odot\ \mathrm{pc}^{-3}$, which will result in a large rate of binary production. The half-mass relaxation time (Spitzer and Hart 1971) is

$$t_{\rm rh} = 0.0600\ M^{1/2} r_h^{3/2} G^{-1/2} m^{-1} \log (0.4N)^{-1}\ .$$

Adopting a value of 10 for the logarithmic term, we find

$$t_{\rm rh} = 8.9 \times 10^8\ \mathrm{yr}\ (m/M_\odot)^{-1} (M/10^8\ M_\odot)^{-1/2} (r_h/1\ \mathrm{pc})^{3/2}\ .$$

This suggests that, if a star cluster, the nucleus of M31 (and possibly M32) is at least as old as $10\ t_{\rm rh}$, old enough that core collapse would be expected if a range of stellar mass were present (Cohn 1984). This possibility may not be ruled out, since Cohn's models indicate that core collapse leads to a power-law light distribution probably consistent (depending on the mass spectrum) with M31 or M32. On the other hand, it is by no means clear that a rapidly rotating object would evolve in this fashion. Although we prefer the black hole interpretation, we cannot rule out the possibility that we have observed very dense, high M/L, core-collapsed star clusters. Observations with a spatial resolution of 0″.1 will probably be decisive.

Assuming that this extra mass is a massive black hole in each case, there are two possible implications. The object in M31 is 5–10 times more massive than the one in M32, closer to the ratio of spheroid luminosities (~ 15) than it is to the ratio of total luminosities (~ 70). If this is not an accident, then bright ellipticals might possess black holes as massive as $10^9\ M_\odot$. In any case, while 10^7 or $10^8\ M_\odot$ is sufficiently massive to power a quasar via accretion near the Eddington limit, it is too light for an object that has been a bona fide quasar. For a luminosity of $10^{12}\ L_\odot$ an accretion rate of 100 $M_\odot\ \mathrm{yr}^{-1}$ is required at 10% efficiency (10% of mc^2 must be converted to luminosity). After a lifetime of $\sim 10^8$ yr, the black hole would have accreted 10^9 $M_\odot$, much too large for either of our candidates. They could, of course, have supported a lower level (as typical of Seyfert nuclei) or briefer period of activity without violating this constraint.

We are grateful to Scott Tremaine for helpful remarks and for permission to use material in advance of publication. During part of this work DOR was supported by NSF grant 8311414.

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