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NEW MEASUREMENTS OF STELLAR KINEMATICS IN THE CORE OF M87

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ABSTRACT

We present new, high signal-to-noise ratio spectra of the core of M87. These data confirm Dressler's claim that the velocity dispersion does not continue to rise within $r = 1$ arcsec, but levels off at $\sigma \sim 360$ km s^{-1}. The line strength of the Mg *b* feature falls sharply in the nucleus due to the contribution of a nonthermal spectrum. The central light spike in M87 is completely explained by this non-thermal component, in contradiction to Dressler's (1980) claim that much of the spike is due to a central star cluster.

Maximum entropy models have been constructed to match the new data. They exclude the possibility of a supermassive black hole $M > 4 \times 10^9\ M_{\odot}$ unless a highly contrived model is accepted. A model with *no* supermassive black hole which has a mild anisotropy in the stellar orbits is a good fit to the data, but a model having only slightly greater anisotropy can accommodate a central mass concentration of up to 10^9 $M_{\odot}$.

Subject headings: galaxies: individual (M87) — galaxies: internal motions — galaxies: nuclei

I. INTRODUCTION

M87 (NGC 4486), a giant elliptical galaxy located in the core of the Virgo Cluster, is a prime candidate for an aging quasar: its nucleus is a radio and X-ray source, and from it emanates an optical jet. Such activity is commonly thought to be the result of accretion of stars and gas onto a supermassive black hole, with an average quasar accumulating of order $10^9\ M_{\odot}$ in its central black hole.

Two studies have claimed to find evidence for a supermassive black hole in M87. Young *et al.* (1978) demonstrated that the light distribution of M87 departs from a King model, peaking-up in the central few arcseconds. This shoulder (not to be confused with the unresolved central luminosity spike) is characteristic of a density cusp that would develop if a compact, extremely massive object occupies the very center of the galaxy. The projected density in such a cusp falls as $r^{7/4}$ for a relaxed stellar system around a black hole, or as $r^{3/2}$ for an unrelaxed system in which the black hole grew by adiabatic accretion (Young 1980). Neither of these are steep enough to account for the central spike in M87, but could account for the residual shoulder in the light distribution after the central spike is removed.

Sargent *et al.* (1978) presented kinematic data which also suggested the presence of a central mass concentration in M87. The velocity dispersion rises steadily from $\sigma \sim 300$ km s^{-1} at $r = 10$ arcsec to $\sigma \sim 360$ km s^{-1} at $r = 1$ arcsecond. In Sargent *et al.* it was suggested that both the photometric and kinematic anomalies could be explained by the presence of a 3–5 $\times 10^9$ $M_{\odot}$ black hole.

The supermassive black hole interpretation for M87 has been challenged from two directions. The assumption by Sargent *et al.* that the velocity distribution function in the core of M87 is isotropic has been criticized by Duncan and Wheeler (1980), and later Binney and Mamon (1982), who claimed that models with *constant* mass-to-light ratios (M/L) could be constructed if the distributions were made sufficiently *anisotropic.* Whether these anisotropic distributions are stable has remained controversial.

The other challenge came on the observational side from Dressler (1980). The model presented in Sargent *et al.* predicted a continuing rise in the stellar velocity dispersion within their last measured point, which was at a radius of about 1″.5. However, spectra obtained on a night of subarcsecond seeing at Las Campanas Observatory gave a nuclear velocity dispersion of only $\sigma = 350 \pm 32$ km s^{-1} at an effective radius of $r \sim 0''.3$, a value much lower than the 500 km s^{-1} predicted by the Sargent *et al.* model for a $5 \times 10^9\ M_{\odot}$ black hole. From these data Dressler also concluded that most of the light in the central spike is stellar rather than nonthermal, and thus proposed that a star cluster inhabits the core. Both of these claims have been challenged, most recently by Filippenko (1988), who correctly points out that, because of atmospheric dispersion, the image of the central spike and its underlying stars could not have been centered in the $1'' \times 1''$ aperture over the entire wavelength range 4000 Å $< \lambda <$ 6000 Å.

The purpose of this paper is to present new spectral observations of the core of M87 and to provide new constraints on the mass of a central supermassive black hole by means of maximum entropy modeling of the stellar dynamics.

II. THE DATA

The spectra used in the present study were obtained by Dressler on 1988 March 16 at the du Pont 2.5 m telescope at Las Campanas Observatory. Observations were made with the 200 mm camera of the "Modular Spectrograph," an instrument built by Paul Schechter which makes use of a transmitting collimator and camera. The detector, a TI 800 × 800 pixel array, sampled the wavelength range 4800–5800 Å at 1.30 Å per pixel. With a spatial resolution of 0″.36 per pixel, the slit width of 0″.72 produced a spectral resolution ~3 Å FWHM for a velocity resolution $\sigma \sim 80$ km s^{-1}, well below the velocity dispersion in M87.

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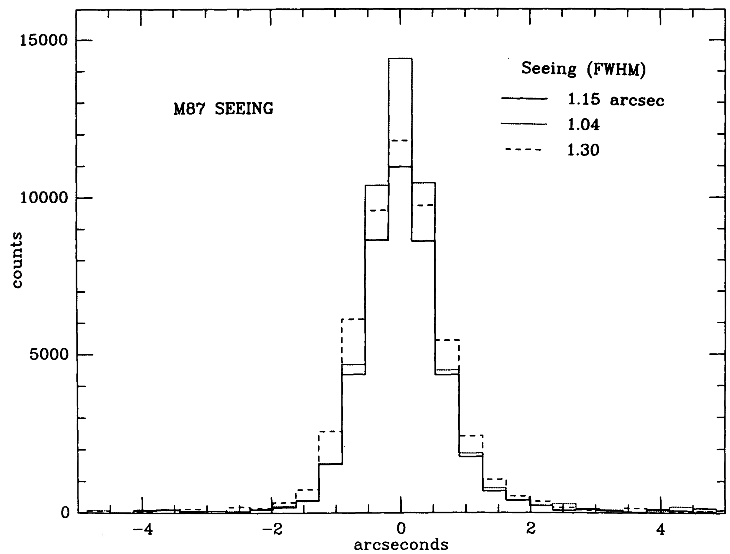

FIG. 1.—The seeing profiles along the slit for the three sets of observations. The best seeing of 1".04 FWHM corresponds to a resolution of $\sigma = 0''.45$.

The mode of operation was crucial. Three sets of observations were taken; for each cycle a nearby star was first placed on the slit and a guided exposure of 200 s was taken to measure the seeing convolved with pointing errors. Reduction of these exposures resulted in the seeing profiles shown in Figure 1 of 1.15, 1.04, and 1.30 arcsec FWHM. The first two sets of observations included two 1000 s exposures of M87; for the final set three 1000 s exposures were taken. During the interval of observation, in which M87 crossed the meridian and the air mass varied from 1.33 to 1.41, the instrument mounting base was rotated through an angle of 45° so that the angle between the chromatic image resulting from atmospheric dispersion and the slit never exceeded 5°. (Using this technique guarantees that light at all colors passes equally well through the slit. The resulting displacement on the detector as a function of color is automatically removed in the centroiding routine that traces the pixel of maximum intensity across the spectral image.) Position angles for the first two sets of observations were 200° and 188°. The final set consisted of two exposures at 170° and one at 155°. A K0 III star was also observed as a spectral standard for use with the Fourier analysis program.

After normal reduction, including bias subtraction and flat-field division, 11 spectra were formed from each observation by binning columns along the slit according to the pattern (16, 8, 4, 2, 1, 1, 1, 2, 4, 8, 16) symmetric across the nucleus. (The outermost spectra are a distance of 8".5 from the nucleus.) The groups of 1000 s exposures were later combined after analysis showed excellent agreement between them. However, the three sets of observations were kept separate, because the position angle across the galaxy is slightly different for each. The signal-to-noise ratio was S/N $\gtrsim$ 30 per angstrom for all 33 spectra.

The present data differ from those used by Dressler (1980) in four important ways. First, use of a long slit allows a continuous sampling of the spectrum. Second, the profile of the seeing has actually been measured. Third, the position angle of the slit has been adjusted to assure that the spatial sampling is independent of wavelength. Fourth, the S/N of the present data is more than a factor of 2 higher than in the earlier study.

III. ANALYSIS

For illustrative purposes, the spectra of all three sets of observations have been co-added to produce Figure 2, which demonstrates the high S/N of the new data. The increase in the strength of emission-lines toward the nucleus is consistent with contamination by a central, unresolved, nonthermal source, although there may be a small contribution from gas associated with the jet. The spectrum of this nonthermal component can be approximated by subtracting the galaxy spectrum at $R = 4''.2$ from the sum of the three central spectra, normalized so as to make the Mg *b* feature disappear. This spectrum, shown in Figure 3, has been used to test the effect of nonthermal contamination on the measurement of velocity dispersion, as discussed below.

Velocity dispersion, line strength, and systemic velocity have been determined by comparing the Fourier transforms of each M87 spectrum with that of a K0 III star, shown in Figure 2. The method is reviewed in Dressler (1984). The Mg *b* region has been chosen in favor of the calcium triplet region, used in our study of M31 and M32 (Dressler and Richstone 1988), due to the higher characteristic velocity dispersion in M87. Because the intrinsic widths of the calcium triplet lines are small, measurement of a high-velocity dispersion ($\gtrsim$300 km s^{-1}) requires high accuracy in determining the continuum level. This is particularly difficult in the calcium triplet region because of the complex spectrum of the night sky. It is obvious that it is also very difficult to measure a velocity dispersion much lower than the intrinsic width of the spectral features; therefore, it follows that features should be chosen whose widths are comparable to the expected dispersion.

The results from the Fourier analysis are shown in Figures 4 and 5. Figures 4*a*, 4*b*, and 4*c* show the individual measurements of the velocity dispersion, systemic velocity, and line strength, respectively, for the three sets of observations. The agreement is very good in all cases. The average values for the combined data are shown in Figure 5, the error estimates coming from intercomparisons of the data in Figure 4.

The principal observational result of this paper is that the velocity dispersion does not rise in the nucleus, but remains flat at a value of ~360 km s^{-1} in the core. The one point that rises significantly above the trend is not in the core and is high in only one of the three measurements; in any event, it is consistent with Gaussian statistical errors. The new data confirm the conclusion of Dressler (1980) that the dispersion does not continue to rise within the core, but the new data have much

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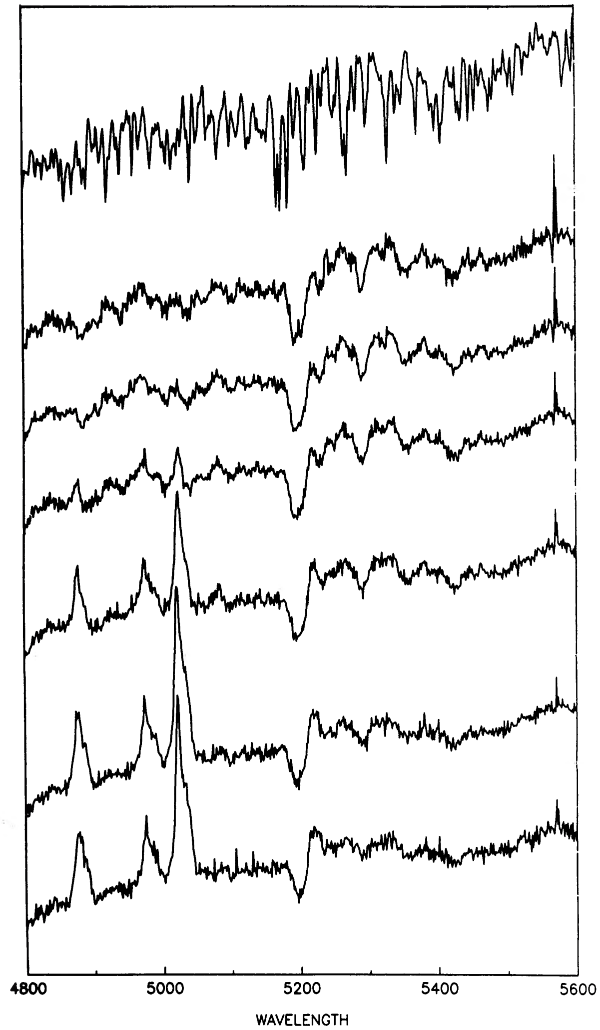

FIG. 2.—Spectra of a K0 III star (*top*) and, starting with the second from the top, spectra of M87 at effective radii of 8.5, 4.2, 2.0, 0.9, 0.4, and 0.1 arcsec from the nucleus. The increasing contamination of the spectra by nonthermal light, as traced by [O III] and Hβ emission, is obvious. The Mg *b* triplet is seen clearly in all spectra, but [N I] λ5200 from the nonthermal component contaminates the red wing.

smaller errors and do not suffer the positional uncertainties that atmospheric dispersion introduced into the previous study. The central three spectra, covering an area 0"72 × 1"08, have a measured dispersion $\sigma = 360 \pm 10$ km s^{-1}. The velocity dispersion falls for $r > 2''$, reaching $\sim$300 km s^{-1} at 10", in agreement with the data of Sargent *et al.*

Laird and Levison (1985) have investigated the coupling between line strength and velocity dispersion measurements with the Fourier technique. They find a small sensitivity that could cause significant error in the measurement of velocity dispersion in extreme cases. We face a related problem in the core of M87. Because the nonthermal component makes a considerable contribution in the central three spectra, it is important to ascertain that this does not prevent accurate measurement of the stellar velocity dispersion. In particular, the presence of emission lines like [N I] λ5200 can artificially raise the continuum level, leading to a measurement of an erroneously high velocity dispersion. (The strong Hβ and [O III] lines are outside the spectral region used for determination of σ.) Different methods of fitting the continuum were adopted, including those which clearly avoided contaminated regions. Little sensitivity was found for the measurement of σ in these tests. A more crucial test, however, was made by forming *synthetic* spectra of known stellar velocity dispersion with an added non thermal component. Model spectra of the stellar component were made by convolving a stellar spectrum with a Gaussian and adding noise to simulate the quality of the data for the M87 core. Spectra were constructed for which the Fourier analysis gave values of σ = 300, 400, 500, and 600 km s^{-1}. These were added to the nonthermal spectrum described above. One such spectrum is shown in Figure 3. Application of the Fourier analysis to these spectra recovered the original velocity dispersions to an accuracy of $\sim$2%, demonstrating that the continuum fitting is not perturbed by the addition of the nonthermal light and that accurate velocity dispersions can be measured for the stellar component. The process was also carried out starting with the spectrum of M87 at R = 4"2 substituted for the stellar template spectrum, with the same result. We conclude that if a high stellar velocity dispersion were present in the core of M87, it could have been measured, despite contamination by nonthermal light.

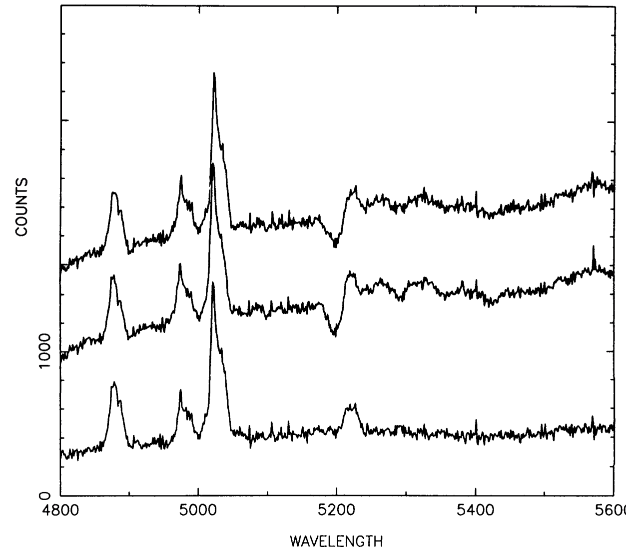

FIG. 3.—The nonthermal component of the nuclear spectrum (*bottom*). This spectrum was obtained by subtracting a renormalized spectrum from r = 4"2 from the spectrum for the central three pixels (*middle*). The top spectrum is a simulation of the nuclear spectrum if the velocity dispersion were 500 km s^{-1}, as described in the text.

The systemic velocity has a noticeable dip reminiscent of the rapid rotation in M31 and M32; however, the full amplitude is only $\sim$60 km s^{-1}, which is negligible in comparison with the velocity dispersion and unimportant for the dynamical modeling discussed below. Again, it is interesting that this feature is mainly driven by just one set of the data (the same one that gave the one high value of σ), suggesting that there is something systematically wrong about these data or that there is a real feature in this region of M87, possibly associated with the jet. (Recall that each data set sampled a different cut across the galaxy due to the rotation of the position angle of observation.)

The line strength has a strong dip that is clearly due to dilution by light from a nonthermal (or lineless thermal) component. Dressler (1980) estimated the dilution by a nonthermal component at less than 20% at the Na D lines, and concluded

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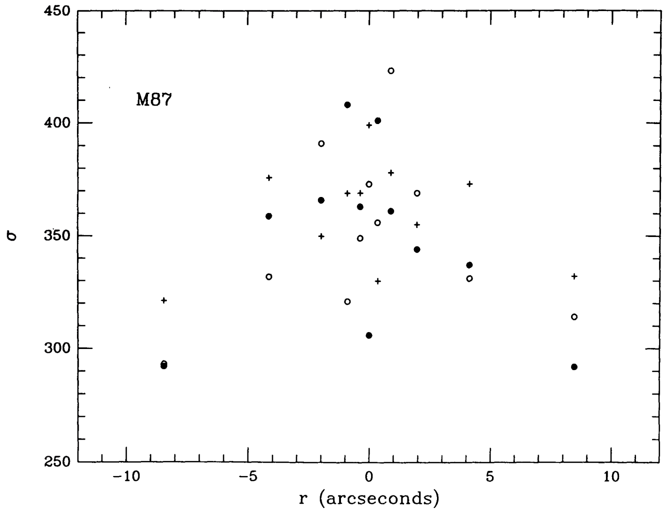

FIG. 4a

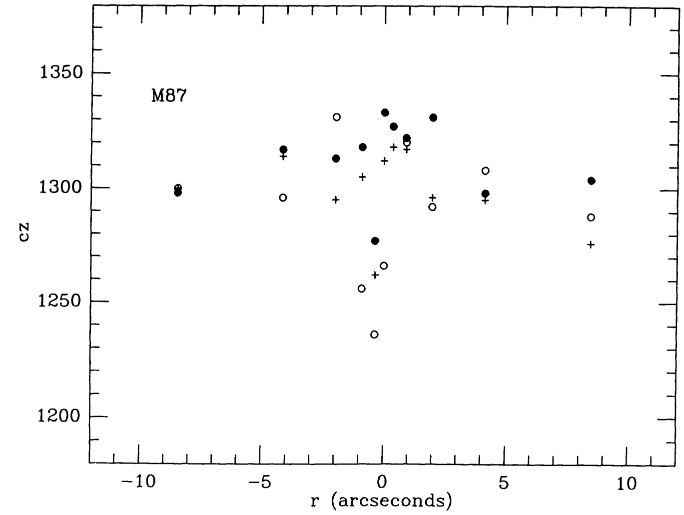

FIG. 4b

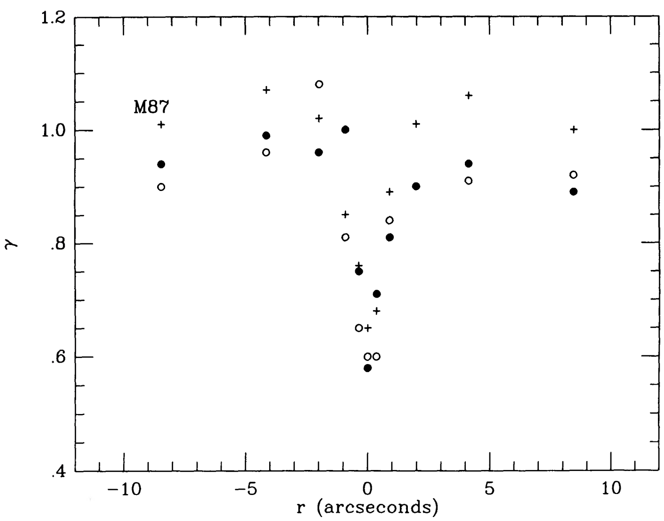

FIG. 4c

FIG. 4.—(*a*) The run of velocity dispersion with radius, as measured with the Fourier technique, for each of the three data sets. (*b*) The run of systemic velocity cz. (*c*) The run of line strength γ. The figure shows the good agreement of the three sets of observations.

that much of the central light spike arises from a central star cluster. However, the present data do not support this interpretation. We demonstrate this in Figure 6 in which we show intensity profiles of continuum light along the slit for the two sets of observations with the best seeing. An apparently unresolved, central light spike is clearly visible. Attributing the drop in line strength to dilution by a nonthermal component results in the shaded region in Figure 6. If unresolved, this nonthermal component would account for $\sim 30\%$ of the light within the $1'' \times 1''$ aperture used by Dressler (1980). The remaining light profile does not peak in the center; therefore, we conclude that there is no evidence for a central star cluster.

Kormendy (1988) has also obtained high spatial resolution spectra of M87 with the CFHT. With his lower S/N spectra he has not attempted to measure kinematics, but he comes to the same conclusion regarding the nonthermal nature of the central spike.

IV. DYNAMICAL MODELING

As pointed out in Dressler and Richstone (1988), a cogent case for the presence of a supermassive black hole requires demonstration of the failure of all reasonable dynamical models with constant M/L. As in that earlier paper, we will exploit the approach developed by Richstone and Tremaine

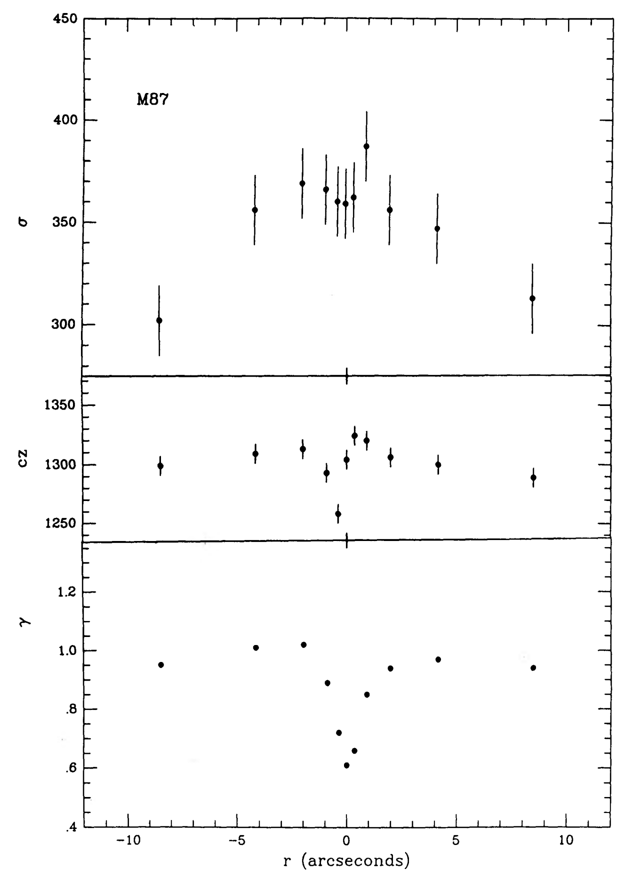

FIG. 5.—Same as Fig. 4, but the average for the three data sets. The velocity dispersion σ does not rise within the inner 2″ but remains constant at ~ 360 km s^{-1}, and the rotation velocity is small. Dilution by nonthermal light is indicated by the drop in γ for $r < 2''$.

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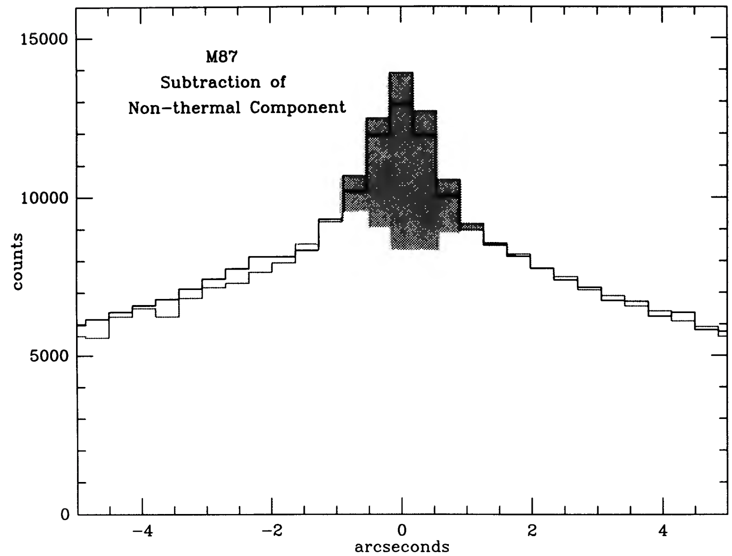

FIG. 6.—Profiles of M87 light entering the slit of the spectrograph for the two exposures of best seeing. The shaded area is that contributed by nonthermal light, as judged by the line-strength parameter γ.

(1988) for modeling stellar dynamical systems, which uses a linear programming technique originally devised by Schwarzschild. In this method, a galaxy is assembled from a library of stellar orbits under a "maximum entropy" constraint in order to reproduce the kinematic data while simultaneously matching the density distribution, which is derived from the luminosity profile assuming some function $M/L = f(r)$. For each solution a distribution function of the stellar energy and angular momentum is determined. The predictions are given in discrete radial velocity bins, less appealing aesthetically than continuous functions, but more practical because the sampling of data and models can be matched exactly. A complete description of the method is given by Richstone and Tremaine (1984, 1985), including a comparison with another complementary approach by Newton and Binney (1984).

In their 1985 paper, Richstone and Tremaine concluded, in agreement with earlier studies, that a constant M/L model for M87 was consistent with the then-available data. From inspection of the distribution function for their constant M/L model, it is clear that this model is not highly contrived. Merritt (1987) has questioned the stability of the Newton and Binney (1984) model, but the Richstone-Tremaine model should be more stable against barlike instabilities because it is not nearly so anisotropic.

The new data allow us to place tighter constraints on the mass of a putative black hole. The results of the modeling are presented in Figure 7, where we show both the run of the internal kinematic parameters—the second moments of the radial and tangential velocity distributions, and the "observables"—the luminosity-weighted projections of velocity dispersion and rotation velocity. The rotation curves represent the maximum amount of rotation permitted, as would result if the angular momenta of all orbits are aligned. The actual rotation can be far less than this, as would be expected in models that are not very anisotropic where the orbits are randomly aligned, for example.

The first point to make is that a rather simple, constant M/L model, with no central black hole, matches the data, as seen in Figure 7*a*. The model is mildly anisotropic: the radial dispersion is about 20% larger than the tangential dispersion in the region $1'' < r < 10''$. Inasmuch as there is nothing pathological or nonphysical about this model, we conclude that a central black hole is not *required* by the available data.

On the other hand, the data do not rule out a supermassive black hole as large as $10^9\ M_\odot$ because, as shown in Figure 7*b*, the observed velocity dispersion would not rise appreciably within $1''$. In this particular model, the tangential dispersion exceeds the radial dispersion for $r < 1''$ (a crossover occurs at $r \approx 1''$), so if the angular momenta of the orbits were aligned, there would be a detectable rotation of about $V \approx 100$ km s^{-1}. However, the model is not very anisotropic, so random misalignment of the orbits is reasonable.

In contrast, Figure 7*c* shows that concealing a $3.6 \times 10^9\ M_\odot$ black hole requires a tangential dispersion more than twice as large as the radial dispersion. These more circular orbits would have to have randomly oriented angular momentum vectors, so that their angular momenta cancel, otherwise there would be a significant rotation $V \sim 130$ km s^{-1}, completely incompatible with the observations. For masses greater than this the situation becomes rapidly worse; for $M > 5 \times 10^9\ M_\odot$ the velocity dispersion measurements alone are sufficient to reject the model. (We note that a modest rise in velocity dispersion well within $r = 1''$, as is seen in Figure 7*c*, would be unobservable with the seeing $\sim 1''$ FWHM available for the data presented here.) A supermassive black hole of 3–5 $\times\ 10^9\ M_\odot$, proposed by Sargent, Young, and collaborators to account for the departures of the luminosity profile from a King law and the rise in the velocity dispersion, seems most unlikely.

Each of these three models is anisotropic to some degree. This raises the question of whether a truly isotropic model can fit the new data. In a sense, this is a return to the original attempt by Sargent *et al.* to make an isotropic model which has a rise in velocity dispersion in the region $1'' < r < 10''$, well within the large core radius of $r \approx 10''$. Sargent *et al.* were able to do so by invoking a very large central mass, which we believe we have now effectively ruled out. However, it is interesting to ask if *any* isotropic distribution of stellar orbits can simultaneously match the luminosity profile and the rise in

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velocity dispersion in the intermediate region. We have constructed a model with less than 5% anisotropy at radii less than 20″. This model has a mass distribution somewhat more concentrated than its light distribution—its M/L declines from ~ 100 at the center to ~ 5 at $r = 30''$. This alternative model could be tested by observations of the stellar population; for example, a test designed to measure the giant/dwarf ratio as a function of radius.

V. CONCLUSIONS

In summary, we find (1) a rising velocity dispersion in the core that levels out within 1″; (2) no significant rotation; (3) a central spike dominated by nonthermal light. No black hole is required to match these observations, but a black hole of $M < 10^9\ M_\odot$ can be fitted in rather comfortably. To rule out masses less than this requires significantly higher resolution. Although we have found an acceptable model with a $3 \times 10^9\ M_\odot$ black hole which matches the data, the model is contrived in the sense that the central stars are on nearly circular orbits which run in opposite directions. It is possible that an accreting mass could hide itself by tangentially biasing an initially isotropic velocity distribution, as discussed by Goodman and Binney (1984). The detailed question of whether that has happened in this case is beyond the scope of this paper.

A substantial improvement in the upper limit on a black hole mass would require better spatial resolution, as will be available with the *Hubble Space Telescope*. However, even with such measurements the prospects of reducing the limit to $10^8\ M_\odot$ are not good, because of the following: The intrinsic stellar dispersion in M87 is very high; therefore, the radius at which the gravitational field of a black hole would dominate the kinematics is smaller than it would be in a galaxy with a more modest velocity dispersion. Furthermore, the large core radius of M87 means that the light distribution is flat within the central regions, so the light from the very center is strongly diluted by contributions from stars along the line of sight. Unless M87 contains a hitherto unknown "core within a core" structure, detection of a relatively small black hole ($\lesssim 10^8\ M_\odot$) will be difficult. These less massive black holes should be more easily found in systems like M31 and M32, not only because the proximity of these galaxies has allowed us to achieve higher spatial resolution (a problem that can be overcome with space-based observations), but also because they have lower velocity dispersions and smaller core radii than very luminous galaxies like M87.

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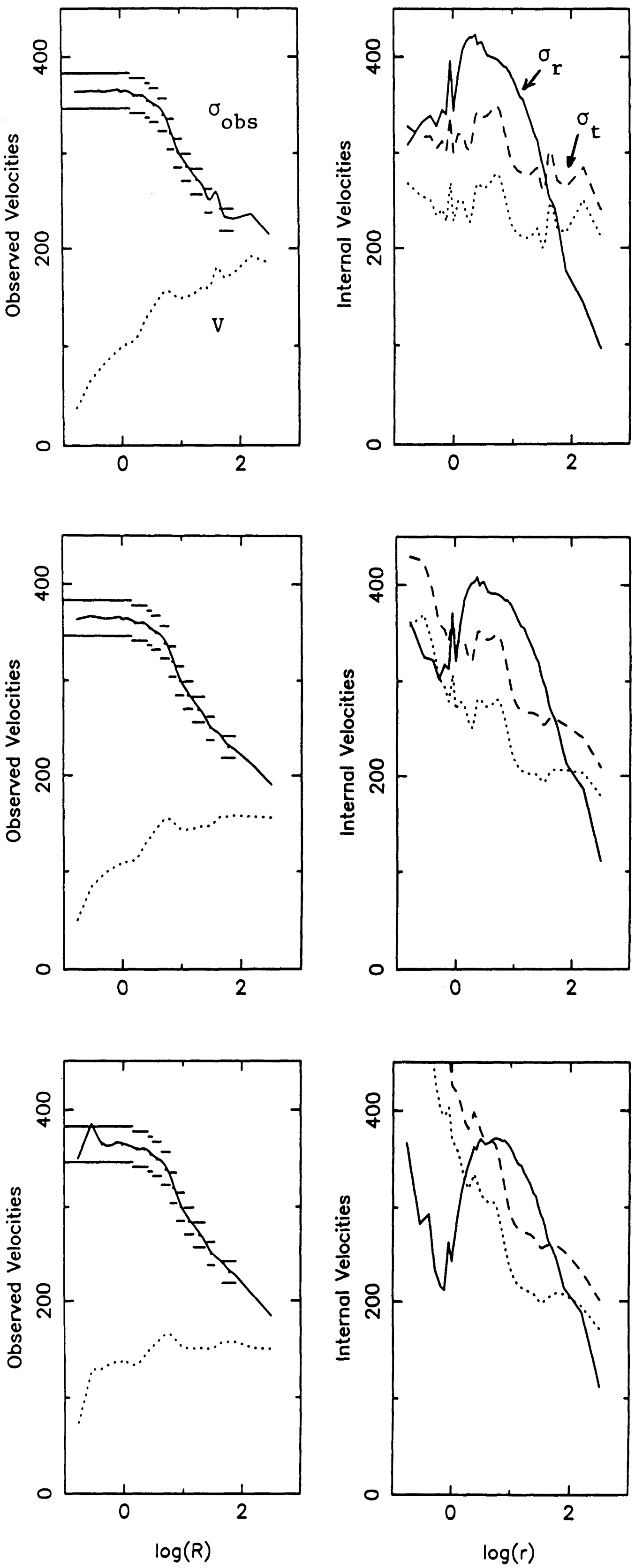

FIG. 7.—Dynamical "maximum entropy" models of M87. The right-hand plots show the model kinematic parameters; σ_r and σ_t are the second moments of the velocity distributions for the radial and tangential components, $\sigma_{t,r} = (V_{t,r}^2)^{1/2}$. The left-hand plots show projected "observables": Predicted σ is compared with the data (*horizontal bars*); V is the maximum rotation possible if the angular momenta of all orbits are aligned. The top panel is a mildly anisotropic, constant M/L model without a massive black hole, which is an acceptable fit to the data. The middle panel shows a model which includes a black hole of $10^9\ M_\odot$, which is a bit more anisotropic but is also an acceptable fit. The bottom panel shows a model with a $3.6 \times 10^9\ M_\odot$ black hole which is very anisotropic and predicts a high rotation rate. Unless the angular momenta of the stellar orbits are arranged to cancel so as to hide the rapid rotation, a somewhat contrived model, such large black hole masses are ruled out.

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