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ON THE STELLAR KINEMATICAL EVIDENCE FOR MASSIVE BLACK HOLES IN GALACTIC NUCLEI EXPECTED WITH THE *HUBBLE SPACE TELESCOPE*

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ABSTRACT

The central line-of-sight velocity distribution, or *velocity profile* (VP), of a stellar system with a massive central black hole has more extended wings than a Gaussian. The importance of these wings is studied for the high spatial resolution absorption-line spectra that are now being obtained with the *Hubble Space Telescope* (*HST*). As an example, the central VP is calculated for an isotropic dynamical model for M87 with a 5×10^9 $M_\odot$ black hole, for observations through a small circular aperture of diameter D. Conventional techniques for the analysis of galaxy spectra that assume Gaussian VPs strongly underestimate the true velocity dispersion (for $D = 0\farcs1$, by more than a factor of 2!). At *HST* resolution it is thus essential to model VP deviations from a Gaussian. An actual VP shape measurement will strongly constrain any dynamical model, but might be difficult to obtain in practice.

Subject headings: black hole physics — galaxies: individual (M87) — galaxies: kinematics and dynamics — line: profiles

1. INTRODUCTION

Massive black holes are believed to be common in the nuclei of galaxies. In an otherwise normal galaxy, a black hole reveals its presence through two effects: it induces a central power-law cusp in the stellar mass density and it causes the rms motion of the stars to increase toward the center proportional to $r^{-1/2}$ (Bahcall & Wolf 1976; Young 1980). The *Hubble Space Telescope* (*HST*) has detected central surface brightness cusps in many galaxies (e.g., Crane et al. 1993). This is consistent with, but does not necessarily imply, the presence of black holes (Kormendy 1994). In general, kinematical data are also required. Black holes have been invoked to interpret ground-based kinematical data for a number of nearby galaxies, but alternative models have not yet been completely ruled out. The spectra that are now being obtained with the repaired *HST* should provide a major step forward. For observations of a (nonrotating) galaxy with a massive black hole through a small centered aperture of diameter D, the stellar velocity dispersion σ_0 satisfies $\sigma_0^2 \approx c_1 + c_2/D$, where c_1 and c_2 depend on the structure of the system and on the black hole mass (Bahcall & Wolf 1976; Tremaine et al. 1994; Fig. 3 below). The central dispersion should thus be significantly larger at the high spatial resolution of *HST* than at ground-based spatial resolution.

Conventional techniques for the analysis of galaxy spectra (e.g., the Fourier quotient technique; Sargent et al. 1977) assume the line-of-sight velocity distributions of the stars, or *velocity profiles* (VPs), to be Gaussian. However, there is no theoretical reason why this should be so. It is thus important that models take into account possible deviations from Gaussian VPs (Kormendy 1988a; Dressler & Richstone 1988). A recent improvement has been the advent of data analysis techniques that allow information on the actual VP shape to be recovered from the data (e.g., Bender 1990; Rix & White 1992; van der Marel & Franx 1993). With these techniques new constraints can be obtained on the dynamical structure of galaxies with suspected black holes (van der Marel et al. 1994a, b).

This letter discusses the importance of VPs for the detection of massive black holes in galactic nuclei with *HST*. In a seminal paper, Bahcall & Wolf (1976) have already emphasized that globular clusters with a massive black hole should have strongly non-Gaussian VPs when observed at high spatial resolution. The discussion here is based on calculations for the galaxy M87, although the main results are valid also for other galaxies. It is a prime example where *HST* observations might finally settle a long-lasting debate: even the highest spatial resolution ground-based M87 absorption-line spectra (van der Marel 1994, hereafter vdM94) can be interpreted equally well with isotropic models with a black hole (Sargent et al. 1978) as with radially anisotropic models without a black hole (Binney & Mamon 1982).

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2. VELOCITY PROFILE CALCULATIONS

We use the parameterization for the M87 surface brightness given in vdM94. It has $I \propto R^{-0.26}$ at small radii, $I \propto R^{-2.23}$ at large radii, and fits the *HST* photometry of Lauer et al. (1992), as well as ground-based photometry out to $\sim 3'$, with a rms residual of only 0.01 mag arcsec^{-2}. We assume M87 to be spherical, not unreasonable given the observed low ellipticity $\epsilon \lesssim 0.1$, and calculate the three-dimensional luminosity density using the well-known Abel integral for spherical systems. With a constant mass-to-light ratio Υ for the stellar population this yields the three-dimensional mass density ρ. The associated gravitational potential is calculated, and the total potential Φ is obtained by adding the contribution of a possible black hole.

We restrict ourselves to isotropic models. The phase space distribution function of the stars is then determined uniquely by Eddington's formula. At any radius r in the galaxy the local (i.e., unprojected) distribution of stars over line-of-sight velocities v_z can be related directly to ρ and $\Psi \equiv -\Phi$, according to (vdM94)

$$\mathscr{L}_{\rm loc}(v_z; r) = \frac{1}{\rho(r)\pi\sqrt{2}} \times \int_0^{\Psi(r)-v_z^2/2} \left[\frac{d\rho}{d\Psi}\right]_{\Psi'} \frac{d\Psi'}{\sqrt{\Psi(r) - v_z^2/2 - \Psi'}} . \quad (1)$$

The normalized VP as observed through a centered aperture of diameter D is

$$\mathscr{L}_A(v_z;\, D) \equiv \int_0^{r_{\max}(v_z)} 4\pi r^2 \rho(r) \mathscr{S}(D/2r) \mathscr{L}_{\rm loc}(v_z;\, r)dr \Bigg/ \int_0^{\infty} 4\pi r^2 \rho(r) \mathscr{S}(D/2r)dr \,, \quad (2)$$

where $r_{\max}(v_z)$ satisfies $\Psi(r_{\max}) \equiv \frac{1}{2}v_z^2$, and $\mathscr{S}(x) \equiv 1 - \sqrt{\max\,(0,\, 1 - x^2)}$. In our nonrotating models the VPs are always symmetric, $\mathscr{L}(v_z) = \mathscr{L}(-v_z)$.

When there is a central black hole, the VP extends to infinitely large velocities. The stars observed at $|v_z| \to \infty$ are asymptotically close to the hole, where $\rho(r) \propto r^{-\delta}$ with $\delta = 1.26$, $\Psi(r) \approx GM_{\rm BH}/r$, and $M_{\rm BH}$ is the mass of the black hole. Equation (1) then yields

$$\rho(r)\mathscr{L}_{\rm loc}(v_z;\, r) \propto \left(\frac{GM_{\rm BH}}{r} - \frac{v_z^2}{2}\right)^{\delta - 1/2} . \quad (3)$$

With $r_{\max}(v_z) = 2GM_{\rm BH}/v_z^2 < D/2$ (for $|v_z| \to \infty$), equation (2) yields

$$\mathscr{L}_A(v_z;\, D) \propto v_z^{-7+2\delta} \quad (M_{\rm BH} \neq 0,\, |v_z| \to \infty) \,, \quad (4)$$

independent of the diameter size D. The wings of the central VP thus fall off as a power law, i.e., more slowly than the exponential wings of a Gaussian (see also Bahcall & Wolf 1976). This is also true for anisotropic models with a central black hole.

We choose the two free parameters of the model to be $M_{\rm BH} = 5 \times 10^9\, M_\odot$ and $\Upsilon = 3.9$ (in I-band solar units). Near the center, the model then provides a reasonable fit to the ground-based velocity dispersions reported in vdM94 (see Fig. 1).

3. APPLICATIONS

Figure 2 shows the predicted VPs for different values of the aperture diameter D. For each VP we determined a number of characteristic quantities, displayed in Figure 3. First, the true velocity dispersion σ_0. Second, the parameters γ and σ of the best-fitting Gaussian to the VP, and the Gauss-Hermite moments h_4 and h_6 that measure the lowest-order deviations of the VP from a Gaussian (van der Marel & Franx 1993). Third, we convolve the VP with the stellar template spectrum used in vdM94, and analyze the resulting "model galaxy spectrum" with the technique of vdM94. It fits a Gaussian VP to the data in pixel space to yield estimates $\hat{\gamma}$ and $\hat{\sigma}$ of the quantities γ and σ defined above, and subsequently fits a Gauss-Hermite series to obtain estimates $\hat{h}_4$ and $\hat{h}_6$ of h_4 and h_6.

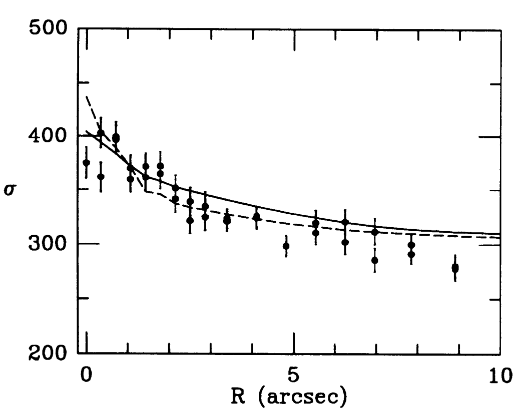

FIG. 1.—Comparison of observed velocity dispersions for M87, obtained by fitting Gaussian VPs to subarcsecond resolution ground-based spectra (vdM94), to predictions of the isotropic model with a $5 \times 10^9\, M_\odot$ black hole described in the text. *Solid curve*: dispersions of the best-fitting Gaussians to the VPs predicted by the model. *Dashed curve*: predicted true velocity dispersions. The curves differ because the predicted VPs are slightly non-Gaussian. Both curves take into account the seeing, slit width, and pixel size for the observations.

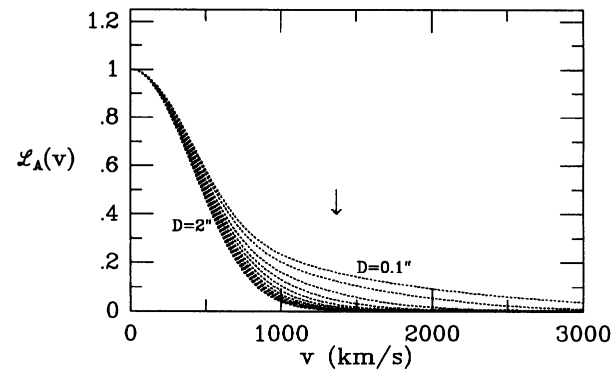

FIG. 2.—Predicted VP shapes for the model described in the text, for observations through a circular aperture of diameter $D = 0\farcs1, 0\farcs2, 0\farcs4, 0\farcs6, \ldots, 2''$, respectively. The VPs are symmetric and only the positive-velocity part is shown. The VPs are all normalized to an amplitude of 1. The arrow indicates the central escape speed due to the gravitational potential of the stars. If there were no black hole in the model, no stars would be observed beyond this velocity.

As D is decreased, the wings of the VP become more extended and the VP deviates more from a Gaussian. This is expressed by the increasingly nonzero values of h_4 and h_6. As expected, the true velocity dispersion varies roughly as $\sigma_0^2 \approx c_1 + c_2/D$, where c_1 and c_2 are constants. For $D = 0\farcs1$ it is as high as $\sigma_0 = 1331$ km s^{-1}. However, the FWHM of the VP increases only relatively little (Fig. 2). A Gaussian VP fit is rather insensitive to the wings, and underestimates both the true velocity dispersion and the true line strength (assumed here to be $\gamma_0 \equiv 1$). For $D = 0\farcs1$ a Gaussian fit yields $\gamma = 0.82$ and $\sigma = 606$ km s^{-1}, more than a factor of 2 smaller than the true velocity dispersion!

The estimates obtained by analyzing the model galaxy spectrum are even worse. For $D = 0\farcs1$ (see Fig. 4) one obtains $\hat{\gamma} = 0.67$ and $\hat{\sigma} = 509$ km s^{-1}. The signatures in the Gauss-Hermite moments are relatively small, $\hat{h}_4 = 0.073$ and $\hat{h}_6 = -0.006$. These values deviate from the quantities (γ, σ, h_4, h_6) obtained by analyzing the VP directly, because the continuum subtraction in the analysis of spectra causes low Fourier frequencies to receive little weight, as illustrated in Figure 5 (see also Kormendy 1988b).

4. DISCUSSION

If M87 has a massive black hole, Gaussian VP fits to *HST* absorption-line spectra should reveal two signatures: a modest increase in the inferred velocity dispersion with respect to ground-based values, and a decrease in the inferred line strength. A substantial theoretical effort, including the construction of distribution functions and the calculation of VPs, is required to accurately estimate the black hole mass from such observations. If the inferred velocity dispersion is incorrectly interpreted as an estimate of the true velocity dispersion, the black hole mass will be significantly underestimated. It

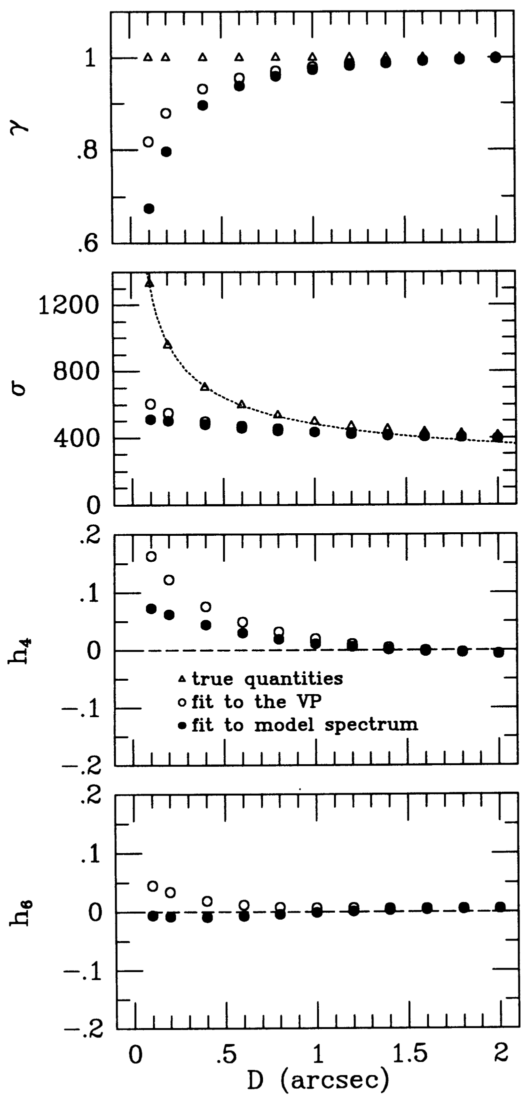

FIG. 3.—Characteristic quantities of the VPs displayed in Fig. 2, as functions of the aperture diameter D. Open triangles denote the true line strength ($\equiv 1$) and velocity dispersion; open circles are obtained by fitting a Gaussian to the VP and calculating the Gauss-Hermite moments using the definition given in van der Marel & Franx (1993); solid circles are obtained by analyzing a model galaxy spectrum, obtained by convolving the VP and a stellar template spectrum. The dotted curve shows a fit of the form $\sigma_0^2 = c_1 + c_2/D$ to the true velocity dispersions.

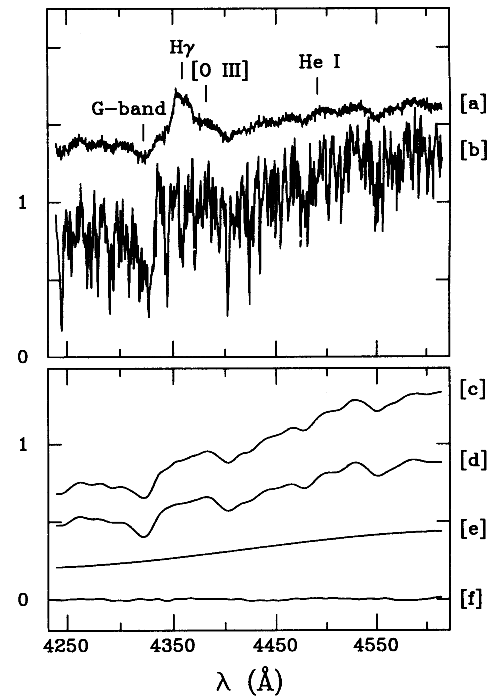

FIG. 4.—Top panel shows normalized ground-based blue spectra from vdM94, of [*a*] the M87 center; and [*b*] a stellar template, shifted to the systemic velocity of M87. The M87 spectrum is offset vertically by 0.5. It has a contribution from nonthermal continuum and shows several emission lines. The most prominent absorption feature in this spectral region is the G band. Spectrum [*c*] in the bottom panel is the convolution of the template spectrum with the $D = 0\farcs1$ VP from Fig. 2. The true velocity dispersion and line strength are both underestimated when this spectrum is modeled as the sum of a low-order polynomial [*e*] and the convolution of the template with a Gaussian [*d*]. The residual [f] = [c] − [d] − [e] is close to zero, yet still indicates that $h_4 > 0$ (cf. Fig. 3). High S/N is required to measure this.

should be possible to disentangle the effect on the line strength from the influence of the nonthermal continuum from the nucleus of M87 (as in vdM94), but the possible presence of intrinsic metallicity and line strength gradients might be a problem.

The ambiguity in the interpretation of Gaussian VP fits can be strongly reduced if an actual measurement of the VP shape is possible. The main difficulty is that the broad wings due to a massive black hole are easily confused with an enhanced continuum level (Fig. 4), or equivalently, that low-frequency information is lost due to continuum subtraction (Fig. 5). This is a problem inherent to all existing techniques, even when they do not use an explicit low-frequency cutoff (such as the Fourier quotient technique). Avoiding continuum subtraction by actually modeling the galaxy's continuum is extremely complicated, as it requires a complete stellar population synthesis. On the other hand, Figure 3 shows that for small apertures one expects to detect $h_4 > 0$, even with the usual continuum subtraction. Any VP analysis requires a high signal-to-noise ratio (S/N $\gtrsim$ 30 per Å; e.g., Rix & White 1992), and hence long integration times (for $D = 0\farcs25$ already $\gtrsim$10 hours for *HST* FOS observations of the M87 center).

Radially anisotropic models without a central black hole can predict high central velocity dispersions (vdM94). However,

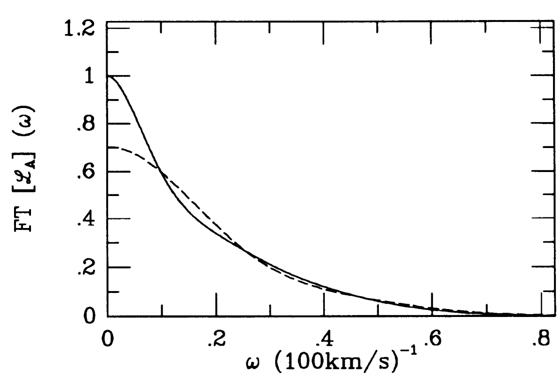

FIG. 5.—Solid curve is the Fourier transform of the VP for $D = 0\farcs1$. The dashed curve is the Fourier transform of the Gauss-Hermite series with the parameters ($\hat{\gamma}$, $\hat{\sigma}$, $\hat{h}_4$, $\hat{h}_6$) determined by analyzing the convolution of the VP and a stellar template spectrum. At low frequencies the fit is very poor because of the continuum subtraction involved in the analysis.

such models can never predict very extensive VP wings, because all observed stars must have velocities $|v_z| \leq v_{esc}(r = 0) = \sqrt{2\Psi(0)}$. Our isotropic model for M87 (without the central black hole) has $v_{esc}(r = 0) = 1365$ km s^{-1}. This quantity is smaller for radially anisotropic models, because these must have a smaller mass-to-light ratio to fit the same kinematical data. Figure 2 thus shows the importance of the VP wings in searching for stellar kinematical evidence for the presence of a black hole.

These results for M87 are valid more generally for any galactic nucleus with a massive black hole, though the details will be different. The importance of the VP wings increases with increasing black hole mass, with decreasing aperture size (Fig. 2) and with increasing cusp steepness δ (eq. [4]). Note in this respect that M87 has only a relatively shallow cusp as compared to many other elliptical galaxies (Kormendy et al. 1994; Jaffe et al. 1994; Ferrarese et al. 1994).

Our M87 models can be scaled down in mass. This decreases the velocity dispersions, but does not change the VP shapes. Gaussian VPs will still provide bad fits. However, the influence of continuum subtraction will be smaller, because the VPs are broader in Fourier space. So in this sense low velocity dispersion systems such as M32 (which has $\sigma \approx 50$ km s^{-1}) are better suited for VP studies than high-dispersion systems such as M87.

HST will not only observe nonrotating galaxies such as M87, but also rapidly rotating systems such as M31, M32, NGC 3115, and NGC 4594. Measurement of the rotation curve will yield additional constraints on the central potential, but VP modeling will again be important. Ground-based observations show the VPs to be strongly asymmetric (van der Marel et al. 1994a). The wings again require special care, since they contribute significantly to the first moment of the VP. Axisymmetric models are required for a proper theoretical interpretation. High rotation velocities should be expected even without a central black hole, since many elliptical galaxies show a nuclear disk when observed at *HST* resolution (Kormendy et al. 1994; van den Bosch et al. 1994).

To use the information in *HST* absorption-line spectra on the presence of black holes in galactic nuclei optimally, it is essential to address the issue of non-Gaussian VPs.

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