INWARD BOUND: THE SEARCH FOR SUPERMASSIVE BLACK HOLES IN GALAXY NUCLEI

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ABSTRACT

Kinematic observations provide dynamical evidence for central dark objects with masses $M_\bullet \simeq 10^6$ to $10^{9.5}\,\mathrm{M}_\odot$ in eight E – Sbc galaxies (Table 1 in Section 2). Indirect arguments suggest but do not prove that these are supermassive black holes (BHs) like those postulated as engines for galactic nuclear activity. This paper reviews BH search techniques, the robustness of the evidence, and BH demographics.

Brightness profiles are inconclusive evidence. In fact, observations contradict our expectation that BHs result in unusually compact nuclei. Galaxies with larger $M_\bullet$ have larger core radii and fainter core surface brightnesses. The exceptionally compact nucleus of M 33 also has the strongest limit on a BH, $M_\bullet \lesssim 5 \times 10^4$ $\mathrm{M}_\odot$. At $0\farcs1$ to $1''$ radius, core structure is dominated not by $M_\bullet$ but by the fundamental plane parameter correlations, i. e., by the virial theorem and galaxy formation.

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To look for BHs, we need velocity measurements. Stellar-dynamical searches reveal central dark objects in M 31, NGC 3115, M 32, NGC 4594, the Galaxy, and NGC 3377. In the best cases, uncertainties in unprojected brightnesses, rotation velocities and velocity dispersions, in velocity anisotropy, and in internal absorption allow no escape from the conclusion that mass-to-light ratios rise at $r < 2''$ by more than a factor of 10 to $M/L \gtrsim 10^2$. Then the remarkable uniformity of $M/L \lesssim 10$ in old stellar populations suggests that we are detecting BHs.

Similarly, gas velocities imply that there are central dark objects in NGC 4258 and M 87. This evidence is less certain: the velocities may not be gravitational. But gas measurements already reach closer to the Schwarzschild radius than do stellar data, and in NGC 4258 they show a Keplerian rotation curve. Gas-kinematic measurements are promising.

If the dark masses are BHs, then we can begin to study demographics. A statistical survey finds central dark objects in $\sim 20\,\%$ of nearby, early-type galaxies. This is broadly consistent with theoretical predictions. Masses $M_\bullet$ are proportional to the mass of stars in the bulge component. Most BH galaxies are remarkably inactive. This is not a problem in the sense that dead nuclear engines are expected and that activity hinders BH detection. But in some cases, the abundance of fuel is not easily reconciled with BH starvation. In any case, flashes caused by the accretion of individual stars may provide a test of the BH picture.

The search is progressing rapidly. Recent analyses of line-of-sight velocity distributions increase our confidence in the best cases. New spectroscopy from seeing-compensated ground-based telescopes and from the *Hubble Space Telescope* should greatly strengthen the case for or against BHs in the next year. This review is complete through 1994 December.

1. INTRODUCTION

The idea that active galactic nuclei (AGNs) are powered by accretion onto supermassive black holes (BHs) is based on compelling theoretical arguments (Salpeter 1964; Zel'dovich 1964; Lynden-Bell 1969, 1978; Lynden-Bell & Rees 1971; see Rees 1984; Begelman *et al.* 1984; Blandford 1990; and Blandford & Rees 1992 for reviews), a broad array of circumstantial evidence, and a few incisive observations. The latter include rapid time variability and superluminal jets, which suggest that AGN engines are relativistically compact. Theory predicts BH masses of $10^6 - 10^{9.5}$ M$_\odot$. But the BH mass function and the distribution of BHs among galaxies depend on AGN lifetimes and are poorly constrained. This much is clear: quasars were overwhelmingly more numerous at $z \gtrsim 2$ than they are now, so dead quasar engines should be hiding in many nearby galaxies.

The weak spot in this picture is the lack of proof that BH engines exist. This motivates many searches. But a great deal is at stake. The BH picture has become our paradigm. This situation is dangerous: it is easy to believe that we have proved what we expect to find.

This paper reviews stellar- and gas-dynamical evidence for BHs. Previous reviews are given by Sargent (1987); Richstone (1988, 1993); Filippenko (1988); Dressler (1989); Davies (1989); Gerhard (1992); Kormendy (1992a, b; 1993, 1994); de Zeeuw 1994; and van der Marel (1994c). Gas is very responsive to non-gravitational forces, so the most definitive searches are based on stellar kinematics. Section 2 summarizes the state of the search and lists the eight detections. Section 3 shows why cuspy brightness profiles are *not* evidence for BHs. After a summary of search techniques, Section 4 discusses the stellar-dynamical BH candidates. An important upper limit is discussed in Section 4.8. Section 5 discusses the detections based on gas dynamics. A preliminary review of BH demographics is given in Section 6. Section 7 considers whether the detected candidates are too inactive to be BHs. Conclusions and a wish list are given in Section 8.

The case is now strong that 10^6- to $10^{9.5}$-$M_\odot$ dark objects have been discovered in a few galaxies. All are objects in which the search is relatively easy because circumstances are favorable (e. g., the center rotates rapidly). In most galaxies, we do not even have limits; when they are available, they are weak. This especially includes the giant ellipticals that motivate us to search because of AGN activity. Despite the difficulty of BH detection, the amount of nuclear dark matter is consistent with theoretical predictions. But the rigor stops here. Suggestions that the dark objects are BHs are based only on indirect astrophysical arguments.

What we need next is a significant iteration in the quality of the data. We need to see whether the BH case gets stronger or weaker as the spatial resolution and modeling techniques improve. We also need better constraints on the radius inside which the dark mass lies to confirm or exclude alternatives to BHs. Improved ground-based instruments and especially the *Hubble Space Telescope* (HST) are beginning to provide this iteration. Early results are encouraging. But the case is not ready to go to the jury. By themselves, neither the dynamics nor the AGN observations are conclusive. Together, they make a compelling picture.

Our title does homage to A. Pais's (1986) book *Inward Bound*, an elegant history of 20^{th}-century physics as it probed to smaller and smaller subatomic length scales. The BH search is similarly a journey. We make incremental improvements in spatial resolution, each expensive in ingenuity and money. This paper reviews the first order of magnitude of the inward journey in radius. But we are still observing at 10^5 Schwarzschild radii. Surprises are still possible on the way to the center.

2. PRESENT STATUS OF THE BH SEARCH

The search can be divided into three parts. (1) Look for dynamical evidence of central dark masses. In practice, we look for high mass-to-light ratios. If M/L increases toward the center to values that are several times larger than normal, this is a meaningful clue because the range of M/L values in old stellar populations is small. Is there any escape from the conclusion that M/L is high? If not, then we have discovered a "massive dark object" (hereafter MDO). It could be a supermassive BH, or it could be a cluster of low-mass stars, brown dwarfs, stellar remnants, or halo dark matter. (2) Once a few MDOs have been found, we need to improve the observations enough so that alternatives to a BH can be confirmed or ruled out. Proof of a BH requires detection of relativistic velocities in orbits at a few Schwarzschild radii. This is not imminent. But in practice, the most plausible alternative to a BH is a cluster of stellar remnants; it would already be important progress if we could rule out such a cluster on physical grounds. When we say that "we have evidence for a BH" in some galaxy, we mean we find such arguments persuasive. When we say "we have found an MDO", we are emphasizing the uncertainty in arguments against BH alternatives. Step 2 of the BH search is just beginning; we will say little about it here. (3) BH astrophysics requires more than the detection of a few examples. Ultimately, we want to know the mass function and frequency of incidence of BHs in various types of galaxies. This requires statistical surveys. Surveys are challenging because BH detectability depends on galaxy type. E. g., BH detection is easier in rotating disk galaxies than in nonrotating giant ellipticals. Type-dependent biases will be a problem. In practice, we make statistical surveys in parallel with step 2. If MDOs turn out not to be BHs, the demographic results will nevertheless be important to our understanding of galaxy nuclei and AGN activity. BH surveys are reviewed in Section 6.

At present, we are nearing the end of step 1. We have dynamical evidence for MDOs in eight objects. Table 1 lists them subjectively in order from most secure to most weak, separately for objects based on stellar and gas dynamics.

But step 1 is not quite finished. For all objects, the MDO discovery observations have been confirmed by at least one other group. Some of these papers improve significantly on the analysis. But none improves much on the discovery resolution. The next iteration in the search – a substantial improvement in spatial resolution – is in progress.

Most of this paper is a review of step 1. How robust is the claim that MDOs have been detected? What kind of evidence should we believe?

3. CUSPY DENSITY PROFILES ARE NOT EVIDENCE FOR BHs

Many papers argue that the brightness profiles of particular galaxies imply that they contain BHs (e. g., Young *et al.* 1978, 1979; Lauer *et al.* 1991a, 1992a, b; Fabbiano *et al.* 1994). The arguments are variations on the theme that BHs produce cuspy potentials and hence cuspy density distributions. This section shows why such arguments are inconclusive.

Figure 1 shows projected brightness profiles of six stellar systems. Identifications are omitted. Which objects show evidence for a BH? Are they the ones with high central densities or small core radii?

The answers are in Figure 2. M 31 and M 32 show stellar-dynamical evidence for high central mass-to-light ratios. Deconvolved HST profiles are shown for both galaxies. To be sure, they are very compact. But M 33's nucleus (Kormendy & McClure 1993) is more compact than that of M 31. It is as small as the limit on a core in M 32, and it is almost as dense. And yet we know that M 33 does not contain a supermassive BH. Kormendy & McClure (1993) find that the central velocity dispersion is only $\sigma = 21 \pm 3$ km s^{-1}. Therefore $M_\bullet \lesssim 5 \times 10^4$ M$_\odot$ (Section 4.8).

In contrast, M 87 contains an MDO of mass $M_\bullet \sim 3 \times 10^9$ M$_\odot$ (Sargent *et al.* 1978; Harms *et al.* 1994). But its highest measured surface brightness is more than 50 times lower than that of the M 33 nucleus, and its core is more than a thousand times larger. At radii $r \lesssim GM_\bullet/\sigma^2 \simeq 1''$ that are dominated by the BH (Peebles 1972; Bahcall & Wolf 1976),

Figure 1 Seeing-corrected, mean brightness profiles of six stellar systems. Can you identify the ones that contain supermassive BHs?

M 87 does not even reach the surface brightnesses seen in normal ellipticals like NGC 3379, in which there is no evidence (circumstantial or otherwise) for a BH.

Finally, the core-collapsed globular cluster M 15 (Lauer *et al.* 1991b) has a smaller core radius than any galactic nucleus. Its central density is much higher than that of M 87. But it shows no evidence for a BH. From Newell *et al.* (1976), Peterson *et al.* (1989), Meylan & Pryor (1993), Dubath *et al.* (1994), Dubath & Meylan (1994), we adopt $M_\bullet < 10^3$ M$_\odot$.

To emphasize this further, Figure 3 shows BH mass versus core parameters as measured with HST (Kormendy *et al.* 1994; Lauer *et al.* 1995; Faber *et al.* 1995). *The correlations are opposite to what we expect.* Far from making cores compact, *larger BH masses are associated with larger cores and lower maximum densities.* These correlations may be upper envelopes of a distribution: only two upper limits are plotted.

The explanation of Figure 3 becomes clear when we plot $M_\bullet$ against bulge luminosity (Figure 14 in Section 6). There is a good correlation: more massive BHs are found in more luminous bulges. But we know that more luminous bulges have larger $r_b \simeq r_c$ and fainter μ_{0V}: these are projections of the fundamental plane correlations (see Kormendy & Djorgovski 1989 for a review). Therefore at $0\farcs1$ resolution it is the virial theorem controlling the formation of the whole galaxy (Faber *et al.* 1987; Djorgovski *et al.* 1988) and not $M_\bullet$ that determines the compactness of the core. BH cusps may dominate over the fundamental plane at still smaller radii, but we will need better resolution to see this.

Figure 2 Figure 1 with object names and BH masses identified.

Figure 3 BH mass as a function of profile break radius r_b ($\simeq$ core radius r_c) and maximum observed surface brightness μ_{0V} (cf. Fig. 4 in Kormendy 1994). HST measurements of r_b and μ_{0V} are from Faber *et al.* (1995). Filled circles and squares show objects with stellar- and gas-dynamical evidence for MDOs. Upper limits on $M_\bullet$ are plotted as crosses. Strong limits on core parameters are indicated by arrows. For the Galaxy, r_b is from r_c as given in Allen (1994); Eckart *et al.* (1994); Genzel *et al.* (1994); and Rieke & Rieke (1994); the horizontal error bar ends at the larger of two values quoted by Rieke and Rieke and by Allen.

We conclude that evidence for BHs based only on surface brightness profiles is not evidence at all (see also Phinney 1989). This includes arguments like: (i) the profile is cuspy; (ii) central densities are high and core radii are small; (iii) the central relaxation time is short, so core collapse is likely. These arguments apply most strongly to M 33, and in M 33, a supermassive BH can be excluded. Unless kinematic measurements prove that mass-to-light ratios rise to large values near the center, high central densities are most likely to be evidence for dissipation (Phinney 1989; Kormendy 1989). Dissipation can produce arbitrarily high densities. Witness planets.

4. STELLAR-DYNAMICAL BH SEARCHES

Sections 4 and 5 review stellar- and gas-dynamical BH searches. Detections are listed in Table 1 (Section 2). Except for M 33 (Section 4.8), we will not discuss $M_\bullet$ upper limits; these can be found in Bower *et al.* (1993) and in van den Bosch & van der Marel (1995).

This subject began with two papers on the stellar dynamics of M 87 (Young *et al.* 1978; Sargent *et al.* 1978). They showed that M 87 contains an $M_\bullet \simeq 3\times10^9$ $M_\odot$ MDO if the stellar velocity distribution is isotropic. We now know that isotropy is unlikely, but these papers nevertheless were seminal. Recently Harms *et al.* (1994) have confirmed the Sargent and Young conclusions using the refurbished HST. This work is based on emission-line spectroscopy, so we discuss it in Section 5.

4.1 *Search Technique*

Dynamical mass measurements are conceptually simple. We need to deal with projection and atmospheric blurring ("seeing"); this is time-consuming, but it is routine. Mainly, the analysis is complicated because we need to be careful. This subject is dangerous. We enter it with expectations. We need to protect ourselves, lest we convince ourselves prematurely that we have proved what we expect to find.

The search technique is best described in the idealized case of spherical symmetry and a velocity ellipsoid that everywhere points at the center. Then the first velocity moment of the collisionless Boltzmann equation gives the mass $M(r)$ within radius r,

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1-\frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1-\frac{\sigma_\phi^2}{\sigma_r^2}\right)\right], \quad (1)$$

where V is the rotation velocity; σ_r, σ_θ, and σ_ϕ are the radial and azimuthal components of the velocity dispersion; G is the gravitational constant. The density ν is not the total mass density ρ, it is the density of the tracer population whose kinematics we measure. We never see ρ, because the stars that contribute most of the light contribute almost none of the mass. In practice, calculations are made assuming $\nu(r) \propto$ volume brightness, i. e., we assume that M/L for the tracer population is independent of radius. This can be (but usually is not) checked using measurements of color or line strength gradients.

All quantities in Equation 1 are unprojected. We observe projected brightnesses, velocities, and velocity dispersions, so we must derive the ranges of unprojected quantities that are consistent with the observations after projection and seeing convolution. This is tricky.

Kormendy (1988a, c, d) and Dressler & Richstone (1988) independently developed a method of deriving unprojected velocities from the data. Beginning with a trial set of unprojected kinematics, they first calculate model spectra projected along each line of sight by adding spectra of appropriate V and σ weighted by the local volume brightness. They then convolve the two-dimensional array of projected spectra with the point-spread function (PSF). Finally, they "observe" the model with their velocity calculator and iterate it until it agrees with the data. Further, Kormendy does not try to prove uniqueness; rather, he constructs fits that bracket the observations in surface brightness $I(r)$ and in projected $V(r)$ and $\sigma(r)$. In particular, he derives low-mass "error bar" models in which V and σ are too small near the center. The above procedure is required because of the complicated response of any velocity calculator to population mixes and to rotational line broadening. It guarantees that non-Gaussian line-of-sight velocity distributions (LOSVDs) are measured in the same way in the galaxies and models. (It does not guarantee that the models have the same LOSVDs as the galaxies; more about this shortly.) If the implied M/L rises rapidly as $r \to 0$, then we have found an MDO.

Some general properties of the mass measurements follow directly from Equation 1. Rotation and random motions contribute similarly to $M(r)$, but the $\sigma^2 r/G$ term is multiplied by a factor that involves uncertainties and that can be less than 1. So rapid rotation is a more secure indicator of large masses than are large velocity dispersions. Second, Equation 1 shows why velocity anisotropy is so important, especially in nonrotating giant ellipticals. HST shows that these have shallow power-law profiles $I \propto r^{-0.1\pm0.1}$ at $r \ll r_b$ (Lauer *et al.* 1992a; Crane *et al.* 1993b; Stiavelli *et al.* 1993; Kormendy *et al.* 1994, Forbes 1994; Forbes *et al.* 1994; Ferrarese *et al.* 1994; Lauer *et al.* 1995). Then $-d\ln\nu/d\ln r \simeq 1.1$. The second term cannot be larger than $+1$. But the third and fourth terms are negative if σ_r is larger than σ_θ and σ_ϕ. They can be as small as -1 each, so they can largely cancel the first two terms. This does not prove that anisotropic models are realistic. But it illustrates why they have been so successful in explaining the kinematics of giant ellipticals without BHs (e. g., M 87: Section 5.1). In contrast, a BH case is more secure if the density gradient is steep, other things being equal. This is one reason why low-luminosity ellipticals like M32 (Section 4.4) and NGC 3377 (Section 4.7) are better BH candidates than giant ellipticals: no core is resolved, so $-d\ln\nu/d\ln r \gtrsim +2$ in Equation 1.

Velocity anisotropy has usually been explored by constructing maximum entropy dynamical models (Richstone & Tremaine 1984, 1988). Once anisotropy becomes the default assumption, it is inherently difficult to prove that an MDO is required: the parameter space to be explored is large, and nature knows more distribution functions than we do. Therefore the biggest advantage of the maximum entropy modeling technique is that it can easily be asked to find the most extreme possible models in the most relevant directions in parameter space. In particular, it can be asked to minimize the central mass (it does so by maximizing the anisotropy). If this fails – if M/L still rises toward the center – then we can be almost certain that an MDO is present.

We say "almost" because published maximum entropy models have had significant limitations. Flattening corrections were made *post hoc* using the tensor virial theorem. Also, the velocity dispersion σ_ϕ in the rotation direction was not completely free: $\sigma_\phi^2 + V^2 = \sigma_\theta^2$. This means, for example, that it was never possible to make *isotropic* models that rotate. Both limitations will be removed in future papers. Like other analyses in astronomy, the above procedures provide results at some level of approximation. Strong BH cases (especially M 31 and NGC 3115) are ones in which the derived M/L is higher than normal by an amount that is substantially larger than the uncertainties.

Progress in the BH search can come from improvements in analysis as well as in observations. In particular, we can exploit LOSVDs. Their calculation and use have been discussed, e. g., by Bender (1990); Rix & White (1992); van der Marel & Franx (1993); Gerhard (1991, 1993a, b); Winsall & Freeman (1993); Kuijken & Merrifield (1993); Dehnen & Gerhard (1993, 1994); Saha & Williams (1994); Evans & de Zeeuw (1994); van der Marel *et al.* (1994b); Bender *et al.* (1994); and Statler (1995). It is convenient to measure departures from Gaussian LOSVDs using an expansion in Gauss-Hermite polynomials H_i (van der Marel & Franx 1993; Gerhard 1993a, b; Dehnen & Gerhard 1993):

$$\mathrm{LOSVD}\,(v) = \frac{\gamma}{\sqrt{2\pi\sigma^2}} e^{\frac{(v-V)^2}{2\sigma^2}} \left[1 + \sum_{i=3}^{n} h_i H_i \left(\frac{v - V}{\sigma} \right) \right], \qquad (2)$$

where γ = line strength. If $h_3 < 0$, then the LOSVD has extra power on the systemic-velocity side of V. If h_4 is negative (positive), then the LOSVD is more square (triangular) than a Gaussian. The h_4 coefficient provides direct observational constraints on the velocity anisotropy: tangentially anisotropic models generally have $h_4 < 0$; radially anisotropic models generally have $h_4 > 0$ (e. g., Gerhard 1991, 1993a, b; van der Marel & Franx 1993; Dehnen & Gerhard 1993; van der Marel *et al.* 1994b). Application of LOSVDs to the BH search has been pioneered independently by R. van der Marel and by O. Gerhard and their collaborators. The following sections discuss the added confidence provided by this second iteration in the analysis.

4.2 *M 31* ($M_\bullet \simeq 3 \times 10^7\ M_\odot$)

M 31 is the strongest BH case because of the rapid rotation and large velocity dispersion in its nucleus (Dressler 1984; Kormendy 1987a, 1988a, c; Dressler & Richstone 1988; Richstone *et al.* 1990). Its dynamics have been measured by four independent groups. And it is the first galaxy for which we have made an iteration in improving the spatial resolution.

M 31 contains the best known example of a nuclear star cluster (see Johnson 1961; Kinman 1965; Sandage 1971 for reviews) that is dynamically distinct from the bulge (Tremaine & Ostriker 1982). Light *et al.* (1974) imaged it with *Stratoscope II*: at $\sigma_* \simeq 0\farcs1$, it is asymmetric; its axial ratio is $\simeq 0.6$, and the brightest spot is near the NE end. Lauer *et al.* (1993) and Crane *et al.* (1993b) observed it with HST; Lauer and collaborators show that the nucleus is double (Figure 4).

The rapid rotation of the nucleus (discovered by Lallemand *et al.* 1960) and its steep central dispersion profile are shown in Figure 5. Dressler & Richstone (1988) and Kormendy (1988a, c) carried out analyses like those described in the previous section. These were complementary: Kormendy considered uncertainties in the light distribution (particularly its flattening) in more detail, and Dressler & Richstone showed that the results are independent of velocity anisotropy. The mass-to-light ratio profiles are somewhat model-dependent, but both papers showed that M/L_V rises near the center to values $\gtrsim 100$ (Figure 5). This implies that M 31 contains an MDO of mass $M_\bullet \simeq 3 \times 10^7$ $\mathrm{M}_\odot$.

Figure 4 HST Planetary Camera V-band isophotes of the nucleus and inner bulge of M 31 after Lucy deconvolution (Lauer *et al.* 1993).

The photometric asymmetry of the nucleus was known in 1988. Dressler, Richstone, and Kormendy also observed asymmetries in the velocity field but averaged over them in their analyses. The double nucleus complicates the BH case. More detailed models should be constructed. However, it is unlikely that M/L_V is normal for an old stellar population: the observed velocities would have to overestimate the equilibrium virial velocities by a factor of ~ 4. Instead, the HST observations are telling us something about the formation of the nucleus.

Figure 5 Rotation, dispersion, and M/L ratio profiles in M 31.

Lauer *et al.* (1993) discuss possible explanations of the double nucleus; none is very attractive. Extinction is unlikely: there is no color gradient. M 31 may have accreted and almost digested a compact elliptical like M 32. But timescales are a problem. At $2r = 0\farcs49 = 1.7$ pc (the projected separation), a relative velocity of 200 km s^{-1} implies a circular orbit period of 50,000 y. Dynamical friction should result in a merger within a few orbital times. Are we just lucky to catch the nuclei *in flagrante delicto*? Two effects may reduce the dynamical friction. If P1 is accreted, it may fortuitously corotate with the stars of P2 (King *et al.* 1995). Or *both* nuclei could be dominated by BHs. This is *ad hoc* but not implausible. We do not know whether either effect is sufficient.

Bacon *et al.* (1994) add new information about the asymmetries by presenting two-dimensional V and σ maps (Figure 6). They confirm the conclusion of Dressler & Richstone (1988) and of Kormendy (1988c) that the rotation curve of the nucleus is symmetric about its center ("P2" in Lauer *et al.* 1993) and not about the brightest point ("P1"). All studies also agree that the center of the nucleus is the center of the bulge. But this is not the point of maximum σ. Instead, the brightest and hottest points are displaced from the rotation center by similar amounts in opposite directions. Also, $\sigma(r)$ drops rapidly to or below the bulge dispersion on the brighter side of the nucleus. It is natural to wonder (Lauer *et al.* 1993) whether P1 is cold. Then the displacement of the $\sigma(r)$ peak from P2 could be due to a contribution from P1 at the center.

Figure 6 Contours of constant velocity (*left*) and velocity dispersion (*right*) in the nucleus of M 31 (Bacon *et al.* 1994). The range of velocities (*white* to *black*) is -120 km s$^{-1} \leq V \leq 120$ km s^{-1} and 140 km s$^{-1} \leq \sigma \leq 240$ km s^{-1}. These CFHT observations have spatial sampling $= 0\farcs39$ and resolution $\sigma_* \simeq 0\farcs37$. The major axis of the nucleus is horizontal; the white dot marks its photometric center.

LOSVD observations by van der Marel *et al.* (1994a) are consistent with this interpretation. They used the William Herschel Telescope (WHT; slit width $= 0\farcs45$, $\sigma_* = 0\farcs32$). They show that the Gauss-Hermite coefficient $h_3(r)$ is opposite in sign to $V(r)$, with a strong negative peak, $h_3 \simeq -0.17$, near P1. This suggests that the LOSVD consists of a hot component that rotates slowly plus a cold one that rotates rapidly.

More definite conclusions require higher spatial resolution. This is expected from the new Subarcsecond Imaging Spectrograph (SIS) on the CFHT and from HST. No absorption-line spectroscopy is available yet from HST. However, a second iteration of spectroscopy on BH candidate galaxies is under way by Kormendy and collaborators using SIS.

SIS removes the main limitation of previous CFHT work: Herzberg Spectrograph resolution was limited by camera optics to FWHM $\geq 0\farcs7$. SIS optics are better than the seeing. The scale is $0\farcs0864$ pixel^{-1}; slit widths of $0\farcs3$ can be used. Tip-tilt guiding is incorporated; by offsetting the guide probe, the observer can center the object on the slit to one-pixel accuracy. As a result, the resolution is limited only by seeing and telescope aberrations. Resolution FWHM $\simeq 0\farcs45$ ($\sigma_* = 0\farcs19$) is reasonably common. Few objects are bright enough to be observed with HST at $< 0\farcs25$ resolution, so SIS remains interesting in the HST era.

Figure 7 shows SIS measurements of the M 31 nucleus (Kormendy & Bender 1995). The LOSVD has two components. The steep central rise in σ seen by previous authors is a feature of P2: P2 is much hotter than the bulge near the center. But P1 is colder than the bulge at all radii. The LOSVDs and the V and σ fits imply that P1 has $\sigma \lesssim 85$ km s^{-1} at the center. This supports the idea that P1 is an accreted low-luminosity stellar system. Since P1 overlaps P2 at the center, it also confirms that the $\sigma(r)$ asymmetry is due to the contribution of P1 at P2.

The accretion hypothesis can be tested. King *et al.* (1995) make a preliminary comparison of the stellar populations of P1 and P2 using a $\lambda \simeq 175$ nm image obtained with HST. In the UV, P2 has a higher surface brightness than P1. But the excess flux is small; it is equivalent to one post-asymptotic-branch giant star. King *et al.* (1995) suggest that it is due to the central radio source (Table 1). They also confirm that P1 is compact (its brightness drops to zero at $r \simeq 0\farcs63$) and faint ($V \simeq 14.8$; $M_V \simeq -9.7$). P1 is no brighter than a large globular cluster, although it is much denser. Most interestingly, King *et al.* (1995) see no sign that the (UV $-$ optical) color of P1 is different from that of the bulge. This does not favor accretion. On the other hand, P1 nowhere contributes more than 55 % of the total surface brightness. It is difficult to measure its metallicity free of contamination from P2. It will be important to see whether HST shows a drop in spectral line strengths at P1.

HST will also be important for the BH case. Meanwhile, the dramatic kinematics seen with SIS (Figure 7) supports the BH detection.

Figure 7 LOSVDs (*top*) and $V(r)$ and $\sigma(r)$ profiles (*bottom*) along the nucleus major axis of M 31 (Kormendy & Bender 1995). Filled circles show the kinematics of the nucleus plus bulge as observed; crosses show the nuclear kinematics after the bulge spectrum is subtracted.

4.3 *NGC 3115* ($M_\bullet \simeq 1 \times 10^9\, M_\odot$)

NGC 3115 is a edge-on S0 galaxy (Sandage 1961) whose bulge provides 94 % of the total light (Capaccioli *et al.* 1987). At $M_B = -19.9$, the bulge is almost as bright as a giant elliptical, but it rotates rapidly enough to be nearly isotropic (Illingworth & Schechter 1982). Kormendy & Richstone (1992, hereafter KR92) showed that its steep central kinematic gradients (Figure 8) make NGC 3115 the strongest BH case after M 31.

KR92 derived dynamical models that bracket the observations after projection and seeing convolution. Figure 8 (left) illustrates the best-fitting isotropic model at three spatial resolutions. The $\sigma_* = 0\farcs44$ lines are for the resolution of the KR92 observations; by construction, they fit the open circles. One iteration of improved spatial resolution is now available. The filled circles in Figure 8 show CFHT SIS measurements obtained with a $0\farcs3$ slit. At $\sigma_* = 0\farcs244 \pm 0\farcs015$, $V(r)$ already reaches its asymptotic value at $1''$, and the apparent central velocity dispersion has risen from 295 ± 9 km s^{-1} to 343 ± 19 km s^{-1}. This is almost exactly the increase predicted by the KR92 models. The middle lines show the

Figure 8 (*left*) Kinematics of NGC 3115 compared with the best-fitting isotropic model (D3) from KR92 as seen at various spatial resolutions. (*right*) SIS data compared with isotropic models D1 – D5 from KR92 as seen at $\sigma_* = 0\farcs25$.

best-fitting isotropic model at $\sigma_* = 0\rlap{.}''244$. It fits the rotation curve well, and it falls slightly below the dispersion profile at the center. Also (Figure 8, right), the isotropic models continue to bracket the data at the improved resolution. These models imply that M/L_V rises toward the center to values much larger than those of old stellar populations (Figure 9). Note that M/L_V has already risen by a factor of 5 at $1''$; contrary to the claim of Rix (1993), this is not a marginal MDO detection. In fact, the MDO dominates gravitationally to $r_\bullet = GM_\bullet/\sigma^2 \gtrsim 1\rlap{.}''8$. We see that $r_\bullet \gg \sigma_*$. If the M/L_V gradient is due to a central dark mass added to stars with constant $M/L_V(r)$, then $M_\bullet \simeq 10^9$ $M_\odot$. The MDO mass can be reduced by allowing σ_r to be larger than σ_θ and σ_ϕ near the center (Equation 1), but KR92 showed that $M_\bullet$ must be $\gtrsim 10^8$ $M_\odot$ or the models predict too little rotation at $r \simeq 1''$ to $2''$. We conclude that a significant iteration in spatial resolution confirms the BH case. This increases our confidence in the MDO detection.

Finally, the top curves in each panel of Figure 8 (left) show the best-fitting isotropic model from KR92 at HST resolution ($0\rlap{.}''25$ aperture and the Faint Object Spectrograph). Kormendy *et al.* (1995a) observed NGC 3115 with HST in 1994 December. They will combine the results with the SIS data and will construct new dynamical models. It is reasonable to expect that these observations will complete step 1 of the BH search for NGC 3115: i. e., they should tell us definitively whether or not an MDO is present.

Figure 9 Mass-to-light ratio interior to radius r for the isotropic models in Figure 8. All models have $M/L_V \simeq 4$ at $r \simeq 4''$ to $24''$; this value is normal for a bulge of $M_B = -19.9$ (Kormendy 1987b, Figure 3). In contrast, M/L_V increases at $r < 2''$ by a factor of $\gtrsim 10$. From KR92.

What *caveats* remain?

Dust absorption appears insignificant. HST shows no dust near the center (Lauer *et al.* 1995). The central color gradient is normal, and the galaxy is only weakly detected by the *IRAS* satellite (see KR92). And the brightness profile is normal (KR92; Lauer *et al.* 1995; Faber *et al.* 1995). For dust to produce high M/L ratios, the central profile and parameters would have to be unlike those in any other galaxy and then made to look normal only because of absorption. This is implausible.

Nuclear bars: Gerhard (1988, 1989) has suggested that nuclear disks are really bars. When these are oriented end-on, we see stars near the pericenters of elongated orbits, so we measure rotation velocities that are larger than circular. This reduces the mass implied by the rotation curve. We do not know whether constant-M/L nuclear bar models can be constructed. However, we know enough about bars to conclude that they are implausible: (i) Noncircular streaming velocities have been measured in the SB0 galaxy NGC 936 (Kormendy 1983). This has an unusually strong bar, but departures from circular motions are only $\pm 20\,\%$. Even if this bar were viewed end-on and even if all of the light came from the bar, the error in $M(r)$ from the V^2r/G term in Equation 1 would be only 40 %. The $\sigma^2 r/G$ term would be unaffected: Kormendy saw no dispersion anisotropy in NGC 936. (ii) In NGC 3115, the end-on nuclear bar would have a true major-axis radius of $\gtrsim 4''$, since $1''$ (where M/L_V looks large) is a pericenter radius. Such a bar would easily be seen in more face-on galaxies. Some galaxies have nuclear bars (see Kormendy 1982 for a review). But we have never seen one as elongated as the main bar in NGC 936, and argument (i) suggests that even this is not enough. Nevertheless, nuclear bar models should be investigated (Gerhard 1992).

Velocity anisotropy should be explored in more detail. That is, the limitations in maximum entropy models noted in Section 4.1 should be removed. For NGC 3115, this will be done in Kormendy *et al.* (1995a).

LOSVDs provide new constraints on the mass distribution that we are only beginning to use in the BH search (Gerhard 1993b; van der Marel *et al.* 1994a, b; van der Marel 1994a, b; Dehnen 1995; Qian *et al.* 1995). Van der Marel *et al.* (1994a) and Bender *et al.* (1994) show that the LOSVDs in rotating systems are usually asymmetric, with extra wings on the systemic-velocity side of the mean V. That is, $h_3(r)$ and $V(r)$ have opposite signs. For NGC 3115, $h_3 \simeq -0.05$ at $r \lesssim 5''$. The above authors emphasize that $V(r)$ as derived by fitting a Gaussian to the LOSVD then overestimates the true velocity moment in Equation 1. Van der Marel *et al.* (1994a) worry that this accounts for the failure of constant-M/L models to fit the kinematics. Similarly, the true velocity dispersion is underestimated when the LOSVD has large wings (van der

Marel 1994a, b). Bender *et al.* (1994, see Figure 3) provide the necessary corrections ΔV and $\Delta\sigma$. At $0\farcs5 \lesssim r \lesssim 5''$ in NGC 3115, $\Delta V \simeq -14$ to -21 km s^{-1}. The important point is that ΔV is almost independent of radius. *The corrected rotation curve then reaches a slightly lower asymptotic value at $r \simeq 1''$ to $5''$. But model rotation curves are always scaled to the asymptotic V; this is how the global M/L ratio is derived. So the main result of the correction is to lower the global (i. e., bulge) M/L_V.* The change is only $\sim 8\,\%$. It is small partly because less than half of $M(r)$ as derived from Equation 1 is due to $V(r)$; the dispersion profile is almost unchanged by the LOSVD correction. *The strength of the BH case is essentially unaffected, because the shape of the rotation curve is almost unchanged.* These remarks are reassuring. Nevertheless, as van der Marel *et al.* (1994a) emphasize, KR92 did not check whether the LOSVDs of their models fit those of the galaxy. Models of NGC 3115 that exploit LOSVDs are planned (Kormendy *et al.* 1995a).

The most serious caveat remains the fact that large M/L ratios do not uniquely imply a BH. Only step 1 of the BH search – the detection of an MDO – is nearing completion. We cannot exclude the possibility that galaxies contain central clusters of stellar remnants or brown dwarf stars. However, old stellar populations have remarkably consistent mass-to-light ratios $M/L_V \simeq 1$ to 10, with $M/L_V \propto L^{0.2}$ (Kormendy 1987a, b; Faber *et al.* 1987; Djorgovski *et al.* 1988; Bender *et al.* 1992, 1993). The increase of M/L_V with L is due to three effects, the metallicity–luminosity correlation (Faber 1973; more luminous galaxies are more metal-rich, so stars emit less V-band light per unit mass because of stronger absorption-line blanketing), the anisotropy–luminosity correlation (Davies *et al.* 1983), and an age–luminosity correlation (Faber *et al.* 1992). Given that old stellar populations contain stars with very large and very small mass-to-light ratios, it is surprising that the scatter in M/L is so small. But the small scatter is the reason why we interpret large nuclear M/L ratios as implying MDOs. Stellar densities in NGC 3115 are not outside the range observed in galaxies that lack MDOs or in globular clusters. These have normal populations. The spectra and colors of NGC 3115 also are normal. Therefore we have no reason to expect a dramatic population gradient, and we see no evidence of one. An extreme population gradient would be required: inside $1''$, the dark star cluster would have to have about five times as much mass as the visible stars. Therefore the most plausible conclusion is that NGC 3115 contains a central BH of mass $M_\bullet \sim 10^9$ M$_\odot$.

To summarize: in NGC 3115, as in M 31, the detection of an MDO is probably secure. But the arguments that we are detecting a BH are not rigorous.

4.4 *M 32* ($M_\bullet \simeq 2 \times 10^6\, M_\odot$)

The first galaxy with convincing evidence for an MDO was the dwarf elliptical M 32; it is now the most thoroughly studied BH candidate. Like M 31, it was long ago known to rotate rapidly near the center (Walker 1962). Dressler (1984) and Tonry (1984, 1987) measured its rotation curve with $\sigma_* \simeq 0''.5$ to $0''.85$ seeing at the Hale telescope; they demonstrated that the velocity dispersion rises significantly toward the center. Tonry (1984, 1987) fitted his data with isotropic dynamical models; these imply that M/L increases toward the center. He concluded that M 32 contains a BH of mass $M_\bullet \simeq (3 \text{ to } 10) \times 10^6\, M_\odot$.

These results were strengthened by Dressler & Richstone (1988), who obtained $\sigma_* \simeq 0''.5$ observations of M 32 with the Hale telescope. Using the techniques of Section 4.1, they showed that velocity anisotropy provides no escape from the conclusion that an MDO is present. More detailed analysis by Richstone *et al.* (1990) further supported the case.

Figure 10 illustrates the kinematics.

Figure 10 Kinematics of M 32 compared with the dynamical models of van der Marel *et al.* (1994b), Qian *et al.* (1995), and Dehnen (1995) kindly recalculated by the above authors for $\sigma_* = 0''.20$.

The conclusions of Tonry, Dressler, and Richstone have now been confirmed by three independent groups. They provide a significant iteration in spatial resolution over the discovery observations, and they strengthen the analysis by fitting LOSVDs. Therefore M 32, with M 31 and NGC 3115, is among the most secure BH candidates.

Carter & Jenkins (1993) observed M 32 with the WHT, a $0\farcs45$ slit, and $\sigma_* = 0\farcs34$. At this resolution, $V(r)$ flattens out to 50 km s^{-1} at $\sim 1''$. Carter & Jenkins do not use the dispersion profile to measure masses, but they note that a high central M/L does not follow from $V(r)$ alone.

Van der Marel *et al.* (1994a) present additional WHT observations, including measurements of Gauss-Hermite coefficients. As in other rotating galaxies, h_3 and V have opposite signs; $h_3 \simeq -0.07$ at $r \gtrsim 1''$. Coefficients $h_4 - h_6$ are nearly zero. Van der Marel and collaborators note that Tonry's (1987) isotropic models do not fit $h_3(r)$; in fact, they have $h_3 \simeq 0$ at all radii. This demonstrates an interesting result: the LOSVDs are intrinsically asymmetric; they are not Gaussians rendered asymmetric by rotational line broadening, projection, or seeing. This is important for modelers who try to decipher the galaxy's dynamics. But it does not have a large effect on the BH search, contrary to worries expressed in van der Marel's paper. This can again be seen by correcting the Gaussian-fit rotation velocities to velocity moments appropriate for Equation 1 using Bender *et al.* (1994). Since $h_3 \simeq$ constant at $r \gtrsim 1''$, $\Delta V \simeq -7$ km s^{-1} is nearly independent of radius (see also Figure 2 in Rix 1993). So the main effect of the correction is again to lower the bulge M/L. This is confirmed by detailed analysis, as follows.

Van der Marel *et al.* (1994b) construct M 32 models with two-integral distribution functions $f(E, L_z)$, where E is total energy and L_z is the axial component of angular momentum. Without MDOs, these models fit $V(r)$ and $h_3(r) - h_6(r)$, but they fail to fit the central dispersion gradient. In fact, they predict that σ falls toward the center at $r < 1''$ (physically: if stars cannot climb out of their own potential well and therefore make a cuspy profile, they must be cold; see, e. g., Binney 1980; Dehnen 1993; Tremaine *et al.* 1994). Similar results are obtained with a moment equation analysis that fits V, σ, and the skewness of the LOSVDs. Good fits to $\sigma(r)$ are obtained when an MDO of mass $M_\bullet = (1.8 \pm 0.3) \times 10^6$ M$_\odot$ is added. These results are in good agreement with the conclusions of Tonry, Dressler, and Richstone.

Qian *et al.* (1995) take the moment equation models one step further by calculating their distribution functions using the contour integral method of Hunter & Qian (1993). They can then derive the complete LOSVDs and not just their skewness. For the $M_\bullet = 1.8 \times 10^6$ M$_\odot$ model, the comparison to V, σ, and $h_3 - h_6$ shows remarkably good agreement along all slit positions measured by van der Marel *et al.* (1994b).

Dehnen (1995) has made further $f(E, L_z)$ models of the van der Marel *et al.* (1994a) observations using a slightly different technique. He recovers $f(E, 0)$ from ρ using a Richardson (1972) – Lucy (1974) algorithm. The distribution function is then multiplied by a guessed function of L_z and used to calculate V, σ, and h_3 – h_6. These are compared to the observations, and the distribution function is iterated until it agrees with all observables. Slit width, pixel size, and seeing are taken into account. Dehnen's results are closely similar to those of van der Marel *et al.* (1994b). In particular, he confirms that such models do not fit the kinematics unless they contain an MDO of mass $M_\bullet \simeq$ (1.6 to 2) $\times 10^6$ $M_\odot$. Again, the models with an MDO provide an excellent fit to $h_3(r)$ – $h_6(r)$ along the major, minor, skew, and offset axes.

Van der Marel *et al.* (1994b), Qian *et al.* (1995), and Dehnen (1995) improve on earlier analyses in several important ways. The models are properly flattened, they fit the non-Gaussian LOSVDs, and they fit kinematic observations at a variety of slit positions, not just along the major axis. The latter point is important: as van der Marel *et al.* (1994b) point out, Tonry's (1984, 1987) models explain the major-axis dispersion gradient as due to rotational line broadening, but without an intrinsic dispersion gradient, they cannot be in dynamical equilibrium along the minor axis. The $f(E, L_z)$ models solve this problem.

They also have an important shortcoming compared to the models of Dressler & Richstone (1988). The distribution functions are restricted to be functions of two integrals; in many cases, they are required to be analytic. We can show that these models fail to fit the data without a BH, but we cannot prove that it is impossible to find a more general distribution function that succeeds without a BH. In contrast, the maximum entropy models can be forced to have the smallest possible M/L as $r \to 0$. When this fails – modulo shortcomings discussed in Section 4.1 – an MDO is required. Thus the distribution function and maximum entropy models are complementary: each has strengths that the other lacks. It is reassuring that they agree. But an exploration of extreme models that successfully fit V, σ, and h_n without the limitations of published maximum entropy models is still needed.

Finally, Figure 10 shows new observations of M 32 obtained with the CFHT and SIS (Kormendy *et al.* 1995a). These provide a further improvement in spatial resolution: the slit width was $0\farcs35$, and the seeing σ_* was $0\farcs20$. At this resolution, the central rotation curve is much steeper; it peaks at $V \simeq 53{\pm}2$ km s^{-1} at $r \simeq 0\farcs85$. The central dispersion profile is slightly steeper; $\sigma(0) \simeq 94 \pm 2$ km s^{-1}. Figure 10 compares the SIS data with the models of van der Marel *et al.* (1994b), Qian *et al.* (1995), and Dehnen (1995) as seen at the present resolution. The fit is good at large radii. But $V(r)$ and $\sigma(r)$ both reach higher maximum values than the models predict. Therefore the BH case gets stronger at SIS resolution. Modeling of the SIS data is in progress.

In summary, five independent groups have observed and modeled M 32. Models without MDOs consistently fail to fit the kinematics. These include maximum entropy models that were instructed to minimize the central M/L. Successful models require that $M_\bullet \simeq 2 \times 10^6$ $M_\odot$. This result has survived improvements in spatial resolution of a factor of 3 since the MDO discovery. Given expectations based on Figure 10 and on the predictions of Dehnen (1995) and Qian *et al.* (1995), HST spectroscopy is feasible. Van der Marel *et al.* (1995) plan to make these observations. Meanwhile, the case for an MDO is already strong.

4.5 *NGC 4594, The Sombrero Galaxy* ($M_\bullet \simeq 5 \times 10^8\, M_\odot$)

The remaining stellar-dynamical BH cases (Sections 4.5 – 4.7) are weaker than those of M 31, M 32, and NGC 3115 because the modeling analyses have explored fewer degrees of freedom on $M(r)$.

NGC 4594 is an almost edge-on Sa galaxy illustrated in the *Hubble Atlas* (Sandage 1961). Its bulge is as luminous as a giant elliptical ($M_B \simeq -21.21$ at 9.2 Mpc distance), but it rotates rapidly enough so that velocity anisotropies are small (Kormendy & Illingworth 1982). This reduces the uncertainties in the mass measurements.

Kormendy (1988d) observed NGC 4594 with the CFHT (slit width = $0\farcs5$, scale = $0\farcs435$ pixel^{-1}, seeing $\sigma_* = 0\farcs40$). The central kinematics reveal a nuclear disk: at $r \simeq 5''$, the rotation curve has an inner peak, and the dispersion profile has a minimum ($\sigma = 181 \pm 6$ km s^{-1}) that is significantly lower than the bulge dispersion ($\sigma \simeq 240$ km s^{-1}). The nuclear disk is also detected photometrically (Burkhead 1986, 1991; Kormendy 1988d; Crane *et al.* 1993b; Emsellem *et al.* 1994a). Its presence guarantees that the LOSVDs are asymmetrical. But the disk is well localized and significantly brighter than the bulge. At $r \simeq 10''$ to $15''$, both the photometry and the kinematics suggest that the disk is negligible; here the major-axis dispersion is equal to that along the minor axis. Therefore Kormendy subtracted the bulge spectrum obtained from the minor axis and scaled to the major-axis bulge profile. He then confined his analysis to the kinematics of the nuclear disk. This is a well-defined kinematic subpopulation that can be used in Equation 1 to measure the total mass distribution. Recently, Kormendy (1994) has shown that asymmetries in the LOSVDs due to superposition of the nuclear disk and bulge were removed by the decomposition; the Kormendy (1988d) models are an adequate fit to the residual LOSVDs.

The machinery of Section 4.1 was used to derive unprojected rotation velocity, velocity dispersion, and brightness profiles that bracket the bulge-subtracted data after projection and seeing convolution. The solutions imply that the mass-to-light ratio rises from normal values $M/L_V \simeq 7.8$ at large radii to $M/L_V > 100$ near the center. (All values in this section have been corrected to the distance scale of Table 1.) Kormendy & Westpfahl (1989) showed that the outer M/L_V remains constant to $\sim 180''$. So a normal old stellar population dominates the bulge over a large radius range. But an MDO is present at $r < 1''$; if $M/L_V(r)$ = constant for the stellar population, then $M_\bullet \simeq 5 \times 10^8\, M_\odot$.

The main shortcoming of the analysis was that velocity anisotropy was not explored. The rapid rotation and the nuclear disk make it unlikely that $\sigma_r \gg \sigma_{\rm tangential}$ (Kormendy & Illingworth 1982; Jarvis & Freeman 1985). Nevertheless, anisotropic models should be constructed.

The kinematics of NGC 4594 have been confirmed by five independent groups. Jarvis & Dubath (1988) observed the galaxy with the ESO 3.6 m telescope, a $2''$ slit, $1\farcs17$ pixels, and seeing $\sigma_* \simeq 0\farcs51$ to $0\farcs64$. Their data agree well with Kormendy's. They estimate the total mass within $3\farcs5$ of the center to be 7×10^8 $M_\odot$ and "conclude that there is strong evidence that NGC 4594 contains a super-massive object, possibly a black hole or massive star cluster." But they calculate no M/L ratios, so they cannot tell how much of the mass is dark. In fact, comparably luminous galaxies typically have core masses $> 10^9$ $M_\odot$ *in stars* (e. g., Kormendy 1982, Table 3). In NGC 4594, the luminosity inside $3\farcs5$ is $L_V \simeq 6 \times 10^8$ $L_\odot$ (Kormendy 1988d, Figure 10), and $M/L_{V,\rm bulge} \simeq 7.8$. So Jarvis and Dubath underestimate the mass inside $3\farcs5$.

Wagner *et al.* (1989: ESO 2.2 m telescope, $1\farcs87$ pixels, $2''$ slit) were the first to examine LOSVDs. These clearly show a superposition of rapidly rotating, cold and slowly rotating, hot components. The cross-correlation peaks at the center and at $\pm 3\farcs6$ agree well with those illustrated in Kormendy (1994). Wagner *et al.* (1989) derive a seeing-corrected mass of $(3 \pm 1.2) \times 10^9$ $M_\odot$ inside $3\farcs8$ radius, but like Jarvis & Dubath (1988), they do not derive M/L ratios.

The kinematics are further confirmed by Carter & Jenkins (1993: WHT, $0\farcs34$ pixels, $0\farcs55$ slit, seeing $\sigma_* \simeq 0\farcs51$). They remark that rotation alone is not rapid enough to imply a large mass-to-light ratio. It is true that the central rise in M/L found by Kormendy (1988d) is largely due to the dispersion gradient. Checking anisotropy is probably more important than Kormendy suggested.

Van der Marel *et al.* (1994a) took additional spectra with a $1\farcs25$ slit, $0\farcs6$ pixels, and seeing $\sigma_* = 0\farcs47$. They agree with previous results. The main new contribution is the measurement of LOSVDs. The maximum amplitude of $h_3 = -0.15$ is reached at $r = 6''$; $|h_3|$ – $|h_6|$ then fall almost to zero at $r = 10'' - 20''$. This is in excellent agreement with the Kormendy (1988d) and Burkhead (1991) conclusion that the nuclear disk dominates near the center but is negligible at intermediate radii.

In summary, the kinematics of NGC 4594 are well confirmed. But none of the published measurements improves on the discovery resolution.

Also, there has been little progress on modeling. Emsellem *et al.* (1994a) model the Kormendy data using multi-Gaussian expansions of the PSF and galaxy light distributions. Again, isotropic models do not fit the dispersion profile unless there is an MDO of mass 5×10^8 M$_\odot$. However, even the MDO model rotates too slowly. Part of the problem is that Emsellem and collaborators fit the composite (not bulge-subtracted) kinematics; this adds to the uncertainties because of the messy LOSVDs.

More definitive results on NGC 4594 should be available soon. Emsellem *et al.* (1994b) have obtained two-dimensional spectroscopy with $0\farcs39$ spatial sampling on the CFHT. Kormendy *et al.* (1995a) have taken CFHT SIS spectra with $\sigma_* = 0\farcs27$; at this resolution, the apparent central velocity dispersion is 282 ± 8 km s^{-1}. They are also scheduled to observe NGC 4594 with HST in 1995 February. The issue of whether NGC 4594 contains an MDO should be settled soon.

4.6 *The Galaxy ($M_\bullet \simeq 2 \times 10^6\, M_\odot$)*

The center of our Galaxy is enormously complicated and well studied. Excellent reviews (Genzel & Townes 1987; Morris 1993; Genzel *et al.* 1994) and conferences (Backer 1987; Morris 1989; Genzel & Harris 1994) discuss the physics in detail. Papers on a possible Galactic BH include Lynden-Bell & Rees (1971); Rees (1987); Phinney (1989); and de Zeeuw (1993). Here we summarize the AGN evidence and gas dynamics briefly and then concentrate on the stellar-dynamical BH search.

The radio source Sgr A* (Genzel *et al.* 1994, Figure 2.2) is assumed to be the Galactic center; this is not certain. Sgr A* is spectacularly tiny. Lo *et al.* (1985) measure a radius of $\theta < (1.1 \pm 0.1) \times 10^{-3}$ arcsec = 9 AU at $\lambda = 1.3$ cm wavelength. Also, $\theta \propto \lambda^2$ due to interstellar electron scattering. Strong limits require short λ; at 3 mm, $\theta \lesssim 0.07 \times 10^{-3}$ arcsec = 0.6 AU (Rogers *et al.* 1994). This is only 15 times the Schwarzschild radius of the 2×10^6 M$_\odot$ MDO suggested by the dynamics. It is easy to be impressed by the small size. But as an AGN, Sgr A* is feeble: its radio luminosity is 10^{34} erg s^{-1} $\sim 10^{0.4} L_\odot$. The infrared and high-energy luminosity is much higher (Genzel *et al.* 1994), but there is no compelling need for a 10^6-M$_\odot$ BH. Mini-AGNs caused by stellar-mass engines are known (e. g., Mirabel *et al.* 1992). So, to find out whether the Galaxy contains a supermassive BH, we need dynamical evidence.

Genzel & Townes (1987) and Genzel *et al.* (1994) review the dynamics of neutral and ionized gas near the center. Velocities of $100-140$ km s^{-1} imply masses of several $\times 10^6$ M$_\odot$ inside 1 pc (Figure 11) *if the gas is in circular motion.* This assumption is not well motivated: as discussed in Genzel *et al.* (1994), stellar winds from luminous young stars combine to make a wind blowing out of the central parsec; a few hundred supernovae are thought to have occurred in the central 10^2 pc in the past 10^4-10^5 y; some noncircular motions are seen, including an expanding bubble of hot gas (Eckart *et al.* 1992). It is surprising that the motions are so close to gravitational. Without confirmation from stellar dynamics, we would not dare to include the Galaxy in Table 1.

Because of optical extinction, stellar velocities are usually measured using K-band CO band heads. From the first papers (Sellgren *et al.* 1987; Rieke & Rieke 1988), masses of 10^6-10^7 M$_\odot$ at $r \lesssim 1$ pc were deduced. McGinn *et al.* (1989) and Sellgren *et al.* (1990) measured spectra of integrated starlight in apertures of $2\farcs7$ – $20''$ diameter. The rotation curve rises in the inner $15'' = 0.6$ pc and then flattens out at $V \simeq 36$ km s^{-1}. The projected dispersion rises from ~ 70 km s^{-1} at $r > 35''$ to 125 km s^{-1} at $r < 20''$. Interestingly, the CO band strength decreases at small radii; the true strength is consistent with zero at $r < 15''$. The authors suggest that the atmospheres of giant stars have been modified (stripped off?) in the dense environment of the nucleus. This limits the resolution to 0.6 pc, not much better than ground-based resolutions in M 31 and M 32. Neglecting projection and anisotropy and assuming that $r_c = 0.4$ pc, McGinn *et al.* (1989) conclude that the mass distribution is inconsistent with the light distribution: it requires $M_\bullet \simeq 2.5 \times 10^6$ M$_\odot$. Sellgren *et al.* (1990) derive $M_\bullet \simeq (5.5 \pm 1.5) \times 10^6$ M$_\odot$.

The best dynamical analyses are by Kent (1992) and by Evans & de Zeeuw (1994). Kent notes that the central K-band starlight is a flattened power law, $\nu \propto r^{-1.85}$. He constructs a flattened, isotropic Jeans equation model that fits the stellar and gas kinematics along the major and minor axes. This requires an MDO of mass $M_\bullet \simeq 3 \times 10^6$ M$_\odot$. Evans & de Zeeuw (1994) make $f(E, L_z)$ models for the same power-law density distribution; these fit the kinematics if $M_\bullet \simeq 2 \times 10^6$ M$_\odot$.

Kinematic measurements of a number of kinds of stars confirm these results (e. g., OH/IR stars: Lindqvist *et al.* 1992; He I stars: Krabbe & Genzel 1993, quoted in Genzel *et al.* 1994). The dynamical mass distribution is compared to that derived from the infrared light distribution in Figure 11. Gas and stellar kinematics agree remarkably well. The conclusion that there is (1 to 3) $\times 10^6$ M$_\odot$ of central dark matter even looks robust to the poorly known core radius of the stars.

However, Haller *et al.* (1995) have remeasured the kinematics with a $1\farcs3$ slit placed at several positions near Sgr A*. From He I lines in hot stars and CO band heads in cool stars, they find masses at $r < 1$ pc that are somewhat lower than those reviewed by Genzel *et al.* (1994). Haller and collaborators raise the possibility that some of the dark matter near the center may be extended in radius. Then $M_\bullet \simeq (1 \text{ to } 2) \times 10^6$ $\mathrm{M}_\odot$.

There is cause for concern in the fact that $M_\bullet$ is decreasing while the MDO detection is not getting more definitive as resolution improves. The Galactic center BH case is fundamentally more uncertain than those of the best candidates. The kinematics are measured using CO bands that disappear in the central 0.5 pc. The observations are sensitive to discreteness and population effects. It is hard to be confident that a particular kinematic tracer is distributed in radius like the 2.2 μm light (which is used to determine $d \ln \nu / d \ln r$ and the stellar mass distribution). Given the peculiar (young? rejuvenated?) stellar population, it is not clear that M/L_K is constant for the stars. And no models have explored anisotropy. On the other hand, we can hope for better spatial resolution than in any other galaxy. The case for an MDO is strong enough to be taken seriously. But further work is needed.

If the Galaxy contains a BH, it is starving in a blizzard of food. This could be embarrassing (Section 7).

Figure 11 Galactic center mass distribution (Genzel *et al.* 1994). The points show dynamical masses derived from various kinematic tracer populations (see text). For two possible core radii, the dashed lines show the mass distribution in stars derived from the K-band brightness distribution assuming $M/L_K = 1.2$.

4.7 *NGC 3377* ($M_\bullet \simeq 8 \times 10^7\, M_\odot$)

NGC 3377 is a normal elliptical galaxy illustrated in the *Hubble Atlas.* At $M_B = -18.8$, it rotates rapidly enough to be nearly isotropic. Its core is tiny, so small radii have large luminosity weight in projection. The axial ratio is 0.5; since no elliptical is much flatter, NGC 3377 must be nearly edge-on. Finally, the distance is only 9.9 Mpc. Therefore NGC 3377 is an excellent target for a BH search.

Kormendy *et al.* (1995b, see Kormendy 1992a) observed NGC 3377 with the CFHT and resolution $\sigma_* \simeq 0\farcs48$. The galaxy is kinematically similar to M 32: $V(r)$ rises rapidly near the center to 100 km s^{-1} and then levels off; $\sigma(r) \simeq 90$ km s^{-1} at $r \gtrsim 2''$ and then rises to 158 ± 11 km s^{-1} at the center. The kinematics are confirmed by Bender *et al.* (1994). Kormendy *et al.* (1995b) show that isotropic kinematic models require an MDO of mass $M_\bullet \simeq 8 \times 10^7\, M_\odot$. They also fail to find anisotropic models that fit without an MDO, but the failure is not large. Therefore this is a weak MDO detection. After M 32, NGC 3377 is only the second elliptical galaxy with stellar-dynamical evidence for an MDO.

4.8 *M 33* ($M_\bullet \lesssim 5 \times 10^4\, M_\odot$)

One BH upper limit deserves discussion. M 33 is a bulgeless Sc galaxy with a nucleus like a giant globular cluster. Kormendy & McClure (1993) observed it with the CFHT and a camera that uses a tip-tilt mirror to partly correct seeing. At resolution $\sigma_* = 0\farcs18$, the limit on the core radius is $r_c < 0.39$ pc. This is as small as the smallest cores in globular clusters. The central surface brightness is one of the highest known (Figure 2). M 33 is an excellent illustration of the fact that an unusually small and dense core is no evidence for a BH unless kinematic measurements show high velocities (Section 3). The central velocity dispersion measured by Kormendy & McClure (1993) is only 21 ± 3 km s^{-1}. The central mass-to-light ratio is $M/L_V \lesssim 0.4$. Since this is required to explain the stellar population, a conservative limit on $M_\bullet$ is the limit on the core mass in stars: $M_\bullet \lesssim 5 \times 10^4$ M$_\odot$. M 33 is the first giant galaxy in which a dead quasar engine can be ruled out.

The central relaxation time, $T_r \lesssim 2 \times 10^7$ y, is so short that core collapse has probably occurred. Also, the center is $\Delta(B - R) = 0.44$ mag bluer than the rest of the nucleus. The color gradient, the F-type spectrum (van den Bergh 1991), and the small M/L ratio imply that the nucleus contains young stars concentrated to the center. Kormendy & McClure (1993) discuss the possibility that the stellar population has been affected by dynamical processes (e. g., stellar collisions).

5. GAS-DYNAMICAL BH SEARCHES

5.1 *M 87 ($M_\bullet \simeq 3 \times 10^9\ M_\odot$)*

M 87 is the father of this subject. Well known for its radio and optical jet (Biretta 1993; Macchetto 1994), it has long been the prototypical AGN galaxy in which to test the BH paradigm. It was the first giant elliptical with CCD photometry; Young *et al.* (1978) found that it has a cuspy core. Sargent *et al.* (1978) showed that its velocity dispersion continues to rise inside the core radius from 278 km s^{-1} at $r = 10''$ to 350 km s^{-1} at $r \simeq 1\overset{''}{.}5$. These observations could be fitted with isotropic dynamical models only if M 87 contained an MDO of mass $M_\bullet \simeq 3 \times 10^9$ M$_\odot$.

But 1978 was the last year in which isotropy could be the default assumption. Illingworth (1977), Binney (1978), and others showed that most giant ellipticals are anisotropic. Models with $\sigma_r > \sigma_{\rm tangential}$ can reproduce the dispersion and brightness profiles of M 87 without an MDO (Duncan & Wheeler 1980; Binney & Mamon 1982; Richstone & Tremaine 1985; Dressler & Richstone 1990). Also, almost all giant ellipticals that are close enough to show resolved cores have profiles like that of M 87 (Lauer 1985a, b; Kormendy 1985, 1987a; HST photometry references in Section 4.1). If cuspy cores were enough to discover BHs, we would know many examples. Similarly, if central gas and dust disks perpendicular to jets (e. g., NGC 4261: Jaffe *et al.* 1993) were enough to reveal BHs, we would have many examples (Kotanyi & Ekers 1979; Kormendy & Stauffer 1987). Then this review could have been written seven years ago, and it would have been mercifully short.

The subsequent history of the BH search in M 87 is reviewed by Sargent (1987), Richstone (1988), Filippenko (1988), Dressler (1989), Kormendy (1993), and van der Marel (1994a). Recently, HST has shown that $I \propto r^{-0.26}$ near the center of M 87 (Lauer *et al.* 1992a), exactly as predicted by Young *et al.* (1978). But this is still not sufficient evidence for a BH (Section 3). Finally, van der Marel (1994a) finds that $\sigma \simeq 400$ km s^{-1} at $r \lesssim 0\overset{''}{.}5$. But he can still explain this with anisotropic models. The stellar-dynamical BH case in M 87 remains ambiguous.

There is hope for progress *via* LOSVDs. BHs make broad power-law wings that extend beyond the escape velocity of the stars (van der Marel 1994a, b). But the LOSVD wings are confused with continuum variations that we do not know how to model. I. e., kinematic measurements and population synthesis are coupled. Exploiting LOSVDs will not be easy.

Gas, on the other hand, tells a clearer story. Using the FWPC2 and HST, Ford *et al.* (1994) have discovered that ionized nuclear gas in M 87 looks like a disk with trailing spiral arms and a major axis that is perpendicular to the jet (Figure 12). Harms *et al.* (1994) used the HST Faint Object Spectrograph and $0\farcs26$ diameter aperture to get spectra centered at $r = \pm 0\farcs25 = 19$ pc along the disk major axis. At a luminosity-weighted mean radius or $\pm 0\farcs22 = 16$ pc, the spectra show emission lines separated by $2V = 916$ km s^{-1}. *If this gas is in circular motion* and if the disk is inclined at 42° as implied by the apparent axial ratio, then M 87 contains a central dark mass of $M_\bullet = 3 \times 10^9$ M$_\odot$ (Table 1). This interpretion is supported by the following arguments, in decreasing order of importance. (i) Velocities at three other positions ($r = 0\farcs35$, $0\farcs56$, and $2''$) agree with the Keplerian disk model. (ii) At the center, the width of the emission lines is FWHM $\simeq 1700$ km s^{-1}. In fact, a large FWHM suggesting that $M_\bullet \simeq 3 \times 10^9$ M$_\odot$ was already seen in ground-based data (van der Marel 1994a, and references therein). (iii) The disk minor axis is within $11° - 20°$ of the position angle of the jet; the inclination of the disk is $i = 42° \pm 5°$, nearly perpendicular to the jet inclination $i = -40°$ inferred by Biretta (1993). (iv) Finally, spiral structure implies disk shearing.

The *caveat* is that gas is easily pushed around. It may not be in circular orbits, in which case it cannot be used to measure $M_\bullet$. We emphasize that non-circular motions are not just an academic worry, they are seen in many active galaxies (e. g., Balick & Heckman 1982; Heckman *et al.* 1993) and non-AGN environments (e. g., Fillmore *et al.* 1986; Kormendy & Westpfahl 1989). The BH case in M 87 can be strengthened (or falsified) by measuring $V(r)$ closer to the center: $0\farcs1$ resolution is feasible, so a test for a Keplerian $V(r)$ is possible.

Figure 12 HST Hα + [N II] image of M 87 (Ford *et al.* 1994). The central ionized gas distribution is elongated perpendicular to the jet.

5.2 *NGC 4258 ($M_\bullet \simeq 4 \times 10^7\, M_\odot$)*

NGC 4258 has an AGN of modest power (Table 1) but great interest. Its optical spectrum shows a low-ionization nuclear emission-line region (LINER, Heckman 1980) with a weak broad-line component (Filippenko & Sargent 1985). Between its normal spiral arms, NGC 4258 has "anomalous" arms seen in Hα (Courtès & Cruvellier 1961; Deharveng & Pellet 1970), radio synchrotron emission (van der Kruit *et al.* 1972; van Albada & van der Hulst 1982), and x-rays (Pietsch *et al.* 1994; Cecil *et al.* 1995). The Hα arms consist of braided components (Ford *et al.* 1986; Cecil *et al.* 1992); the velocity field is complicated (above papers; Rubin & Graham 1990; Dettmar & Koribalski 1990). The canonical explanation is that the nucleus emits jets in the disk plane; these interact with disk gas to produce the anomalous arm emission (above papers; Martin *et al.* 1989; Plante *et al.* 1991). NGC 4258 is therefore a good – albeit unusual – example of the BH paradigm.

A powerful new BH probe is provided by the detection of H_2O maser emission (Claussen *et al.* 1984; Claussen & Lo 1986) including components ± 900 km s^{-1} from the systemic velocity (Nakai *et al.* 1993). Greenhill *et al.* (1995b) show that the systemic-velocity source consists of many masers along a line $0\farcs00026 \times 0\farcs00005 = 0.009 \times 0.002$ pc in extent that is perpendicular to the inner radio jet. Velocities are tightly correlated with position: $dV/dx = 270$ km s^{-1} $(0\farcs001)^{-1} = 7430 \pm 40$ km s^{-1} pc^{-1} along the above line. Greenhill *et al.* (1995b), Watson & Wallin (1994), and Haschick *et al.* (1994) suggest that the masers are in a thin annulus of radius 0.1 pc. Individual maser velocities drift by ~ 9 km s^{-1} y^{-1}, consistent with centripetal acceleration $dV/dt = V^2/r$ in the part of the annulus that is between us and the central source (Haschick *et al.* 1994; Greenhill *et al.* 1995a). Then the high-velocity components imply a rotation velocity of 900 km s^{-1} and a mass $M_\bullet = 2 \times 10^7$ M$_\odot$. These conclusions are model-dependent, but they can be tested.

In an important paper, Miyoshi *et al.* (1995) find strong evidence in favor of the disk model. With the Very Long Baseline Array, they confirm that the high-velocity masers are located $0\farcs005$ to $0\farcs008$ on either side of the central line of sources. The masing physics suggests that they radially span the edge-on torus where it is tangent to the line of sight. Then the path length to us is long at constant velocity, allowing strong maser amplification. Based on this assumption, Miyoshi *et al.* (1995) derive the rotation curve shown in Figure 13. Remarkably, $V(r) = 2180\ (r/0\farcs001)^{-1/2}$ km s^{-1} $= (832 \pm 2)\ [r/(0.25\ \mathrm{pc})]^{-1/2}$ km s^{-1} is Keplerian to high precision. This is a powerful argument for the annular disk model. If the rotation is circular, then the mass interior to $0\farcs005 = 0.18$ pc is $M_\bullet = 4.1 \times 10^7$ M$_\odot$.

If Fig. 13 is correct, then the $M_\bullet$ measurement is more secure than any previous one based on gas dynamics, including that of M 87. This work is vulnerable on at least three counts: (i) The interpretation depends critically on the assumed geometry. The assumptions are conservative in the sense that they minimize $M_\bullet$. But the conclusion that $V \propto r^{-1/2}$ depends on the geometry, too: if the maser sources are differently distributed along the line of sight, then V could vary differently with r. Our confidence in the mass measurement depends on the Keplerian rotation curve. (ii) As usual, it is not certain that gas velocities measure mass. (iii) We do not know that the detected mass is dark. This work also has clear strengths: (i) the gas is molecular; being fragile, it is less likely to have noncircular velocities; (ii) $V(r)$ looks Keplerian, (iii) in terms of (rotation velocity)/(speed of light), the measurements get closer to the BH than in any other candidate except M 87; (iv) there are no uncertainities about the velocity dispersion or its anisotropy; and (v) the gas disk is perpendicular to the jet. Finally, (vi) if $M_\bullet$ were spread out over the central 0.18 parsec, the density would be $\sim 1.6 \times 10^9$ M$_\odot$ pc^{-3}. This is 70 times higher than in the Galaxy (the closest competitor). On the other hand, the *stellar* density at the Galactic center is $\sim 10^8$ M$_\odot$ pc^{-3} (Eckart *et al.* 1993). A 1.6×10^9 M$_\odot$ pc^{-3} star cluster in not excluded, although it would evolve quickly and possibly violently.

Masers are a potentially powerful tool for BH searches. They allow us to probe tiny radii in great physical detail. E. g., acceleration and proper motion measurements can decisively test the NGC 4258 nuclear disk model. Finally, masers are preferentially found in AGN galaxies (Braatz *et al.* 1994), so we may look forward to closer connections between dynamical searches and other parts of the BH paradigm (Section 8).

Figure 13 Rotation curve for maser sources in NGC 4258, from Miyoshi *et al.* (1995). The line is the Keplerian $V(r)$ given in the text.

6. BH DEMOGRAPHICS

Kormendy's CFHT BH search is being extended to 14 E – Sb galaxies with $M_B \lesssim -17.5$ and distance $\lesssim$ 10 Mpc. Evidence for MDOs is seen in $\sim$20 % of these galaxies (M 31, NGC 3115, and NGC 3377). Failures often occur where detection is unlikely because of nuclear starbursts or because the galaxy is too face-on. An example (not from the statistical sample) is NGC 1316 = Fornax A. The central dispersion is only 222 ± 4 km s^{-1} despite an unusually small and dense core (Schweizer 1980; Kormendy 1987b; Fabbiano *et al.* 1994). The core has $M/L_V \simeq 1.5$, presumably due to an ongoing starburst (Schweizer 1980). In such a case it is impossible to conclude anything about whether there is a BH.

It is no accident that MDOs have been found only in galaxies with favorable conditions; i. e., in edge-on bulges with rapidly rotating nuclear disks and in rotating ellipticals. Despite this, we have already found $\gtrsim 10^8$ M$_\odot$ of dark matter per L^* of galaxy luminosity (L^* = characteristic luminosity of the Schechter 1976 luminosity function). This is approximately the mass in dead quasars that is predicted by energy arguments (Sołtan 1982; Rees 1984; Chokshi & Turner 1992).

With eight detections, we can start to look at demographics. If MDOs are BHs, then Fig. 14 shows that BH mass correlates with bulge luminosity. The mean BH mass fraction is $<M_\bullet/M_{\rm bulge}> = 0.0022^{+0.0016}_{-0.0009}$ (we averaged $\log M_\bullet/M_{\rm bulge}$ from Table 1). Omitting the Galaxy, which has the smallest $M_\bullet/M_{\rm bulge} = 0.00017$, $<M_\bullet/M_{\rm bulge}> = 0.0032^{+0.0018}_{-0.0012}$. M 33 is consistent with this correlation, but also with the hypothesis that supermassive BHs are found only in bulges.

Figure 14 BH mass as a function of bulge absolute magnitude. The symbols are the same as in Figure 3. As in Figure 3, the correlation may be only the upper envelope of a distribution that extends to smaller $M_\bullet$.

Figure 15 Correlations with distance D of detected BH mass (*left*) and BH mass divided by bulge mass (*right*).

Figure 15 shows the correlations of $M_\bullet$ and $M_\bullet/M_{\rm bulge}$ with distance. It illustrates the selection effects in the search. Not surprisingly, $M_\bullet$ correlates well with distance. Giant galaxies like M 87 and NGC 4594 are rare; if $M_\bullet \propto M_{\rm bulge}$, then we are unlikely to find 10^9-$\mathrm{M}_\odot$ BHs nearby. This is why the upper-left part of the diagram is empty. On the other hand, 10^7-$\mathrm{M}_\odot$ BHs cannot be detected much outside the Local Group. This ensures that the lower-right part of the diagram will remain empty until we get better spatial resolution.

There is little correlation of $M_\bullet/M_{\rm bulge}$ with D. Most BH detections were approximately equally difficult, a point made also by Rix (1993). NGC 3115 has the largest fractional BH mass and is one of the most definitive detections. M 31 and the Galaxy have small fractional BH masses; a detection was possible in M 31 because the nucleus rotates rapidly and in the Galaxy because the center is so nearby.

7. ARE MDOs TOO BLACK TO BE BLACK HOLES?

If MDOs are BHs, they should accrete nearby matter and radiate some of its binding energy. This insight provides a test of the presence of BHs.

An old stellar population produces 0.015 $\mathrm{M}_\odot$ $(10^9\ L_\odot)^{-1}$ y^{-1} of gas (Faber & Gallagher 1976). For example, gas shed by the bulge of M 31 ($L = 6\times 10^9\, L_\odot$), if accreted at a steady rate onto a BH at 10 % efficiency ($\epsilon_{0.1} \equiv 1$), would provide a luminosity of 10^{11} $L_\odot$. Just the stars that are gravitationally bound to the BH (i. e., at $r \lesssim 6$ pc) already generate $10^8\ \epsilon_{0.1}\, L_\odot$. This greatly exceeds the luminosity of either nucleus.

The situation looks worse in our Galaxy. Geballe *et al.* (1987, and references therein) estimate that IRS 16 emits a wind with velocity $v_w \simeq 700$ km s^{-1} and mass flow rate $\sim 4 \times 10^{-3}$ M$_\odot$ y^{-1}. If all of it were accreted onto a BH, its luminosity would be $10^{43}\,\epsilon_{0.1}$ erg s^{-1} $\simeq 10^{10}\,\epsilon_{0.1}\ L_\odot$. The luminosity of Sgr A* is tremendously uncertain but unlikely to be larger than 10^{40} erg s^{-1} (Genzel *et al.* 1994). This estimate considerably exceeds any output actually observed, but it falls short of the expected accretion luminosity by a factor of $10^3\,\epsilon_{0.1}$. On the other hand, Melia (1992a, 1994) and Melia *et al.* (1992) argue that only part of the wind is accreted, i. e., the gas that passes within $r \simeq 2GM_\bullet/v_w^2$ of the BH. Then the accretion rate is $\sim 10^{-4}$ M$_\odot$ y^{-1}. Melia calculates the resulting spectrum; it agrees with observations over 11 decades in frequency provided that $M_\bullet \simeq (1$ to $2) \times 10^6$ M$_\odot$. The model has problems – it predicts a radio source size that is three times larger than the observed limit at 3 mm (Section 4.6) – but it is reasonably successful. A different model is proposed by Falcke *et al.* (1993a, b), Falcke (1994), and Falcke & Heinrich (1994). They suggest that a dense accretion disk currently accumulates most of the above inflow; then the BH accretion rate is only 10^{-7} to $10^{-8.5}$ M$_\odot$ y^{-1}. However, their disk radiates more efficiently, so it also fits the observed spectrum. Similar models fit M 31 (Melia 1994b; Falcke & Heinrich 1994). So: the accretion physics is still being debated, but there is no clear luminosity problem.

The Falcke model illustrates the easy escape from any BH luminosity problem: we can hypothesize non-steady accretion. It is possible that normal nuclei cycle between an accreting, low-level AGN state and a non-accreting, normal state.

A second fuel source for nuclear BHs is accretion of stars (e. g., Lacy *et al.* 1982; Rees 1988; Goodman & Lee 1989; Phinney 1989; Evans & Kochanek 1989; Rees 1990, 1993, 1994). A BH will tidally disrupt main-sequence stars on relativistic orbits. For sufficiently low-mass BHs, tidal disruption occurs outside the Schwarzschild radius. Half of the stellar mass is likely to be accreted, with an energy output of $10^{53}\ m_*\ \epsilon_{0.1}$ erg. Stars that are initially on doomed orbits will be destroyed within an orbital timescale of the formation of the BH. Later, stars are destroyed at the rate at which these orbits are repopulated.

The rate of repopulation of the "loss cone" (actually more nearly a cylinder) by two-body gravitational interactions is a well studied but very complicated subject originally motivated by the expectation that BHs form in globular clusters. There are two regimes. (i) Sufficiently close to the hole, stars scatter into or out of the loss cone on timescales that are longer than the orbital time. Stars scattered into the cone die almost instantly and the loss cone is empty. In this case, the calculation of the disruption rate is complicated by the necessity to treat this empty part of phase space as a boundary condition on the evolution of the phase space density of stars. (ii) Farther from the hole, the timescale for small changes in rms angular momentum is short compared to an orbital time, so the loss cone is populated. Estimates of stellar disruption are complicated by the likelihood that stars will scatter out of the loss cone before reaching the perilous environs of the BH. In either case, it is clear on dimensional grounds that the stellar destruction rate is bounded from above by $dN/dt = N/t_r$, where t_r is the half-mass relaxation time and N is the number of stars bound to the BH (that is, with $r < r_{\rm cusp} \equiv GM_\bullet/\sigma^2$). Improving on this limit is difficult. The reader is referred to a very lucid review by Shapiro (1985) and to Cohn & Kulsrud (1978), particularly their Equation 66:

$$dN/dt = 0.018\ M_8^{2.33}\ n_4^{1.60} \left[\frac{\sigma^2}{(100\ {\rm km\ s^{-1}})^2}\right]^{-2.88} m_*^{1.06}\ r_*^{0.40}\quad {\rm y}^{-1}. \quad (3)$$

Here $M_8 = M_\bullet/(10^8 M_\odot)$, n_4 is the stellar density at the cusp radius $r_{\rm cusp}$ in units of 10^4 pc^{-3}, and m_* and r_* are the typical stellar mass and radius in solar units.

Applying these equations to M 31, for $M_8 = 0.3$ (Table 1), $r_{\rm cusp} \simeq 6$ pc, and $n_4 = 1$ (Lauer *et al.* 1993), we find a stellar disruption rate of 10^{-4} y^{-1}. This is consistent with Rees (1988) and with Goodman & Lee (1989). What happens to the shattered star? Tidal breakup occurs at a radius $r_t = 2.3 \times 10^{13} M_8^{1/3} m_*^{-1/3} r_*$ cm. The Schwarzschild radius of the BH is $r_s = 3.0 \times 10^{13} M_8$ cm. So for $M_8 < 1$, solar-mass main-sequence stars are disrupted outside the Schwarzschild radius and the fireworks should be visible. Note that the rate of breakup flashes could be greatly enhanced over the above estimate by the accretion of a second BH or even of a secondary nucleus. Since one or both of these things may be happening in M 31, the current rate of stellar breakup flashes could be much larger than the above estimate.

The least certain aspect of this problem is the duration and spectrum of a flash. The stream of bound debris from the shattered star will self-intersect within months. The gas should shock and transfer angular momentum efficiently. Rapid relativistic perhelion precession probably precludes the formation of an elliptical disk, so the timescale for the event is likely to be $\lesssim 1$ y. On the other hand, Cannizzo *et al.* (1990) note that at late times there is a self-similar disk accretion solution that may preserve a power-law decay for many years. If they are correct, then the inactivity of M 31 is a serious argument against a nuclear BH.

We are unaware of any calculation of the spectrum of the flashes. If the debris forms dust rapidly and becomes optically thick, then the radiation will be reprocessed in a region significantly larger than r_t, and most of the signal will emerge in the infrared (as emphasized by Rees). If, on the other hand, the stellar orbital angular momentum is aligned with that of the BH, or if the BH has negligible angular momentum, then the debris may orbit in a plane and the luminosity may be dominated by the inner edge of the accretion disk. Then the temperature could be 500,000 K. The resulting spectrum would peak in the extreme ultraviolet or soft x-ray band (Sembay & West 1993). Given a large sample with diverse angular momenta, x-ray and infrared flashes both probably occur.

Considering the possibly short duty cycle and its uncertainties, the absence of activity in M 31 or in any other BH candidate is not terribly disturbing. Some low level AGNs noted by Filippenko & Sargent (1985, 1987) may even be powered by stellar breakup flashes. A key test of the BH paradigm is nevertheless implied. A survey of 10^4 galaxies should yield one stellar breakup flash per year at luminosities exceeding those of supernovae. Periodic imaging of a set of clusters of galaxies should be informative very quickly (Rees 1994). It is even possible that several hundred x-ray flashes have already been detected in the *ROSAT* all-sky survey (Sembay & West 1993).

8. CONCLUSION

Have we discovered BHs in galaxy nuclei? Rigorously, we have not. Dynamical proof requires measurement of relativistic velocities near the Schwarzschild radius, $r_s \simeq 2\,M_8$ AU $\simeq M_8 \times 10^{-5}$ pc. Even for M 31, this is 3×10^{-6} arcsec. HST spectroscopic resolution is only $0\overset{''}{.}1$. What dynamical searches have contributed is the first solid evidence for massive dark objects (MDOs) in galaxy nuclei. In Section 2, we called this step 1 of the BH search. The dynamics also show that $M_\bullet$ is in the range expected for quasar engines, and they tell us a little about MDO demographics. Are MDOs BHs? The arguments are inconclusive. Steps 2 and 3 – proof that MDOs are (or are not) BHs and the study of BH statistics – are barely begun.

If the BH picture is compelling, it is because of the combination of dynamical searches and AGN evidence. A review of AGNs is beyond the scope of this paper, but it is useful to recall the observations that point most directly to BHs. (i) Superluminal jets show that AGN engines are relativistically compact. (ii) AGN engines remember jet ejection directions for a long time, suggesting that they are good gyroscopes. (iii) Rapid time variability and very long baseline interferometry show that AGN engines are tiny. (iv) The prodigious energy output of quasars requires that AGN engines be very efficient.

These are also the strongest arguments against the best alternative to the BH picture: that AGNs are powered by starbursts (e. g., Terlevich &

Melnick 1985; Terlevich *et al.* 1987, 1993; Filippenko 1989, 1991, 1992b, 1993; Heckman 1991; Terlevich 1992; Tenorio-Tagle *et al.* 1992; Terlevich & Boyle 1993; meetings devoted to this subject include Filippenko 1992a; Beckman *et al.* 1993). It is difficult to imagine that a starburst can produce a superluminal jet or a jet that stays collimated over a Mpc. Something like a BH is required even if AGNs are partly powered by starbursts. In addition, starburst energy conversion efficiencies are a factor of ~ 10 lower than those of BHs, so the starburst model predicts MDO masses of $\gtrsim 10^{10}$ $M_\odot$ for dead quasars. If such massive MDOs existed within 15 Mpc of us, we would not be struggling to find them. Other arguments against the extreme starburst hypothesis are given in Heckman (1994). But no observation conflicts with the idea that starbursts play a role in quasar formation (Sanders *et al.* 1988a, b), and it is possible that some low-level AGNs are powered entirely by starbursts (see the above references; Filippenko *et al.* 1993). Meanwhile, AGN observations and theory, and now the results of the dynamical searches, make a compelling picture in favor of the BH paradigm.

Still, we cannot help but note that this rosy picture is not developing as a correct paradigm should. The dynamical searches and AGN results have remained almost decoupled. The galaxies with stellar-dynamical evidence for BHs are spectacularly inactive. Table 1 lists nuclear radio continuum fluxes. M 31 contains the lowest-luminosity radio AGN known (Crane *et al.* 1992, 1993a). Sgr A* and M 32 are comparably weak. Because of its inactivity, NGC 3115 has been used as an emission-line–less spectral standard in searches for low-level AGNs (Filippenko & Sargent 1985; Ho *et al.* 1993). Among stellar-dynamical BH cases, only NGC 4594 is somewhat active. It contains a LINER (Heckman 1980), i. e., a dwarf Seyfert 1 nucleus (Hα width at zero intensity ~ 5400 km s^{-1}: Filippenko & Sargent 1985, 1987). But NGC 4594 is an order of magnitude lower in radio luminosity than M 87. Even M 87 is a weak radio galaxy. In contrast, many AGNs that are no farther away show no dynamical evidence for BHs. To be sure, as Dressler has said, BHs are not easily discovered when we have a searchlight in our eyes. Also, there is every reason to expect dead AGNs all around us. But our confidence is not helped by the fact that galaxies with MDOs are so inactive while AGN BHs are so elusive.

This is why the M 87 and NGC 4258 results (Section 5) are so welcome. M 87 epitomizes the AGN paradigm. Now the detection of a nuclear gas disk perpendicular to the jet and with velocities implying a BH of just the right mass is the first direct contact between BH searches and the rest of the paradigm. It will be important to check whether the disk is in Keplerian rotation and hence whether the velocities measure mass. But the apparent detection of a Keplerian rotation curve in NGC 4258 already increases our confidence in gas-dynamical BH searches.

Which leads us to our "top ten" wish list:

1 – We need to address any lingering doubts about the best BH cases. This requires at least one iteration in improved spatial resolution over the discovery observations plus dynamical models that explore the boundary between extreme models with constant M/L and ones that contain BHs.

2 – Theory may help us to eliminate some models. Reducing M/L requires radial anisotropy; such models may be unstable (e. g., Merritt 1987; Stiavelli *et al.* 1993; Bertin *et al.* 1994, and references therein).

3 – Shortcuts for the identification of BH candidates would be helpful. For example, Kormendy (1992a, b, 1993) showed that BH candidates deviate from the core fundamental plane correlations: they have large apparent central velocity dispersions for their core parameters.

4 – Further work on emission-line velocity fields is promising.

5 – Our ultimate goal is to understand BH demographics. At a minimum, we want to know the frequency of occurrence and mass function of BHs as a function of Hubble type. This will be expensive.

6 – Surely the most fundamental challenge is to show whether or not MDOs are BHs. Our observations are 10^5 Schwarzschild radii away from the action. The obvious way to get closer is to look at more energetic photons. One possibility is x-ray spectroscopy. But gas will always be responsive, and gas-dynamical searches will always be uncertain.

The issue is important. Even if AGNs are not *primarily* starbursts, starbursts happen, and Terlevich and collaborators correctly point out that they leave remnants. In detecting MDOs, could we just be finding those dead star clusters? In fact, given our present ignorance, can we even be sure that MDOs are not concentrations of halo dark matter?

7 – So: work on alternatives to the BH paradigm is still desirable.

8 – How did BHs form? Kormendy (1988b) points out that core relaxation times are almost everywhere so long that BH formation via dynamical evolution – e. g., core collapse – seems impossible. Rees (1984) suggests formation mechanisms that do not depend on relaxation; we do not know which (if any) are correct. The problem is particularly acute because quasars turned on so early in the history of the Universe: BHs must have formed quickly (e. g., Rees 1990, 1993). As long as BH formation remains obscure, we have a glaring hole in the AGN paradigm.

9 – Should MDOs be so inactive? Predictions of flaring frequencies (Section 7) may lead to tests of the BH picture.

10 – More generally, we need to look for points of contact between dynamical BH searches and the AGN paradigm. Confidence and progress both are at stake.

This review is being written at a time of unusually rapid progress. We discussed ongoing work as much as possible. But stay tuned: by the time this paper appears, HST should begin to provide stellar-dynamical results on the most important BH candidates.

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