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SUPERMASSIVE BLACK HOLES IN GALACTIC NUCLEI

Observational Evidence and Some Astrophysical Consequences

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Abstract. I review the status of observational determinations of central masses in nearby galactic nuclei. Results from a variety of techniques are summarized, including ground-based and space-based optical spectroscopy, radio VLBI measurements of luminous water vapor masers, and variability monitoring studies of active galactic nuclei. I will also discuss recent X-ray observations that indicate relativistic motions arising from the accretion disks of active nuclei. The existing evidence suggests that supermassive black holes are an integral component of galactic structure, at least in elliptical and bulge-dominated galaxies. The black hole mass appears to be correlated with the mass of the spheroidal component of the host galaxy. This finding may have important implications for many astrophysical issues.

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1.MOTIVATION

The discovery of quasars in the early 1960's quickly spurred the idea that these amazingly powerful sources derive their energy from accretion of matter onto a compact, extremely massive object, most likely a supermassive black hole (SMBH; Zel'dovich & Novikov 1964; Salpeter 1964; Lynden-Bell 1969) with $M \simeq 10^6 - 10^9\ M_\odot$. Since then this model has provided a highly useful framework for the study of quasars, or more generally, of the active galactic nucleus (AGN) phenomenon (Rees 1984; Blandford & Rees 1992). Yet, despite its success, there is little empirical basis for believing that this model is correct. As pointed out by Kormendy & Richstone (1995, hereafter KR), our confidence that SMBHs must power AGNs largely rests on the implausibility of alternative explanations. To be sure, a number of characteristics of AGNs indicate that the central engine must be tiny and

that relativistic motions are present. These include rapid X-ray variability, VLBI radio cores, and superluminal motion. However, solid evidence for the existence of SMBHs in the centers of galaxies has, until quite recently, been lacking.

As demonstrated by Soltan (1982), simple considerations of the quasar number counts and standard assumptions about the efficiency of energy generation by accretion allows one to estimate the mean mass density of SMBHs in the universe. The updated analysis of Chokshi & Turner (1992) finds $\rho_\bullet \approx 2 \times 10^5 \varepsilon_{0.1}^{-1}\ M_\odot\ \mathrm{Mpc}^{-3}$ for a radiative efficiency of $\varepsilon = 0.1\varepsilon_{0.}$ Comparison of $\rho_\bullet$ with the B-band galaxy luminosity density of $1.4\times10^8 h\ L_\odot\ \mathrm{Mpc}^{-3}$ (Lin et al. 1996), where the Hubbl constant $H_0 = 100h$ km s^{-1} Mpc^{-1}, implies an average SMBH mass per unit stellar luminosity of $\sim 1.4\times10^{-3} \varepsilon_{0.1}^{-1} h^{-1}\ M_\odot / L_\odot$. A typical bright galaxy with $L_B^* \approx 10^{10} h^{-2}\ L_\odot$ potentially harbors a SMBH with a mass $\gtrsim 10^7 \varepsilon_{0.1}^{-1}\ h^{-3}\ M_\odot$. These very general arguments lead one to conclude that "dead" quasars ought to be lurking in the centers of many nearby luminous galaxies.

The hunt for SMBHs has been frustrated by two principal limitations. The more obvious of these can be easily appreciated by nothing that the "sphere of influence" of the hole extends to $r_h \simeq GM_\bullet / \sigma^2$ (Peebles 1972; Bahcall & Wolf 1976), where G is the gravitational constant and σ is the velocity dispersion of the stars in the bulge, or, for a distance of D, ~ 1" $(M_\bullet / 2 \times 10^8\ M_\odot)(\sigma / 200\ \mathrm{km\ s^{-1}})^{-2}(D/5\ \mathrm{Mpc})$. Typical ground-based observations are therefore severely hampered by atmospheric seeing, and only the heftiest dark masses in the closest galaxies can be detected. The situation in the last few years has improved dramatically with the advent of the *Hubble Space Telescope (HST)* and radio VLBI techniques. The more subtle complication involves the actual modeling of the stellar kinematics data, and in this area much progress has also been made recently as well.

Here I will highlight some of the observational efforts during the past two decades in searching for SMBHs, concentrating on the recent advances. Since this contribution is the only one that discusses nuclear BHs aside from that in the Milky Way (Ozernoy, these proceedings) and in NGC 4258 (Miyoshi, these proceedings), I will attempt to be as comprehensive as possible, although no claim to completeness is made, as this is a vast subject and progress is being made at a dizzying pace. To fill in the gaps, I refer the reader to several other recent review papers, each of which has a slightly different emphasis (KR; Rees 1998; Richstone 1998; Ford et al. 1998; van der Marel 1999).

2. EARLY CLUES FROM PHOTOMETRY

The prospect of finding massive BHs in globular clusters motivated much early effort to investigate the distribution of stars resulting from the adiabatic growth of a BH in a preexisting stellar system. The central density deviates strongly from that of an isothermal core and instead follows a cuspy profile $\rho(r) \propto r^{-3/2}$ (Young 1980) or steeper if two-body relaxation (Peebles 1972; Bahcall & Wolf 1976) or different initial density profiles (Quinlan, Hernquist, & Sigurdsson 1995) are taken into account. The discovery that the centers of some giant elliptical galaxies obey this prediction generated much enthusiasm for the existence of SMBHs. In the well-known case of M87 (Young et al. 1978), Lauer et al. (1992) have since shown that the central cusp persists to the limit of the resolution of the *HST* (0".1).

However, as emphasized by Kormendy (1993; see also KR), photometric signatures alone do not uniquely predict the presence of a SMBH. The cores of most galaxies are now known to be nonisothermal. And moreover, contrary to naïve expectations, galaxy cores with high central surface brightnesses and small core radii, far from being the ones most likely to host SMBHs, are in fact *least* expected to do so. This apparently contradictory statement can be most easily understood by considering the so-called fundamental-plane relations for the spheroidal component of galaxies (Faber et al. 1987; Bender, Burstein & Faber 1992). More luminous, more massive galaxies tend to have more massive central BHs (Section 7), but they also have larger, more diffuse cores. Indeed, high-resolution photometric studies of early-type galaxies (Nieto et al. 1991; Crane et al. 1993; Jaffe et al. 1994; Lauer et al. 1995) find that the central surface brightness profiles either continue to rise toward the center as $I(r) \propto r^{-\gamma}$, with $\gamma \approx 0.5$-1.0 (the "power-law" galaxies) or they flatten at some characteristic radius to a shallower slope of $\gamma \approx 0.0$-0.3 (the "core" galaxies). The power-law galaxies are invariably lower luminosity, lower mass systems compared to those with distinct cores.

In summary, photometric signatures alone cannot be used as reliable indicators for the presence of SMBHs. Instead, we must turn to the more arduous task of obtaining kinematic measurements.

3. METHODS BASED ON STELLAR KINEMATICS

Contrary to the ambiguity of light profiles, the Keplerian rise in the velocity dispersion toward the center, $\sigma(r) \propto r^{-1/2}$, is a robust prediction for a wide variety of dynamical models containing a central massive dark object (MDO; Quinlan et al. 1995). Sargent et al. (1978) noticed that the innermost velocities of M87 were consistent with such a prediction, and, assuming an

isotropic velocity distribution, they inferred that the center of this galaxy contained a dark mass of ~ 5×10^9 $M_\odot$, presumably in the form of a SMBH. The central rise in $\sigma(r)$, unfortunately, can be insidiously mimiced by an anisotropic velocity distribution, and therefore an MDO is *not* required by the data for this object (Duncan & Wheeler 1980; Binney & Mamon 1982; Richstone & Tremaine 1985; Dressler & Richstone 1990; van der Marel 1994a). This degeneracy presents a serious difficulty for many mass determinations based on stellar kinematic data. An extensive and lucid discussion of this vast subject was presented by KR, and many of the details will not be repeated here. Nonetheless, an abbreviated synopsis is needed to motivate the topic.

Following the notation of KR, the radial variation in mass can be expressed by the first velocity moment of the collisionless Boltzman equation,

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

where V is the rotational velocity, σ_r is the radial and σ_θ and σ_ϕ the azimuthal components of the velocity dispersion, and ν is the density of the tracer population. In practice, several simplifying assumptions are adopted: (1) the mass distribution is spherically symmetric; (2) the mean rotation is circular; and (3) ν is proportional to the luminosity density, or, equivalently, that M/L does not vary with radius.

A brief scrutiny of the above equation indicates that the effects of velocity anisotropy can have a large and complicated effect on the derivation of $M(r)$ because the terms inside the bracket significantly affect the $\sigma_r^2\, r / G$ term. If $\sigma_r > \sigma_\theta$ and $\sigma_r > \sigma_\phi$, each of the last two terms will be negative and can be as large as -1. The central brightness distributions of the spheroidal component of most galaxies typically have $-(d\ln \nu / d\ln r) \gtrsim +1.1$ for luminous, nonrotating systems and $\gtrsim +2$ for low intermediate-luminosity systems (e.g., Faber et al. 1997). Since $-(d\ln \sigma_r^2 / d\ln r) \leq +1$, it is apparent that, under suitable conditions, all four terms can largely cancel one another. As emphasized by KR, all else being equal, smaller, lower luminosity galaxies such as M32 potentially yield more secure mass determinations than massive galaxies like M87 because less luminous systems tend to have (1) steeper central light profiles, (2) a greater degree of rotational support, and (3) less anisotropy.

The principles behind the stellar kinematics analysis are conceptually straightforward but in practice technically challenging. Given the set of observed quantities $I(r)$, $V(r)$, and $\sigma(r)$, the goal is to derive a range intrinsic values for these quantities after accounting for projection and the blurring effects of seeing. Much of the machinery for these tasks has been developed and extensively discussed by Kormendy (1988a, b) and Dressler & Richstone (1988). The sensitivity of the results to the effects of anisotropy are examined through maximum-entropy dynamical models (Richstone & Tremaine 1984, 1988) to see whether conclusions regarding the presence of MDOs can be obviated by a suitable exploration of parameter space. Perhaps the most serious limitation of these maximum-entropy models is that they do not properly take flattening into account.

The last several years have seen a resurged interest in improving the techniques of analyzing stellar kinematics data. In the context of SMBH searches, Gerhard (1993), van der Marel et al. (1994a, b), Dehnen (1995), among others, have stressed the importance of utilizing the full information contained in the velocity profile or line-of-sight velocity distribution (LOSVD) of the absorption lines, which are normally treated only as Gaussians. A system with significant rotation, for instance, can leave a measurable skewness on the LOSVD, while various degrees of anisotropy would imprint symmetric deviations from a Gaussian line shape. Neglecting these subtleties can lead to systematic errors in the measurement of $V(r)$, but in the cases best studied so far these effects do not seem to have been severe (KR). Furthermore, the line profile should develop weak, high-velocity wings if a SMBH is present (van der Marel 1994b), although the currently available data do not yet have the requisite quality to exploit this tool.

Yet another advance has focused on the development of dynamical models with two-integral phase-space distribution functions, $f(E, L_z)$, E being the total energy and L_z the angular momentum in the symmetry axis (van der Marel et al. 1994b; Qian et al. 1995; Dehnen 1995). Such models are properly flattened, and they generate predictions for the LOSVDs; on the other hand, it is not clear whether imposing a special dynamical structure is too restrictive. This limitation will be eliminated by fully general, axisymmetric three-integral models (van der Marel et al. 1998; Cretton et al. 1999; Gebhardt et al. 1998).

There are currently 10 galaxies with published MDO measurements determined from stellar kinematical data (Table 1). Of these, only three (M81: Bower et al. 1996; NGC 3379: Gebhardt et al. 1998; NGC 4342: van den Bosch 1998) come solely from *HST* data; the remaining ones, although many by now confirmed with *HST*, were initially discovered from high-quality ground-based observations (see KR for a detailed account of each object). Kormendy and collaborators, in particular, making use of the excellent seeing conditions and instrumentation on the CFHT, continue to make progress in this area. Two new MDOs have been reported recently based on CFHT data: the low-luminosity elliptical galaxy NGC 4486B has $M_{MDO} = 6 \times 10^8$ $M_\odot$

(Kormendy et al. 1997b), and NGC 3377, another close cousin, has $M_{MDO} = 2.3 \times 10^8$ $M_\odot$ (Kormendy et al. 1998). This demonstrates the important fact that even in the *HST* era ground-based observations continue to play an important role in SMBH searches.

The new observations with *HST*, thus far all acquired using the Faint Object Spectrograph (FOS), provide an important contribution by increasing the angular resolution by about a factor of 5 compared to the best ground-based data available. In all cases studied (NGC 3115: Kormendy et al. 1996; NGC 4594: Kormendy et al. 1997a; M32: van der Marel et al. 1997; M31: Ford et al. 1998), the velocity dispersions continue to rise toward smaller r and the maximum rotational velocity has generally increased (Fig. 1). In the case of NGC 3115, the FOS spectra are of sufficient quality to reveal wings in the LOSVD that extend up to ~ 1200 km s^{-1} (Kormendy et al. 1996). The *HST* data thus considerably bolster the case for a MDO in these objects. The improvement in angular resolution additionally strengthens our confidence that the MDOs might indeed be SMBHs. A reduction of the size scale by a factor of 5 increases the central density by more than two orders of magnitude. Although in general this is still not enough to rule out alternative explanations for the dark mass (Section 6), it is clearly a step in the right direction.

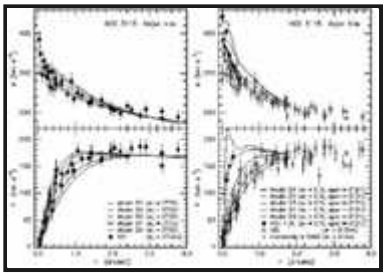

Figure 1. Stellar kinematic data for NGC 3115 compared with various dynamical models (see Kormendy et al. 1996). The *left* panel shows the best ground-based data, and the *right* panel the same data with new *HST* data superposed for comparison. Both V and σ rise much more steeply with radius in the new *HST* data.

I conclude this section with a few remarks on the dark mass in the Galactic Center (see Ozernoy in these proceedings for more details), which, in my view, is now the most compelling case of a SMBH in any galactic nucleus. From analysis of an extensive set of near-IR radial velocities of individual stars, coupled with additional measurements from the literature, Genzel et al. (1996; see also Krabbe et al. 1995) found a highly statistically significant rise in the radial velocity dispersion between 5 and 0.1 pc from the dynamical center. Assuming an isotropic velocity distribution, the observations require a dark mass of ~ 3×10^6 $M_\odot$ within $r = 0.1$ pc and $M/L_K \geq 100$; the dark mass must have a density in excess of 10^9 $M_\odot$ pc^{-3}, which argues strongly for it being a SMBH. These conclusions, and a suspicion nearly three decades old (Lynden-Bell & Rees 1971), have finally been vindicated by recent measurements of stellar proper motions within the central 1 pc region using high-resolution K-band astrometric maps (Eckart & Genzel 1996, 1997; Genzel et al. 1997; Ghez et al. 1998). The main results are the following: (1) the stellar radial velocities agree with the proper motions, which implies that on average the velocities are close to isotropic; (2) the combined velocities imply a dark mass (Fig. 2) within 0.006 pc of 2.61×10^6 $M_\odot$ (Genzel et al. 1997 quote a statistical error of ± 0.15 and a combined statistical and systematic error of ± 0.35); (3) the density, therefore, has an astonishingly high value of $> 2 \times 10^{12}$ $M_\odot$ pc^{-3}, which leaves almost no room to escape the conclusion that the dark mass must be in the form of a SMBH (Section 6). The presence of a large mass is also supported by the detection of several stars, within 0.01 pc from the central radio source Sgr A*, moving at speeds in excess of 1000 km s^{-1}. From the velocities of the fast-moving stars and the near stationarity of Sgr A*, Genzel et al. further use equipartition arguments to constrain the mass of the radio core itself ($\geq 10^5$ $M_\odot$), which, when combined with the exceedingly small upper limit for its size ($r < 4 \times 10^{-6}$ pc), would imply a density of $> 3 \times 10^{20}$ $M_\odot$ pc^{-3}.

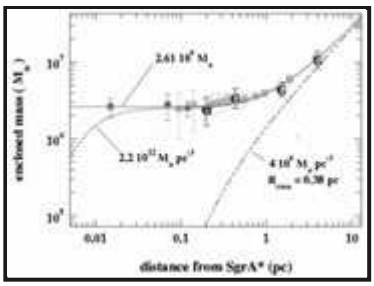

Figure 2. Enclosed mass versus radius for the Galactic Center derived from stellar radial velocities and proper motions (from Genzel et al. 1997). The points labeled with "G" come from gas kinematics. The *thick dashed* curve is a model for the stellar cluster with a total mass density of 4×10^6 $M_\odot$ pc^{-3}; the *solid* curve denotes the sum of this cluster and a point mass of 2.61×10^6 $M_\odot$; and *thin dashed* curve is the sum of the stellar cluster and an additional dark cluster with a central density of 2.2×10^{12} $M_\odot$ pc^{-3}.

4. METHODS BASED ON GAS KINEMATICS

Unlike the situation for stars, gas kinematics are much easier to interpret if the gas participates in Keplerian rotation in a disklike configuration. But there are two caveats to remember. First, gas can be easily perturbed by nongravitational forces (shocks, radiation pressure, winds, magnetic fields, etc.). Indeed, in the case of the Galactic Center, it was precisely this reason that its central mass, which had been estimated for some time using gas velocities (Lacy et al. 1980), could not be accepted with full confidence prior to the measurement of the stellar kinematics. Second, there is no *a priori* reason that the gas should be in dynamical equilibrium, and therefore one must verify empirically that the velocity field indeed is Keplerian. The optically-emitting ionized gas in the central regions of some spirals show significant noncircular motions (e.g., Fillmore, Boroson, & Dressler 1986). NGC 4594 is a striking example. Kormendy et al. (1997a) showed that the emission-line rotation curve near the center falls substantially below the circular velocities of the stars, and hence the gas kinematics cannot be used to determine the central mass.

4.1. Optical Emission Lines

The sharpened resolution of the refurbished *HST* has revealed many examples of nuclear disks of dust and ionized gas (Fig. 3). The nuclear disks typically have diameters ~ 100-300 pc, with the minor axis often aligned along the direction of the radio jet, if present. Some examples include the elliptical galaxies NGC 4261 (Jaffe et al. 1993), M87 (Ford et al. 1994), NGC 5322 (Carollo et al. 1997), and NGC 315 (Ho et al. 1997), and the early-type spiral M81 (Devereux, Ford, & Jacoby 1997). I will highlight here only three cases; Table 1 gives a complete list of objects and references.

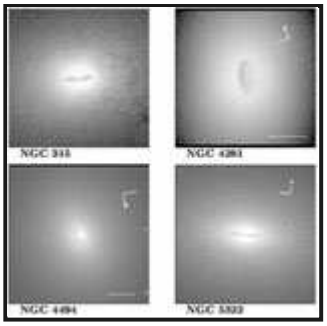

Figure 3. Nuclear disks from *HST* optical images. Each image is 35" on a side.

The first object for which the nuclear gas disk was used to determine the central mass was M87. Harms et al. (1994) used the FOS to obtain spectra of several positions of the disk and measured a velocity difference of ± 1000 & km& s^{-1} at a radius of 0".25 (18 pc) on either side of the nucleus. Adopting an inclination angle of 42° determined photometrically by Ford et al. (1994), the velocities were consistent with Keplerian motions about a central mass of (2.4± 0.7) × 10^9 $M_\odot$. Since the implied $M / L_V \approx 500$, Harms et al. concluded that the central mass is dark, most likely in the form of a SMBH. The case for a SMBH in M87 has been considerably strengthened through the recent reobservation with *HST* by Macchetto et al. (1997), who used the long-slit mode of the Faint Object Camera to obtain higher quality spectra extending to r = 0".05 (3.5 pc). The velocities in the inner few tenths of an arcsecond are well fitted by a model of a thin disk in Keplerian rotation (Fig. 4), although the inclination angle is not well constrained (47°-65°). The rotation curve at larger radii falls below the Keplerian curve, possibly indicating a warp in the disk (Macchetto et al. 1997) or substantial perturbations due to spiral shocks (Chakrabarti 1995). For i = 52°, M_{MDO} = (3.2± 0.9) × 10^9 $M_\odot$, and $M / L_V \gtrsim 110$. If, instead, a Plummer potential is assumed, the distributed dark mass can have a core radius no larger than ~ 5 pc. So, in either case, a density ~ 10^7 $M_\odot$ pc^{-3} is implied.

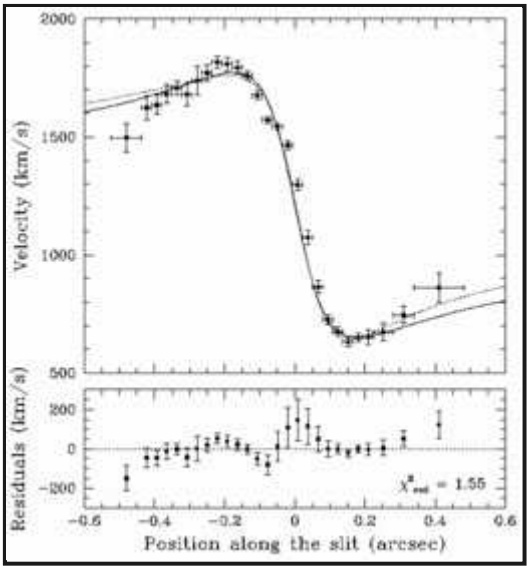

Figure 4. Optical emission-line rotation curve for the nuclear disk in M87. The two curves in the upper panel correspond to Keplerian thin disk models, and the bottom panel shows the residuals for one of the models (see Macchetto et al. 1997).

The mildly active nucleus of NGC 4261 contains a rotating disk of dust and ionized gas as well (Ferrarese, Ford, & Jaffe 1996); like M87, the disk is slightly warped and shows traces of weak spiral structure. Although the FOS data for this object are rather noisy, they indicate that the gas largely undergoes circular motions. The mass interior to r = 15 pc is M_{MDO} = (4.9± 1.0) × 10^8 $M_\odot$, and M/L_V has an exceptionally high value of 2 × 10^3.

The installation of the imaging spectrograph STIS in 1997 at long last gives *HST* an efficient means to obtain spatially resolved spectra of the central regions of galaxies. Much progress in the field is anticipated in the near future. A taste of what might be expected can be seen in the early-release observations of M84 by Bower et al. (1998; Fig. 5). M84 is almost a twin of M87 in terms of luminosity, and its central dark mass (1.5×10^9 $M_\odot$), too, is similar.

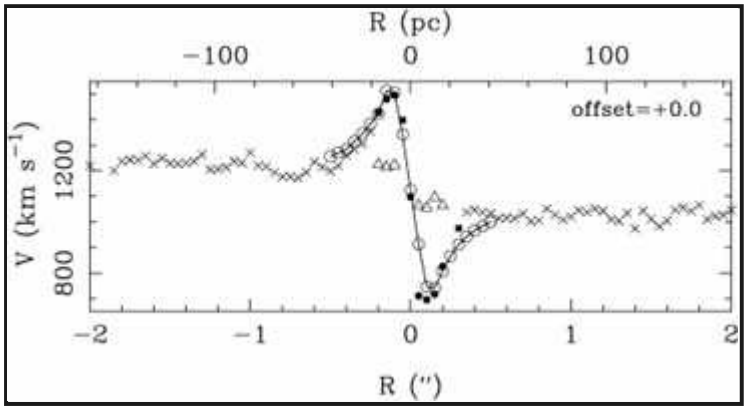

Figure 5. Optical emission-line rotation curve for the nuclear disk in M84 obtained with STIS on *HST* (Bower et al. 1998). The kinematics can be well fitted with a thin Keplerian disk model, which is plotted as open circles connected by the solid line.

Lastly, I mention an interesting, unconventional case. The radio galaxy Arp 102B belongs to a minority of AGNs that display so-called double-peaked broad emission lines. Several ideas have been proposed for the peculiar line profiles in this class of objects, but the favored explanation is that the lines originate from a relativistic accretion disk (Eracleous et al. 1997). During the course of a long-term optical monitoring of Arp 102B , the intensity ratio of the two peaks of the Hα line displayed sinusoidal variations with a period of 2.2 years for several years (Newman et al. 1997). The periodic signal was interpreted as arising from a "hot spot" in the accretion disk. By modeling the line profile from the epochs when the hot spot was quiescent, one can estimate the radius and inclination angle of the spot's orbit, and, combined with its period, the enclosed mass. The mass within r = 0.005 pc turns out to be 2.2×10^8 $M_\odot$, consistent with a moderately luminous (M_B & ≈ -20 mag) elliptical (see Section 7).

4.2. Radio Spectroscopy of Water Masers

Luminous 22-GHz emission from extragalactic water masers are preferentially detected in galaxies with active nuclei, where physical conditions, possibly realized in a circumnuclear disk (Claussen & Lo 1986), evidently favor this form of maser emission. With the detection in NGC 4258 of high-velocity features offset from the systemic velocity by ~ ± 900 & km& s^{-1} (Nakai, Inoue, & Miyoshi 1993), Watson & Wallin (1994) already surmised that the maser spectrum of this Seyfert galaxy can be interpreted as arising from a thin Keplerian disk rapidly rotating around a mass of ~ 10^7 $M_\odot$. But the solid proof of this picture came from the high-resolution ($\Delta\theta$ = 0".0006 × 0".0003; Δv = 0.2 & km& s^{-1}) VLBA observations of Miyoshi et al (1995) who demonstrated that the maser spots trace a thin (< 0.003 pc), nearly edge-on annulus with an inner radius of 0.13 pc and an outer radius of 0.26 pc. The systemic features lie on the near side of the disk along the line-of-sight to the center (Fig. 6); the high-velocity features delineate the edges of the disk on either side and follow a Keplerian rotation curve to very high accuracy ($\lesssim$ 1%). The implied binding mass within 0.13 pc is 3.6×10^7 $M_\odot$, which corresponds to a density of > 4×10^9 $M_\odot$ pc^{-3}. In fact, one can place a tighter constraint on the density. The maximum deviation of the velocities from a Keplerian rotation curve limits the extent of the central mass to $r \lesssim$ 0.012 pc (Maoz 1995), from which follows that the density must be > 5×10^{12} $M_\odot$ pc^{-3}.

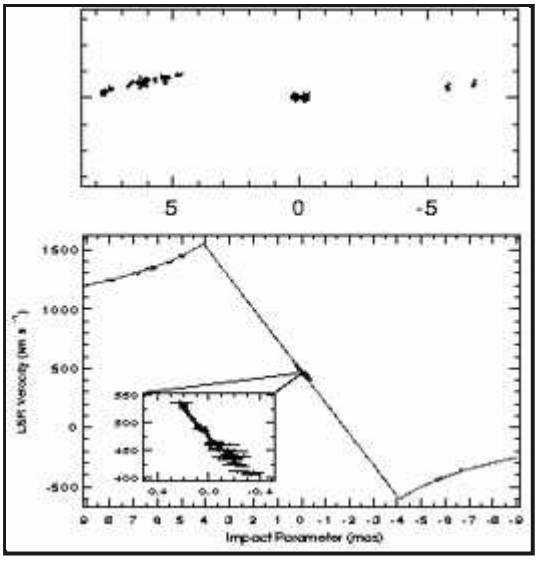

Figure 6. Water maser emission in NGC 4258 (Miyoshi et al. 1995). *Top:* spatial distribution of the maser features; *bottom:* rotation curve. Adapted from Greenhill (1997).

Two, possibly three, additional AGNs have H_2O megamasers suitable for tracing the central potential. The spectrum of the maser source in the Seyfert nucleus of NGC 1068 also exhibits satellite features (± 300 & km& s^{-1}) offset from the systemic velocity (Greenhill et al. 1996). The redshifted and blueshifted emission again lie on a roughly linear, 2-parsec feature passing through the systemic emission (Greenhill 1998). The rotation curve in this instance is sub-Keplerian, possibly because the disk has nonnegligible mass, and the derived mass (1.7×10^7 $M_\odot$ within a radius of 0.65 pc) is less certain.

The maser in the nucleus of NGC 4945 shows a position and velocity distribution reminiscent of NGC 4258 as well: high-velocity features symmetrically straddle the systemic emission. Greenhill, Moran, & Herrnstein (1997) interpret the data, which in this case is considerably less accurate because of its location in the southern sky, in terms of an edge-on disk model and derive a central mass of 1.4×10^6 $M_\odot$ within $r = 0.3$ pc. This result is quite surprising because, as an Scd spiral, NGC 4945 is expected to be essentially bulgeless. If the dark mass in its center is truly in the form of a SMBH, then SMBHs evidently can form without a bulge.

The H_2O megamaser source in NGC 3079 is potentially useful for mass determination. Here, however, the complex spatial distribution of the emission regions and the large intrinsic widths of the lines complicate the analysis, and the interpretation of the data may not be unique. Trotter et al. (1998) tentatively assign a central mass of 1×10^6 $M_\odot$ to this galaxy.

4.3. Determining Central Masses of Active Galactic Nuclei

I mention one other method for determining masses in the central regions of galaxies, specifically in AGNs. Although AGNs largely provide the motivation for searching for SMBHs, ironically it is precisely in these objects that conventional techniques used to measure masses fail. The bright continuum emission of the active nucleus nearly always completely overpowers the stellar absorption lines near the center, and in many cases the narrow emission lines are significantly affected by nongravitational forces.

An approach taken in the past attempts to utilize the broad [(1-few) $\times 10^3$ & km& s^{-1}] emission lines that are thought to arise from the so-called broad-line region (BLR), a tiny, dense region much less than a parsec from the central source. Assuming that the line widths trace gravity, the mass follows from $\eta\, v^2 r_{\rm BLR} / G$, where $\eta \approx$ 1-3 depending on the kinematic model adopted. The BLR radius has traditionally been estimated from photoionization arguments (e.g., Dibai 1980; Wandel & Yahil 1985; Wandel & Mushotzky 1986; Padovani, Burg, & Edelson 1990), but recent variability studies indicate that the BLR is much more compact than previously thought (Netzer & Peterson 1997).

TABLE 1

MASSES DETERMINED FROM STELLAR AND GAS KINEM

Galaxy (1)	Hubble Type (2)	D (Mpc) (3)	B_T^0 (mag) (4)	B/T (5)	Ref	M_B(bul) (mag) (6)	M_{MDO} ($M_\odot$) (7)	Radius (pc) (8)	De ($M_\odot$
Milky Way	Sbc	0.008	—	—	—	−17.51	2.6×10^6	0.006	2.2
M31	Sb	0.72	3.36	0.24	1	−19.38	7.5×10^7	0.30	6.(
M32	E2	0.72	8.72	1.0	—	−15.57	3.4×10^6	0.30	3.(
M33	Scd	0.795	5.75	—	2	−10.21	$<5\times10^4$	<0.39	
M81	Sab	3.6	7.39	0.25	1	−20.39	4×10^7	2.6	5.4
M84	E1	16.8	10.01	1.0	—	−21.12	1.5×10^9	8.1	6.1
M87	E0	16.8	9.46	1.0	—	−21.67	3×10^9	3.5	1.1
NGC 205	dE5	0.72	8.79	1.0	—	−15.49	$<9\times10^4$	0.35	
NGC 1068	Sb	14.4	9.47	0.23	4	−19.73	1.7×10^7	0.65	1.2
NGC 3079	SBc	20.4	10.41	0.10	4	−18.59	1.3×10^6	0.64	1.2
NGC 3115	S0-	6.7	9.74	0.94	1	−19.39	2×10^9	1.7	9.1
NGC 3377	E5	8.1	11.07	1.0	—	−18.47	2.3×10^8	11.4	3.1
NGC 3379	E1	8.1	10.18	1.0	—	−19.36	6×10^7	3.9	2.4
NGC 4258	SABbc	6.8	8.53	0.16	4	−18.64	3.6×10^7	0.012[a]	4.9
NGC 4261	E2	35.1	11.36	1.0	—	−21.37	4.9×10^8	16.9	2.4
NGC 4342	S0-	16.8	13.37	1.0	—	−17.76	3.0×10^8	20.3	8.(
NGC 4395	Sm	2.6	10.57	—	3	−7.27	$<8\times10^4$	0.35	
NGC 4486B	E0	16.8	14.26	1.0	—	−16.87	6×10^8	12.2	7.8
NGC 4594	Sa	9.2	8.38	0.93	1	−21.36	1×10^9	4.4	2.8
NGC 4945	SBcd	5.2	7.43	0.05	4	−17.89	1.4×10^6	0.3	1.2
NGC 6251	E0	92.0	13.22	1.0	—	−21.59	7.5×10^8	44.4	2.(
NGC 7052	E4	55.5	12.73	1.0	—	−20.99	5×10^8	—	
Circinus	Sb	4.0	8.32	—	—	−14.51[b]	$<4\times10^6$	11.0	
Arp 102B	E0	96.6	14.94	1.0	—	−19.98	2.2×10^8	0.0048	4.7

REFERENCES.— (1) Kormendy & Richstone 1995; (2) Kormendy & McClure 1993; (3) Filippenko & Ho 1998; (4) Simien & de Vau 1998; (7) van der Marel et al. 1997; (8) Bower et al. 1996; (9) Bower et al. 1998; (10) Macchetto et al. 1997; (11) Jones et al. 199 Kormendy et al. 1996; (15) Kormendy et al. 1998; (16) Gebhart et al. 1998; (17) Miyoshi et al. 1995; (18) Ferrarese, Ford, & Jaffe 1997b; (21) Kormendy et al. 1997a; (22) Greenhill, Moran, & Herrnstein 1997; (23) Ferrarese, Ford, & Jaffe 1998; (24) van der Marel 1997.

NOTE.— Cols.: (1) Galaxy name; (2) Hubble type from de Vaucouleurs et al. 1991; (3) distance from Tully 1988 or derived by ass blue magnitude corrected for Galactic and internal extinction, from de Vaucouleurs et al. 1991; (5) ratio of bulge to total luminosity b column; (6) absolute blue magnitude of the bulge component; (7) mass of the MDO, taken from the study given in the last column; (radius and M_{MDO}; (10) mass-to-light ratio (in the V band) of the MDO; (11) method used: "G" = gas kinematics; "S" = stellar kin

[a]Upper limit on size based on arguments by Maoz 1995.

[b]Bulge luminosity estimated assuming $M/L_B = 6$, where $M = 5\sigma_0^2 R_u/G$ is the mass of the bulge, σ_0 is the central velocity disp et al. (1998), $\sigma_0 \approx 80$ km s^{-1} and $R_u \approx 80$ pc.

The continuum output from AGNs typically varies on timescales ranging from days to months in the UV and optical bands. Because the emission lines are predominantly photoionized by the central continuum, they vary in response to the changes in the continuum, but with a time delay (lag) that corresponds to the light-travel distance between the continuum source and the line-emitting gas. "Reverberation mapping" (Blandford & McKee 1982), therefore, in principle allows one to estimate the luminosity-weighted radius of the BLR, although in practice the complex geometry and ionization structure of the BLR complicate the interpretation of the "sizes" derived by this method (see Netzer & Peterson 1997 for a recent review).

If the widths of the broad emission lines reflect bound gravitational motions, as seems to be the case in most well-studied objects (Netzer & Peterson 1997; but see Krolik 1997), then, adopting a reasonable kinematic model (e.g., randomly moving clouds), the virial mass can be estimated from $v^2 r_{BLR} / G$. If, instead, the clouds are infalling, as has been claimed in some cases, the mass will be smaller by a factor of 2. One of the uncertainties in the application of this simple formalism lies in the choice of v. What is appropriate? One reasonable choice might be $v = (\sqrt{3} / 2)$FWHM, the full width at half-maximum of a representative broad line. Yet another ambiguity is which line to use, since not all broad emission lines have the same widths. Ultraviolet or high-ionization lines, for instance, generally have broader profiles than optical or low-ionization lines. For the purposes of this exercise, I simply chose the line for which the most data exist (Hβ) in order to obtain as large a sample as possible.

TABLE 2

MASSES DETERMINED FROM REVERBERATION MAPPI

Galaxy (1)	Hubble Type (2)	D (Mpc) (3)	B_T^0 (mag) (4)	B/T (5)	M_B(bul) (mag) (6)	r_{BLR} (ltd) (7)	F
3C 120	S0:	132	13.63	0.24	–20.42	44	
Ark 120	S0/a	121	13.64	0.86	–21.61	39	
Fairall 9	S?	188	13.50	0.08	–20.13	23	
Mrk 79	SBb	89	13.32	0.20	–20.12	18	
Mrk 110	Pair?	141	16.00	—	—	20	
Mrk 279	S0	118	14.43	0.06	–17.87	10	
Mrk 335	S0/a	103	13.85	0.64	–20.73	17	
Mrk 509	comp	138	13.00	0.12	–20.39	80	
Mrk 590	Sa:	105	13.66	0.47	–20.63	21	
Mrk 817	S?	126	14.50	0.50	–20.88	16	
NGC 3227	SABa	20.6	11.18	0.52	–19.68	17	
NGC 3516	SB0:	38.9	12.14	0.61	–20.27	7	
NGC 3783	SBa	38.5	12.04	0.33	–19.68	8	
NGC 4151	SABab	20.3	10.71	0.36	–19.72	5	
NGC 4593	SBb	39.5	11.43	0.48	–20.76	4	
NGC 5548	S0/a	67.0	12.81	0.47	–20.50	19	
NGC 7469	SABa	65.2	12.64	0.40	–20.44	5	

NOTE.— Cols.: (1) Galaxy name; (2) Hubble type from de Vaucouleurs et al. 1991; (3) di derived by assuming $H_0 = 75$ km s^{-1} Mpc^{-1}; (4) total apparent blue magnitude corrected extinction, from de Vaucouleurs et al. 1991; (5) ratio of bulge to total luminosity (host gala too disturbed to yield a reliable photometric decomposition; (6) absolute blue magnitude of th (in light days) between the continuum and the Hβ light curves; (8) FWHM of the broad Hβ er derived from r_{BLR} and FWHM(Hβ).

[a]All Seyfert 1 nuclei studied to date with reverberation mapping of the Hβ line. Optical m 390.3, but it was not included because the profiles of its Balmer lines are very complicated. Ref have been omitted for brevity.

Table 2 lists the derived masses for the 17 Seyfert 1 galaxies that have been monitored extensively in the optical; eight of the objects appear in the compilation of Peterson et al. (1998). Since the masses of MDOs derived from gas and stellar kinematics show a loose correlation with the bulge or spheroidal luminosity of the host galaxies (Section 7; Fig. 8 *a*), we can ask whether those derived from reverberation mapping follow such a correlation. I have estimated the *B*-band luminosities of the bulges of the Seyferts based on published surface photometry of the host galaxies (taking care to exclude the contribution of the AGN itself, which often can be significant). Figure 8 *b* indicates that, at a fixed bulge luminosity, the masses from reverberation mapping are *systematically lower* than the masses obtained using conventional techniques, on average by about a factor of 5. It is encouraging that this admittedly crude method of mass estimation is not *too* far off the mark. Notably, the scatter of M_{MDO} at a fixed luminosity is quite comparable in the two samples, and the constant offset suggests that one of the underlying assumptions in the mass estimate is incorrect. Since the line width affects the mass quadratically, it is conceivable that some measure of the line profile other than the FWHM is more appropriate.

5. INDIRECT, BUT TANTALIZING EVIDENCE

Lastly, one additional piece of evidence, although it does not give a direct measure of the central mass, cannot go unmentioned -

namely the recent detection in AGNs of the broad iron Kα line at 6.4 keV. This line has been known for some time to be a common feature in the hard X-ray spectra of AGNs, and it is thought to arise from fluorescence of the X-ray continuum off of cold material, presumably associated with the accretion disk around the SMBH (e.g., Pounds et al. 1990). The spectral resolution of the existing data, however, was insufficient to test the predicted line profile (Fabian et al. 1989). The *ASCA* satellite provided the much-awaited tell-tale signs in the deep exposure of the Seyfert 1 galaxy MCG-6-30-15 (Tanaka et al. 1995): the Fe Kα line exhibits Doppler motions that approach relativistic speeds (~ 100,000 km s^{-1} or 0.3c!) as well as an asymmetric red wing consistent with gravitational redshift. The best-fitting disk has an inner radius of 6 Schwarzschild radii. The relativistic Fe Kα line, now seen in a large number of sources (Nandra et al. 1997; Fig. 7), provides arguably the most compelling evidence to date for the existence of SMBHs. Other mechanisms for generating the line profile are possible, but implausible (Fabian et al. 1995). Detailed modeling of the line asymmetry has even the potential to measure the spin of the hole, but this is still very much a goal of the future given the current data quality and uncertainties in the modeling itself (e.g., Reynolds & Begelman 1997; Rybicki & Bromley 1998).

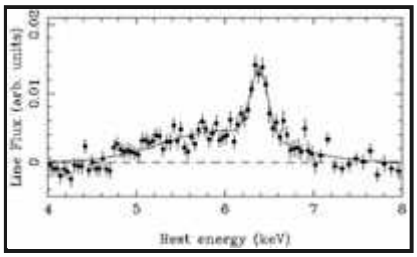

Figure 7. The Fe Kα line in the composite spectrum of Seyfert 1 nuclei (Nandra et al. 1997). The solid line is a fit to the line profile using two Gaussians, a narrow component centered at 6.4 keV and a much broader, redshifted component.

6. ARE THE MASSIVE DARK OBJECTS *REALLY* BLACK HOLES?

Thus far we have rigorously shown only that many galaxies contain central MDOs, not that the dark masses must be in the form of SMBHs. Direct proof of the existence of SMBHs would require the detection of relativistic motions emanating from the vicinity of the Schwarzschild radius, $R_S = 2GM_\bullet / c^2 \approx 10^{-5}(M_\bullet / 10^8\ M_\odot)$ pc. Even for our neighbor M31, R_S subtends 3×10^{-6} arcseconds, and the Galactic Center only a factor of 2 larger. We are clearly still far from being able to achieve the requisite angular resolution and in the meantime must rely on indirect arguments.

One approach seeks to identify some observational feature that might be taken as a fingerprint of the event horizon or of physical processes uniquely associated with the environment of a BH. One such "signature" might be the broad Fe Kα line discussed in Section 5; another is the high-energy power-law tail observed in some AGNs and Galactic BH candidates (Titarchuk & Zannias 1998). And yet a third possibility is the advection of matter into the event horizon (Menou, Quataert, & Narayan 1999).

A different strategy appeals to the dynamical stability of the probable alternative sources of the dark mass (Goodman & Lee 1989; Richstone, Bower, & Dressler 1990; van der Marel et al. 1997; Maoz 1998). The absence of strong radial gradients in the stellar population, as measured by variations in color or spectral indices, implies that the large increase in M / L toward the center cannot be attributed to a cluster of ordinary stars. On the other hand, the underluminous mass could, in principle, be a cluster of stellar remnants (white dwarfs, neutron stars, and stellar-size BHs) or perhaps even substellar objects (planets and brown dwarfs). To rule out these possibilities, however exotic they might seem, one must show that the clusters cannot have survived over the age of the galaxy, and hence finding them would be highly improbable.

As most recently discussed by Maoz (1998), the two main processes that determine the lifetime of a star cluster are evaporation, whereby stars escape the cluster as a result of multiple weak gravitational scatterings, and physical collisions among the stars themselves. Exactly which dominates depends on the composition and size of the cluster, and its maximum possible lifetime can be computed for any given mass and density. Maoz (1998) shows that in two galaxies, namely the Milky Way and NGC 4258, the density of the dark mass is so high ($\gtrsim 10^{12}\ M_\odot\ pc^{-3}$) that it cannot possibly be in the form of a stable cluster of stellar or substellar remnants: their maximum ages [~ (1-few) × 10^8 yr] are much less than the ages of the galaxies. The only remaining constituents allowed appear to be subsolar-mass BHs and elementary particles. This constitutes very strong evidence that the MDOs - at least in two cases - are most likely SMBHs. In the following discussion, I will adopt the simplifying viewpoint that

all MDOs are SMBHs, bearing in mind that at the current resolution limit we cannot yet disprove the dark-cluster hypothesis for the majority of the objects.

7. THE BLACK-HOLE MASS/BULGE MASS RELATION

Does $M_\bullet$ depend at all on other properties of the host galaxies? A much-discussed possibility is that $M_\bullet$ scales with the mass of the spheroidal component of the host (Kormendy 1993; KR; Faber et al. 1997; Magorrian et al. 1998; Richstone 1998; Ford et al. 1998; van der Marel 1999). The significance of the scatter in the correlation, or whether any correlation exists at all, is not yet certain. It is somewhat disconcerting that different authors plotting the same objects do not always arrive at the same conclusion. The discrepancies can often be traced to different assumptions about distances, source of bulge-to-disk decomposition, and even apparent magnitudes adopted for the host galaxies (e.g., extinction is not always corrected). The set of host galaxy parameters I adopt is compiled in Table 1.

Figure 8 *a* illustrates that there indeed appears to be a trend of $M_\bullet$ increasing with bulge mass (luminosity). It is encouraging to note that the central masses derived from gas and stellar kinematics do not show any obvious systematic offsets relative to one another. No obvious differentiation by Hubble type is evident either. As has been noted by others, the scatter of $M_\bullet$ at a given luminosity is considerable, at least a factor of 10, perhaps up to 100. The scatter may have been exacerbated slightly by four possibly anomalous points. NGC 4486B is a companion to M87, and it appears to have been tidally truncated; its original luminosity was probably higher. On the other hand, the bulge luminosity of NGC 4945 could very well have been overestimated. Its bulge-to-disk ratio was found using the relation of Simien & de Vaucouleurs (1986), which may be inappropriate for a galaxy of such late Hubble type (Scd). Finally, the masses of M81 and NGC 3079 are quite uncertain and probably have been underestimated.

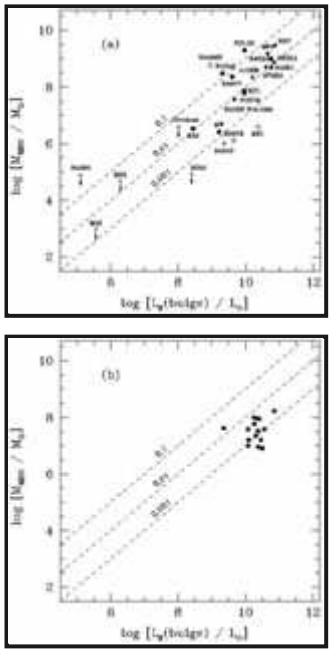

Figure 8. (*a*) Log $M_\bullet$ versus log L_B(bulge) for the objects listed in Table 1. The typical uncertainty of $M_\bullet$ is probably about a factor of 2. Open symbols denote points that may have an exceptionally large uncertainty in either of the two variables (see text). Masses derived from stellar kinematics are plotted as *circles*, those from gas kinematics as *squares*, the unconventional case of Arp 102B as a *triangle*, and five upper limits as *crosses*. Lines of constant mass to luminosity ratio are also shown. (*b*) Same as in (*a*), but for the Seyfert galaxies listed in

Table 2 (except Mrk 110).

The trend is much more significant when five upper limits are included. NGC 205, a dwarf elliptical companion of M31, contains a blue, compact nucleus with characteristics resembling an intermediate-age globular cluster. Its core radius, determined from *HST* photometry, combined with a ground-based measurement of its velocity dispersion yields an upper limit of 9×10^4 $M_\odot$ for any dark mass (Jones et al. 1996). The bulgeless, late-type (Scd) spiral M33 also has a stringent upper limit on its central mass. Its nuclear cluster is extremely tiny (core radius $\lesssim$ 0.39 pc), and its central velocity dispersion is 21 km s^{-1}; Kormendy & McClure (1993) put an upper limit of $M_\bullet \leq 5 \times 10^4$ $M_\odot$. NGC 4395 in some ways resembles M33, but it is even more extreme. The nucleus is optically classified as a type 1.8 Seyfert (broad Hα and Hβ present), emits a largely nonstellar featureless continuum that extends into the UV (Filippenko, Ho, & Sargent 1993), and displays variable soft X-ray emission and a compact flat-spectrum radio core (Moran et al. 1999). These properties alone would be unremarkable were it not for the fact that the nucleus has an absolute blue magnitude of only -9.8 and lives in a Magellanic spiral 2.6 Mpc away! Filippenko & Ho (1998) detected the Ca II infrared triplet lines in absorption from echelle spectra taken with the Keck telescope, from which they were able to estimate the strength of the stellar component contributing to the nuclear light (M_B = -7.3 mag) and the central stellar velocity dispersion ($\sigma \approx 30$ km s^{-1}). Combining the velocity dispersion with a cluster size ($r \lesssim 0.7$ pc) obtained from *HST* images, Filippenko & Ho limit the central mass to $\lesssim 8 \times 10^4$ $M_\odot$. The Circinus galaxy is thought to house a Seyfert nucleus, and if it contains a SMBH, its mass within $r \approx 10$ pc has been constrained to be $\lesssim 4 \times 10^6$ $M_\odot$ (Maiolino et al. 1998). The last upper limit shown in the figure pertains to the globular cluster M15; following KR, I adopt an upper limit of $M_\bullet = 1 \times 10^3$ $M_\odot$.

However, before reading too much into this diagram, we should ask whether the apparent correlation might arise from selection effects. The absence of points on the upper left-hand corner is probably real; there is nothing preventing us from detecting a massive BH in a small galaxy. Yet, we should be cautious, because very few low-mass galaxies have been studied so far, most of the effort having been focused on luminous, early-type systems. On the other hand, the empty region on the lower right-hand corner could be an artifact. Small masses are difficult to detect at large distances, and most luminous galaxies are far away. So the apparent correlation *could* be an upper envelope. Future observations are needed to settle this issue.

The median value of $M_\bullet / L_B(bul)$ for the 20 detected objects is 0.012, which translates into a mass ratio of 0.002 for $M / L_B \approx 6$ typical for old stellar populations (van der Marel 1991). That is, on average about 0.2% of the bulge mass is locked up in the form of a SMBH. Magorrian et al. (1998) constructed axisymmetric $f(E, L_z)$ models for a sample of 32 early-type (mostly E and S0) galaxies having both *HST* photometry and ground-based stellar kinematics data, and they concluded that the data are consistent with nearly all of the galaxies having SMBHs. The 29 detected objects have a median $M_\bullet / M_{bul} \approx 0.005$, higher than found here. However, as Magorrian et al. realize, the assumption of a two-integral distribution function may have caused them to overestimate $M_\bullet$ (cf. van der Marel 1999). Interestingly, quasars possibly also obey a similar $M_\bullet$-M_{bul} relation. McLeod (1998) finds that, for the most luminous quasars, there exists a minimum host luminosity that increases with nuclear power. Assuming that the quasar luminosities correspond to energy generation at the Eddington rate, $M_\bullet / M_{bul}$ is again ~ 0.002 (McLeod 1998).

With regard to the dead quasar prediction discussed in Section 1, recall that we expect to find on average a 10^7 $M_\odot$ BH for every $L_B \approx 10^{10}$ $L_\odot$ galaxy, or $M_\bullet / L_B(bul) \approx 3.3 \times 10^{-3}$ $M_\odot / L_\odot$ since bulges contribute typical 30% of the galaxy light in *B* (Schechter & Dressler 1987). Evidently, if $\varepsilon = 0.1$, we have already found about three times that value. This implies that either ε is smaller than 0.1, or that quasars do not make up all of the AGN population.

8. ARE SUPERMASSIVE BLACK HOLES UBIQUITOUS?

They certainly have not been found in every case that has been looked. Kormendy has undertaken a systematic survey of a modest sample of galaxies (E-Sb), and his detection rate has been about 20% (KR). But, of course, many factors conspire against the detection of MDOs, and this estimate should be regarded as firm lower limit. If one takes seriously the $M_\bullet$- M_{bul} relation described above, it is possible that *every* bulge contains a SMBH with an appropriately scaled size. This view is supported by the statistical analysis of Magorrian et al. (1998). In fact, the detection of an MDO in NGC 4945 (Section 4.2) and the presence of a *bona fide* AGN in NGC 4395 indicate that perhaps even some galaxies without bulges may have SMBHs.

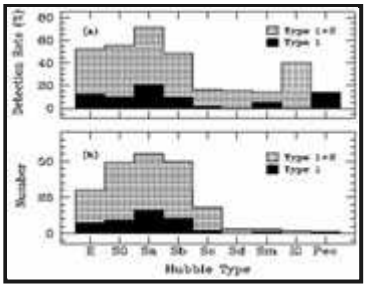

Figure 9. (*a*) Detection rate and (*b*) number distribution of AGNs as a function of Hubble type in the spectroscopic survey of Ho et al. (1995, 1997). "Type 1" AGNs (those with broad Hα) are shown separately from the total population (types 1 and 2).

Additional support for this picture comes from the growing evidence that nonstellar nuclear activity is very common in galaxies, much more so than conventionally believed based on the statistics of bright AGNs and quasars. A recent spectroscopic survey of a large, statistically complete sample of nearby galaxies finds that over 40% of all bright ($B_T \leq 12.5$ mag) galaxies have nuclei that can be classified as "active," and the percentage is even higher among early-type systems (E-Sbc), approaching 50%-75% (Ho, Filippenko, & Sargent 1997). Most of the nearby AGNs have much lower luminosities than traditionally studied active galaxies, and a greater heterogeneity in spectral types is found (low-ionization nuclei, or LINERs, are common, for example), but the evidence is overwhelming that many of these nuclei are truly accretion-powered sources (see Filippenko 1996; Ho et al. 1997). Moreover, intrinsically weak, compact radio cores are known to be present in a significant fraction of elliptical and S0 galaxies (Sadler, Jenkins, & Kotanyi 1989; Wrobel & Heeschen 1991), almost all of which spectroscopically qualify as AGNs (Ho 1998).

Within the conventional AGN paradigm, the observed widespread nuclear activity implies that SMBHs are a generic component of many, perhaps most, present-day bulge-dominated galaxies, consistent with the picture emerging from the kinematic studies. This is a remarkable statement. It implies that SMBHs should not be regarded as "freaks of nature" that exist in only a handful of galaxies; rather, they must be accepted and understood as a normal component of galactic structure, one that arises naturally in the course of galaxy formation and evolution.

9. SOME IMPLICATIONS AND FUTURE DIRECTIONS

The SMBH hunting game is rapidly becoming a rather mature subject. I think we have progressed from the era of "the thrill of discovery" to a point where we are on the verge of using SMBHs as astrophysical tools. In this spirit, let me remark on a few of the ramifications of the existing observations and point out some of the more urgent directions that should be pursued.

A. The $M_\bullet$-M_{bul} relation. The apparent correlation between the mass of the central BH and the mass of the bulge, if borne out by future scrutiny, has significant implications (see below). From an observational point of view, the highest immediate priority is to populate the $M_\bullet$-$M_{\rm bul}$ diagram with objects spanning a wide range in luminosity, with the eventual aim of deriving a mass function for SMBHs. The samples should be chosen with the following questions in mind. (1) Is the apparent trend a true correlation or does it instead trace an upper envelope? (2) If the relation is real, is it linear? (3) What is the magnitude of the intrinsic scatter? And (4) is there a minimum bulge luminosity (mass) below which SMBHs do not exist?

In the near future, the most efficient way to obtain mass measurements for relatively large numbers of galaxies is to exploit the capabilities of STIS on *HST*. Several large programs are in progress. Although VLBI spectroscopy of H_2O masers delivers much higher angular resolution, this technique is limited by the availability of suitably bright sources. Conditions which promote H_2O megamaser emission evidently are realized in only a tiny fraction of galaxies (Braatz, Wilson, & Henkel 1996).

B. The formation of SMBHs. The $M_\bullet$-$M_{\rm bul}$ relation offers some clues to the formation mechanism of SMBHs. How does a galaxy know how to extract a constant, or at least a limiting, fraction of its bulge mass into a SMBH? An attractive possibility is by the normal dynamical evolution of the galaxy core itself. The spheroidal component of nearby galaxies can attain very high central stellar densities - up to 10^5 $M_\odot$ pc^{-3} (Faber et al. 1997) - and some with distinct nuclei have even higher concentrations still (Lauer et al. 1995). Although most galaxy cores are unlikely to have experienced dynamical collapse (Kormendy 1988c),

the *innermost* regions have much shorter relaxation times, especially when considering a realistic stellar mass spectrum because the segregation of the most massive stars toward the center greatly accelerates the dynamical evolution of the system. Lee (1995, and these proceedings) shows that, under conditions typical of galactic nuclei, core collapse and merging of stellar-size BHs can easily form a seed BH of moderate mass. Alternatively, the seed object may form via the catastrophic collapse of a relativistic cluster of compact remnants (Quinlan & Shapiro 1990). In either case, subsequent accretion of gas and stars will augment the central mass, and, over a Hubble time, may produce the distribution of masses observed. It is far too premature to tell whether SMBHs form through the secular evolution of galaxies, as suggested here, through processes associated with the initial formation of galaxies (e.g., Rees 1984, 1998; Silk & Rees 1998), or both, depending on the galaxy type (elliptical vs. spiral galaxies). But the stage is set for a serious discussion. More sophisticated modeling of the growth of SMBHs that take into account a wider range of initial conditions in galactic nuclei (e.g., relaxing the adiabatic assumption or adopting more realistic density profiles for the stellar distribution) may eventually yield testable predictions (see, e.g., Stiavelli 1998).

C. Influence of SMBHs on galactic structure. Norman, May, & Van Albada (1985) showed through *N*-body simulations that a massive singularity in the center of a triaxial galaxy destroys the box-like stellar orbits and hence can erase the nonaxisymmetry, at least on small scales. This has several important consequences. First, it implies that the presence of a SMBH can influence the *global* structure and dynamics of galaxies. Second, the secular evolution of the axisymmetry of the central potential points to a natural mechanism for galaxies to self-regulate the transfer of angular momentum of the gas from large to small scales. This negative-feedback process may limit the growth of the central BH *and* the accretion rate onto it, and hence may serve as a promising framework for understanding the physical evolution of AGNs. Merritt & Quinlan (1998) find that the timescale for effecting the transition from triaxiality to axisymmetry depends strongly on the fractional mass of the BH; the evolution occurs rapidly when $M_\bullet / M_{\rm bul} \gtrsim 2.5\%$, remarkably close to the observational upper limit (Fig. 8 *a*).

D. The origin of central cores. It is not understood why giant ellipticals have such shallow central light profiles. "Cores" do not develop naturally in popular scenarios of structure formation, and even if they form, they are difficult to maintain against the subsequent acquisition of the dense, central regions of satellite galaxies that get accreted (Faber et al. 1997). Moreover, the very presence of a SMBH, whether it grew adiabatically in a preexisting stellar system or the galaxy formed by violent relaxation around it (Stiavelli 1998), ought to imprint a more sharply cusped light profile (see Section 2) than is observed. An intriguing possibility is that cores were created as a result of mergers, where one or more of the galaxies contains a BH. As the single (Nakano & Makino 1998) or binary (Makino 1997; Quinlan & Hernquist 1997) BH sinks toward the center of the remnant due to dynamical friction, it heats the stars, thereby producing a "fluffy" core. If this interpretation is correct, it would provide a simple, powerful tool to diagnose the formation history of galaxies.

E. Why are the black holes so black? It has been somewhat puzzling how the BHs can remain so dormant. No doubt the dwindled gas supply in the present epoch, especially in ellipticals, is largely responsible for the inactivity. Yet the accretion rate cannot be zero; even in the absence of inflow from the general interstellar medium, some gas is shed through normal mass loss from the innermost evolved stars, and occasionally such stars get tidally disrupted (see below). If SMBHs are indeed present, the radiative efficiency of the accretion flow must be orders of magnitude lower than that of "standard" optically thick, geometrically thin disks. Such a situation may be realized in accretion flows where advection becomes important when the accretion rate is highly sub-Eddington (Narayan & Yi 1995; Abramowicz et al. 1995; Nakamura et al. 1996; Chakrabarti 1996). Sgr A* at the Galactic Center has a bolometric luminosity of only ~ 10^{37} ergs s^{-1}, or $L_{\rm bol} / L_{\rm Edd} \approx 3 \times 10^{-8}$ (Narayan, Yi, & Mahadevan 1995); in the case of the LINER nucleus of M81 (Ho, Filippenko, & Sargent 1996), $L_{\rm bol} \approx 10^{41}$ ergs s^{-1} and $L_{\rm bol} / L_{\rm Edd} \lesssim 10^{-4}$. The spectral energy distributions emitted by both objects differ dramatically from those of luminous AGNs and can be approximately matched by advective-disk models.

F. Tidal disruption of stars. The prevalence of SMBHs suggested by the existing evidence predicts a relatively high incidence of tidal disruptions of stars as they scatter into nearly radial orbits whose pericenters pass within the tidal radius of the BH (Rees 1998, and references therein). For a typical stellar density of 10^5 stars pc^{-3}, $M_\bullet = 10^6$-10^8 $M_\odot$, and σ = 100-300 km s^{-1}, a solar-type star will be disrupted once every 10^2-10^4 years. (BHs more massive than 10^8 $M_\odot$ will swallow the star whole.) Roughly half the debris becomes unbound and half gets captured into an accretion disk which undergoes a bright flare (~ 10^{10} $L_\odot$) lasting a few months to a year. The spectrum is expected to be mainly thermal and to peak in the extreme-UV and soft X-rays. The contribution to the near-UV and optical bands is uncertain; it depends on assumptions concerning the geometry of the accretion disk (thick or thin) and on whether an optically thick envelope can form. For plausible parameters, Ulmer (1998) estimates that a 10^7 $M_\odot$ BH will produce a flare with an absolute magnitude of about -20 in *U* and -18.5 in *V*. The realization that SMBHs may be even more common than previously thought provides fresh motivation to search for such stellar flares; some observational strategies are mentioned by Rees (1998). Here, I wish to stress that quantifying the rate of stellar disruptions can be used as a tool to study the demography of SMBHs out to relatively large distances and hence should be regarded as complementary to the kinematic searches.

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