11. Black-Hole Powering of AGN and Jets

BLACK HOLES AND GALAXY CENTERS [1,2]

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1. Introduction

The study of supermassive galactic black holes (BH) has moved beyond discovery to maturity. The are now ~ 15 reliable detections. The mass of a central black hole apparently correlates with the mass of the hot component of its galactic host. It may be that every normal galaxy has a supermassive black hole carrying about 10^{-3} of its bulge mass, with important consequences for the structure and evolution of the core of the galaxy. The most recent major review is by Kormendy & Richstone (1995, KR).

2. Supermassive Black Holes: Fossil Relics of the Quasar Era?

In the standard paradigm of black hole powered accretion, the observed quasar luminosity function predicts the density of black holes that once powered quasars. The locally measured energy density in quasar light is

$$\rho c^2 = \int_0^\infty \int_0^\infty \mathrm{L\Phi(L|z)dL(dt/dz)dz}, = 1.3 \times 10^{-15}\,\mathrm{erg\ cm^{-3}} \qquad (1)$$

where $\Phi(L|z)$ is the quasar luminosity function at a given redshift z, and t is time (Soltan 1982, Chokshi & Turner 1992). This estimate is independent of H_0 and Ω_0, but depends on bolometric corrections to the quasar luminosities used to derive the luminosity function above. The present density

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[2] On behalf of the "Nuker" Team: E. Ajhar, R. Bender, G. Bower, A. Dressler, S. M. Faber, K. Gebhardt, R. Green, C. Grillmair, J. Kormendy, T. R. Lauer, J. Magorrian, S. Tremaine and the author.

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of those black holes is simply the mass equivalent of that energy, divided by the efficiency ϵ of conversion of gravitational energy into light outside the horizon. Its numerical value (independent of H_0 and Ω_0) is about

$$\rho_u = \frac{u}{\epsilon c^2} = 2.2 \times 10^5 \left(\frac{\epsilon}{0.1}\right)^{-1} M_\odot \, \mathrm{Mpc}^{-3}. \tag{2}$$

Clearly some quasars are events in galaxies, although it is not clear whether certain environments or Hubble types predispose a galaxy to a quasar phase (see Bahcall *et al.* 1997). Therefore, it is interesting to compare the black hole density to the galaxy density (for example, from Loveday *et al.* 1992), which is $j = 1.4 \times 10^8 h \, L_\odot/\mathrm{Mpc}^3$. The ratio of the mean black hole mass density to the mean galaxy luminous density is

$$\Upsilon = \frac{\rho_u}{j} = 0.714 \times 10^{-3} h^{-1} \left(\frac{\epsilon}{0.1}\right)^{-1} \left(\frac{M_\odot}{L_\odot}\right). \tag{3}$$

Another interesting prediction of the black hole accretion model for quasars is the black hole mass, which is bounded from below by the radiated energy, as follows.

$$M_\bullet = \frac{L_Q \, \tau}{\epsilon \, c^2} = 7 \times 10^8 \, M_\odot \left(\frac{L}{10^{12} \, L_\odot}\right) \left(\frac{\tau}{10^9 \, \mathrm{yrs}}\right) \left(\frac{\epsilon}{0.1}\right)^{-1}, \tag{4}$$

where τ is the quasar lifetime.

3. Black Hole Masses from Three Sources

3.1. GAS DISKS

Some of the prettiest evidence for central black holes in galaxies comes from gas disks observed with HST (see Ford in this volume and references therein). If the gas is in circular streamlines, then the encircled mass can be easily estimated in the same manner as rotation curves of spiral galaxies:

$$M_r = v^2 r / G, \tag{5}$$

where v is the observed velocity (corrected for disk inclination) and r is its distance from the center. The complication in this case is to convince oneself that the observed gas really is in orbit around the massive object, rather than flowing out, and to estimate the inclination of the disk. In the important case of M87, the disk model is supported by the detailed velocity mapping of Macchetto *et al.* 1997.

3.2. MASERS

The presence of maser sources in apparently Keplerian rotation on miliarc-second scales in several AGN's brings an unprecedented resolution to this problem (Miyoshi *et al.* 1995, Greenhill *et al.* , 1996, Greenhill et al. 1997 and Sofue this volume). In these cases, the emitted light must be passing through long distances with small velocity gradients, so it seems likely that we are preferentially seeing edge-on disks along lines tangent to the flow direction, and that the interpretation of these velocities in terms of eqn 5 is reasonable (Greenhill *et al.* 1996 discusses some complications).

3.3. STELLAR DYNAMICS

Interpretation of dynamics of stars is the most difficult of these methods because an observed profile of velocity moments rising sharply toward the galactic center can either be interpreted in terms of the mass distribution or in terms of the anisotropy of the phase-space distribution funtion. We make use of a penalized maximum-likelihood method (Merritt 1997) to derive full line-of-sight velocity distributions from the observed absorption-line spectra of the galaxies, and an orbit-based maximum entropy method (Richstone *et al.* 1998) to interpret the velocities so inferred. This method, valid for axisymmetric mass and light distributions, is similar to the spherical maximum entropy method described by Richstone and Tremaine (1988), which was itself based on Schwarzschild's (1979) method. It is also nearly identical to the method used by Cretton *et al.* (1997) and van der Marel (this volume) and their collaborators. All of these methods have at their core the following basic procedure:

1. Choose a mass distribution consistent with the observed light distribution (it may but need not include a mass point at the center);
2. Compute the gravitational field of that mass distribution;
3. Survey the orbits in the gravitational field, saving their density distribution;
4. Force the sum of the density distributions of the individual orbits, weighted by a non-negative occupation number for each orbit, to match the observed light distribution of the galaxy;

That set of orbits (if one exists) is a dynamical model for the galaxy.

In the results reported below and hereafter, we are using a new version of the program which operates in a general axisymmetric mass distribution, and which matches the entire line-of-sight velocity distribution of the stars in the model against the observations.

4. The Black Hole Mass — Bulge Luminosity Relation

Figure 1 contains a scatter plot of detected black hole mass versus the mass of the hot component of the host galaxy. Except for the maser sources, point in the figure is a dynamically estimated central dark mass where there is

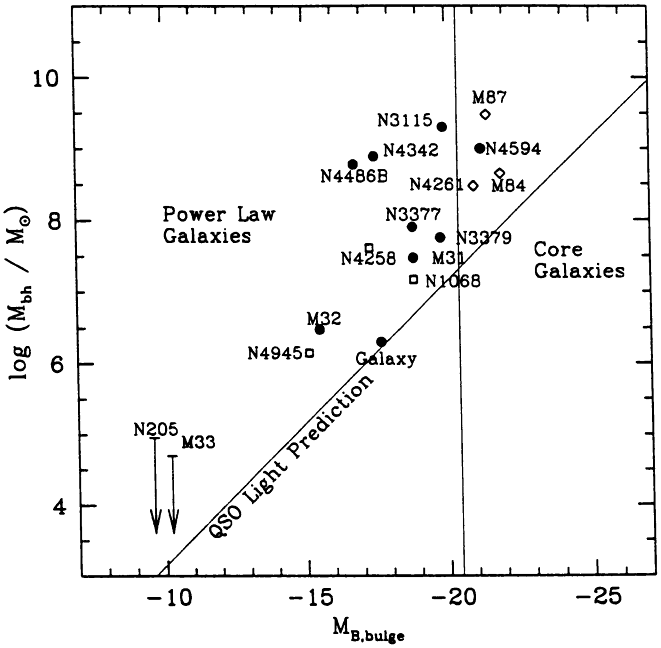

Figure 1. Black hole mass versus spheroid magnitude. Filled circles are black hole detections by stellar dynamics. Diamonds are black hole masses from gas disks. Squares are masses from masers. The spheroid magnitude is the blue magnitude of the "hot" component of the galaxy (the entire elliptical or the bulge of a Spiral or S0). The vertical line approximately divides spheroids into *Cores* and *Power Laws* (Lauer 1995), and the diagonal line is the black hole mass prediction from quasars assuming $M_\bullet = \Upsilon L_{bulge}$, with Υ determined from the quasar distribution in luminosity and redshift and assuming a luminous efficiency of 10% (eqn 3).

good dynamical evidence for the mass coupled with an absence of light to account for that mass in terms of stars. In the case of the maser sources, there is evidence for a large mass in a very small volume (see the talks by Sofue and by Maoz in this volume). The data in Figure 1 are updated from Kormendy 1993 and KR. with newer data for maser objects as reported in §3.2, and new or improved masses from Kormendy *et al.* 1997 for NGC 4486B, Kormendy *et al.* 1998 for NGC 3377, Gebhardt *et al.* 1997 for NGC 3379, Bower *et al.* 1997 for M84, van der Marel *et al.* 1997 for M32 and van den Bosch 1997 for NGC 4342. In three cases, Hubble data provides a significant gain in resolution over ground-based data, confirming the older analyses.

Although the number of points in the figure is small, several interesting features are immediately clear.

1. Objects are displayed using each of the three methods described in §3. They do not clearly separate out by method (except for the known

fact that luminous ellipticals are more likely to have cold gas than faint ellipticals). The analysis methods are rather different, and (especially the maser approach) have different inferred minimum detectable masses for the objects observed. Thus the possible systematic errors and selection biases are different. If they were larger than the spread of masses shown they would be visible in the form of a segregation of objects of one kind or another in Figure 1.

2. Spiral, S0 and Elliptical galaxies, as well as AGN (spirals) are all represented, with no clear segregation by Hubble type.
3. The results are roughly consistent with the quasar accretion paradigm if most galaxies have supermassive black holes.

5. The Density of Supermassive Black Holes

The distribution of black hole masses with galaxy bulge luminosities is interesting in its own right, but it prompts two additional questions: what is the fraction of galaxies that contain black holes in the mass range implied by the scatter plot in Figure 1, and to what extent is the form of the distribution determined by selection. We have developed a statistical model of the BH distribution to address these questions (Magorrian *et al.* 1997).

The basic assumption of this model is that the question of whether a galaxy contains a supermassive black hole or not can be addressed in terms of a probability of finding a BH as a function of various properties of the galaxy. In the Magorrian *et al.* paper we further *assume* that this function can be parametrized in terms of $x = M_\bullet/m_{bulge}$, in the sense that the probability of finding a BH of mass $M_\bullet$ is $fp(x)$, where p is normalized on the interval $0 < x < \infty$, so f is the fraction of galaxies with supermassive black holes. The best parameters of p are found using Bayes' theorem with a flat "prior". A simple choice for p is a normalized log-Gaussian,

$$p\,dx \propto \exp\left[-\frac{[log(x) - log(x_0)]^2}{2\Delta^2}\right]dx. \tag{6}$$

We find the most probable parameters, given a sample of 32 reasonably dust-free objects with HST photometry and ground-based kinematics (dispersion and rotation profiles) drawn from the literature without regard to prior suspicion of a present BH. [1] Each galaxy in this sample was then modelled as a with a constant but unknown M/L, unknown inclination and unknown central black hole mass using a two-integral (energy and z angular momentum) distribution function, to derive the most probable values

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[1] Our investigations only refer to "normal" galaxies that lie on or near the fundamental plane or Tully-Fisher relation. We cannot make any statements about black holes in LSB, dwarf or irregular galaxies.

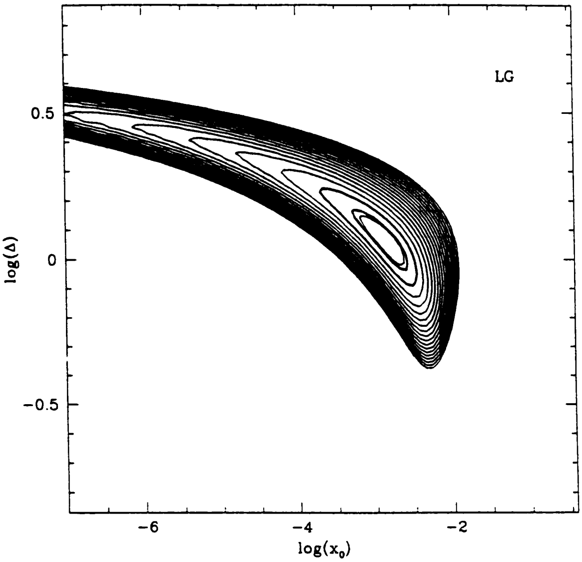

Figure 2. Likelihood contours from a Bayesian (or, equivalently in this case, a Maximum-Likelihood) estimate of the parameters of equation 6 from Magorrian *et al.* 1997.

of the three unknowns. Four objects (with kinematically decoupled cores) failed this procedure for any choices of the parameters. Of the remainder, all but one required a large central mass for any model to match the data. For five galaxies in this set also analyzed by Schwarzschild's method the BH masses agree quite well. The results for this parameterization are shown in Figure 2.

The best fit for the parameters of eqn 6 are $f = 0.97$, $x_0 = 1.5 \times 10^{-3}$ and $\Delta = 1.2$. This translates to a rather broad distribution in $x = M_\bullet / m_{bulge}$, about an order of magnitude wide, and implies that 97% of galaxies have supermassive black holes, with masses typically 10^{-2} to 10^{-3} of their bulge mass (see Magorrian *et al.* for details).

6. Implications for Galaxies

If supermassive black holes are "standard equipment" in the centers of normal galaxies, there are (at least) five important consequences.

Even without a supermassive black hole, ***stochastic orbits*** may play an important role in the evolution of the systems, as suggested by Merritt & Fridman (1996, 1997, and Merritt 1997). The fraction of phase space covered by stochastic orbits is a strong function of the central concentration of the mass density. Thus, the addition of a black hole increases the role of those orbits. Merritt and Quinlan 1997 have also suggested that the destruction of triaxial structures (bars) by stochastic orbits limits the value of $x = M_\bullet/m_{bulge}$ to $x \lesssim 10^{-2}$, but there are other accretion mechanisms than bar-driven angular momentum transfer, and the distribution of x is probably more nearly centered on $x \sim 10^{-3}$ than $x \sim 10^{-2}$.

Rees (1988) and Goodman and Lee (1989) suggest that *stellar breakup flares* will occur in galaxies with supermassive black holes below about $10^8 M_\odot$. The results discussed above suggest that many galaxies are candidates.

Tremaine 1995 has argued that the "double nucleus" of M31 (Lauer *et al.* 1993) is an *eccentric disk* composed of stars on elliptical orbits around the black hole. The presence of a BH is not crucial for the presence of the ring, but it is critical for its eccentricity. The presence of multiple nuclei or (at lower relative resolution) off-center or skew nuclei should not be extraordinary if BH are common. NGC 4486B (Lauer *et al.* 1996) is a possible second case of this phenomenon.

The survival of the *core fundamental plane* (Faber *et al.* 1997) against accretion of low mass high SB galaxies is a known problem. Minske & Richstone 1998 numerically confirm Weinberg's 1997 estimate of resonant tidal heating of smaller galaxies during accretion, but argue that he did not reasonably approximate the core fundamental plane in his dismissal of the problem. Massive black holes would, however, destroy dense dwarf galaxies so long as they encounter the center of the larger galaxy while on a rather elongated orbit, thus permitting the suvival of the core fundamental plane.

If black holes form during the epoch of galaxy formation, the black hole probably forms out of the lowest angular momentum gas associated with the densest part of the galaxy or sub-galaxy (see Eisenstein & Loeb 1995, who argue for a seed mass of $\sim 10^5 M_\odot$). During subsequent hierarchical merging, if slingshot ejection is insignificant, a set of proto-sub-galaxies containing black holes will build the observed relationship through a succession of mergers in which the black holes merge as well as the proto-bulges (Haehnelt & Rees 1993). One can imagine a variety of alternate scenarios, such as Merritt & Quinlan's, that tap a small fraction of reservoir of mass in the bulge.

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