Supermassive Black Holes

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Introduction

This paper discusses black holes as they relate to active galactic nuclei (AGNs), reviewing active galaxy types, a unified model requiring a common energetic power source, and supermassive black holes as suitable candidates. It then discusses the search for such objects in galactic nuclei, and theories on their formation.

Black Holes

A black hole is a compact object whose gravity is so strong that light cannot escape. That is, the escape velocity at the surface is greater than the speed of light. Escape velocity is $V_e = \sqrt{\frac{2Gm}{r}}$ so an object is a black hole if $\sqrt{\frac{2Gm}{r}} > c$. We can rearrange this as $r < \frac{2Gm}{c^2}$, giving the Schwarzschild Radius (Schwarzschild 1916). A non-rotating object is a black hole if it is smaller than its Schwarzschild Radius.

Active Galaxies

Active Galaxies (often called AGNs because their nuclei are their main feature) are highly luminous and highly variable, and are divided into many types, including:

Quasars, typically 1000 times the luminosity of our Galaxy, emitting nonthermal radiation containing broad emission lines. About half are powerful radio sources while half are radio-quiet, and there is no good explanation for this dichotomy yet (Freedman and Kaufmann III 2002). Most are visible at redshift $z \gtrsim 2$, dying when the Universe was $\sim 5 \times 10^9$ years old (Kormendy and Shields 2000).

Seyfert Galaxies, spirals with bright compact nuclei and strong emission lines (Seyfert 1943). *Type-1 Seyferts* show both narrow and broad lines from small nuclei and are often polarized, while *type-2* have only narrow lines and much larger nuclei (Freedman and Kaufmann III 2002 27-3).

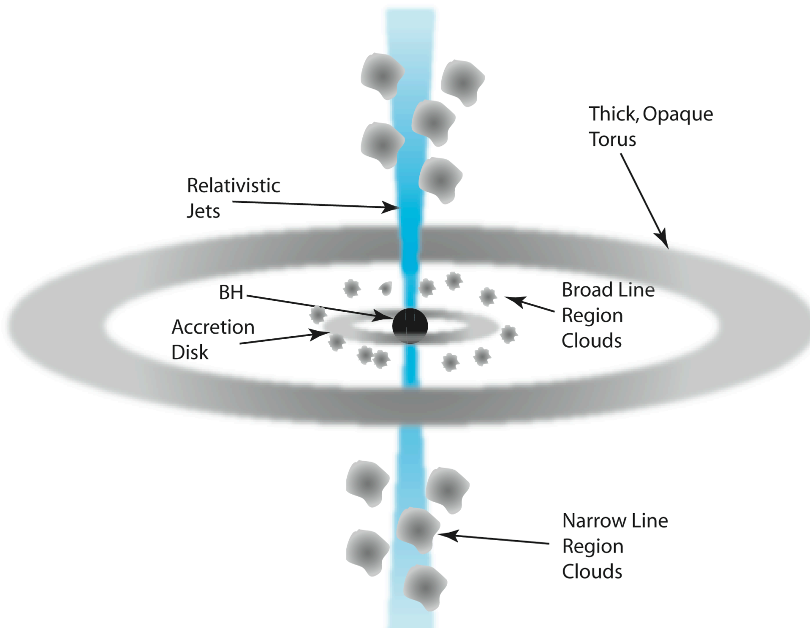
Radio Galaxies, giant ellipticals with bright nuclei, a jet emitting synchrotron radiation, and powerful radio emissions, generally from large lobes at the ends of the jets, 5 to 10 diameters from the host.

BL Lac objects, named for BL Lacertae, the first detected. They vary by a factor of 20-25, have a nonthermal spectrum with no emission lines, are often polarized, and often emit superluminal[1] blobs.

Unified Model

Salpeter (1964) first proposed that AGNs could be powered by accretion of matter into black holes, then Lynden-Bell (1969) proposed a SMBH as the power source for Sgr-A in our Galaxy.

We now have a unified model for AGNs [diagram based on (Freedman and Kaufmann III 2002)]:



The centre is a rotating *SMBH* orbited by a gas *accretion disk*. As friction consumes energy, gas spirals inward and is intensely heated by compression. This heating is efficient, reaching 10% of $e = mc^2$ conversion (stellar fusion is only 0.7% efficient) (Kormendy and Shields 2000). Variations in the infall cause variations in luminosity.

Outside the disk, a *broad line region* (BLR) is a group of gas clouds whose rapid orbital velocity Doppler shifts their emission lines. The mixture of shifts seen from a given viewpoint results in broadened lines.

The core produces twin *jets* and the region's turbulent plasma generates an intense magnetic field which, anchored to the gravitational well, is twisted into a helix shape

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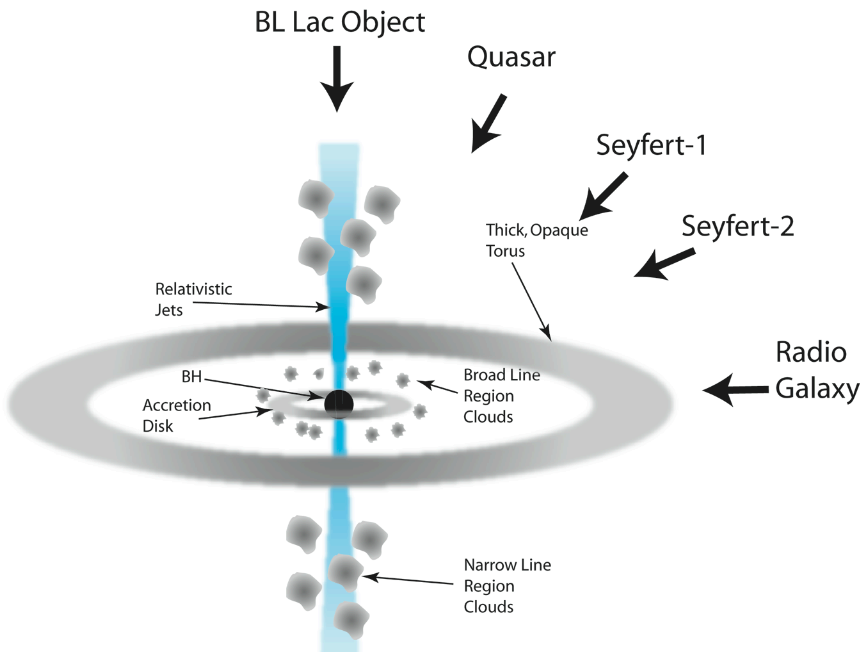
1 An illusion caused by viewing angle and relativistic speeds.

along the spin axis. The outflowing particles follow the magnetic field lines in spiral-shaped trajectories, emitting synchrotron radiation and, at relativistic speeds, this is concentrated in the direction of the beams.

Further out is a thick *torus* of dust, contributing to the different appearances of the system by obscuring the core and broad line regions from certain points of view (Barvainis 1995).

Finally, above the rotation poles of the black hole, another collection of gas clouds are irradiated by the jets and produce well defined emission lines, earning the name *Narrow Line Region* (NLR).

All the major types of AGNs can be explained with this model, by changing the viewing angle and internal parameters (Ferrarese and Ford 2005):



If the jet is pointed straight toward us, it outshines all other features, and we see the brilliant core of a BL Lac. Looking edge-on to the disk, the torus hides the core, and we see only the radio lobes where the jets interact with the interstellar medium, producing a double-lobe Radio Galaxy.

Quasars and Type-1 Seyferts result when we observe from above the pole, but not directly into the jet, seeing both the BLR and NLR. As we move toward the disk, our view of the BLR is obscured by the torus, giving us a Type-2 Seyfert. At intermediate stages, we still see BLR light reflected from the clouds in the NLR, polarized, as reflected light often is.

Searching for SMBHs in AGNs

The active phase of AGNs ended $1.5\times10^{8}-10^{9}$ years ago, but the total mass function of the universe suggests local galaxies were once active and should contain quiescent SMBHs (Marconi, Risaliti et al. 2004). This permits searching for SMBHs in both AGNs and local galaxies.

Search Methods

Lynden-Bell and Rees (1971) outlined the signs that would indicate a SMBH in a nucleus. The search method is to locate candidate Massive Dark Objects (MDOs) by looking for the dynamical effect of their gravity on surrounding material, then eliminate the possibility they are objects other than black holes (Kormendy and Richstone 1995). Once a candidate MDO has been located, its mass is determined using a variety of techniques, depending on the information available.

The Eddington Limit, $L_E = \frac{4\pi GMm_p c}{\sigma_T}$, limits the luminosity of an object fuelled by accretion before radiation pressure counters accretion. Since AGNs are fuelled by runaway processes, there is no good reason to assume their luminosity would peak at any lower value, and, given their luminosity, we can use this limit to estimate their mass (Ferrarese and Ford 2005).

More precise estimates measure orbiting material. *Stellar kinematics* is accurate, since star motions are gravitational, but long observation times are required. *Gas dynamics* requires shorter observation times, but is complex since gas responds to additional forces (Marconi, Pastorini et al. 2006).

Sometimes we are fortunate to discover *molecular masers* in orbiting gas. Their luminosity and known frequency enable precise velocity calculations and mass estimates. NGC 4258, with an orbiting water maser, was measured this way (Miyoshi, Moran et al. 1995).

Ferrarese and Pogge (2001) describe *Reverberation Mapping*, which does not require resolving details, and so can be used at greater distances and closer to nuclei. By studying the spectrum of a BLR, we estimate the nucleus size (from variability) and rotation speed (from line widths). Then, assuming the system is in a stable state, we can use the *virial theorem* $M_{total} = \frac{2\bullet R_{total} v^2}{G}$ to estimate the total mass. Wu et al (2002) outline a similar approach in which radius and surface brightness are obtained by observation, then a fundamental plane equation gives velocity dispersion, enabling the virial theorem to be used.

Search results

Appendix 1 (pg. 7) gives a sample of SMBH reports from recent journals. I highlight three cases here.

The **Milky Way** nucleus has been extensively studied since first being associated with a strong radio source in Sagittarius (Piddington and Minnett 1951). The source, Sgr-A*, was discovered in 1974 (Balick and Brown). Proper motion studies of stars in the region (Ghez, Klein et al. 1998) and ten years' observation of a star orbiting the nucleus (Schodel, Ott et al. 2002) have enabled accurate mass estimation, while rapidly varying X-Ray emissions (Baganoff, Bautz et al. 2001) and VLBI imaging (Shen, Lo et al. 2005) have constrained the size to less than 1.01 AU.

Sgr-A* is not alone. Young stars in this region hostile to star birth were probably dragged from a remote birthplace by an Intermediate Mass Black Hole (IMBH) (Hansen and Milosavijevic 2003), which has been recently discovered (Maillard, Paumard et al. 2004).

M31 has also been extensively studied, since it can be resolved better from the ground than can our next-nearest neighbours even from space telescopes (Kormendy 1988). M31 has a double nucleus, P1 and P2, P2 being the galactic centre (Lauer, Faber et al. 1993). These may, in fact, be the same object, appearing as an artefact of viewing angle on some kind of eccentric disk (Tremaine 1995). M31 might even be a *triple* nucleus: a cluster of blue stars embedded in P2 has a different spectrum from P2 and Bender argues it should be called a different nucleus, P3 (2005). The active nucleus may have recently been imaged in X-Rays (Garcia, Williams et al. 2005).

Elliptical galaxy **M87** is important as the first use of gas dynamics to detect a SMBH, $M_\bullet = (3.2 \pm 0.9) \times 10^9 M_\odot$ (Macchetto, Marconi et al. 1997).

Confirmed Sightings?

We have found MDOs that could be SMBHs and could not be anything else. In a sufficiently small region, clusters of other massive objects or single exotic objects would be short-lived, violating the principle that we should not assume we are observing at a "special time" in the history of the Universe (Marconi, Pastorini et al. 2006); or they would collapse and become a SMBH anyway (Melia and Falcke 2001). For example, all alternatives to a SMBH have been eliminated on such grounds for Sgr-A* [(Reynolds 2005) and (Miller 2006)].

No MDO has yet been constrained to less than its Schwarzschild radius, although Sgr-A* is now within a factor of 10-20 (Shen, Lo et al. 2005). However, in a different approach, Broderick and Narayan (2006) proved Sgr-A* has an event horizon by showing the assumption that it does not contradicts observed data.

Visual confirmation of an SMBH has not yet been achieved. Although we can never see a black hole, we could see its Event Horizon by looking for the dark shadow surrounding it, itself surrounded by a bright ring of refracted light, but we need much higher resolution. The shadow of the SMBH in Sgr-A* would have the apparent size of a tennis ball on the Moon as observed from the Earth (Reynolds 2005).

Formation of Supermassive Black Holes

Because Quasars are found at extreme distances, we need a model for the formation of SMBHs when the universe was only 1 or 2 billion years old: a mechanism that can start in the conditions of the early Universe, and can quickly generate a SMBH (Ferrarese 2003).

Some common mechanism seems to link the formation of SMBHs with galactic bulges (Cattaneo, Haehnelt et al. 1999). Locally, SMBH mass is always about 0.2% of bulge mass (Kormendy and Shields 2000) while, at high redshift, they correlate but the proportion varies with approximately $(1+z)^{3/2}$ [(Wyithe and Padmanabhan 2006) and (Peng, Impey et al. 2006)]. Masses of SMBHs also correlate almost perfectly with velocity distribution in bulges, and with jet power (Liu, Jiang et al. 2006); however, we don't know which is cause and which is effect.

Appendix 2 (pg. 8) shows the *Rees framework* for possible paths to SMBH formation.

Most theories assume seeding by small black holes, which merge and accrete matter until stabilizing at the Eddington limit. The theories differ in the nature and formation of the seeds.

One possibility is that Population-III stars quickly produce black holes, which then merge to MDOs (Volonteri and Rees 2005). Instabilities such as galactic mergers then trigger the inflow of material needed to build up SMBH mass (Di Matteo, Springel et al. 2005), possibly accelerated by early accretion of dark matter (Munyaneza and Biermann 2005).

However, stellar black holes are not ideal seeds since many interaction models eject them from the nucleus. Intermediate Mass Black Holes avoid some of the ejection problems, and the first, with $M_\bullet = 700 M_\odot$ has recently been discovered (Ebisuzaki, Makino et al. 2001).

Although this hierarchical build-up is the favoured theory, there are other possibilities. For example, a galactic-sized gas cloud could collapse directly to a SMBH if there were a mechanism for disposing of the angular momentum that would otherwise result in a disk. The multiple bars in unstable barred galaxies can transport momentum outward, and could permit direct collapse to a SMBH (Begelman, Volonteri et al. 2006).

Conclusion

The study of galactic nuclei mixes theoretical and observational astronomy. When first observed, Active Galaxies formed a complex family. The theoretical black hole concept permitted simplification of this family to a unified model based on a SMBH. Theory then suggested how to search for such objects, observation found them to be very common, and they are now helping to shape theories of the formation of all types of galaxies in the early universe.

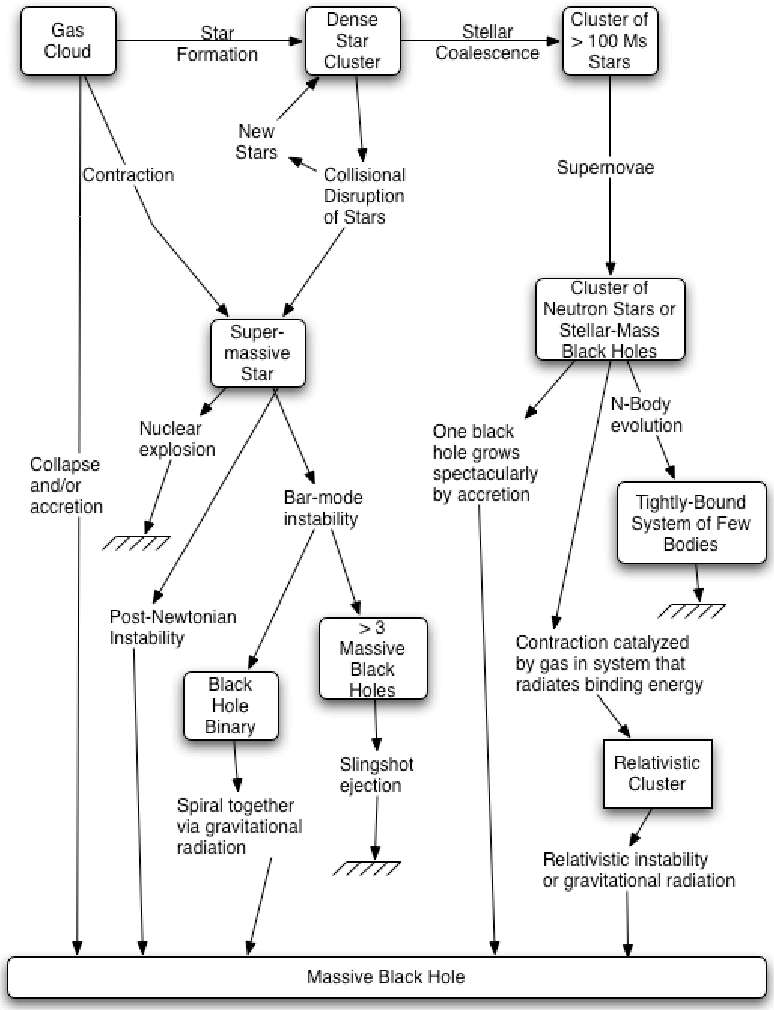
Appendix 1: SMBH Mass Observations

The following are summarized from a variety of recent journal publications. When multiple reports existed for a single object (which was common) I used the most precise or most recent.

Galaxy	Mass (Solars)	Error ±	Radius Less Than
3C273	1.00E+09		
3C345 (2 cores)	7.10E+08		
Centaurus A	1.10E+08	.10E+8	< .6 pc
Circinus	1.70E+06	.30E+6	
Cygnus A	2.50E+09	.70E+9	50 pc
IC2560	2.80E+06		
M31	3.00E+07		5 pc
M32	3.00E+07		
M84	2.94E+08		
M87	3.00E+09		
Milky Way	3.70E+06	.15E+7	1 AU
NGC1023	6.00E+07	.14E+8	
NGC1068	1.00E+07		
NGC3079	1.00E+06		
NGC3115	1.00E+09		
NGC3245	2.10E+08	.50E+8	
NGC3377	8.00E+07		
NGC3379	1.00E+08		
NGC4151	1.00E+09		< 60 pc
NGC4258	3.50E+07		0.5 ly
NGC4261	5.00E+08		
NGC4342	3.00E+08		
NGC4374	1.00E+09		
NGC4594	1.00E+09		
NGC4945	1.00E+06		
NGC5793	1.00E+07		
NGC6251	6.00E+08		
NGC7052	3.00E+08		

Appendix 2: Paths for Formation of Supermassive Black Holes

The following framework is redrawn from Rees (1984):



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