

# Violence in the Hearts of Galaxies - Aberration or Adolescence?

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Violent activity in the nuclei of galaxies has long been considered a curiosity in its own right; manifestations of this phenomenon include distant quasars in the early Universe and comparatively nearby Seyfert galaxies, both thought to be powered by the release of gravitational potential energy as material from the host galaxy accretes onto a central supermassive black hole (SMBH). Traditionally, the broader study of the formation, structure and evolution of galaxies has largely excluded active galactic nuclei. Recently however, this situation has changed dramatically, both observationally and theoretically, with the realisation that the growth and influence of the SMBH, the origin and development of galaxies and nuclear activity at different epochs in the Universe may be intimately related. The most spectacular fireworks seen in distant quasars, may be relatively easy to explain since the era of greatest quasar activity seems to coincide with turbulent dynamics at the epoch of galaxy formation in the young, gas-rich Universe. Ubiquitous black holes are believed to be a legacy of this violent birth. Alternatively, black holes may be the seeds which drive galaxy formation in the first place. Closer to home, and hence more recently in the history of the Universe, a fraction of comparatively ordinary galaxies, similar to our own, have re-ignited their central engines, albeit at a lower level of activity. Since these galaxies are more established than their younger and more distant counterparts, the activity here is all the more puzzling. Whatever the mechanisms involved, they are likely to play an important role in galaxy evolution. I review the intriguing evidence for causal links between supermassive black holes, nuclear activity and the formation and evolution of galaxies, and describe opportunities for testing these relationships using the next generation of earth-bound and space-borne astronomical facilities.

**Keywords:** Black holes;AGN;quasars;galaxy evolution

## 1. Introduction

Over the last 50 years, astronomers have been intrigued by enormously energetic objects called Active Galactic Nuclei (AGN), a violent phenomenon occurring in the nuclei, or central regions, of some galaxies with intensities and durations which cannot easily be explained by stars, thus providing some of the first circumstantial evidence for theoretically-predicted supermassive black holes. Despite their intriguing properties they were largely viewed as interesting but unimportant freaks in the broader study of galaxy formation and evolution, leading astronomers studying the properties of galaxies to exclude the small fraction of galaxies with active centres

as irritating aberrations. Here I describe the discovery of AGN and the variety of classifications that followed; I describe some features of unifying models of the central engine that attempt to explain the varied properties of different AGN classes that give rise to the classification. The search for supermassive black holes in AGN and non-active galaxies is discussed along with the developing realisation that all galaxies with significant bulge components might harbour dormant supermassive black holes as remnants of a past adolescent period of quasar activity and therefore possess the potential to be re-triggered into activity under the right conditions, making nuclear activity an integral part of galaxy formation and evolution.

## 2. The Early Studies of Active Galactic Nuclei

The discovery of AGN began with the development of radio astronomy after World War II when hundreds of sources of radio waves on the sky were detected and catalogued (e.g. Third Cambridge Catalogue (3C) - Edge *et al.* 1959 and its revision (3CR) - Bennett 1961), but the nature of these strong radio emitters was unknown. Astronomers at Palomar attempted to optically identify some of the catalogued radio sources; Baum & Minkowski (1960) discovered optical emission from a faint galaxy at the position of the radio source 3C295 and, on studying the galaxy's spectrum, or cosmic bar-code, measured its redshift and inferred a distance of 5000 million light years, making it the most distant object known at that time. Distances can be inferred from Hubble's law whereby the more distant an object, the faster it appears to be receding from us, due to the expansion of the Universe. Chemical elements present in these objects emit or absorb radiation at known characteristic frequencies and when observed in a receding object, the observed frequency is reduced or *redshifted* due to the Doppler effect; the same physical process that causes a receding ambulance siren to be lowered in pitch after it passes the observer.

Attempts to find visible galaxies associated with other strong radio sources such as 3C48, 3C196 and 3C286 failed and only a faint blue, star-like object at the position of each radio source was found - thus leading to their name 'quasi-stellar radio sources', or 'quasars' for short. The spectrum of these quasars resembled nothing that had previously been seen for stars in our Galaxy and these blue points remained a mystery until Maarten Schmidt (1963) concentrated on 3C273, for which an accurate radio position was known (Hazard, Mackey & Shimmins 1963). The optical spectrum of the blue source associated with the radio emitter seemed unidentifiable until Schmidt realised that the spectrum could be clearly identified with spectral lines emitted from hydrogen, oxygen and magnesium atoms if a redshift corresponding to 16% of the speed of light was applied. The same technique was applied successfully to 3C48 (Greenstein & Matthews 1963) and demonstrated that these objects are not members of our own galaxy but lie at vast distances and are super-luminous. Indeed, the radiation emitted from a quasar ( $L \gtrsim 10^{13} L_{\odot}$ , where the Sun's luminosity is  $L_{\odot} = 3.8 \times 10^{26}$  Watt) is bright enough to outshine all the stars in its host galaxy. Such energies cannot be produced by stars alone and it was quickly realised that the release of gravitational potential energy from material falling towards, or being accreted by, a *supermassive black hole* at the galaxy centre,  $\sim 100$  times more energy efficient than nuclear fusion, was the only effective way to power such prodigious outputs (Lynden-Bell 1969).

A black hole is a region of space inside which the pull of gravity is so strong that nothing can escape, not even light. Two main kinds of black holes are thought to exist in the Universe. *Stellar-mass* black holes arise from the the collapsed innards of a massive star after its violent death when it blows off its outer layers in a spectacular supernova explosion; these black holes have mass slightly greater than the Sun but are compressed into a region only a few kilometres across. In contrast, *supermassive black holes*, which lurk at the centres of galaxies, are 10 million to 1000 million times more massive than the Sun and contained in a region about the size of the Solar System. The emission of radiation from a supermassive black hole appears at first to be contradictory; however, the energy generating processes take place outside the black hole's point-of-no-return, or *event horizon*. The mechanism involved is the conversion of gravitational potential energy into heat and light by frictional forces within a disk of accreting material, which forms from infalling matter that still possesses some orbital energy, or angular momentum, and so cannot fall directly into the black hole.

Radiation from AGN is detected across the electromagnetic spectrum and today, nuclear activity in galaxies has been detected over a wide range of luminosities, from the most distant and energetic quasars, to the weaker AGN seen in nearby galaxies, such as Seyferts (Seyfert 1943), and even the nucleus of our own Milky Way.

### 3. AGN Orientation - Looking at it from All Angles

After the initial discovery of radio-loud AGN, the advent of radio interferometry soon led to detailed images of these strong radio emitters (e.g., Bridle & Perley 1984; Bridle *et al.* 1994) which revealed remarkable long thin jets of plasma emanating from a central compact nucleus and feeding extended lobes, often at considerable distances from the AGN, millions of light years in the most extreme cases. The radio emission is synchrotron radiation produced by electrons spiraling around magnetic fields in the ejected plasma; figure 1 shows a radio image of the classic radio galaxy Cygnus A in which the nucleus, jets and lobes are visible. These dramatic jets and clouds of radio-emitting plasma were interpreted as exhaust material from the powerful central engine (Scheuer 1974; Blandford & Rees 1974).

#### (a) *Too fast to believe - the remarkable jets in radio-loud AGN*

The sharpest radio images, made repeatedly over many years using networks of radio telescopes spanning the globe, resulted in 'movies' of the motion of material in the jets. The blobs of plasma in these jets were apparently being ejected at many times the speed of light,  $c$ , appearing to violate fundamental laws of physics. It was quickly realised that such *superluminal* motion, was an optical illusion caused by the plasma moving at *relativistic* speeds, i.e.  $\gtrsim 0.7c$ , and being ejected towards us at an angle close to our line of sight (e.g., Blandford & Rees 1978). Relativistic motion appears to be present for jet matter over hundreds of thousands of light years and the detailed physical driving mechanisms remain an area of active study. The relativistic motion of jet matter has an enormous impact on the appearance of these objects and is possibly the single-most important contributor to the variety of observed morphological types.

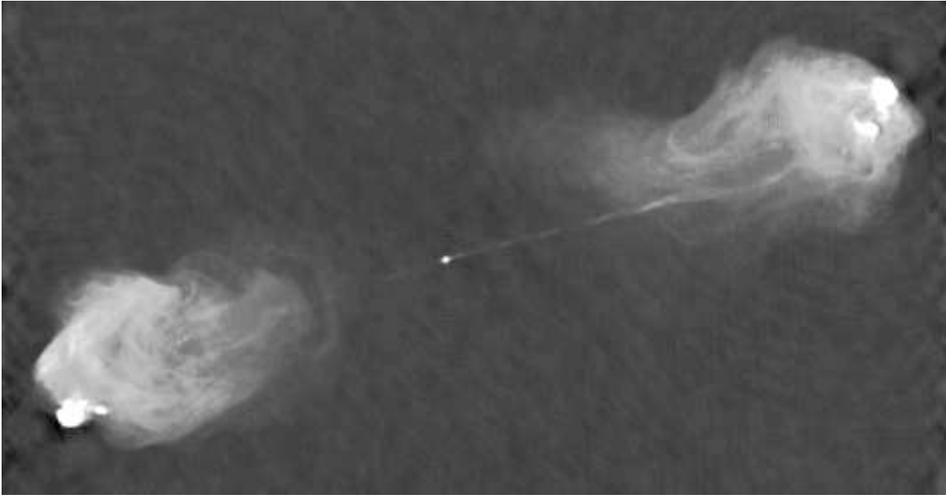


Figure 1. 6-cm radio image of the classic radio galaxy Cygnus A (courtesy Chris Carilli)

The fast motion of jet material also causes extreme apparent brightening, or Doppler boosting, of the radiation and greatly amplifies any flickering, or variability, in the light levels. Today, the wide range of observed radio structures, brightnesses and levels of variability can be understood in terms of the angle at which we view the high-speed plasma jet. *Radio galaxies* like Cygnus A are orientated perpendicular to our line of sight, lying in the plane of the sky, appear rather symmetrical, and as expected, show no variability or superluminal motion. At the other extreme are bright, compact and highly variable *BL Lac objects*, which are being observed head-on. Figure 2 shows a sketch of this model in which a jet of plasma is ejected from either side of the central engine at relativistic speeds; object classification depends on the angle of the jet to our line of sight. Objects viewed at intermediate angles are seen as either extended, ‘lobe-dominated’ quasars or relatively compact, ‘core-dominated’ quasars (see also Urry & Padovani 1995).

(b) *Obscuring-Doughnuts in Radio-Quiet AGN*

*Radio-quiet* quasars and Seyferts are known to be  $\sim 10$  times more common, but 100 to 1000 times weaker at radio wavelengths and significantly less extended than their *radio-loud* cousins (Goldschmidt *et al.* 1999), but orientation still has important effects, this time on the optical properties. Optical spectroscopy provides a powerful diagnostic tool for the physical conditions in astronomical objects; as described earlier chemical elements have a characteristic spectral signature and physical conditions within a gas can be inferred from distortions of this chemical bar-code. In particular, broadening of the spectral lines indicates a spread in gas-cloud velocities, whilst the relative brightnesses of spectral lines indicate the intensity of ultraviolet radiation incident upon the gas.

Measurements of the optical spectra of Seyfert nuclei show spectral lines from gas ionised (i.e. gas in which atoms have been stripped of one or more electrons) by strong ultraviolet radiation that is too intense to be produced by a collection of stars and is instead thought to originate from the accretion disk. All Seyfert

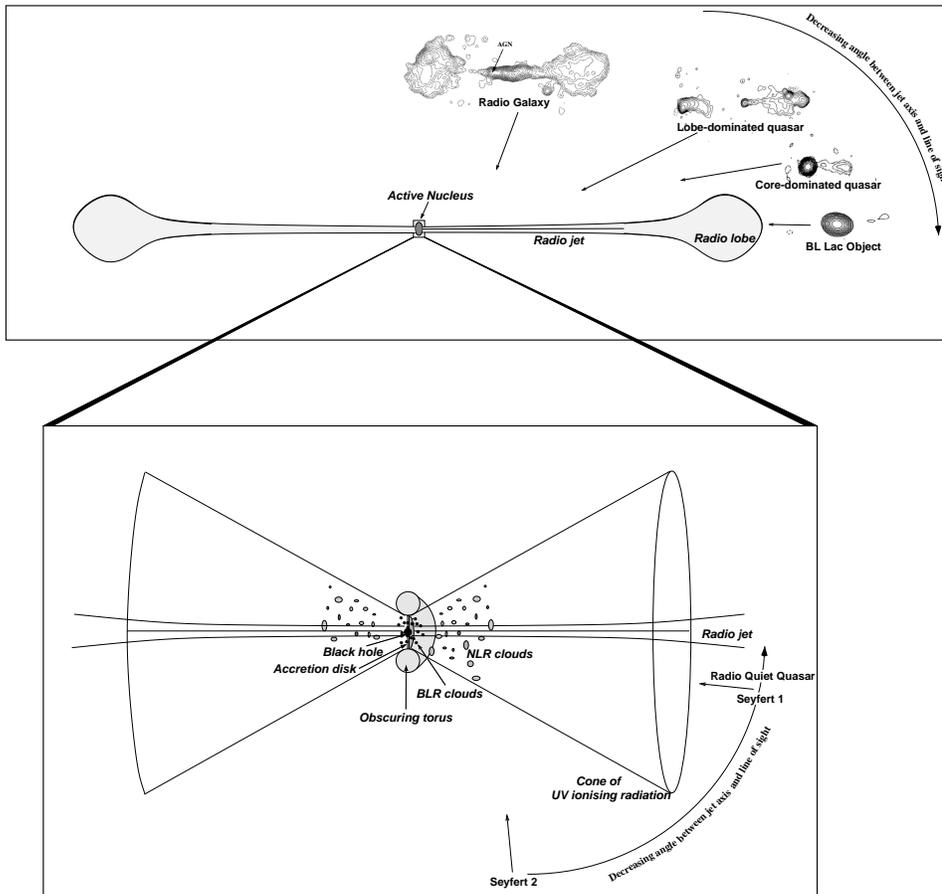


Figure 2. Top: Radio-loud unification scheme, in which the observed AGN type depends on the observer's viewing angle to the ejection axis of the radio jet. Bottom: Sketch of an AGN central engine with a central black hole surrounded by (a) an accretion disc that emits cones of ultraviolet ionising radiation and defines the radio jet launch direction, (b) a torus of dust a gas that accounts for the different observed kinds of radio-quiet AGN by blocking our view of the accretion disc and dense, rapidly-moving ionised gas clouds in the broad-line region (BLR) when viewed edge-on (type 2 objects). Less-dense ionised clouds in the narrow-line region (NLR) lie above the plane of the torus and are visible from all angles.

nuclei contain a region of ionised gas, the Narrow Line Region (NLR), extending over several hundred light years where the spectral line-widths correspond to gas velocities of a few hundred  $\text{km s}^{-1}$  and densities are moderate (electrons per unit volume  $n_e \sim 10^3 - 10^6 \text{ cm}^{-3}$ ). Closer in, within  $\sim 0.1$  light year of the black hole, is the Broad-Line Region (BLR), a much denser region of gas ( $n_e \sim 10^9 \text{ cm}^{-3}$ ) that shows gas velocities up to  $10,000 \text{ km s}^{-1}$ . Seyferts were originally classified into two types; type-1 Seyferts that show evidence for both a BLR and an NLR, and type-2 Seyferts that show only an NLR (Khachikian & Weedman 1971, 1974).

The mystery of the missing BLRs in type-2 Seyferts was solved elegantly in 1985 when Antonucci & Miller discovered a hidden BLR in the *scattered* light spectrum

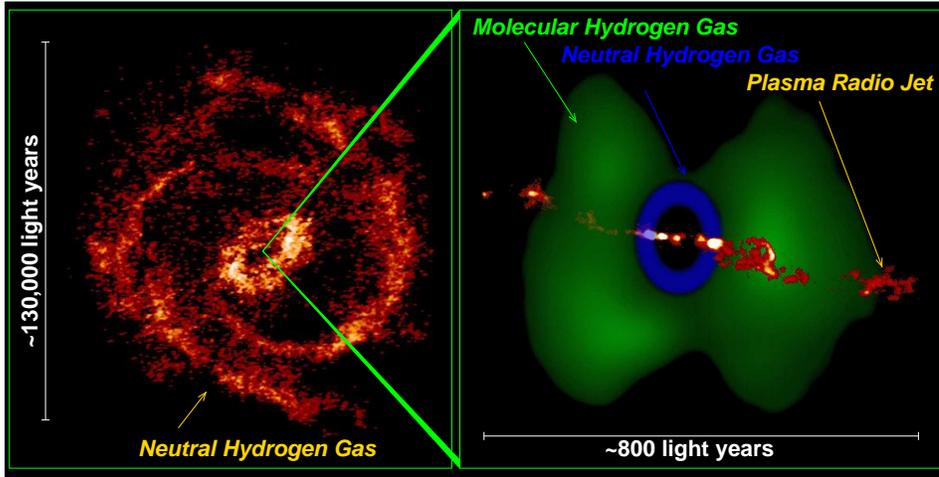


Figure 3. Left: Radio image of neutral hydrogen gas in the spiral Seyfert host galaxy NGC 4151 (Mundell *et al.* 1999); Right: composite image of the central regions of NGC 4151 showing a 1.4-GHz radio image of the well-collimated plasma jet surrounded by an obscuring torus of molecular hydrogen imaged at  $2.2\mu\text{m}$  (Fernandez *et al.* 1999) and an inferred inner ring of neutral hydrogen from absorption measurements (Mundell *et al.* 2002).

of the archetypal Seyfert 2 galaxy NGC 1068, which closely resembled that of a Seyfert type 1. This discovery led to the idea that the BLR exists in all Seyferts and is located inside a doughnut, or torus, of molecular gas and dust; our viewing angle with respect to the torus then explains the observed differences between the unobscured, broad-line Seyfert 1s, viewed pole-on, and the obscured, narrow-line Seyfert 2s, viewed edge-on. Hidden Seyfert 1 nuclei can then be seen in reflected light as light photons are scattered into the line of sight by particles above and below the torus acting like a “dentist’s mirror” (Antonucci & Miller, 1985; Tran 1995; Antonucci 1993; Wills 1999). The lower panel of Figure 2 shows a sketch of a Seyfert nucleus with the different types of AGN observed as angle between line of sight and torus axis increases. Figure 3 shows an image of the molecular torus in NGC 4151, surrounding the mini, quasar-like radio jet emanating from the centre of the galaxy, as predicted by the unification scheme.

Radio quiet quasars also have broad and narrow lines and are considered to be the high luminosity equivalents of Seyfert type 1 galaxies. A population of narrow-line quasars, high luminosity equivalents to obscured Seyfert 2s, are predicted by the unification scheme but, until now, have remained elusive. New optical and infrared sky surveys are beginning to reveal a previously undetected population of red AGN (Cutri *et al.* 2001) with quasar type 2 spectra (Djorgovski *et al.* 1999) and weak radio emission (Ulvestad *et al.* 2000). A significant population of highly obscured but intrinsically luminous AGN would alter measures of AGN evolution, the ionisation state of the Universe and might contribute substantially to the diffuse infrared and X-ray backgrounds.

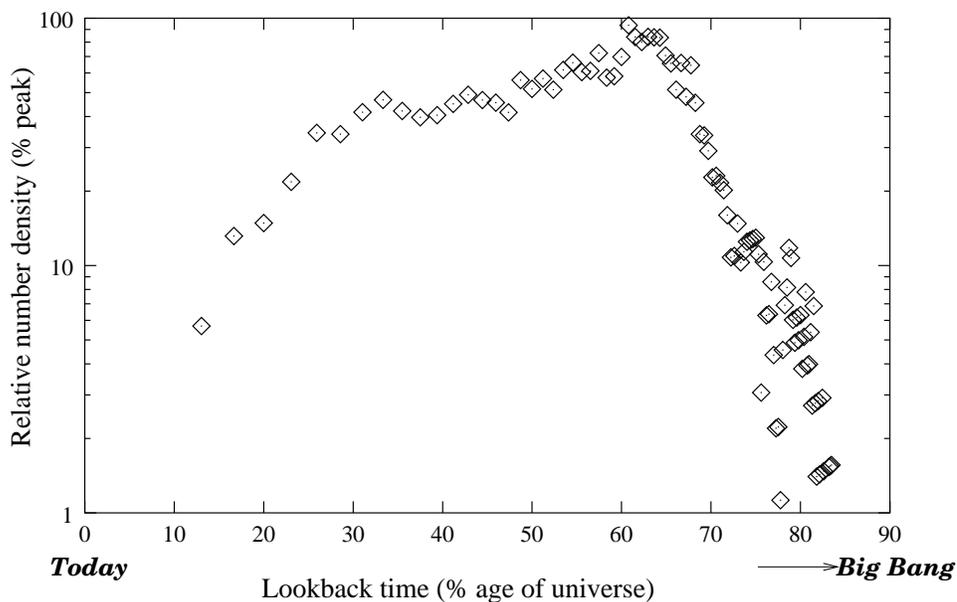


Figure 4. Relative number of galaxies per unit volume of space (as a fraction of the peak value) detected in the Sloan Digital Sky Survey, as a function of *look-back time* i.e. time running backwards from now to the Big Bang [using data from Schneider *et al.* (2002)].

(c) *Further unification?*

The presence of gas emitting broad and narrow optical lines in radio-loud AGN and the discovery of mini radio jets in Seyferts (e.g. Wilson & Ulvestad 1982) led to further consistency between the two unification schemes. Nevertheless, the complete unification of radio-loud and radio-quiet objects remains problematic, particularly in explaining the vast range in radio power and jet extents, and might ultimately involve the combination of black hole properties, such as accretion rate, black hole mass and spin, and orientation (Wilson & Colbert, 1995; Boroson 2002).

#### 4. Searching for Supermassive Black Holes

Although incontrovertible observational proof of the existence of supermassive black holes (SMBHs) has yet not been found, evidence is mounting to suggest the presence of massive dark objects, or large mass concentrations at the centres of galaxies. Black holes, by definition, cannot be ‘seen’ and instead one must look for the consequences of their presence. The presence of SMBHs has been inferred indirectly from the energetics of accretion required to power luminous AGN and explain rapid flux variability and, more directly, from kinematic studies of the influence of the black hole’s gravitational pull on stars and gas orbiting close to it in the central regions of both active and non-active galaxies. Theoretical models rule out alternatives to a supermassive black holes such as collections of brown or white dwarf stars, neutron stars or stellar-mass black holes which would merge and shine or evaporate too quickly (Maoz 1995, 1998; Genzel *et al.* 1997, 2000).

*(a) Quasar lifetimes and the black hole legacy*

Soon after the discovery of quasars it became clear that they were most common when the Universe was relatively young with the peak of the quasar epoch at redshift  $z \sim 2.5$  or a *look-back time* of 65% of the age of the Universe (See Figure 4); today bright quasars are rare and weaker Seyferts dominate instead. The number of dead quasars or relic, dormant black holes left today can be estimated by applying some simple arguments to the quasar observations. Soltan (1982) integrated the observed light emitted by quasars, and, assuming the power source for quasar light is accretion of material by a supermassive black hole with a mass-to-energy conversion efficiency of 10% and that the black hole grows during the active phase, predicted the total mass in relic black holes today. Knowing the number of galaxies per unit volume of space (e.g. Loveday *et al.* 1992), if one assumes that all galaxies went through a quasar phase at some time in their lives, then each galaxy should, on average, contain a  $\sim 10^8 M_\odot$  black hole as a legacy of this violent, but short-lived period ( $\sim 10^7$  to  $\sim 10^8$  years). Alternatively, if only a small fraction of galaxies went through a quasar phase, the active phase would have lasted longer ( $> 10^9$  years) and the remnant SMBHs would be relatively rare, but unacceptably massive ( $> 10^9 M_\odot$ ) (e.g. Cavaliere *et al.*, 1983; Cavaliere & Szalay 1986, Cavaliere & Padovani 1988).

More complex models including quasar evolution (e.g. Tremaine 1996; Faber *et al.* 1997) and the effects of galaxy growth (e.g. Haehnelt & Rees 1993) favour short-lived periods of activity in many generations of quasars, or a mixture of continuous and recurrent activity (Small & Blandford 1992; Cen 2000; Choi, Yang & Yi 2001). The complex physics of accretion and black hole growth, however, remain an area of active study (e.g. Blandford & Begelman 1999; Fabian 1999). Nevertheless, the range of black hole mass of interest is thought to be  $M_\bullet \sim 10^6$  to  $10^{9.5} M_\odot$ , with the lower mass holes being ubiquitous (Kormendy & Gebhardt 2001).

*(b) Irresistible black holes - dynamics of gas and stars*

Although the prodigious energy outputs from powerful quasars offer strong circumstantial evidence that supermassive black holes exist, most notably in driving the ejection and acceleration of long, powerful jets of plasma close to the speed of light (Rees *et al.* 1982), it has not, until recently, been possible to make more direct kinematic measurements of the black hole's gravitational influence. The mass of a central object, the circular velocity of an orbiting star and the radius of the orbit are related by Newton's Laws of motion and gravity. Precise measurements of the velocities of stars and gas close to the centre of a galaxy are then used to determine the mass of the central object.

The strongest dynamical evidence for black holes comes from studies of the centre of our own Galaxy and a nearby Seyfert, NGC 4258; a decade of painstaking observations of a cluster of stars orbiting around the mildly active centre of the Milky Way, within a radius of 0.07 light years of the central radio source Sgr A\*, suggest a central mass of  $M_\bullet = (2.6 \pm 0.2) \times 10^6 M_\odot$  (Eckart & Genzel 1997; Genzel 1997, 2000; Ghez 2000). Discovery of strong radio spectral lines, or megamasers, emitted from water molecules in a rapidly rotating nuclear gas disc at the centre of NGC 4258 implies a centre mass  $M_\bullet = (4 \pm 0.1) \times 10^7 M_\odot$  concentrated in a region smaller than 0.7 light years (Miyoshi *et al.* 1995), again small enough to rule out anything other

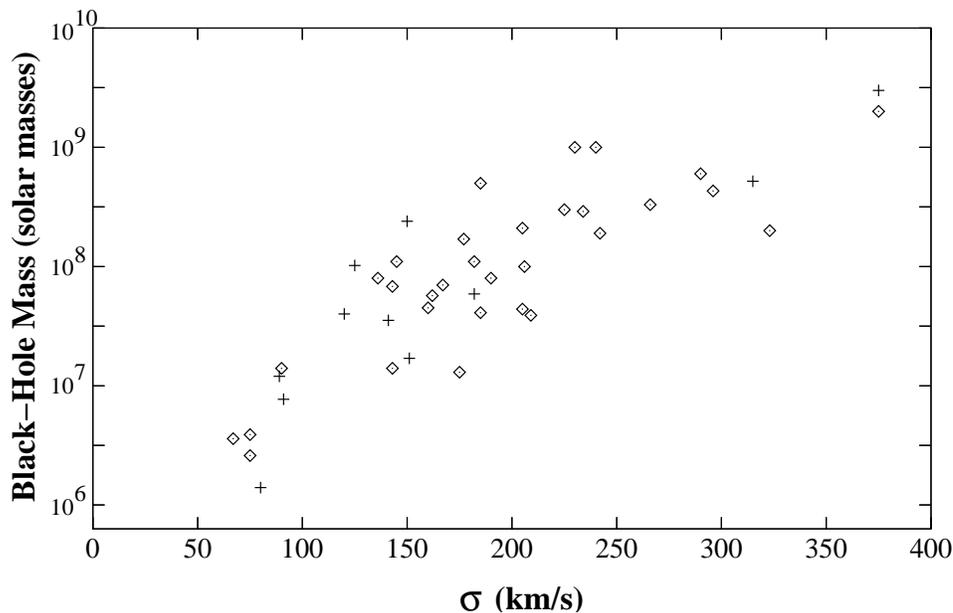


Figure 5. Black hole mass against host galaxy bulge stellar velocity dispersion for nearby AGN (open diamonds) and non-active galaxies (+ symbols) [using data from Kormendy & Gebhardt (2001) and Ferrarese *et al.* (2001)].

than a black hole (Maoz 1995, 1998). Precision measurements of black hole masses in other galaxies using a variety of techniques, although challenging and still model dependent, have become increasingly common (e.g. Maggorian *et al.* 1998; Bower *et al.* 1998; Gebhardt *et al.* 2000) and now more than 60 active and non-active galaxies have black hole estimates.

## 5. Black Hole Demographics - the Host Galaxy Connection

In general, galaxies consist of two main visible components - a central ellipsoidal bulge and a flat disc structure commonly containing spiral arms - together making a structure resembling two fried eggs back-to-back. Elliptical galaxies have no discs and are dominated by their bulges, maintaining their shapes by the random motions of their stars; spiral galaxies, like our own Galaxy and nearby Andromeda have prominent discs and are supported mainly by rotation, with rotation speeds between  $200 \text{ km s}^{-1}$  and  $300 \text{ km s}^{-1}$ . Some spiral galaxies contain a bar-like structure that crosses the nucleus; the spiral arms then begin at the ends of the bar and wind outwards. If the bar is narrow and straight it is classed as a ‘strong’ bar and if oval-shaped (essentially an elongated bulge) it is ‘weak’. Dynamical simulations have revealed that in the region of the bar, stars do not travel on circular orbits as they do in the disk, but instead follow more elongated elliptical, or ‘non-circular’ paths.

With the great progress made recently in measuring the mass of central supermassive black holes in a significant number of active and non-active galaxies, correlations with their host galaxy properties are now possible. Maggorian *et al.* (1998) confirmed the correlation between the brightness of a galaxy bulge (and

hence stellar mass) and the mass of its central black hole (e.g. Kormendy & Richstone 1995) establishing a best fit to the linear relation of  $M_{\bullet}=0.006M_{bulge}$ , despite a large scatter. A much tighter correlation was subsequently discovered between the velocity dispersion ( $\sigma$ ) of stars in the host galaxy bulge and the central black hole mass (e.g. Gebhardt *et al* 2000; Ferrarese & Merrit 2000). The velocity dispersion is a measure of the range of random speeds present in star motions and is potentially a more reliable galaxy mass indicator than total starlight; the greater the spread in speeds, the more massive the galaxy bulge. The tightness of the correlation points to a connection between the formation mechanism of the galaxy bulge and central black hole although the physics involved are not yet known. The  $M_{\bullet}-\sigma$  relation for a mixture of nearby active and non-active galaxies (Figure 5), measured using a variety of techniques, shows the relationship between bulge and black hole is very similar for both, although investigations continue to establish the precise form of the correlation and whether it is universal for active and non-active galaxies. If universal, this relationship would provide exciting confirmation that non-active galaxies contain dormant versions of the same kind of black holes that power AGN.

No correlation exists between galaxy disc properties and black hole mass, and disc galaxies without bulges do not appear to contain supermassive black holes (e.g. Gebhardt *et al.* 2001), suggesting discs form later and are not involved in the process that intimately links the black hole and bulge.

## 6. AGN and their Environment

### (a) *The violent early Universe*

The relationships between black holes and their host galaxies are increasingly compelling but unanswered questions remain concerning the relationship between star formation, galaxy formation, quasar activity and black hole creation in the early Universe. Observations of faint galaxies in the Hubble Deep Field suggested a peak in star formation history that matches that of the quasar epoch (e.g. Madau *et al.* 1996) implying a close link between star formation and quasar activity. More recent measurements, however, suggest that the star formation activity may be constant for redshifts greater than 1 with the onset of substantial star formation occurring at even earlier epochs, at redshifts beyond 4.5 (Steidel *et al.* 1999). An increasing number of new quasars are also being found at redshifts greater than 4 (Fan *et al.* 2001; Schneider *et al.* 2002) providing constraints for cosmological models of galaxy formation and continuing the debate on the relationship between quasar activity, star formation and the creation of the first black holes (e.g. Haiman & Loeb 2001).

The life cycle of an AGN involves a mechanism to trigger the infall of gas to create an accretion disc and continued fuelling, or replenishment, of this brightly-shining accretion disc. A number of models have suggested that at intermediate to high redshifts it may be moderately easy to trigger and fuel AGN, where galaxies might be more gas rich, star formation is vigorous and collisions between galaxies are common (Haehnelt & Rees 1993). Kauffman & Haehnelt (2000) suggest a model in which galaxy and quasar evolution at early times was driven by mergers of gas-rich disc galaxies, which drove the formation and fuelling of black holes and created today's elliptical galaxies, thereby tying together host galaxy and black hole

properties. As the Universe ages, a decreasing galaxy merger rate and available gas supply and increasing accretion timescales produce the decline in bright quasars.

An alternative hypothesis, linking black hole and bulge growth with quasar activity, involves strong bars in early galaxies (Sellwood 1999); early disc galaxies developed strong bars which were highly efficient at removing angular momentum from disc gas and funnelling it towards the centre to feed and grow a black hole. This represents the bright quasar phase in which the black hole grows rapidly, but on reaching only a few percent of the mass of the host disc, the central mass concentration soon destroys the bar due to an increasing number of stars that follow random and chaotic paths, thereby choking off the fuel supply and quenching the quasar. In addition, the increase in random motion in the disc leads to the creation of a bulge. A disc might be re-built some time later if the galaxy receives a new supply of cold gas, perhaps from a ‘minor merger’ whereby a small gaseous galaxy or gas-cloud falls into the main disc and is consumed by the disc without causing significant disruption, and without significantly affecting the black hole mass. This scenario nicely accounts for the relationship between black hole masses and bulge properties and lack of correlation with disc properties.

An important unknown parameter in these models is the amount of cold gas in progenitor disc galaxies and how it evolves with time; it is expected that the Universe was more gas-rich in the past (Barger *et al.* 2001), but observations of neutral hydrogen (HI) and molecular gas such as carbon monoxide (CO) with new generation facilities, such as Atacama Large Millimeter Array (ALMA), the Giant Metrewave Radio Telescope (GMRT), the Extended Very Large Array (EVLA) and the proposed Square Kilometre Array (SKA), will offer exciting opportunities to measure the gaseous properties of distant galaxies directly to further our understanding of galaxy formation and evolution and its relationship to quasar and star-formation activity.

(b) *Re-activating dormant black holes in nearby galaxies*

While the most luminous AGN might coincide with violent dynamics in the gas-rich universe at the epoch of galaxy formation (Haehnelt & Rees 1993), nuclear activity in nearby galaxies is more problematic since major galaxy mergers, the collision of two equal-mass disc galaxies, are less common and galaxy discs are well established; reactivation of ubiquitous ‘old’ black holes is therefore likely to dominate. Host-galaxy gas represents a reservoir of potential fuel and, given the ubiquity of supermassive black holes, the degree of nuclear activity exhibited by a galaxy must be related to the nature of the fuelling rather than the presence of a black hole (e.g., Shlosman & Noguchi 1993; Sellwood & Moore 1999). Gravitational, or tidal forces exerted when two galaxies pass close to one another may play a role in this process, either directly, when gas from the companion, or outer regions of the host galaxy, is tidally removed and deposited onto the nucleus, or by causing disturbances to stars orbiting in the disc and leading to the growth of structures such as bars, in which stars travel on elliptical paths and drive inflows of galactic gas (e.g. Toomre & Toomre 1972; Simkin, Su & Schwarz 1980; Shlosman, Frank & Begelman 1989; Mundell *et al.* 1995; Athanassoula 1992; Mundell & Shone 1999).

Numerous optical and IR surveys of Seyfert hosts have been conducted but as yet show no conclusive links between nuclear activity and host galaxy environment.

Neutral hydrogen (HI) is an important tracer of galactic structure and dynamics and may be a better probe of environment than the stellar component. HI is often the most spatially extended component of a galaxy's disc so is easily disrupted by passing companions, making it a sensitive tracer of tidal disruption (e.g. Mundell et al., 1995). In addition, because gas can dissipate energy and momentum through shock waves (Mundell & Shone, 1999), whereas collisions between stars are rare, the observable consequences of perturbing the HI in galactic bars are easily detectable. However, despite the diagnostic power of HI, until recently few detailed studies of HI in Seyferts have been performed (Brinks & Mundell 1996; Mundell 1999).

The strength of a galaxy collision, which depends on initial galaxy properties such as mass, concentration, distance and direction of closest approach, ranges from the most violent mergers between equal mass, gas-rich disc galaxies, to the weakest interaction in which a low mass companion, perhaps on a fly-by path, interacts with a massive primary. In this minor-merger case the primary disc is perturbed but not significantly disrupted or destroyed. Indeed, Seyfert nuclei are rare in strongly interacting systems, late-type spirals and elliptical galaxies (Keel et al. 1995; Bushouse 1996) and sometimes show surprisingly undisturbed galactic discs despite the presence of HI tidal features (Mundell et al. 1995). Seyfert activity may therefore involve weaker interactions or minor mergers between a primary galaxy and a smaller companion or satellite galaxy, rather than violent major mergers (e.g. De Robertis, Yee & Hayhoe 1998). A key question is whether the gaseous properties of normal galaxies differ from those with Seyfert nuclei and a deep, systematic HI imaging survey of a sample of Seyfert and normal galaxies is now required.

## 7. Unanswered Questions and Prospects for the Future

Studies of galaxies and AGN are being revolutionised by impressive new sky surveys, such as SLOAN and 2DF, which have already significantly increased the number of known galaxies and quasars in the Universe. In the next decade and beyond, prospects for understanding AGN and their role in galaxy formation and evolution are extremely promising given the number of planned new instruments spanning the electromagnetic spectrum.

- We do not yet know whether galaxies grow black holes or are seeded by them; NGST (Next Generation Space Telescope) will find the smallest black holes at the earliest times and allow us to relate them to the first galaxies and stars.
- The amount of cold gas in galaxies through cosmic history is a key ingredient in star-formation, quasar activity and galaxy evolution models but is still unknown. The study of gas at high redshifts with ALMA, the GMRT and the EVLA will revolutionise our understanding its role in these important phenomena and provide powerful constraints for cosmological models.
- Current models of AGN physics - fuelling, accretion discs and the acceleration of powerful radio jets - remain speculative; detailed studies of X-ray emitting gas, e.g. with the highly ambitious X-ray space interferometer MAXIM, might offer valuable new insight into the energetics and physical structure of this extreme region.
- Finally, the detection and detailed study of gravitational waves, using the space-based detector LISA, from massive black holes living in black-hole binary systems or in the very act of merging will prove the existence of SMBHs and perhaps provide insight into the origin of the difference between radio-loud and radio-quiet AGN.

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