Formation et évolution des galaxies
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Active Galaxies

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Abstract.

This lecture provides an introduction to Active Galactic Nuclei including basic observational properties, classification of AGN, the black hole and accretion disk scenario, as well as a brief review of AGN in the context of galaxy evolution and the AGN-starburst connection.

Contents

1 Introduction

Active Galactic Nuclei (AGN) are bright, compact cores located at the centres of some galaxies. The "active" in active galaxies refers to the fact that the radiation from these nuclei cannot be explained as radiation emitted by stars, or, as radiation from gas heated by stars. Galaxies which harbor such nuclei are called Active Galaxies.

The extraordinary nature of active galaxies is manifest in their extreme properties. These include very high central surface brightness, extreme velocities of ionized gas clouds, collimated jets of relativistic particles, and radiation which spans a very broad range of frequencies. Such properties are indicators of the wide range of energetic processes present in active galaxies. The energy for these processes is thought to be ultimately derived from the loss of gravitational binding energy via accretion of gas onto a super-massive black hole at the heart of the active nucleus.

These lectures aim to serve as a basic introduction to active galaxies, and to connect the subject of AGN to the "Galaxy Evolution" theme of this summer school. The basic introduction covers the observational properties and classification of the different types of active galaxies, plus a review of the arguments for the black hole and accretion disk scenario. We describe the unified model for AGN and discuss the current evidence for the existence of super-massive black holes. The role of AGN in galaxy evolution is however a much less mature topic. This review tries to summarize some of the current and emerging ideas in this field, including the hot topics of jet induced star formation, the merging galaxies scenario for the triggering of star formation and AGN activity, and the "AGN-starburst connection".

2 Discovery and Classification of AGN

The first detections of AGN are attributed to Fath (1909) and Slipher (1917) whose photographic spectroscopy revealed the presence of strong emission lines in the nuclear spectrum of NGC 1068. Hubble (1926) also noted these lines and found other similar objects, namely NGC 4051 and NGC 4151. Seyfert was the first to group these galaxies into a distinct class, now known as Seyfert galaxies. These galaxies were originally selected on the basis of bright stellar-like (unresolved) cores, and Seyfert found that several of these (NGC 1068, NGC 1275, NGC 3516, NGC 4051, NGC 4151 and NGC 7469) showed high excitation emission lines (Seyfert 1943). Seyfert noted that these lines were wider than the absorption lines in normal galaxies, and that the hydrogen lines are sometimes broader than the other lines. Based on these observations, Woltjer

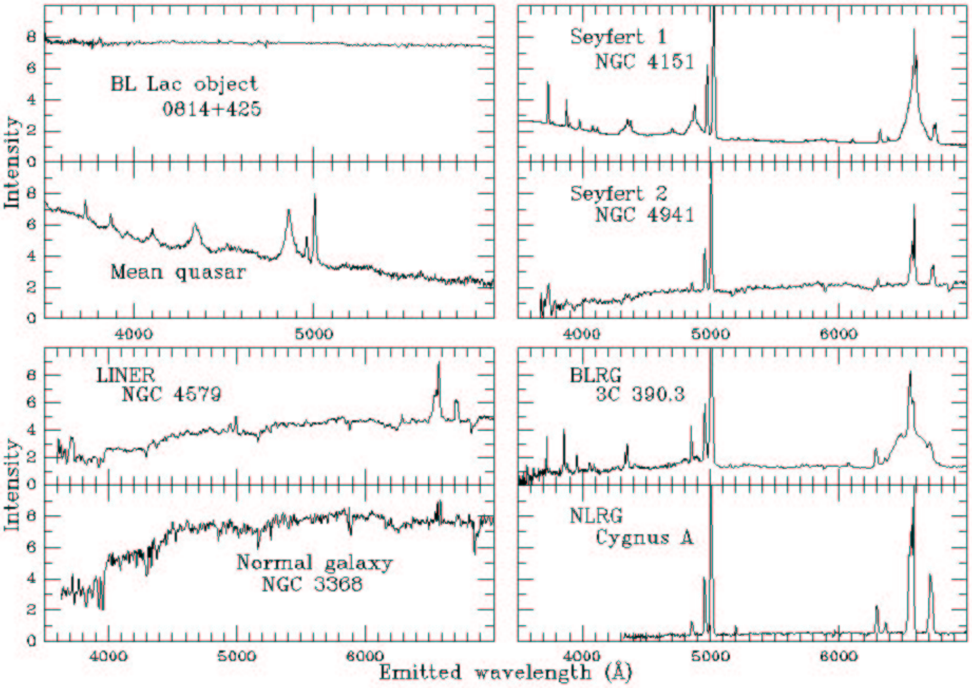

Figure 1: *Spectra of different types of active galaxies (Keel 2002).*

(1959) made the first attempt to understand the physics of AGN. He noted that the unresolved nuclei implied a size of 1-100 pc, and that if the material producing the wide emission lines were gravitationally bound, then the central mass must be of order 10^{10} $M_{\odot}$.

It became evident with the discovery of quasars, radio galaxies, BL Lac objects and Low Ionization Nuclear Emission Line Region (LINER) galaxies, that activity in galaxies occurs over a wide range in scale and luminosity. The classification of AGN remains a somewhat confusing subject because there are gaps in our understanding of the phenomenon. Some of the differences between types may be due to the way we observed them rather than fundamental differences between types. Nevertheless, we now describe the generally recognized classes.

2.1 Seyfert Galaxies

Seyfert nuclei generally occur in Spiral galaxies, and are characterized by high excitation emission line spectra (Fig. 1). Type 2 Seyferts show narrow (200-500 km s^{-1}) emission lines of forbidden and permitted species (see Osterbrock 1989 for the physics of "forbidden" and "permitted lines"). Type 1 Seyferts show a second set of broad (up to 10^4 km s^{-1})

permitted lines superposed on the narrow lines. The narrow line spectra correspond to ionized gas at densities of $n_e \simeq 10^3 - 10^6$ cm^{-3}, based on the [SII] emission line density diagnostic. The absence of broad forbidden lines in type 1 Seyferts indicates high densities of at least $n_e \simeq 10^9$ cm^{-3}. Further subdivisions into types 1.5, 1.9 on the relative strengths of broad and narrow lines have been introduced by Khachikian and Weedman (1974). Seyfert nuclei exhibit weak featureless continuum emission which is apparent in the dilution of the stellar absorption lines in the host galaxy. Seyferts are also strong infrared, ultraviolet, and X-ray sources, but have relatively weak radio emission.

2.2 Radio galaxies

Radio Galaxies are distinguished by their giant double-lobe radio structures of optically thin synchrotron radiation (Fig. 2). Classical radio galaxies have symmetric linear jets that extend well beyond the optical extent of the host galaxy and terminate in large extended radio lobes. The linear extent of these sources may be as large as 4 Mpc, which is approaching the size of clusters of galaxies. Radio galaxies are further subdivided into luminosity and morphological classes; Fanaroff and Riley class I (FR I) (Fanaroff & Riley 1974) sources are less luminous and are dominated by bright jets rather than lobes, whereas FR II sources are brighter and have edge brightened radio lobes. Edge brightening in FR IIs is probably due to shock heating as the radio plasma interacts with the intergalactic medium, whereas FR I jets are likely subsonic. Radio galaxies also have a strong unresolved radio emitting nucleus, but in contrast to the extended lobes the core emission is self-absorbed which produces a flatter radio spectrum.

Optical spectra of Radio Galaxies (Fig. 1) show both broad lines (BLRG) and narrow lines (NLRG) which are analogs to the Seyferts type 1 and 2 respectively. Radio galaxy hosts are almost always elliptical galaxies, and are often the brightest galaxy in a cluster. Some radio galaxy hosts exhibit blue colours and evidence for recent star formation. The connection between jets and star forming regions in radio galaxies will be explored in section 6.

2.3 Quasars

Quasars were not initially identified with Seyfert galaxies because of their stellar appearance, and the importance of quasars was not recognized until Schmidt (1963) identified the quasar emission lines as the well known Balmer series, but at a redshift of $z = 0.158$. This makes quasars the most luminous objects known in the universe, and the most active of AGN. Compared to Seyfert galaxies the stellar features of the quasar host are very weak, and the narrow lines are weaker with respect

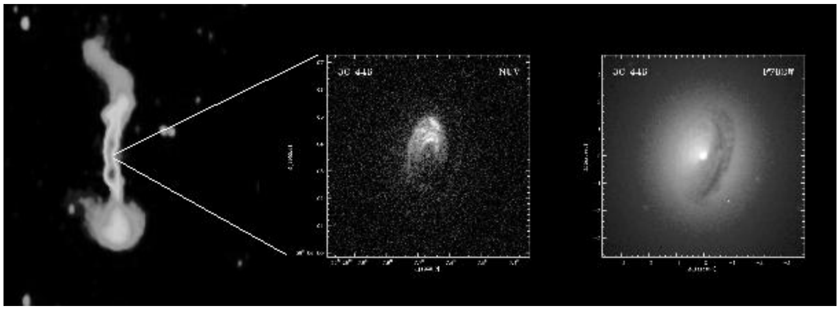

Figure 2: *Radio, UV and optical images of the radio galaxy 3C449.*

to the broad lines (see Fig. 1). The quasar analogs of type 2 objects, that is quasars with narrow lines only, are extremely rare objects and an important missing piece in the puzzle of AGN taxonomy (see Sect. 5 on unification).

2.4 Blazars

The object BL Lacertae was originally identified as a highly variable star, but now along with the "Optically Violent Variable" quasars forms a class of AGN which are characterized by strong continuum variability from X-ray to radio wavelengths. These objects are now collectively known as Blazars and are thought to be dominated by a strong radiation relativistically beamed close to the line of sight. Their spectra are generally featureless, see Fig. 1, although extremely weak emission lines and galaxy host features have been detected in some cases. Blazar emission is highly polarized (few %) and all blazars are radio sources.

2.5 LINERs

Low ionization nuclear emission region (LINER) galaxies represent the low activity end of the active galaxy scale. Recent studies suggest that low level LINER activity may occur in $^1/_3$ of all galaxies (Ho, Filippenko & Sargent 1997). Spectroscopically LINERs are distinguished from Seyferts by their weaker and lower ionization emission lines. LINERs are sometimes considered low luminosity seyfert galaxies, but LINER spectra may also be produced by shock heated gas in starburst driven winds, or cooling flows.

The characteristics of the various types of AGN are listed in Table 1. The single most common characteristic of AGN is that they all are X-ray sources (Elvis et al. 1978).

Table 1: *AGN properties*

Type	Pointlike	Broad Lines	Narrow Lines	Radio	Variable	Polarized
Radio Loud Quasars	Yes	Yes	Yes	Yes	Some	Some
Radio Quiet Quasars	Yes	Yes	Yes	Weak	Weak	Weak
Broad Line Radio Galaxies	Yes	Yes	Yes	Yes	Weak	Weak
Narrow line Radio Galaxies	No	No	Yes	Yes	No	No
OVV quasars	Yes	Yes	Yes	Yes	Yes	Yes
BL Lac objects	Yes	No	No	Yes	Yes	Yes
Seyfert type 1	Yes	Yes	Yes	Weak	Some	Weak
Seyfert type 2	No	No	Yes	Weak	No	Some
LINERs	No	No	Yes	No	No	No

3 Black hole and accretion disk paradigm

As shown in the previous section, AGN come in many types. What they all have in common is extremely large energy output from a very small volume. This amounts to as much energy as produced by 10^{12} stars in a volume of less than 1 pc^3. The fundamental question about AGN is how the energy we detect as radiation is generated. The current model is of a hot accretion disk surrounding a supermassive black hole. In this scheme energy is generated by the gravitational infall of material which is heated to high temperatures in a dissipative accretion disk. The basic principles involved are the conversion of gravitational potential energy into radiation, the loss of angular momentum of infalling material, and viscous heating in the accretion disk to radiate the converted potential energy. We now summarize the physical arguments which underlie this view following the procedures in Peterson (1997) and Krolik (1999).

Firstly, limits on the mass and accretion rate can be obtained by considering the balance between radiation pressure and gravity. For gas to fall inwards toward the black hole and accretion disk, the outward force due to radiation pressure from the nucleus must be less than the gravitational pull:

$$|F_{radiation}| \leq |F_{gravity}| \tag{1}$$

Expressing the radiation force in terms of the luminosity L, the Thomson scattering cross section of the electron σ_e, the radius r, balanced against the gravitational force in terms of the mass of the black hole M we obtain:

$$\frac{\sigma_e L}{4\pi c r^2} \leq \frac{GM(m_e + m_p)}{r^2} \tag{2}$$

The radial dependencies of the radiative and gravitational forces cancel giving the maximum luminosity for a spherically accreting system as :

$$L \leq \frac{4\pi G c m_p}{\sigma_e} M \tag{3}$$

This simplifies to

$$L \simeq 1.26 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{ergs s}^{-1} \tag{4}$$

and we find the corresponding minimum mass for the source of luminosity L:

$$M = 8 \times 10^5 L_{44}\, \mathrm{M}_\odot \tag{5}$$

where $L_{44} = L/10^{44}$ erg s^{-1} $\sim$ 1 for a Seyfert Nucleus. This means that for a typical Seyfert the central mass must be of order 10^6 M$_\odot$, while for a quasar of luminosity $L(Quasar) \sim 10^{46}$erg s^{-1}, the mass of the central object must be greater than 10^8 M$_\odot$.

Since the details of the processes involved in converting the potential energy into radiation are not well understood, the usual procedure is to adopt a parametrization where we express the energy that is liberated by way of conversion of potential energy into radiation as a fraction of the rest mass energy.

$$E = \eta\ m\ c^2 \tag{6}$$

where η is the efficiency factor for the conversion of gravitational potential energy into radiation. If we equate the luminosity of the central source to the rate at which energy is supplied in this manner we obtain

$$L = \left(\frac{\mathrm{d}E}{\mathrm{d}t}\right) = \eta \left(\frac{\mathrm{d}m}{\mathrm{d}t}\right) c^2 = \eta \dot{M} c^2 \tag{7}$$

where $\dot{M}$ is the accretion rate, and which for a typical AGN can be expressed as

$$\dot{M} = \frac{L}{\eta c^2} \simeq 1.8 \times 10^{-3} \left(\frac{L_{44}}{\eta}\right) \mathrm{M}_\odot\ \mathrm{yr}^{-1} \tag{8}$$

The rate of conversion of gravitational potential energy $U = GMm/r$ into radiation is expressed:

$$L \simeq \frac{\mathrm{d}U}{\mathrm{d}t} = \frac{GM}{r}\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{GM\dot{m}}{r} \tag{9}$$

To estimate the amount of potential energy available by accreting onto a black hole we consider the loss of gravitational binding energy available from falling into the central source from infinity to the radius of the last stable orbit allowed for a black hole. The last stable orbit depends on the spin of the black hole, but it is typically ∼5 Schwarzschild radii:

$$R_S = \frac{2GM}{c^2} \simeq 3 \times 10^{13} M_8 \,\mathrm{cm} \tag{10}$$

So the rate of conversion of potential energy into radiation by falling to within $5R_S$ of the central source is:

$$L \simeq \frac{dU}{dt} = \frac{GM\dot{m}}{5R_S} = \frac{GMc^2\dot{m}}{10\,GM} = 0.1\dot{m}c^2 \tag{11}$$

By comparison with equation 7, this “suggests” that η is approximately 0.1. That is, if a particle falls to within five Schwarzschild radii of the central object it may radiate as much as 10% of its rest mass energy.

3.1 Angular Momentum

The above arguments show that the gravitational potential energy is an ample supply for fuelling an AGN. The difficulty for the accretion scenario is not the amount of gas required, but it is instead the angular momentum considerations that must be satisfied. Most of the angular momentum of infalling gas must be lost before it even reaches the accretion disk. We can see this with the following simple argument. The specific angular momentum of infalling gas at a radius r is simply:

$$\frac{|\mathbf{L}|}{m} = (GMr)^{1/2} \tag{12}$$

Consider a test mass falling into a 10^7 $\mathrm{M}_\odot$ central object from a distance of 10 kpc, to the outer edge of the accretion disk at 0.01 pc. The initial angular momentum must be calculated using the total interior mass, comprising the black hole mass plus the mass of the stars and gas within that radius which may be of order 10^{11} $\mathrm{M}_\odot$. The interior mass within a radius of 0.01 pc is dominated by the 10^7 $\mathrm{M}_\odot$ black hole. The ratio of the angular momentum at 10 kpc to that at 0.01 pc is:

$$\left(\frac{10^7 \times 0.01\,\mathrm{pc}}{10^{11} \times 10^4\,\mathrm{pc}}\right)^{1/2} \simeq 10^{-5} \tag{13}$$

We see from this simple calculation that the angular momentum of the infalling test mass must decrease to only 10^{-5} of its initial value before it even gets to the radius of the accretion disk. It is for this reason that gravitational interactions with other galaxies, or exchange of angular momentum in interacting systems are thought to play a major role in the AGN process because these interactions can provide a mechanism for removing angular momentum from the infalling gas.

The structure of the accretion disk depends on parameters such as the magnetic field strength, the accretion rate and the presence or absence of coronae. A detailed review of the structure and processes in accretion disks can be found in Krolik (1999). A very simplified model of such a thin accretion disk is of concentric rings of hot gas locally emitting as black bodies at their local temperature defined by the rate of loss of binding energy at that radius. This yields a temperature structure for the disk:

$$T(r) \simeq 6.3 \times 10^5 \left(\frac{\dot{M}}{\dot{M}_E}\right)^{1/4} M_8^{-1/4} \left(\frac{r}{R_S}\right)^{-3/4} \mathrm{K} \tag{14}$$

For a 10^8 $\mathrm{M}_\odot$ black hole, the inner part of the disk corresponds to photon energies in the extreme UV or soft X-ray range (whereas galactic black-holes, $\sim 1.0\mathrm{M}_\odot$, have their emission peak in the hard-X-ray range). It is this continuum radiation, generated in the accretion disk, which is thought to be responsible for the UV and optical continuum emission which ionizes the circumnuclear gas in AGN.

The accretion disk is also considered to be the launch site for jets and winds seen in active galaxies. The production of jets, and their high level of collimation is obviously strongly related to the axial symmetry of the rotating accretion disk. Detailed models of jet production can be found in Krolik (1999). A simplified view of jet production is displayed in Figure 3 where the magnetic field lines that thread the ionized region of an accretion disk are locked into the rotation of the disk, producing tightly wound axial field. Energetic charged particles rotating around these lines, may escape the AGN region along the polar axes to produce the large scale jets we observe in radio galaxies.

4 Evidence for black holes

The presence of a black hole at the center of an AGN is almost universally accepted, yet solid proof of their existence remains elusive.

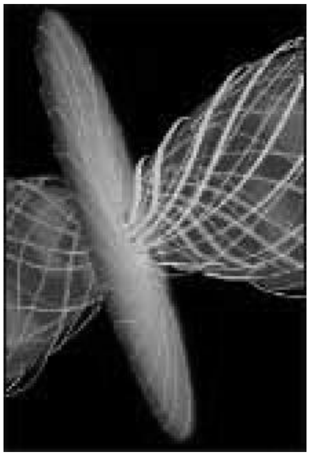

Figure 3: *Accretion disks: Launch site for jets. Magnetic field lines anchored in a rotating accretion disk may provide the mechanism for forming jets seen in radio galaxies.*

The best supporting evidence for the existence of supermassive black holes comes from measuring the motion of gas in the vicinity of AGN, and inferring the interior mass from orbital constraints. The most spectacular results include the dynamical studies of the circumnuclear gas in M87 by Ford et al. (1994) and Harms et al. (1994). These studies were able to probe circumnulcear gas motions on scales of $\sim$ 10 pc for the nearest AGN. Observations at higher spatial resolution have been made possible by the discovery and use of water masers as dynamical probes. In a few special cases, of nearby AGN with favorably aligned gas disks, the gas dynamics has been measured on scales of 0.1pc. The spectrum of the water maser emission in the most famous of these cases, NGC 4258 (Fig. 4, Miyoshi et. al 1995) shows bulk motion of gas in the nucleus at velocities of +/-1000 km s^{-1} with respect to the velocity of the galaxy. The inferred interior mass density in this case is orders of magnitude higher than any other feasible object, thus providing strong evidence for a black hole. Other strong evidence for black holes comes from the profile of the Fe Kα emission line which has been observed in numerous Seyfert galaxies. The best studied of these is MCG-6-30-15 (Tanaka et al. 1995) which shows a Fe Kα line so broad that if its width is interpretted as doppler broadening, then the emitting gas must be moving relativistically indicating a relativistically deep potential well consistent with a black hole.

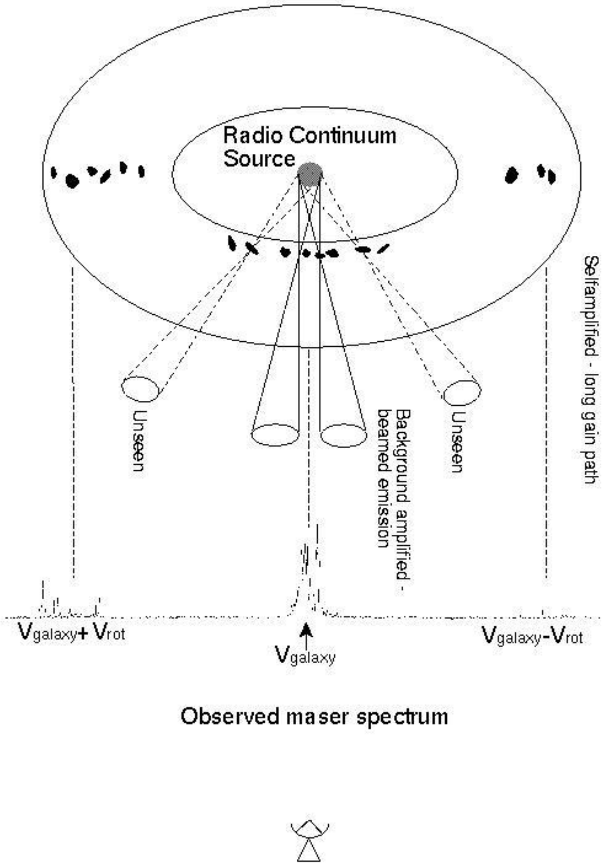

Figure 4: *Maser Emission in AGN disks. Maser emission provides and important probe for measuring dynamics of gas in AGN disks on scales as small as 0.1pc. A favourable alignment of the disk to the line of sight is required to make such measurements.*

5 Unified Model of AGN

A key observation in the understanding of Seyfert galaxies was the discovery of broad lines (characteristic of type 1 Seyferts) in the polarised spectrum of NGC 1068, the closest, brightest Seyfert 2 galaxy (Antonucci & Miller 1985, Miller, Goodrich, & Mathews 1991). This indicates that NGC 1068 has a Seyfert 1 nucleus that we do not view directly, but which we can see in the scattered (hence polarised) light. This led to the unified theories for AGN which seek to explain differences between broad line and narrow line AGN as due to viewing angle effects. In these models the nucleus and the broad line region are surrounded by an optically thick "torus". The differences between broad and narrow

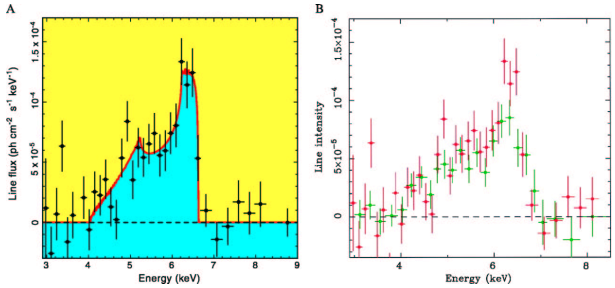

Figure 5: *Kα emission line profile in the Seyfert galaxy MCG-6-30-15 from Fabian (1999). This X-ray line comes from hot gas within 6 to 30 Schwarzschild radii of the black hole. The shape of the line is skewed by gravitational redshift due to the deep potential well of the central black hole.*

line objects can then be ascribed to an orientation effect in which broad line objects are oriented so that the line of sight includes the nucleus and broad line region, whereas in a narrow line object the line of sight to the nuclear region is obscured by the torus, leaving only the larger narrow line region visible. This scenario also explains the conical narrow emission line regions observed in some Seyfert 2 galaxies as shadowing of the ionizing radiation from the nucleus by the torus. A cartoon of such a unified model is displayed in Figure 6.

The unified models have provided a convenient framework for understanding many of the properties of AGN, however there are many caveats in attempting to explain all the observed features of AGN with such a simplistic model. The model has been applied in various ways not only to Seyfert galaxies, but to Radio Galaxies where the torus axis aligns with the axis of the radio jets, and to blazars where the orientation of the line of sight is thought to be directly down the axis of the torus. A review of the statistical tests of the unified schemes and their relationship to the accretion disk and the spin of the black hole may be found in Antonucci 1993, and Urry & Padovani 1995. A somewhat alternative view involving the influence of outflows and shocks can be found in Dopita (1997).

In the unified model of AGN we should expect to find type 2 quasars, yet these have proven elusive and this has been the source of some doubt about the relevance of the unifed obscuring models of AGN for the high power quasars. However, recently the first type-2 QSOs have been reported Norman et al. (2002) in the deep X-ray images taken as part of the Chandra Deep Field-South campaign.

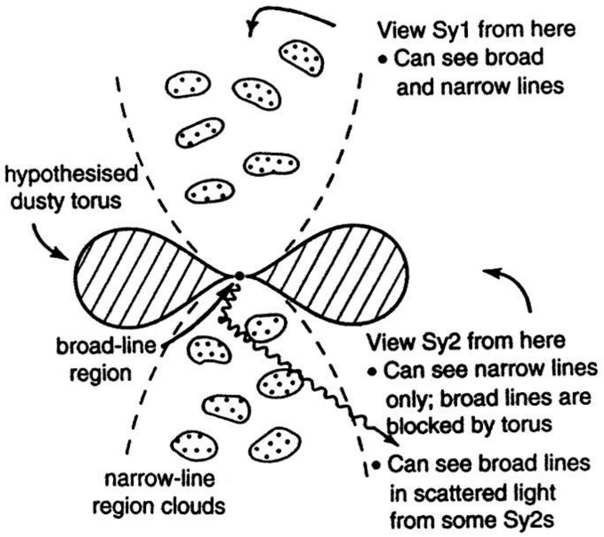

Figure 6: *Unified scheme for AGN.*

6 Host galaxies, triggering and evolution

Studies on the relationships between the AGN and their hosts galaxies have tried to address the questions of “what kinds of galaxies do AGN reside in?”, and “are AGN hosts different from normal galaxies?”. In general these studies have found the AGN can occur in almost all types of galaxies. Some studies suggest a higher proportion of AGN host galaxies have morhological irregularities such as rings and evidence for interaction. This has led to the interaction and merger scenarios for triggering AGN activity, and the idea that starburst activity and AGN activity may indeed be linked via such a mechanism.

Mergers of galaxies provide an very effective way for both stars and gas to lose angular momentum and fall into the nuclear regions.These processes, as well as streaming motions along bars have been invoked as a means to distort the gravitational potential of the host galaxy and allow loss of angular momentum and infall. Signs of recent mergers are detected in some AGN, and in fact some AGN have multiple nuclei. The connection to starburst activity arises because mergers are also thought to provide the energy and gas to fuel bursts of star formation in otherwise evolved galaxies. The possibility of strong links between the processes of galaxy evolution, star formation and the triggering/fueling of AGN has made this a current hot topic. As described in Cid Fernandes et al. (2001), scenarios for connections between starbursts and AGN range from those in which the starburst is an integral part of the AGN system (Sanders et al. 1988, Terlevich, Tenorio-Tagle, Franco, & Melnick

1992) to scenarios where the AGN and the processes in the host galaxy are completely independant. Proponents of a strong link between AGN triggering and starburst activity suggest that starburst induced turbulence in the interstellar medium may be responsible for the final stages of infall of gas required to trigger AGN accretion (von Linden et al. 1993). Others have pointed out that compact star clusters may actually form a supermassive black hole (Norman & Scoville 1988, Williams, Baker, & Perry 1999). Those who favour scenarios where AGN and starburst activity are independant, argue that the associations between AGN and starbursts arise simply because of the common cause, of a merger, or gas infall events. Cid Fernandes et al. (2001) points out that the range of theoretical possibilites for AGN-starburst connections is so wide that it is likely that this field can only progress by obtaining more input from detailed observations. Identifying AGN and starbursts is relatively straight forward with current observational techniques, but detailed models will require accurate starburst ages, gas dynamics and black holes masses. With such information we may be able to address the questions such as "is the star formation rate connected to the accretion rate?", and, "does the AGN evolve in parallel to the starburst around it?".

Studies of some individual objects have started to address these questions. A good example is the study of the AGN activity, and star formation in 3C 236, a nearby radio galaxy, by O'Dea et al. 2001. This radio galaxy is dominated by its enormous 4 Mpc scale classical radio jets and lobes that extend well beyond the optical extent of the host galaxy. It is also a member of the new class of objects called "double-double" sources (Schoenmakers et al. 2000) referring to the presence of an inner, smaller radio jet (2 kpc in this case). A connection between the AGN activity and the star formation history of this galaxy was suggested when ultraviolet observations of the elliptical host of 3C 236 revealed four bright, blue star forming regions with ages that appear to be related to the epochs of AGN activity in this galaxy.

Based on the optical-UV colours, the ages of these star forming regions show two out of the four regions with relatively young ages of order $\sim 10^7$ yr, while the other two are older with ages of order $\sim 10^8$-10^9 yr. The ages of the older star forming regions are comparable to the estimated age of the giant radio source, suggesting that the star formation may have been triggered around the same time as the AGN activity giving rise to the giant radio jets. O'Dea et al. use dynamical and spectral aging arguments to suggest that the fuel supply to the AGN, that is the supply of gas available to accrete onto the black hole, was interrupted for $\sim 10^7$ yr, and has now been restored resulting in the inner 2 kpc scale radio source. That is, the two distinct epochs of star formation, are related to the two distinct epochs of radio activity.

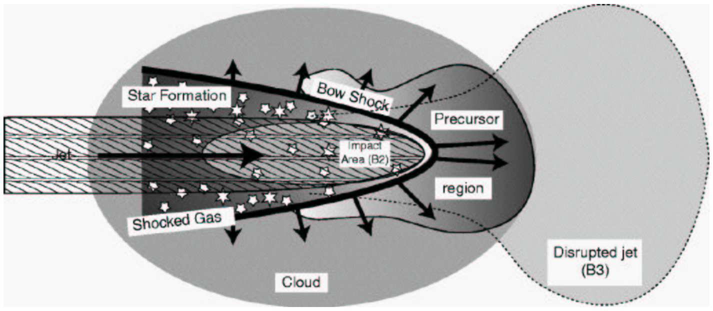

Figure 7: *Jet induced star formation. As a powerful radio jet ploughs through the ISM of the host galaxy, it forms a bow-shock sturcture. In the jet-induced star formation scenario, stars form in the compressed gas in the wake of the bow-shock.*

The above example suggests that common epochs of AGN activity and star formation may be triggered by a common infall event of gas which fuels both processes. More direct connections between radio jets and star formation, whereby jets cause star formation ("jet-induced star formation"), have also been considered by a number of authors: Rees 1989, Begelman & Cioffi 1989, Daly 1990, Chambers et al. 1996. It is proposed that star formation can be triggered by the compression caused by jets as they plough through the ISM of the host galaxy. And further, that jet-induced star formation may help to explain both the alignment effect, and the UV excesses observed in high redshift radio galaxies. A diagram of this scenario is displayed in Fig. 7.

Observational evidence for jet-induced star formation is difficult to obtain. Bicknell et al. (2002) argue that the emission line ratios, ion abundance, dynamics of the gas, and the presence of P-Cygni profiles in the spectra of the high redshift radio galaxy 4C 41.17 can be explained as star formation caused by passage of the radio jet. Other examples include blue filaments in Centaurus A (Mould et al. 2000), and jet, or shock induced star formation in 3C 171 (Clark et al. 1998).

Opponents to these theories of jet induced star formation argue that the extreme heating of the ISM, and the total dynamical disruption of the environment, produced by shocks caused by the passage of a radio jet, may actually be too hostile for star formation to be viable.

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