Active Galaxies

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• A brief review of AGNs

• The supermassive black hole paradigm

• Relation to galaxy formation
The Population of Active Galactic Nuclei

An AGN: if one or more of the following properties are observed in a galaxy:

1. a compact nuclear region much brighter than a region of the same size in a normal galaxy;

2. nonstellar (i.e. nonthermal) continuum emission;

3. strong emission lines;

4. observable variabilities in continuum and/or in emission lines.
• Seyfert Galaxies: a bright point-like (star-like) image with absolute-magnitude $M_B > -21.5 + 5 \log h$. A host is almost always revealed to be a spiral galaxy (mostly Sa and Sb). Nonthermal continua and strong emission lines.

• Radio Galaxies: Selected by their strong radio emission. Clearly, a fiducial frequency must be chosen to define the emission power. Powerful radio galaxies have $P_{1.4\text{GHz}} \gg 10^{25} \text{WHz}^{-1}$, tend to be associated with luminous elliptical galaxies, show classical double-lobed structure and jet-like structure.

• Quasars: The radio characteristics of Quasi-Stellar Radio Sources (quasars, or radio quasars) are similar to those of powerful radio sources, but their optical images are unresolved (at $\theta \sim 1''$), luminous ($M_B \ll -21.5 + 5 \log h$) nuclei with strong broad emission lines in their optical spectra. The optical nuclei tend to be variable especially. In many ways, the optical properties of quasars resemble those of Seyfert nuclei, except that their luminosity is higher.
• Quasi-stellar objects (QSOs): These are objects that have the same optical characteristics as quasars but in which no strong radio emission is detected. QSOs are much more abundant than radio quasars; there are more than 10 QSOs for each quasar.
The Supermassive Black–Hole Paradigm
In the supermassive paradigm, an AGN is assumed to be powered by a supermassive black hole accreting surrounding gas.

Because the gas generally has angular momentum, the accreted gas is most likely in the form of an accretion disk.

The energy source is the gravitational potential of the central black hole.
The Central Engine

Consider a simple spherical model where a central source with luminosity $L$ is surrounded by a gas distribution $\rho(r)$. Radiation flux at a radius $r$ is $L/(4\pi r^2)$ and radiation pressure is:

$$P_{\text{rad}}(r) = \frac{L}{4\pi r^2 c}.$$ 

For ionized gas, radiation pressure force on a unit volume of gas

$$F_{\text{rad}} = \sigma_T P_{\text{rad}}(r) n_e(r).$$

$\sigma_T$: Thompson cross section. This force must be smaller than the gravitational force on the gas for the gas to stay:

$$|F_{\text{rad}}| \leq F_{\text{grav}} = \frac{GM\rho(r)}{r^2}. \quad (1)$$
Eddington luminosity

For a given central mass $M$: the maximum luminosity is

$$L_E \equiv \frac{4\pi G c m_p}{\sigma_T} M \approx 1.28 \times 10^{46} M_8 \text{ erg sec}^{-1},$$

($M_8 \equiv M / 10^8 M_\odot$).

To achieve a given luminosity, the minimal mass

$$M_E = 8 \times 10^7 L_{46} M_\odot.$$

where $L_{46} \equiv L / (10^{46} \text{ erg sec}^{-1})$. For bright quasars with $L \sim 10^{46} \text{ erg sec}^{-1}$, a black hole of $\gg 10^8 M_\odot$ is required.
Fueling of an AGN

The accretion ‘luminosity’:

\[ L = \left( \frac{GM}{r} \right) \dot{M}, \]

where \( \dot{M} \): the mass accretion rate at radius \( r \).

Efficiency from rest mass of accreted gas to radiation:

\[ \eta \equiv \frac{L}{(\dot{M}c^2)} = \frac{1}{2} \left( \frac{R_S}{r} \right), \]

where \( R_S = \frac{2GM}{c^2} \approx 10^{-2} M_8 \) light days is the Schwarzschild radius of mass \( M \). Taking \( r \sim 5R_S \), we have \( \eta \sim 0.1 \). higher than the efficiency, \( \eta = 0.007 \), with which hydrogen is burned into helium! Accretion must be very relativistic!
At $\eta \sim 0.1$, an accretion rate $\dot{M} \sim 2\,M_\odot\,\text{yr}^{-1}$ is required to power a bright quasar with luminosity $L = 10^{46}\,\text{erg\,sec}^{-1}$.

The Eddington luminosity corresponds to a mass accretion rate

$$\dot{M}_E = \frac{L_E}{\eta c^2} \approx 2.2M_8(\eta/0.1)^{-1}M_\odot\,\text{yr}^{-1}.$$  

This is the highest possible accretion rate in the simple spherical model. Super-Eddington accretion is allowed if accretion of mass occurs primarily in the equatorial plane of a disk while radiation escapes from the polar zones.
The formation of supermassive blackholes

If the growth of a supermassive black hole is through radiative accretion, the mass accretion rate is

\[ \dot{M} = \frac{L}{\eta c^2} = \left( \frac{L}{L_E} \right) \frac{M}{\eta t_E}, \]

where \( t_E \equiv \sigma T_c / (4\pi G m_p) \approx 4.4 \times 10^8 \text{ yr} \) is the Eddington time. If \( L/L_E \) and \( \eta \) are independent of time, then

\[ M(t) = M_0 \exp \left( \frac{t}{t_{bh}} \right), \]

where \( M_0 \) is the mass of the black hole at an initial time \( t = 0 \), and

\[ t_{bh} = \left( \frac{L}{L_E} \right)^{-1} \eta t_E \approx 4.4 \times 10^7 \left( \frac{\eta}{0.1} \right) \left( \frac{L}{L_E} \right)^{-1} \text{ yr} \]

is the timescale for the black-hole mass to increase by a factor of \( e \).
The time required for a black hole to grow to be a supermassive one with $M \sim 10^8 M_\odot$ depends on the seed mass $M_0$ which, in turn, depends on how the black hole was initially created. In broad terms, there are three possibilities for the initial creation of a black hole (cf. Rees 1984):

- the collapse of an isolated massive star,
- the merger and accretion of neutron stars, and
- the collapse of a gas cloud.

$M_0$ is of the order of $10 M_\odot$ in the first two cases. $M_0$ in the third possibility is uncertain.
If $M_0 \sim 10 \, M_\odot$, about 16 $e$-folds is required to reach $M = 10^8 \, M_\odot$. The time interval required is

$$t \approx 16 t_{bh} \approx 6 \times 10^8 (\eta/0.1)(L_E/L) \, \text{yr}.$$ 

If $L \ll L_E$ and $\eta \sim 0.1$, we will have problem in growing the black hole to the required mass within a Hubble time at $z \sim 5$.

Possible solutions:

(1) Super-Eddington rate (so that $L \gg L_E$): Can be achieved if accretion is anisotropic: so that outgoing radiation is separated from infalling material.

(2) Radiative efficiency low so that $\eta \ll 0.1$: $\eta$ is constrained to be $\sim 0.1$ by radiative properties of the accretion disk for the last few $e$-folds. A more likely scenario: an early phase where $\eta \ll 0.1$. 
The Formation of AGNs

Whether or not an AGN will form depends on whether or not it is fed with gas at sufficiently high rate. The typical rate required is $\sim 2 \text{M}_{\odot}\text{yr}^{-1}$. The timescale for the accretion is $M/\dot{M} \sim \eta t_E \sim 5 \times 10^7 \text{yr}$.

Fuelling of an AGN also requires a copious amount of gas be transported towards the center of the host galaxy in a short time scale.

Total mass involved quite small: $10^8 \text{M}_{\odot}$, but needs to get rid of angular momentum: $j \sim (GMR)^{1/2}$, From $R \sim 10\text{kpc}$, $M = 10^{11}\text{M}_{\odot}$, to $R \sim 0.1\text{pc}$, $M = 10^8\text{M}_{\odot}$, $j$ reduced by a factor of $10^4$.

Two possibilities:

gas flow driven by gaseous mergers

Gas flow driven by bar instability
An encounter of two gas-rich disk galaxies. The stellar distribution is shown on the left; each frame is about $80 \times 96 \text{kpc}$. Times (-60, 60, 150, 300, 420 Myr, from top to bottom) are given with respect to pericenter at $t = 0$. Hot gas is shown in the middle, color codes temperature. Cool gas is shown on the right.
Relation to galaxy formation
Some ideas

Early gas rich collapse and mergers may be responsible for both the formation of bulges and massive black holes.

• Simple scaling relation: the black hole mass is assumed to scale with certain properties of the dark matter halo

• Supply-driven models: Mass accretion rate is determined by the amount of cold gas with low-angular momentum

• Self-regulating modes: The energy output from the AGN limits the fuel supply

All models at the moment are phenomenological!