Active Galaxies

The AGN population & Supermassive black holes

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Normal galaxies v. Active galaxies

The emission of "normal" galaxies is dominated by the stellar population. Their SED is therefore just thermal radiation, spanning \sim 4000Å to \sim 20,000Å.

The emission of active galaxies, on the other hand, extends to much shorter and longer wavelengths than is expected from a collection of stars, gas, and dust. This emission covers the entire electromagnetic spectrum and is therefore *not* thermal in origin.

In addition, the optical and ultraviolet parts of the spectra of active galaxies contain strong, broad emission features not present in the spectra of "normal" galaxies.

This non-thermal emission comes from a region only a few pc across at the centers of these active galaxies. This central region is known as the active galactic nucleus (AGN).

Despite its small size, an AGN's luminosity is often much brighter than that of the entire host galaxy!

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An object is considered to be an AGN if it has at least one of these following properties:

- Compact nuclear region much brighter than a region of the same size in a normal galaxy
- Non-stellar (non-thermal) continuum emission
- Strong (possibly broad) emission lines
- Variability in the continuum emission and/or the emission lines on a relatively short timescale

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Types of AGN

Several types of galaxies are known to have an AGN.

The following types were discovered by radio astronomers, and hundreds of thousands are now known:

- Quasars (and QSOs)
- Radio galaxies

These were discovered by visible-light astronomers, and thousands are now known:

- Seyfert galaxies
- **Blazars** (BL Lacertae objects and OVVs)

Note that active galaxies are vastly outnumbered by normal galaxies.

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Discovered in the 1940s by Carl Seyfert, these are **spiral galaxies** with starlike nuclei, often brighter than the rest of the galaxy, with ionized gas associated with the centers.

Type 1 Seyferts Very broad recombination lines ($\sim 10^3$ km/s in width) associated with the nuclei. Example: NGC 4151.

Type 2 Seyferts Narrow-line spectra $(\lesssim 10^2 \text{ km/s})$ at the nucleus. Example: NGC 1068.

Low-luminosity Seyfert galaxies are LINERs (low-ionization nuclear emission line regions).







Left: NGC 4151, the "Eye of Sauron," showing X-rays in blue (NASA/CXC), H11 emission in yellow (Kapteyn Telescope), and H1 emission in red (VLA). Right: NGC 1068, shown in an X-ray/visible composition from NuSTAR and HST.

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M106 (NGC 4258)

- Very short jet, oriented roughly along the galaxy's axis, seen in nucleus.
- The rest of the jet is apparently entrained in the disk of the galaxy.

M106 in X-rays from jet-driven shocks (blue) and visible light from normal galactic processes (red). Second visible image from R. Gendler.



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Discovered in the 1950s, radio galaxies appear to consist of a pair of extended radio lobes on either side of a visible, elliptical galaxy.

As radio interferometric measurements improved, radio galaxies were shown to also possess compact and pointlike central objects coincident with the galactic nuclei and connected to the lobes by narrow, usually straight jets.

The lobes themselves have fine filamentary structure. Many have hot spots as the ends of the jets, and one lobe is always brighter than the other.

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3C 348: Hercules A

Supergiant elliptical galaxy 3C 348 plus radio source Hercules A (VLA + HST).



Quasars and QSOs

Quasar = quasi-stellar radio source QSO = quasi-stellar object These objects are unresolved, luminous, blue, and highly variable.

They have a single narrow jet, often exhibiting apparent superluminal motion.

Hubble-ACS photo-negative image of 3C 273 (from J. Bahcall, Princeton).



The archetypical quasar 3C 273



The luminosity of 3C 273, the first QSO discovered, is dominated by its starlike central core, visible in all three images above. It also has a jet but no "counterjet" visible on the other side of the quasar.

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The "shadow" of a quasar's black hole

In 2019, the EHT collaboration revealed the world's first image of the light in orbit around an AGN.





Reality v. simulation

The image on the left is of M87's supermassive black hole. The center image is the result of a simulation (with "infinite" resolution), and the image on the right is the center simulation image blurred to match the telescope's systematics. M87 April 6 GRMHD Blurred GRMHD







What are we seeing?

Image of M87's black hole

Simulation of a black hole



Blazars

Blazars are bright and starlike. Only recently has very faint luminosity been detected around them to indicate that they are the nuclei of galaxies.

The spectra from blazars are smooth, making it hard to measure Doppler shifts. That is why BL Lacertae was first thought to be an object in the Milky Way (Hoffmeister 1929) until the host galaxy was observed in the 1960s (Schmitt 1968).

OVVs (optically violent variables) are blazars with strong emission lines present. It is thought that these are the same as BL Lac objects whose main source of luminosity is fainter at the moment (so that the emission line features are not washed out by the continuum).

Most blazars are strong pointlike radio sources with significant variability. Stars are not. This was the first real indication that blazars are distant galaxies.

In fact, the variability implies a huge luminosity produced in a very small volume, implying the presence of a supermassive black hole.

The Eddington luminosity

Around a black hole, most of the material is ionized gas, so an electron or proton is going to experience the gravitational force and radiation pressure.

The effective area of an electron or proton that is subject to radiation is its cross section. The cross section for an electron is the Thomson cross section,

$$\sigma_e = \sigma_T = \frac{8\pi e^4}{3m_e^2 c^4}$$

The cross section is inversely proportional to the mass, so an electron has a larger cross section than a proton.



The Eddington luminosity

The net radiation force on the electron is

$$F_{\rm rad} = \frac{dp_{\rm rad}}{dt}$$

Recall that, for photons, E = pc, so

$$F_{\mathrm{rad},e} = \frac{d}{dt} \left(\frac{E}{c}\right) = \frac{1}{c} \frac{dE}{dt}$$

dE/dt is the power absorbed by the electron from the luminosity, so

$$F_{\mathrm{rad},e} = \frac{1}{c} fA$$
$$= \frac{L\sigma_e}{4\pi cr^2}$$
$$= \frac{2e^4L}{3m_e^2 c^5 r^2}$$

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The Eddington luminosity

Each electron will drag a proton with it, since the electromagnetic force dominates. The gravitational force exerted by the black hole on each proton is much larger than that on an electron.

Accretion takes place if $F_{\text{grav},p} + F_{\text{grav},e} > F_{\text{rad},p} + F_{\text{rad},e}$, or, to a good approximation, $F_{\text{grav},p} > F_{\text{rad},e}$.

Thus, in order to accrete while shining at luminosity *L*, the mass *M* of the black hole must be such that $\frac{GMm_p}{r^2} > \frac{2e^4L}{3m_r^2c^5r^2}$:

$$L < \frac{3GMm_pm_e^2c^5}{2e^4} \equiv L_E \qquad \text{given } M$$
$$M > \frac{2e^4L}{3Gm_pm_e^2c^5} \qquad \text{given } L$$

where L_E is the Eddington luminosity.

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