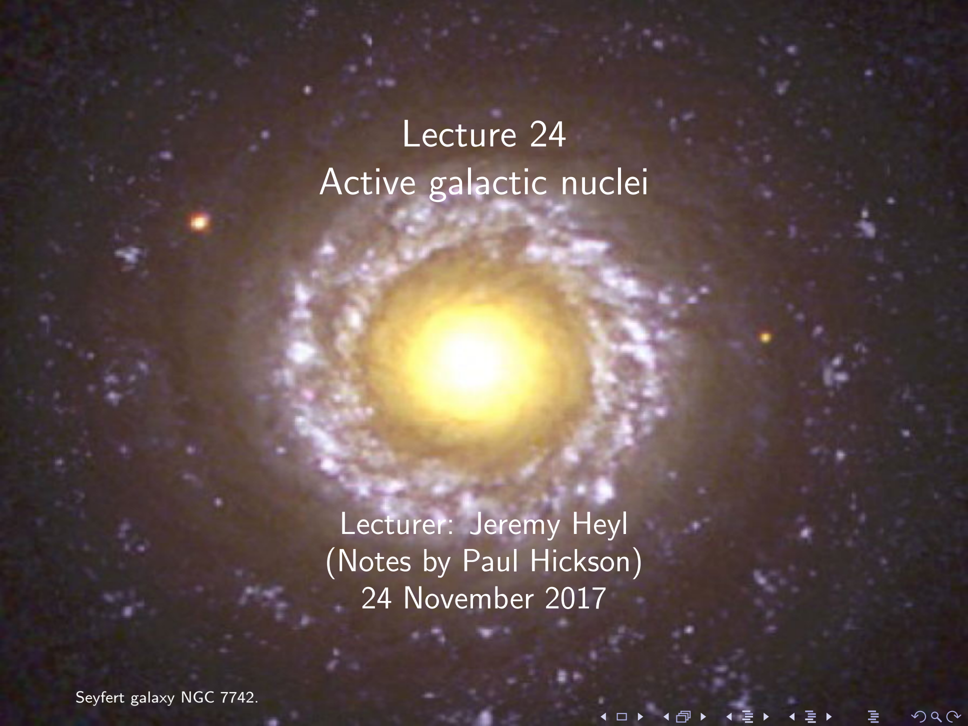

Lecture 24
Active galactic nuclei

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(Notes by Paul Hickson)
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Seyfert galaxy NGC 7742.

Active galaxies

Many galaxies display phenomena that are not related to the usual processes of star formation.

These may include

- a bright star-like nucleus
- broad emission lines
- narrow emission lines
- optical continuum radiation
- jets
- radio lobes
- strong X-ray and/or gamma-ray emission
- rapid variability

All can be traced to an "active nucleus".

Active galaxies

Types of active galaxies include

- Seyfert galaxies (types 1 and 2)
- quasars - quasi-stellar objects (QSO) and quasi-stellar sources (QSS)
- radio galaxies - narrow-line radio galaxies (NLRG) and broad-line radio galaxies (BLRG)
- N-galaxies
- blazars - BL Lac objects and optically-violent variables (OVV)
- low-ionization nuclear emission region galaxies (LINER)

Seyfert galaxies

Seyfert galaxies are spiral galaxies having a bright star-like nucleus and/or broad emission lines. The luminosity of the central source can be as high as $10^{11} L_\odot$

Seyfert 2 show "narrow" lines, with $\sigma \sim 1000$ kms. This radiation comes from clouds within a kpc or so of the nucleus.

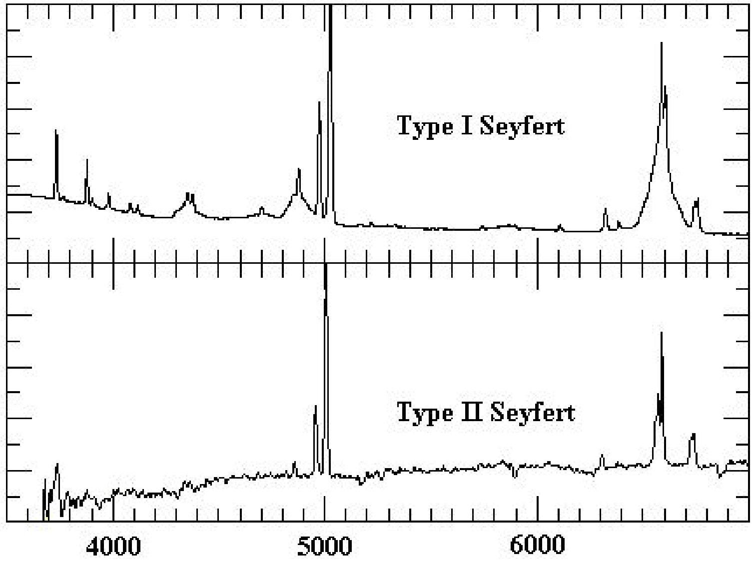
NGC 1097, astronomyforum.net

Seyfert 1 also have "broad" permitted lines, with $\sigma \sim 10,000$ km/s. These originate within a parsec of the centre.

Most are not strong radio sources, however, radio jets have been detected in some.

About 10% of Sa and Sb galaxies have Seyfert nuclei.

Seyfert galaxy spectra



Bill Keel, Univ. of Alabama

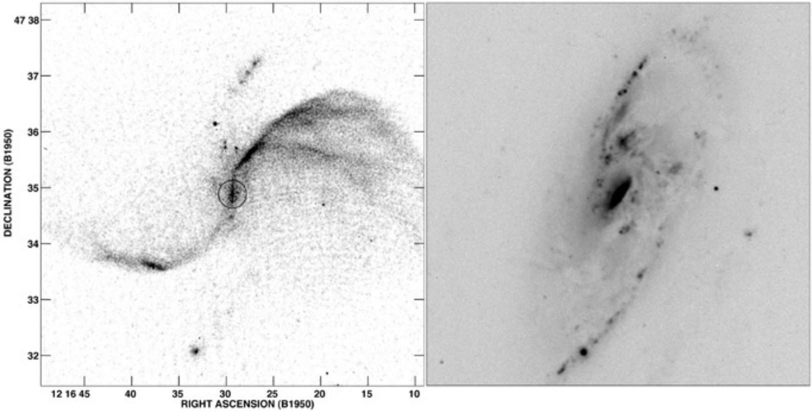


Fig 9.2 (G. Cecil)'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Seyfert 2 galaxy NGC 4258 (Sbc). Left, a radio map at 20 cm shows oppositely directed twin jets (within the circle), channelling radio-bright plasma from the nucleus to lobes at east and west, and HII regions in the spiral arms. Right, an image in the U band at 3700 Å shows the bright center, and brilliant knots of young stars in the spiral arms. At distance $d \simeq 7$ Mpc, 1 arcmin $= 2$ kpc.

The central source

The high velocities of the emission lines indicate a massive central object,

$$M \sim V^2 R/G \sim 10^7 - 10^9 M_\odot.$$

This is almost certainly a black hole. The Schwarzschild radius

$$r_\mathsf{S} = \frac{2GM}{c^2} \simeq \frac{3M}{M_\odot} \text{ km}$$

is in the range $0.1 - 10$ AU.

The central object emits continuous radiation from radio to X-ray wavelengths. This is thought to originate from an accretion disk surrounding the black hole, and a jet of particles that it creates.

Gas clouds near the nucleus orbit at high speed. The gas is photoionized by radiation from the central source and emits the broad lines from recombination radation.

Since only permitted lines are seen to be broad, the density here must be greater than $\sim 10^{14}$ atoms m^{-3}.

The central source

The brightness of the continuum source fluctuates on time scales as short as a few days. One can put an upper limit on its size from the timescale Δt of the fluctuations

$$R \lesssim c\Delta t$$

The broad-line luminosity has been seen to follow the continuum luminosity variations, with a delay of a few days, confirming the photoionization model.

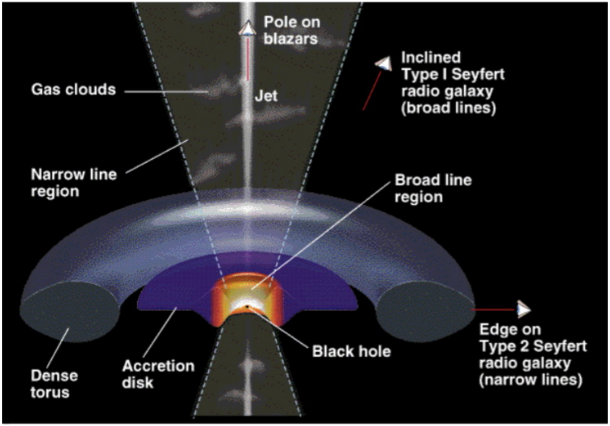
A dusty torus is presumed to surround the accretion disk and broad-line region. In Seyfert 2 galaxies, the dust blocks our view of the nuclear region, so only the larger narrow-line region is seen.

In some Seyfert 2 galaxies, weak broad lines can be seen in polarized light, due to reflection off the dust. Seyfert 2 galaxies also have weaker "soft" X-ray flux as only the higher energy "hard" X-rays ($E \gtrsim 1$ keV) can penetrate the dust.

A simple model for an active nucleus.

Energetic twin jets emerge at near-light speeds along the spin axis of the central accretion disk.

Radiation from the disk and jet photoionizes the dense fast-moving clouds of the broad-line region, which is often $\lesssim 1$ pc across.



Wadsworth Publishing Company/ITP

The more diffuse and slower-moving gas of the narrow-line region is at larger radii. Observers looking near the axis would see a Seyfert 1 nucleus but from the side would see a Seyfert 2.

The Eddington luminosity

Arthur Eddington was the first to realize that there is a limit to the luminosity of a central source that shines by converting infalling gas into energy.

Photons from the source exert an outward force on the gas that can overcome the gravitational force, cutting off the flow of gas.

A photon of energy E carries momentum E/c. Therefore, the radiation force on an electron at distance r is given by

$$F_{\mathsf{L}} = \frac{L}{4\pi r^2 c}\sigma_T$$

where $\sigma_{\mathsf{T}} = 6.653 \times 10^{-29}$ m^2 is the Thompson cross-section (the classical cross section for the scattering of a photon by an electron).

The Eddington luminosity

The gravitational force is

$$F_{\mathsf{G}} = \frac{GMm_p}{r^2},$$

where m_p is the mass of the proton (which is coupled to the electron by the strong electrostatic force).

The forces are equal when the luminosity equals the **Eddington luminosity**

$$L_{\mathsf{E}} = \frac{4\pi GMm_p c}{\sigma_{\mathsf{T}}} \simeq 1.3 \times 10^{31} \frac{M}{M_\odot}\ \mathsf{W} \simeq 30000 \frac{M}{M_\odot} L_\odot.$$

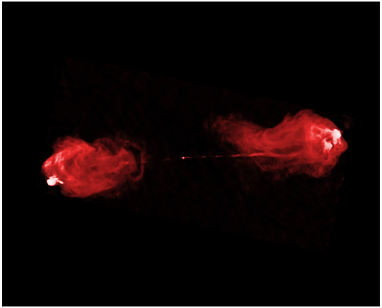
This tells us that a source having luminosity $L = 10^9 L_\odot$ would require a mass of $M > 10^7 M_\odot$ if it is fueled by spherical accretion.

Radio galaxies

Some galaxies have radio emission exceeding $10^8 L_\odot$. These are called **radio galaxies**.

Often, the emission comes from twin radio lobes far outside the visible galaxy.

Narrow "jets" can be seen connecting the radio lobes to the nucleus of the galaxy.



Cygnus A, NRAO/VLA.

Some radio galaxies also show broad emission lines in their nucleus, much like Seyfert galaxies.

However, radio galaxies are almost always elliptical galaxies.

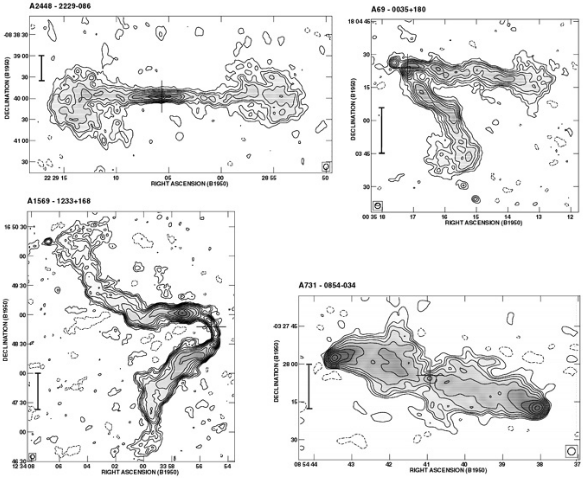


Fig 9.4 (M. Ledlow) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Four radio galaxies, observed at 20 cm: galaxy luminosity L is measured in the R band, radio power P in units of 10^{25} W Hz^{-1} at 20 cm. Clockwise from top left: a twin jet with $L \simeq 6L_*$, $P \simeq 1$; a narrow-angle tail source ($L \simeq 3L_*$, $P \simeq 1$); an edge-brightened classical double ($L \simeq 1.4L_*$, $P \simeq 7$); and a wide-angle tail ($L \simeq 2L_*$, $P \simeq 1.7$). The scale bar shows 50 kpc.

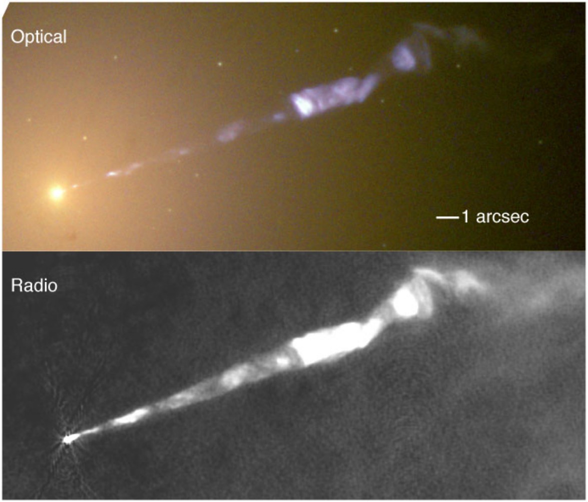


Fig 9.5 (J Biretta/HST) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

A one-sided jet in the elliptical galaxy M87.Top, invisible light near 8000 Å, from the Hubble Space Telescope, the jet emerges from the glare of the galaxys center; round white spots are globular clusters. Below, the image at 2 cm shows the radio-bright plasma; 1 arcsec $\simeq 80$ pc.

Radio emission

The radio emission is produced by **synchrotron emission** produced by relativistic electrons moving in a magnetic field.

The spectrum can be fit by a power law $F_\nu \propto \nu^{-\alpha}$, with a cutoff at low and high frequencies.

The spectral index α is usually in the range $0.7 \lesssim \alpha \lesssim 1.2$, with the smaller values (flatter spectra) found for the nucleus and inner jet.

The radio lobes consist of a plasma of electrons, ions and magnetic fields. Their total energy content can be as large as $10^{53} J$, which is equivalent to the energy emitted by $10^{10} L_\odot$ over a Gyr.

The most luminous radio galaxies have radio luminosities of up to $10^{12} L_\odot$. Dividing this into the above energy gives a timescale,

$$t \sim E/L \sim 10 \text{ Myr}$$

indicating that either radio galaxies have short lives, or that the lobes are continously replenished from the central source.