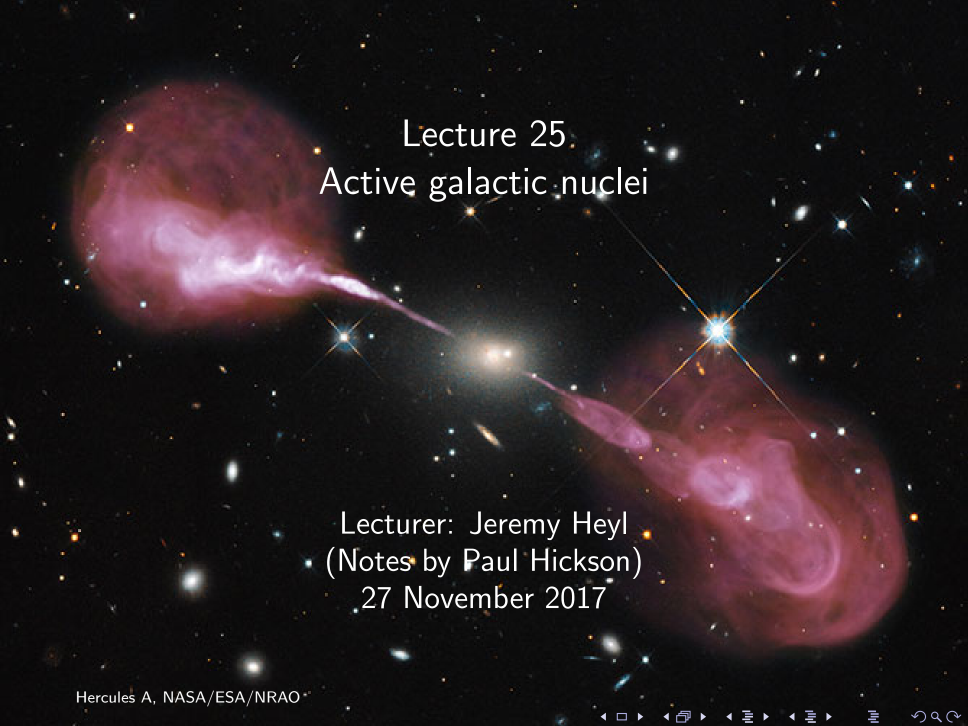

Lecture 25
Active galactic nuclei

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(Notes by Paul Hickson)
27 November 2017

Hercules A, NASA/ESA/NRAO

Quasars

Quasars are galaxies with very bright star-like nuclei. Their luminosities exceed $10^{11} L_\odot$.

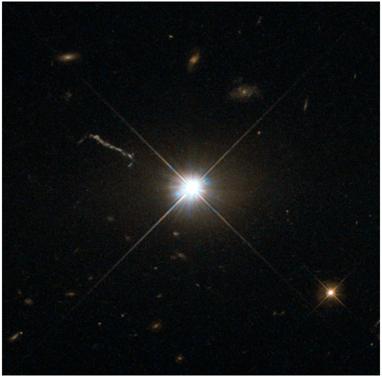
Their spectra show broad emission lines, like Seyfert 1.

They are relatively rare and generally have high redshift.

Quasi-stellar objects (QSO) are radio-quiet

Quasi-stellar sources (QSS) are radio-loud

They are often found in interacting systems or small groups of galaxies.



3C 273, NASA/ESA HST.

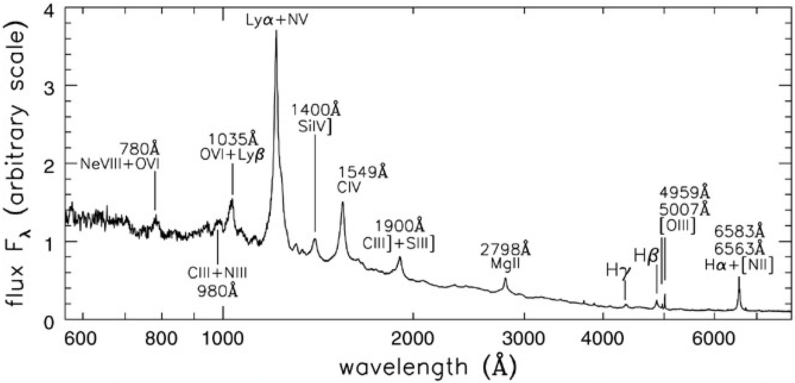


Fig 9.1 (Telfer et al.) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The ultraviolet and optical spectrum of an 'average' radio-quiet quasar.

Quasar properties

Quasars spectra show strong continuum radiation that increases in the UV. This is believed to be synchrotron radiation from jet of relativistic particles emanating from the nucleus.

Some also show an excess in the visible (the *blue bump*) that is believed to be due to thermal radiation from an accretion disk.

Radio-loud quasars show stronger radio emission from the central core, and have flatter spectra, than do radio galaxies.

Many quasars, and their energetic relatives, blazars, emit more power in X-rays or even gamma-rays, than in the UV, optical, IR and radio combined.

Some quasars show broad absorption lines with widths up to 10,000 km/s. These are blue shifted with respect to the quasar and thus represent an outflow of dense gas ($\sim 10^{25} - 10^{27}$ m^{-3}) moving a speeds $\sim 0.1c$. The nature and origin of this flow is unknown.

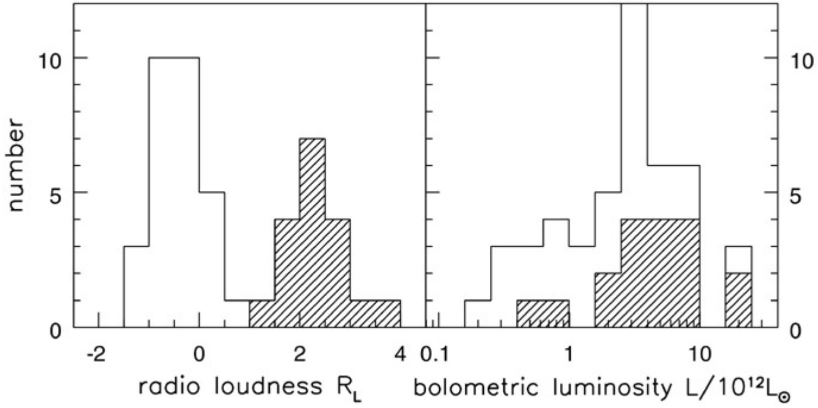


Fig 9.8 (J. McDowell) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Left, radio loudness $R_L = log_{10}[L_\nu(5\ \text{GHz})/L_\nu(\ \text{B band})]$ for a sample of 137 quasars. Right, radio-loud objects (those with $R_L > 1$, shaded) are rarely found among the less luminous quasars with $L < 10^{12} L_\odot$.

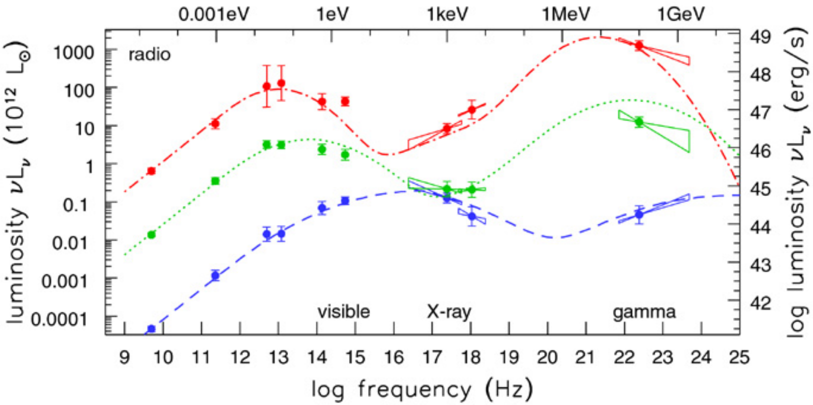


Fig 9.9 (G. Fossati) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Average spectral energy distributions for blazars, grouped by radio power: the most radio-bright are also the most luminous in γ-rays. The lower-energy peaks in the ultraviolet and X-ray regions represent synchrotron radiation from electrons in the jet; these photons scatter from the same spiralling electrons to produce the γ-ray peak. When the electrons are more energetic, both peaks move to higher frequency.

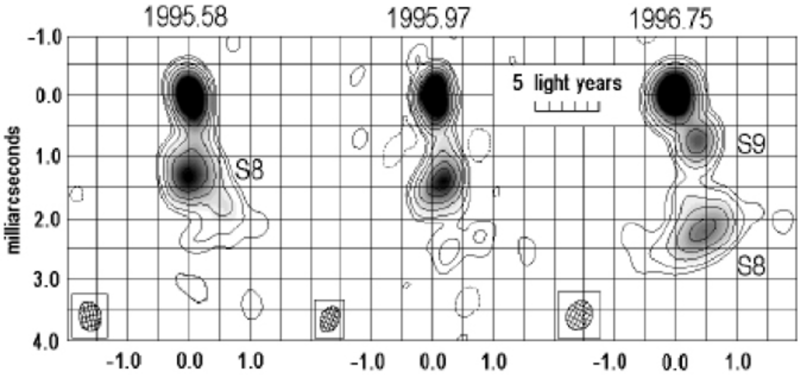


Fig 9.10 (G. Denn) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Radio maps at 22 GHz of the blazar BL Lac; the scale bar is 5 light-years long, assuming that $H_0 = 67$ km s^{-1} Mpc^{-1} . Blob S8 moves in a corkscrew path away from the core at apparent speed $\sim 3c$. The hatched ellipse shows the telescope beam; a point-like source would appear with roughly this size and shape.

Relativistic jets

Interferometric imaging of the cores of quasars and radio galaxies, at radio wavelengths, reveals luminous blobs moving outward from the central source.

In about half of the cores, **superluminal** motion is seen: the blobs appear to be moving faster than light. This is actually an illusion caused by relativistic effects.

Referring to the figure on the next slide shows, suppose that the blob is moving a speed V at a small angle θ to the line of sight. As it moves from point S to point T, we see it move transversely a distance $V\Delta t \sin\theta$.

The time interval between reception of a photon emitted towards us by the blob at S and another emitted at T is $\Delta t - v\Delta t \cos\phi/c$. Therefore, the apparent transverse speed of the blob is

$$v_{\text{obs}} = \frac{v\Delta t \sin\theta}{\Delta t - v\Delta t \cos\theta/c} = \frac{v\sin\theta}{1 - v\cos\theta/c}.$$

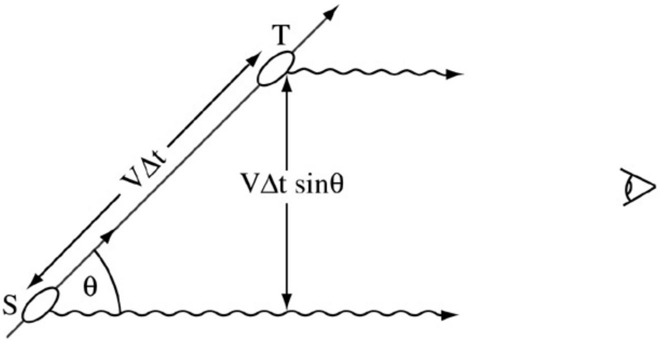


Fig 9.11 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Luminous blobs ejected at angle θ to the line of sight can appear to move superluminally across the sky if their speed $V \simeq c$.

Superluminal motion

Defining $\beta = v/c$, we can write this as

$$V_{\mathsf{obs}} = \frac{\beta \sin\theta}{1 - \beta\cos\theta} c.$$

If θ is small and $\beta \simeq 1$, this becomes

$$v_{\mathsf{obs}} \simeq \frac{\beta\theta}{1 - \beta} c \simeq 2\gamma^2\theta c,$$

where $\gamma = 1/\sqrt{1 - \beta^2}$ is the **Lorentz factor**.

If $\gamma > 1/\sqrt{2\theta}$ the apparent transverse velocity will exceed the speed of light.

Observed expansion speeds in blazars can be as high as $10c$. Typical Lorentz factors are likely in the range $\gamma \sim 5 - 10$.

Relativistic beaming

For an emitter approaching the observer at an angle θ, the radiation is blue-shifted by the relativistic Doppler shift

$$\frac{\nu}{\nu_0} = \frac{1}{\gamma(1-\beta\cos\theta)} \simeq 2\gamma.$$

This increases the apparent luminosity.

Also, the rate at which photons are received by a stationary observer is greater than the rate that they are emitted by the moving blob, by the same factor. This also increases the apparent luminosity.

Furthermore, a photon emitted at angle α_0 to the velocity vector, in the rest frame of the blob, is seen by the observer to be moving at a smaller angle α according to the relativistic aberration formula,

$$\cos\alpha = \frac{\cos\alpha_0 + \beta}{1+\beta\cos\alpha_0}$$

Relativistic beaming

For example, for a photon emitted perpendicular to the velocity ($\alpha_0 = \pi/2$), $\cos\alpha = \beta$ so

$$\sin\alpha = \sqrt{1-\beta^2} = \frac{1}{\gamma}.$$

If the emission is isotropic in the rest frame of the blob, and $\gamma >> 1$, 50% of the photons will be seen to be confined to a narrow cone of half angle $\alpha \simeq \gamma^{-1}$. This increases the intensity of the radiation by a factor of $\sim \gamma^2$.

Altogether, the intensity of a relativistic jet pointing towards us is boosted by a factor $\sim \gamma^4$, which can be very large.

Also, the timescale of fluctuations is reduced by a factor $\sim \gamma^{-1}$ so we see more rapid variability.

Intergalactic gas

Quasar spectra show numerous narrow absorption lines, at lower redshifts that the quasar itself. These are due to absorption by individual clouds intergalactic gas between us and the quasar.

Mostly hydrogen lines are seen, such as Ly-α. However lines of Mg, C, O and other metals are also seen.

The clouds range in density. The densest are mostly neutral while the fraction of neutral gas isn most diffuse clouds is less than 10^{-3}.

Some Ly-α absorption lines are broad and have essentially zero flux at the line centre. This indicates that the cloud is optically-thick, with column densities exceeding 2×10^{24} atoms m^{-2}. These are the **damped Ly-**α lines.

It is not known whether these gas clouds are intergalactic, or actually the disks of galaxies that are too faint to be seen at these high redshifts.

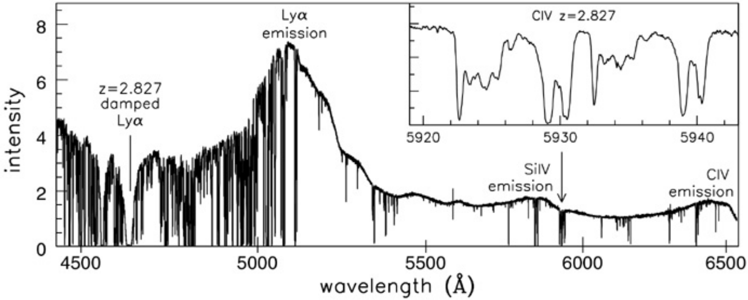


Fig 9.12 (L. Lu, M. Rauch) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The spectrum of quasar 1425 + 6039 with $z_{\text{em}} = 3.173$: broad Ly-α emission at 1216 Å is redshifted to the visible region. At shorter wavelengths, narrow absorption lines of the Ly-α forest are dense. The squarish profile at 4650 Å is a damped line of Ly-α, at $z_{\text{abs}} = 2.827$. The arrow shows absorption at the same redshift in the CIV doublet with rest wavelength near 1550 Å: the inset reveals distinct absorption components from multiple gas clouds.

The Lyman-α forest

Spectra of high-redshift quasars show many absorption lines at wavelengths shortward of Ly-α (1216Å). The is due to Ly-α absorption in the gas clouds along the line of sight, which have a lower redshift than the quasar.

These numerous lines are called the **Ly-α forest**.

At wavelengths shorter than of the Lyman limit (912Å $= 13.6$ eV), photons can ionize hydrogen. Clouds of neutral hydrogen become effectively opaque at these wavelengths.

One would therefore expect to see no flux in quasar spectra below the Lyman limit, and not much flux below the Lyman-α line. This is called the **Gunn - Peterson effect**.

In fact we can see some flux at these wavelengths even in the highest-redshift quasars. This indicates that the intergalactic medium is highly ionized, at least as far back as a redshift of ~ 6.