Lecture 10 : Active galaxies (II)
Radio galaxies

Although at some level all galaxies emit radio waves due to cosmic rays spiralling around the interstellar magnetic fields, the objects which are called '**radio galaxies**' are really pathological cases. One defines the radio-loudness by the ratio $R = F_{\nu_r}/F_\nu(4400\AA)$, where ν_r is the observing frequency in the radio band. One finds that if $R \geq 30$ (for $\nu_r = 5$ GHz) is taken to be the dividing line between radio quiet and loud galaxies, then about $\sim 15\%$ of quasars are radio loud. But even the strongest radio galaxy has $L_r < 0.01 L_{bol}$.

Powerful radio galaxies, like PKS 2356-61 shown below, usually have two lobes on the two opposite sides of the central galaxy (seen as the central blue 'blob' in the centre of the picture). The radio power emitted by PKS 2356-61 at 20cms is $\sim 5 \times 10^{26}$ W/Hz, and the power emitted in the range 10MHz-10GHz is approx 10^{36} W.

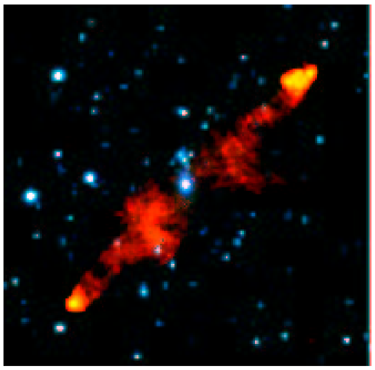

Figure 1: PKS 2356-61 is a powerful radio galaxy. The radio emission, shown in red-yellow is superposed on the optical field.

An example of a low powered radio galaxy is 3C 31 with a much lower luminosity. Notice the difference in the appearance of the two radio sources. This has led to an important classification of radio galaxies, called Fanaroff-Riley class I and II (Fanaroff and Riley 1974).

FR I radio galaxies have the brightest emitting region *less* than half of the distance from the core to the extremity of the radio source. They are therefore brightest at the center and decrease in surface brightness towards the edges, or in other words, they are core-dominated. FRII sources have the brightest emitting region *more* than half the distance from the core to the extremity of the source, that is, they are limb-brightened or lobe-dominated.

Interestingly FRI and FRII are divided by a sharp boundary in the optical- radio luminosity plane. The so-called Owen-Ledlow diagram (Owen & Ledlow 1996) shows that FRI galaxies have luminosities at 1.4 GHz (νL_ν) smaller than $6 \times 10^{40} L_{R,44}^2$ erg/s, where L_R is the R band luminosity of the host galaxy.

The spectrum also correlates with the FR classes. FRII radio galaxies often have a steep spectrum, that is faily well described by a power law $F_\nu \propto \nu^{-\alpha}$, with $0.5 \leq$

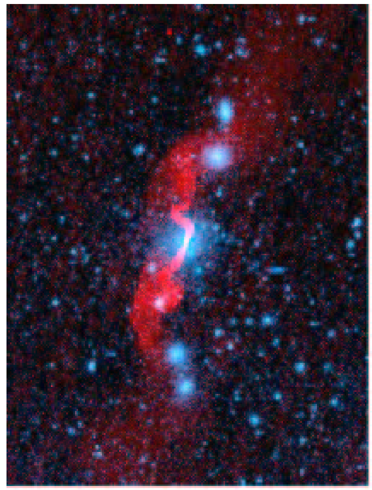

Figure 2: 3C 31 is a low powered radio galaxy.

$\alpha \leq 1$. FRI galaxies have spectra that are flatter in F_ν, although with some bumps present. The correlation, however, is not perfect. In some radio galaxies (the so-called 'Gigahertz peaked sources (GPS)' and 'Compact steep spectrum sources (CSS)') the radio emission is confined to a small extent although the spectrum does not have any flat part.

1 Synchrotron emission

The radio emission is usually thought to arise from synchrotron mechanism involving highly relativistic particles moving in a magnetic field. The critical frequency of synchrotron emission is given by $\nu_c = \frac{3}{4\pi}\frac{qB\gamma^2 \sin\alpha}{m}$. For a magnetic field of about 10 μ G (1 nT), one requires $\gamma \sim 10^4$ for electrons for them to emit in radio frequencies. If the underlying energy distribution of electron is a power law with index p, that is, if $N(\gamma)d\gamma \propto \gamma^{-p}d\gamma$ (number density of particles in the interval γ and $\gamma + d\gamma$), then the resulting synchrtoron spectrum has a power law with index $j_\nu \propto \nu^{-\alpha}$, with $\alpha = (p-1)/2$. An index of about 0.8 therefore means $p = 2.6$.

When the emitting region is optically thick, especially for compact cores, the spectrum rises as $\propto \nu^{5/2}$ for low frequencies, and after a turnover, when the opacity is lower than unity, it falls as $\propto \nu^{-\alpha}$ as above. The rise at low freqencies has never been seen, but the flat spectra of compact cores is usually interpreted as being the result of superposition of radiation from several self-absorbed synchrotron sources, the spectral discrepancy being attributed to inhomogeneity.

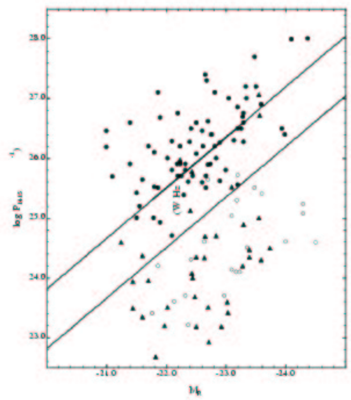

Figure 3: The Owen-Ledlow diagram

1.1 Minimum energy

The emitting region is essentially a giant bowl containing a soup of high energy particles, radiation and magnetic field. One can estimate the total energy of the system following an argument by Burbidge (1958, ApJ, 127,48). The source luminosity depends on the population of the relativistic electrons, their spectral index and the magnetic field. There is however a favoured value of the field strength, given a specified spectrum, source luminosity and volume—the one that minimizes the total energy of the emitting region. for a power law spectrum of the electrons, $N(E) = N_0 E^{-p}$, the energy in relativistic electrons is given by

$$U_{rel} = \int_{E_1}^{E_2} N(E) E dE = \frac{N_0}{2-p}(E_2^{2-p} - E_2^{2-p}), \quad (1)$$

for a pair of energy cutoffs (E_1, E_2). If the energy loss due to synchrotron radiation is denotes as $dE/dt = -\beta B^2 E^2$, where β is a constant, then the source luminosity is,

$$L = \int_{E_1}^{E_2} N(E) \beta E^2 B^2 dE = \frac{N_0}{3-p} \beta B^2 (E_2^{3-p} - E_1^{3-p}). \quad (2)$$

One observes the source at one frequency, so that we can write the energy as $E_j^2 = w_j/B$ for the two limiting frequencies, or energies, in the integral. Writing N_0 in terms of the source luminosity, we have

$$U_{rel} = C_{rel} \frac{L}{B^{3/2}}, \quad (3)$$

where we have absorbed all constant factors into C_{rel}. The magnetic field energy is of course,

$$U_{mag} = C_B B^2 V, \quad (4)$$

where C_B is a constant depending on the source geometry. The total energy is then,

$$U = C_{rel} B^{-3/2} L + C_B B^2 V \,. \tag{5}$$

If we now assert that the most likely value of magnetic field is such that U is minimized, we then get (by differntiating with respect to B and equating to zero),

$$B_{min} = \left(\frac{3 C_{rel} L}{4 C_B V}\right)^{2/7} . \tag{6}$$

Interestingly, this value of B ensures that $U_B = 3/4 U_{rel}$, that is, it is close to equipartition of particle and magnetic energy. The minimum pressure scales as $u_{min} \propto (L/V)^{4/7}$. To get an idea of the numbers involved, one has, for typical parameters of a FR2 radio galaxy,

$$B_m \sim 2.5 \times 10^{-6} (\frac{L_{43}}{r_{100}^3})^{2/7} \nu_{l9}^{(1-2\alpha)/7} \, \mathrm{G} \tag{7}$$

where L_{43} is the monochromatic luminosity at 1 GHz in units of 10^{43} erg/s, $\nu_{l9} = \nu_l / 1$ GHz (the lower limit of frequency; the factor C_{rel} depends strongly on the lower limit, for $2 < \alpha < 3$), and r_{100} is the lengthsclae of the source in units of 100 kpc. Interestingly, the corresponding energy density is very close to that of the CMBR. This means that energy loss at high redshift would depend strongly on CMBR.

The corresponding minimum energy is

$$E_m \sim 2 \times 10^{57} L_{43}^{4/7} r_{100}^{9/7} \nu_{l9}^{(2-4\alpha)/7} \, \mathrm{erg} \,, \tag{8}$$

1.2 Spectral aging

Given the energy loss rate of electrons, one can write the time dependence of the energy of a single particle, as (assuming an initial energy of E_0),

$$E = \frac{E_0}{1 - \beta B^2 E_0 t} \,. \tag{9}$$

One can then define a synchrotron lifetime of the particles as,

$$t \sim 2.4 \times 10^9 (\gamma / 10^4)^{-1} B_{\mu G}^{-2} \, \mathrm{yr} \,. \tag{10}$$

The radio spectrum changes systematically as the electrons age with time and move through the distribution function to lower energies. The maximum brightness therefore shifts to lower frequencies.

The life time, say for electrons corresponding to 10GHz photons, is much shorter than the jet propagation times extending over scales from 100 kpc to 1 Mpc. The spectrum of radiation from lobes is harder than it would be if the electrons were aging as they traverse the distance to the lobes. One then needs to reaccelerate electrons at the hotspots.

1.3 Sidedness of jets

Consider the radiation from the ject in the lab and the rest frame of the jet. The frequencies are related by the Doppler factor $\delta = \Gamma^{-1}(1-\beta\cos\theta)^{-1}$, in the following way (primed quantities refer to the rest frame),

$$\sin\theta' = \delta\sin\theta \qquad \nu = \delta\nu' \tag{11}$$

The emissivity of synchrotron radiation is a power law in frequency,

$$j_{\nu'} = j_\nu(\nu'/\nu)^{-\alpha} = \delta^\alpha j_\nu \,. \tag{12}$$

Suppose the thickness of the jet is D and the angle it makes in the sky is θ. In the rest frame, $I_{\nu'} = j_{\nu'}D/\sin\theta'$. Also, we know that $I_\nu/\nu^3 = I_{\nu'}/\nu'^3$.

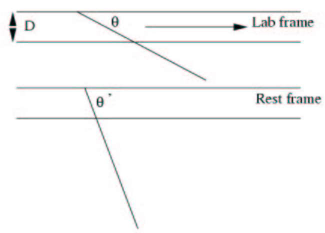

Figure 4:

This means that,

$$I_\nu = \delta^{2+\alpha}\left(\frac{j_\nu D}{\sin\theta}\right) \tag{13}$$

where the first factor is a relativistic Doppler boosting factor. It is a very sensitive function of θ especially near $\theta = 0$. For example, near $\theta = 0$, $\delta \sim 2\Gamma$; for $\Gamma = 5$ and $\alpha = 0.6$, one can have $\delta^{2+\alpha} \sim 400$. And for a jet viewed side-on, $\theta \sim \pi/2$, $\delta \sim 1/\Gamma$ and the 'dimming' factor can be as small as 0.015 for the same parameters.

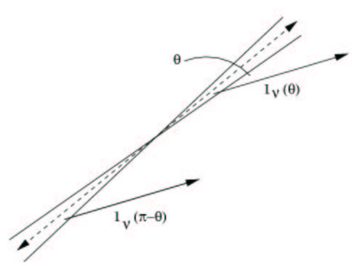

Figure 5:

For two oppositely directed jets, with otherwise similar parameters, the ratio of surface brightness would be,

$$\frac{I_\nu(\theta)}{I_\nu(\pi-\theta)} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{2+\alpha}. \tag{14}$$

For typical parameters, e.g., $\theta = 30°$, $\Gamma = 5$, $\beta \sim 0.9798$ and $\alpha = 0.6$, the ratio is ~ 670.

1.4 Hotspot dynamics

The relativistic material in the jet (of density ρ_j and velocity v_j) drives a shock against the ambient medium (with density ρ_a), driving the hotspot with a velocity v_h. There is a contact discontinuity between these two media. One can drive the velocity of the hotspot by balancing the momentum flux density or the pressure at the contact discontinuity. On the side of the ambient medium the ram pressure is $\rho_a v_h^2$. For the relativistic jet material, the momentum flux density is $w\Gamma^2\beta^2$, where $w = \rho_o c^2 + p$ is the relativistic enthalpy. For the relativisitic plasma, one has $w \sim 4p$. One has after balancing,

$$\beta_h = \left(\frac{w}{\rho_a c^2}\right)^{1/2} \Gamma_j \beta_j. \tag{15}$$

For typical values of $p_j \sim 10^{-9}$ dyne, and $n_a \sim 10^{-3}$ per cc, one has $\beta_h \sim 0.07\Gamma_j\beta_j$. From the Doppler boosting idea of jet luminosity, one knows that $\Gamma_j \sim 5$, which shows that the hotspot advances non-relativistically.

The jet material produces a 'cocoon' of relativistic plasma around the jet and the radio-luminous lobe, and this serves as a 'waste-basket' of relativistic particles. The cocoon gas flows backward along the outside of the jet, perhaps adding to the pressure of confinement of the jet.

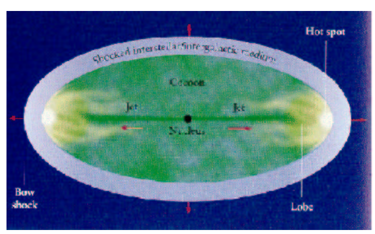

Figure 6: Schematic diagram showing the cocoon and the shocked intergalactic medium.

1.5 Entrainment in FR1 sources

The jets in FR1 sources are relativistic to begin with, as evidenced from the surface brightness asymmetry from relativistic beaming, within a parsec scale length of the central engine. They become symmetrical however at a lengthscale of a few kiloparsecs. It is believed that 'entrainment' of ambient material, from the ISM, decelerates the jet. The details are still under scrutiny though.

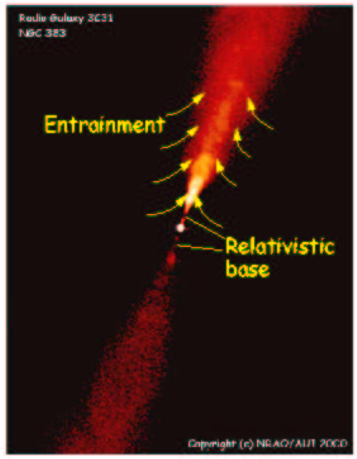

Figure 7: 3C31 once again.

Final remarks

The question one then asks if the difference between FR1 and 2 source is caused by ‘nature’ or ‘nurture’. There are some arguments for the possibility that the central engines might be different. It is thought that FR1s are powered by sub-Eddington accretion due to ADAF. The models cannot however explain all parts of the FR1 spectra though (Di Matteo et al 1998).

It is also possible that the FR1/2 division is due to the environment. This hypothesis requires that FR1s exist in region of high ambient density, and there are some evidences for that (Zirbel 1997), but this cannot be the only story since some classical FR2s are found in cluster (3C34 Best, Longair and Rottgering 1996). It is certain that both factors contribute towards the FR1/2 division but dominant factor remains uncertain.

Another outstanding question is what makes a AGN radio-quiet and radio-loud. We have seen that only $5-10\%$ of AGN are radio-loud, defined as R_{ro} =flux at 5 GHz/flux at 4400 $\AA > 10$ (Kellerman et al 1989). Recent FIRST survey shows that the distribution is not bimodal as was earlier thought. Also, the host galaxies and the environments of the two types of AGNs are also not very different. The X-ray spectra are however very different, with Fe Kalpha lines in radio-loud AGNs being narrower, which probably says that the accretion process itself in radio loud galaxies is different from radio-quiet ones (Sambruna et al 2002) The jury is still out on this.