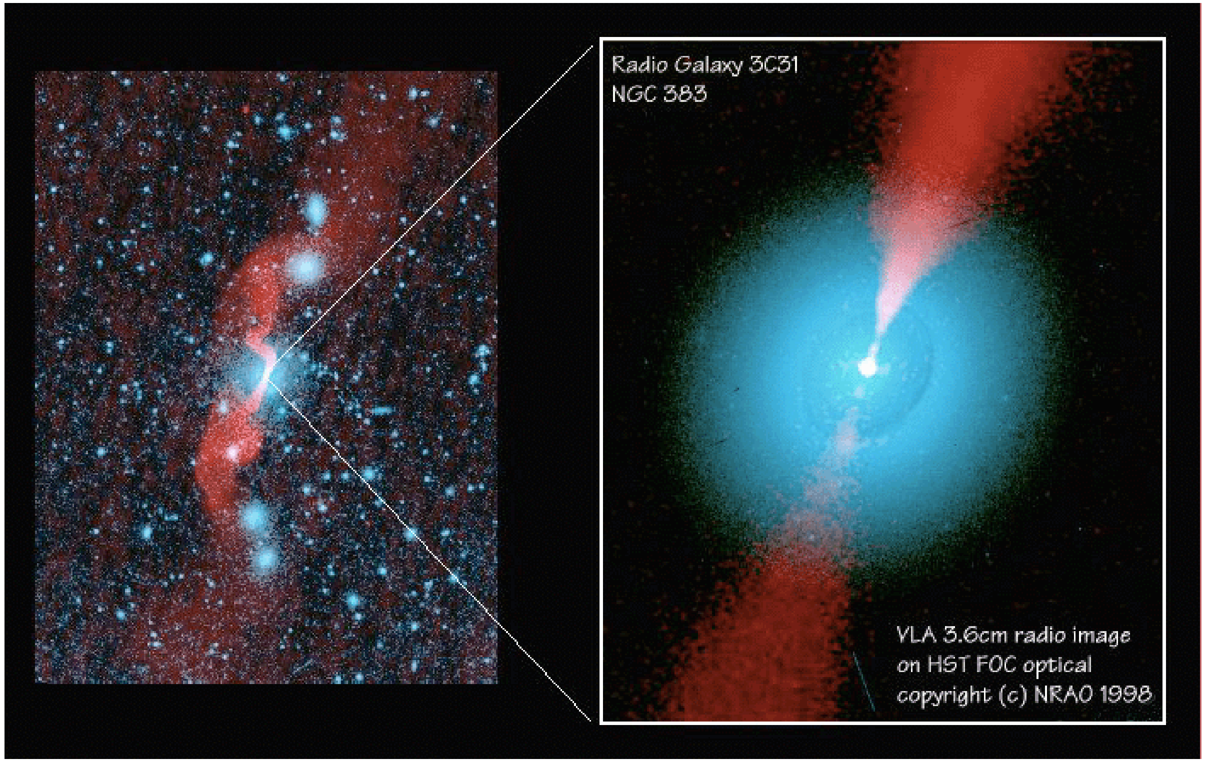
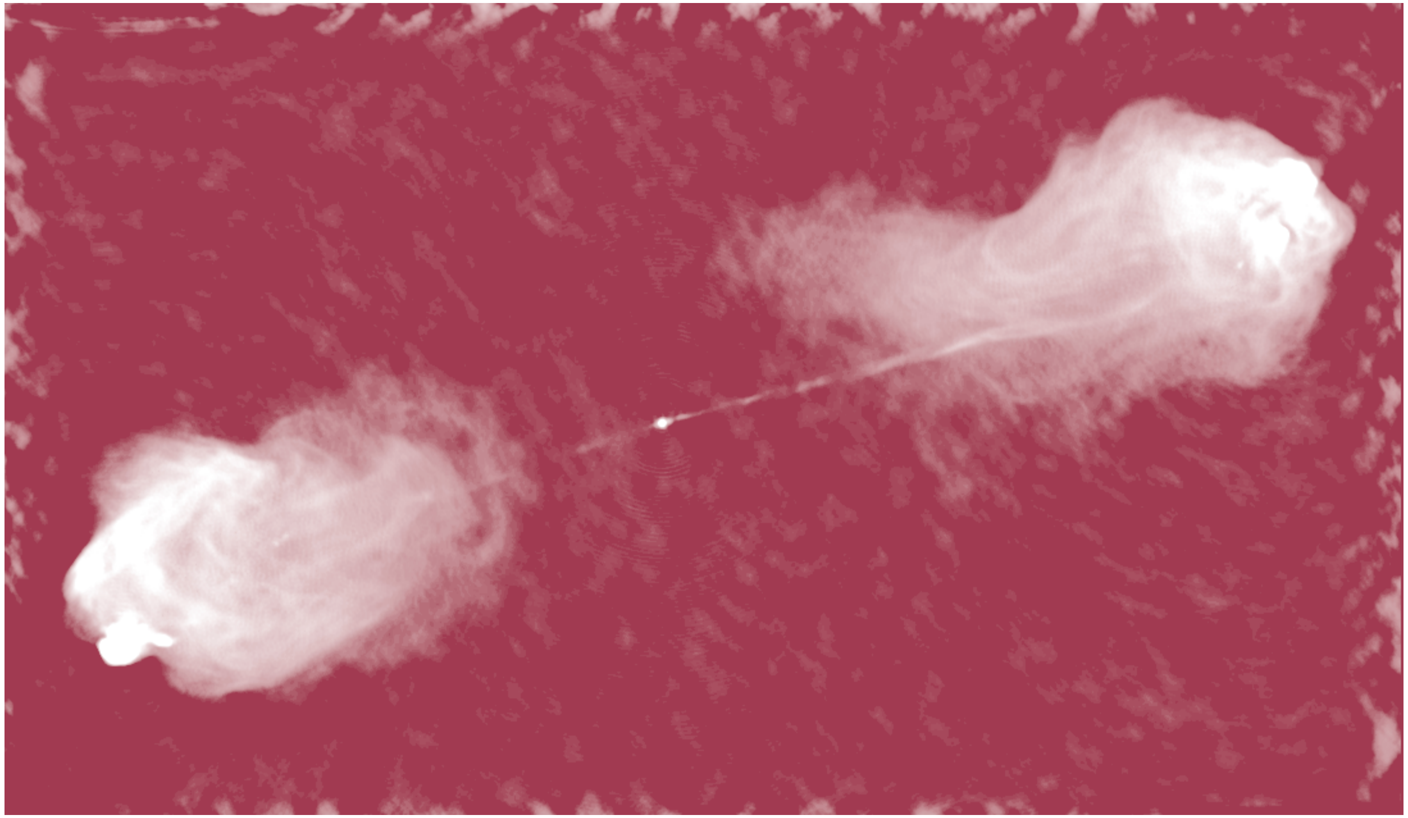
Radio Galaxies

1 Fanaroff-Riley Class

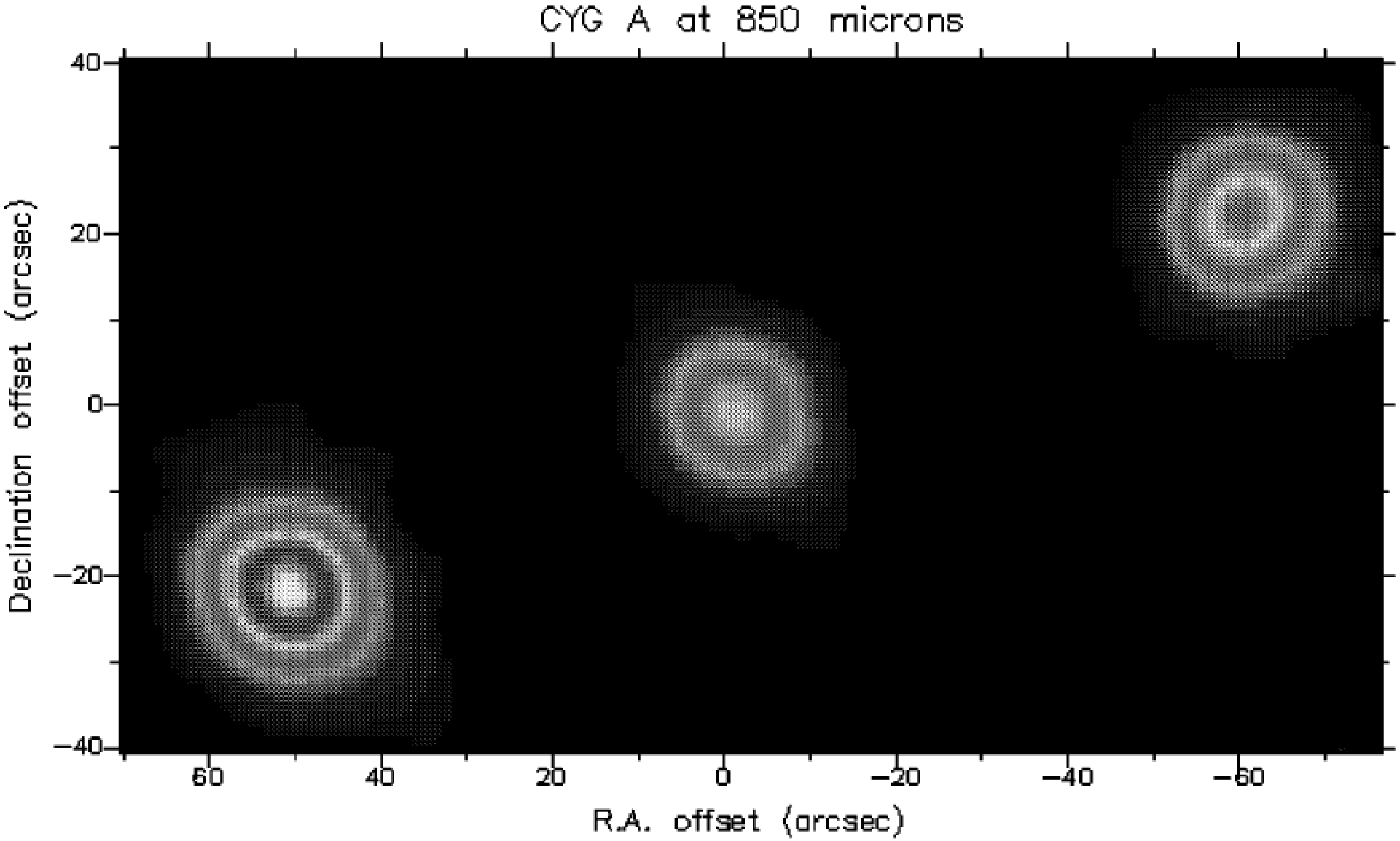


Radio-optical overlay of the prototype FR 1 radio galaxy 3C 31

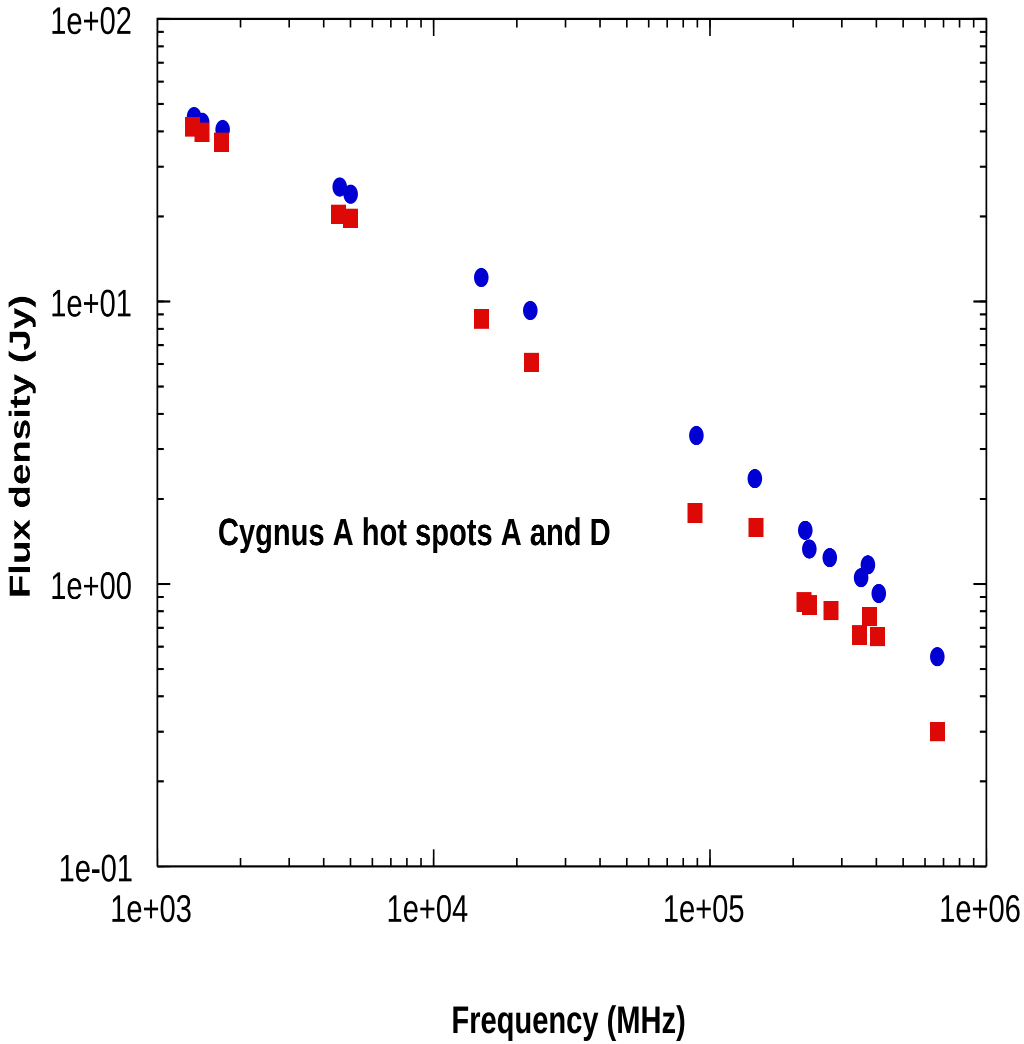
Credits: Alan Bridle and Robert Laing



The prototype FR 2 radio galaxy, Cygnus A.Note the difference in the jet structure compared to 3C 31. Dreher, Carilli and Perley, ApJ, **316**, 611



Cygnus A at 850 microns. Only the hot spots and core are visible. Robson et al. MNRAS, **301**, 935



Flux density plot of the hots spots of Cygnus A, utilising microwave to mm data. Data from Robson et al. (1998).

2 Fluence

The flux density of a source measures the power per unit area incident on a telescope. Units $\mathrm{W\ m^{-2}\ Hz^{-1}}$.

The power per unit area integrated over a band is

$$\left.\frac{dP}{dA}\right|_{\mathrm{band}} = \int_{\nu_1}^{\nu_2} F_\nu d\nu$$

Logarithmic ranges

We have also seen that it is often more appropriate to express spectra in logarithmic units. This is especially the case with nonthermal spectra which are often power-laws over a wide range of frequency. In order to deal with the large ranges over which spectra are measured, we take the expression for the integrated power and write in the following way:

$$\left.\frac{dP}{dA}\right|_{\text{band}} = \int_{\nu_1}^{\nu_2} F_\nu d\nu = \int_{\nu_1}^{\nu_2} \nu F_\nu \frac{d\nu}{\nu}$$

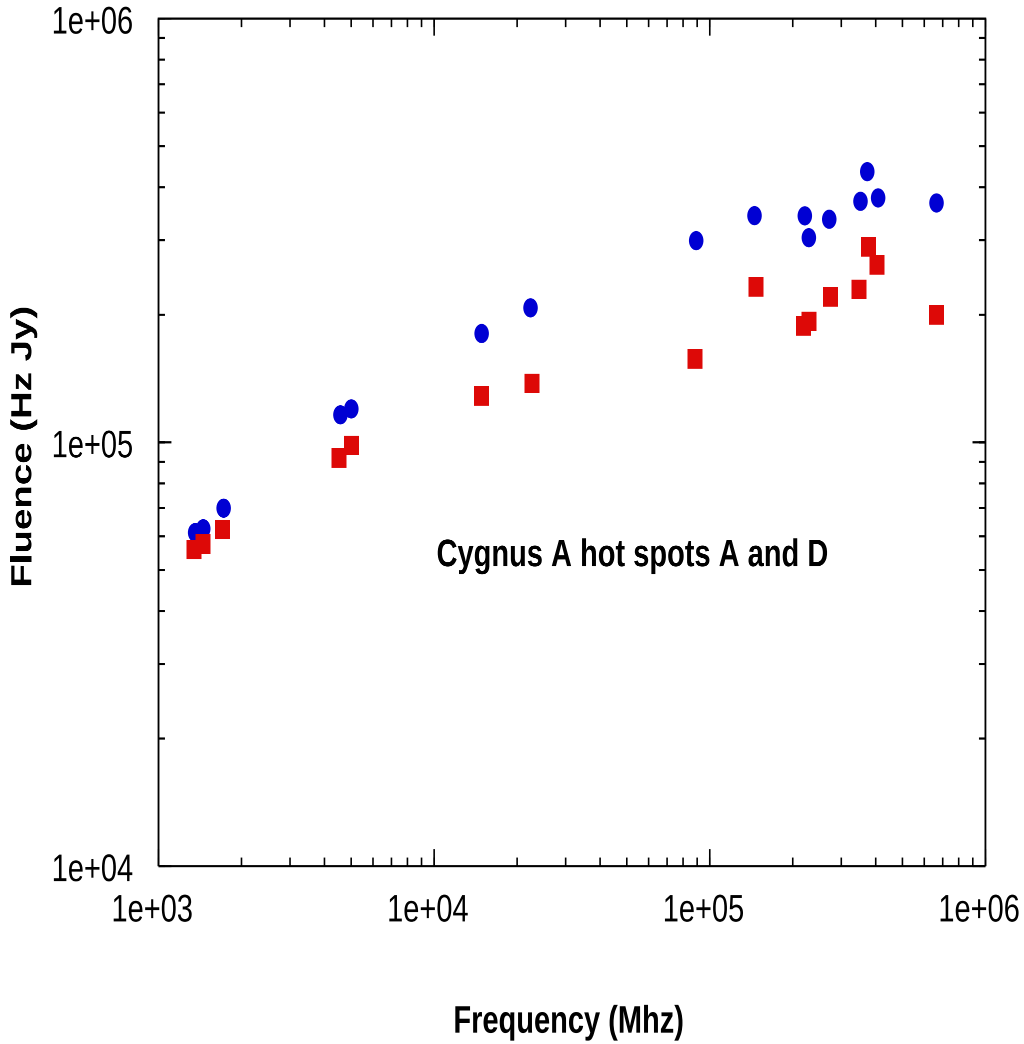
$$= \int_{\ln\nu_1}^{\ln\nu_2} \nu F_\nu d(\ln\nu)$$

The quantity

$$\nu F_\nu = \text{Power per unit area per } \ln\nu$$

is known as the ***fluence***. Plots of fluence give a good way of directly visualising what part of the spectrum dominates the emission from an astrophysical source.

2.1 Fluence from the hot spots of Cygnus A



This plot of the fluence from the hot spots of Cygnus A shows that the emission is dominated by the region of $10^{11} - 10^{12}$ Hz

The plot of the fluence also shows more readily where the spectrum changes slope – or “breaks”.

3 Minimum energy conditions

3.1 Cygnus A example

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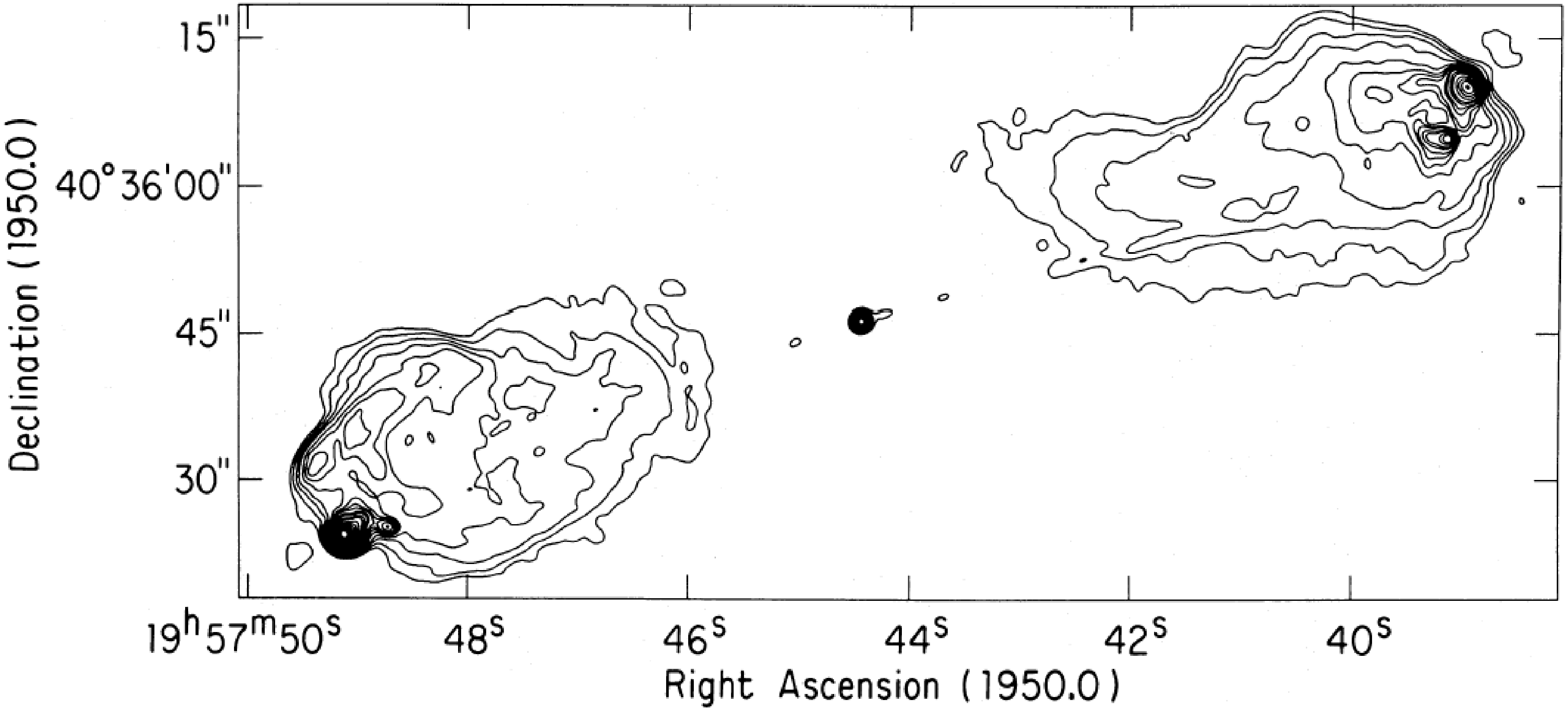


FIG. 1.—Cygnus A at 5 GHz with 1″ resolution. The contour levels are at 0.075, 0.2, 0.5, 1, 2, 3, 4, 5, 7.5, 10, 15, 20, 30, . . . , 80, 90% of the maximum brightness of 14.5 Jy per beam. The morphological features displayed here are typical of high-luminosity radio sources. The jet and filaments are best seen in a gray-scale plot, especially at high resolution, such as in Fig. 4. See Fig. 1 of Paper I.

Recall the minimum energy parameters for a synchrotron emitting plasma:

$$B_{\min} = \frac{m_e}{e}\left[\frac{a+1}{2}(1+c_E)C_2^{-1}(a)\frac{c}{m_e}\left(\frac{I_\nu \nu^\alpha}{L}\right)f(a,\gamma_1,\gamma_2)\right]^{\frac{2}{a+5}}$$

$$\varepsilon_{p,\min} = \frac{2}{a+1}\frac{B_{\min}^2}{\mu_0}$$

where

$$f(a,\gamma_1,\gamma_2) = (a-2)^{-1}\gamma_1^{-(a-2)}\left[1-\left(\frac{\gamma_2}{\gamma_1}\right)^{-(a-2)}\right]$$

Inputs required

$$L = \text{Distance through source}$$

Angular size corresponding to L

$$H_0 \approx 70 \text{ km s}^{-1} \text{ Mpc} = \text{Hubble constant}$$

$$z = \text{Redshift of source}$$

$$I_\nu = \text{Surface brightness}$$

$$\alpha = \text{spectral index} \Rightarrow a = 2\alpha + 1 \text{ and } C_2(a)$$

$$c_E = 0 \text{ for electron-positron plasma}$$

$$1\,\text{Mpc} = 3.09 \times 10^{22} \text{ m}$$

For relatively nearby sources:

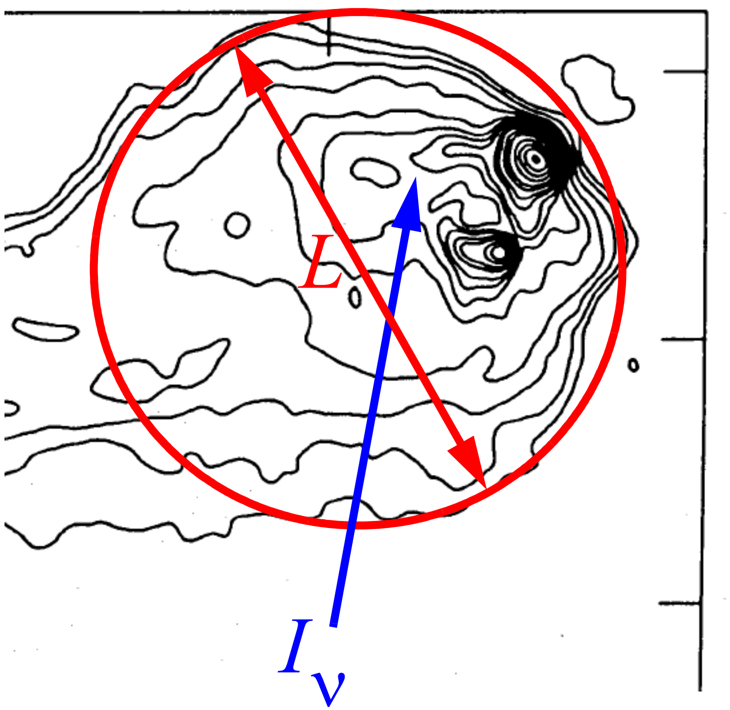
$$D = \frac{cz}{H_0} \qquad L = D\theta \qquad \theta = \text{angular size}$$

Cygnus A:

$$z = 0.056075 \Rightarrow D = 243 \text{ Mpc}$$

$$1'' = 243 \times \frac{\pi}{180} \times \frac{1}{3600} \times 3.09\times10^{22} \text{ m}$$

$$= 3.64\times10^{19} \text{ m}$$



The aim of the following is to obtain a rough estimate of the total energy in the lobe.

- Assume that the red-circled region is approximately spherical.
- For the total energy in this region we ignore the emission from the small hot spot regions
- Assume that the surface brightness from the indicated region is the result of integrating a constant emissivity through a "sphere" of diameter L
- The total energy in the sphere is then $\frac{\pi}{6}\varepsilon_{\min}L^3$.

3.2 Spreadsheet calculation

This sort of calculation can easily be coded in a FORTRAN program. However, it is the sort of calculation that has such a large number of inputs that it lends itself well to a spreadsheet.

A template spreadsheet is available on the course web page.

The result of that calculation is that the total minimum energy in particles and field is approximately 8.6×10^{51} Joules. If we allow a factor of 2 for the rest of the lobe (including hot spots) and another factor of 2 for both lobes, then we have a total minimum energy of approximately 3.4×10^{52} Joules.

4 Implications

4.1 Mass equivalent

3.4×10^{52} Joules is a large amount of energy to have accumulated in any part of the Universe and this is a **minimum** (but probably indicative).

The mass equivalent of this amount of energy is

$$M = \frac{E}{c^2} \approx 1.9\times10^{5} \text{ solar masses}$$

Since Mc^2 is the absolute maximum amount of energy that can be extracted from a mass, then this amount of mass represents the absolute minimum mass that is involved in the production of this energy.

4.2 Nucleosynthesis

Stars "burn" heavier and heavier elements until they reach Iron at which point the nuclear reactions become endothermic rather than exothermic. The maximum amount of energy that can be obtained from a star is

$$E_{\text{max}} = 0.07\% \times M_* c^2$$

Therefore, if all the energy in a radio lobe were to be obtained from stars the mass of stars involved is:

$$M_* \approx \frac{3.4\times10^{52}}{0.007c^2} \approx 2.7\times10^7 \text{ solar masses}$$

Supernovae

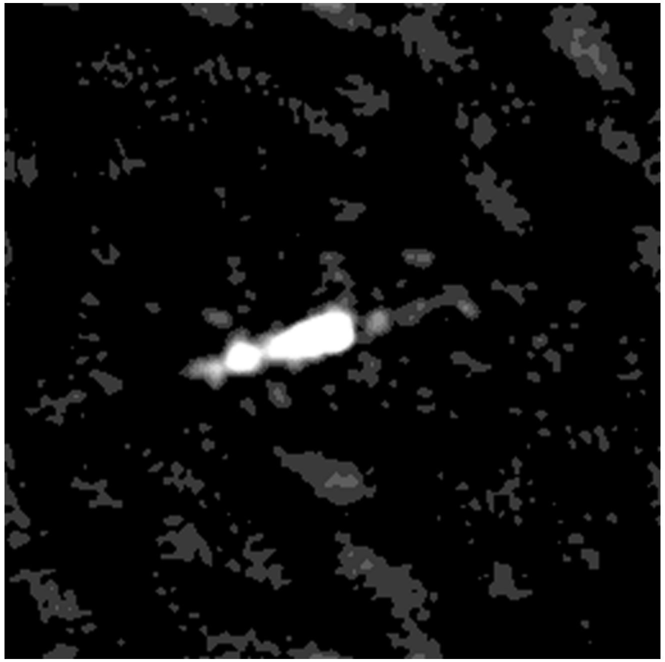
If this were to be the source of energy, one would also have to explain how the energy was channelled into radio emitting particles rather than optical and IR radiation. The standard approach has been to invoke supernovae which are known to produce radio emission.

If we assume that every supernova produces approximately 10^{44} Joules of energy then the number of supernovae required is about

$$\frac{3.4\times10^{52}}{10^{44}} \approx 3\times10^{8}$$

For reasons we shall not go into at this stage, the ages of radio galaxies such as Cygnus A is estimated to be of order 10^{7-8} yrs. Hence, the total emission from Cygnus A requires about 3 – 30 SNe/yr.

4.3 The size of the emitting region - Imaging



VLBI image of Cygnus A (Carilli, Bartel & Linfield, AJ, 1991, **102**, 1691)

We have seen that the Cygnus A lobes are fed by jets whose origin is an unresolved (at $1''$ resolution) region in the centre of Cygnus A.

This is A VLBI image of Cygnus A at ***2 mas*** resolution. At the distance of Cygnus A

$$1 \text{ mas} = 1.2 \text{ pc}$$

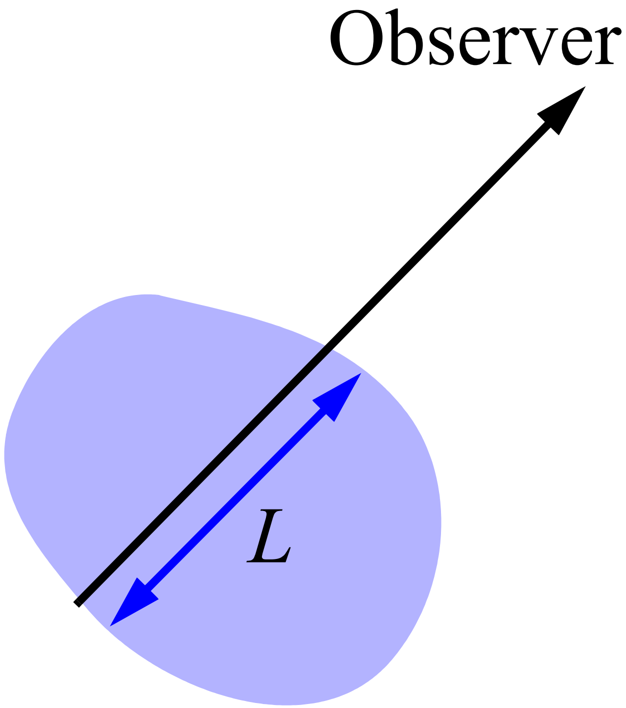
Even at this resolution there is still an unresolved core. So that the 3-30 SNe per year would have to be occurring from within this volume.

Compare this to about 1 SNe per 100 years from our entire Galaxy.

4.4 The size of the emitting region - time variability

The nuclei of all active galaxies – including radio galaxies – are observed to vary on timescales as short as 1 day. The variability in the radio region of the spectrum can be explained in terms of interstellar scintillation by the medium of our own galaxy. However, the variability in optical and X-ray emission cannot be explained in this way.

Naive estimate of size from time variability



If an emitting region varies more rapidly than it takes a light ray to travel through it, then the variability would be washed out.

Hence if a source varies on a timescale of Δt then the size, L, of the emitting region satisfies:

$$L < c\Delta t = 2.6\times10^{13}\left(\frac{\Delta t}{1\,\mathrm{day}}\right)\ \mathrm{m} = 8.4\times10^{-4}\left(\frac{\Delta t}{1\,\mathrm{day}}\right)\ \mathrm{pc}$$

This estimate will be modified later when we incorporate relativistic effects. However, the indication from this estimate is that the timescale is very small compared to the smallest scales that are resolvable with current technology.

If we invoke conventional sources of power, then we require either:

- A stellar mass density exceeding 4.5×10^{16} solar masses per cubic parsec
- Or ~10 SNe per year from within a volume of 10^{-3} parsec.

4.5 Black holes

The above arguments gradually led to the realisation that black holes provide an appealing mechanism for the production of energy in radio galaxies and active galactic nuclei, generally.

Power liberated by a black hole

If a mass Δm spirals into a black hole then an amount of energy

$$\Delta E_{\mathrm{acc}} \approx 0.3 \Delta m c^2$$

can be liberated. This is the binding energy of the lowest stable orbit in a maximal Kerr black hole gravitational field. For general accretion onto a black hole, we put for the energy liberated by accretion:

$$\Delta E_{\mathrm{acc}} = \alpha \Delta m_{\mathrm{acc}} c^2$$

where

$$\Delta m_{\mathrm{acc}} = \text{Accreted mass}$$

In a radio galaxy, this energy appears in the radio lobes after being transported out from the nucleus in jets. Hence, the mass accreted by the black hole is

$$\Delta m_{\text{acc}} \approx \frac{E_{\text{lobes}}}{\alpha c^2}$$

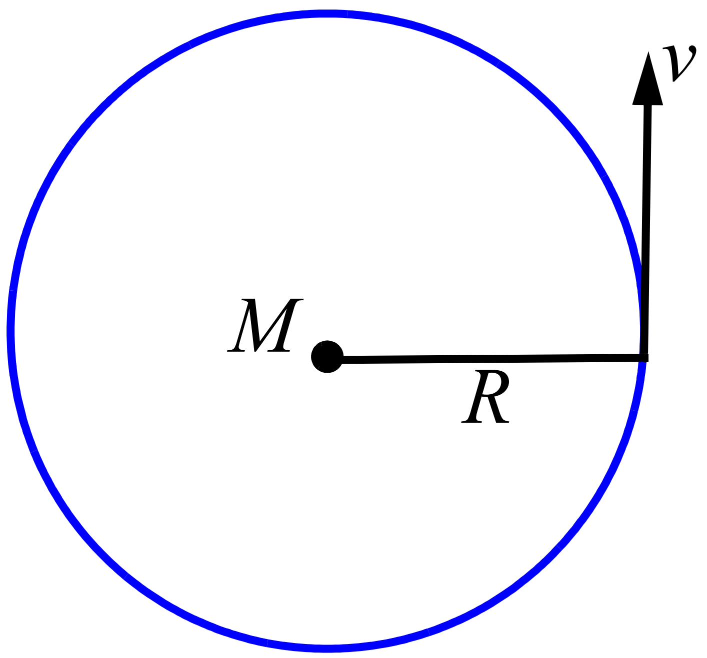
For Cygnus A

$$\Delta m_{\text{acc}} \approx 1.9 \times 10^6 \left(\frac{\alpha}{0.1}\right)^{-1} \text{ solar masses}$$

This represents a lower limit on the mass of the black hole.

5 Evidence for black holes

5.1 Keplerian velocity of matter orbiting a black hole



If we have a lump of matter of mass m (e.g. cold gas, star) orbiting a black hole, then

$$\frac{mv^2}{R} = \frac{GMm}{R^2}$$

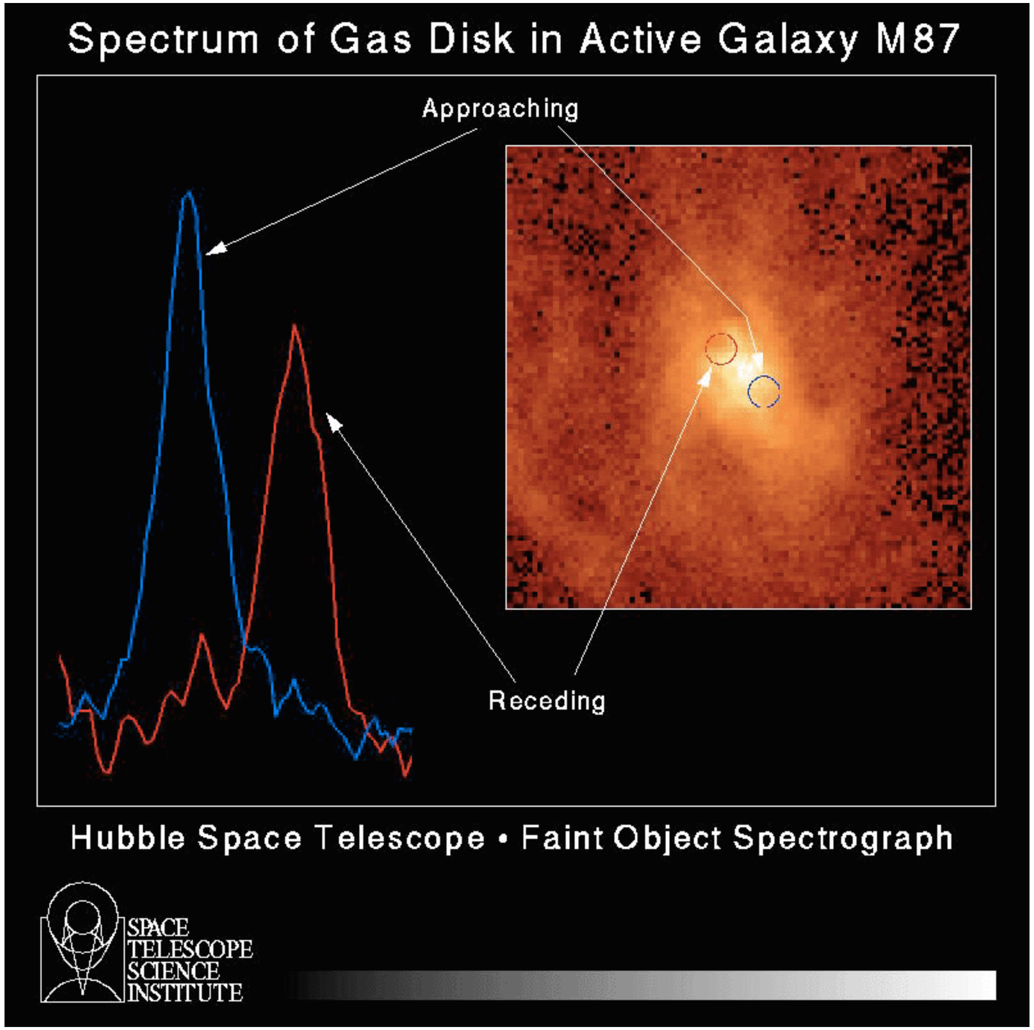
$$\Rightarrow v = \sqrt{\frac{GM}{R}}$$

Numerically,

$$v = 208\ \text{km/s} \left(\frac{M}{10^7 M_O}\right)^{1/2} \left(\frac{R}{\text{pc}}\right)^{-1/2}$$

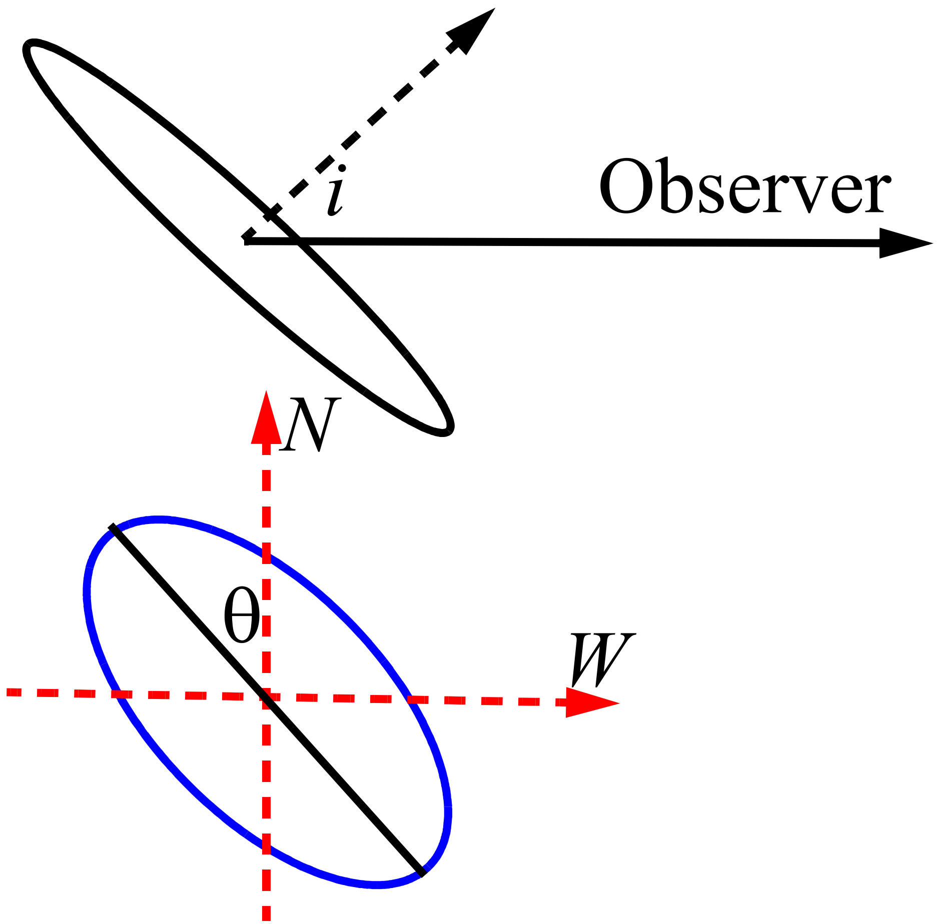
This sort of velocity can be detected very easily via optical or radio spectroscopy (depending on the circumstances).

5.2 The gaseous disk in M87



The gaseous disk in M87 as observed by HST. This press release image is from the work of Holland Ford and collaborators.

The gas velocity was measured from observations of the $H\alpha + [NII]$ lines.



Geometry

Allowing for inclination and orientation on the plane of the sky:

$$i = \text{Angle of inclination}$$

$$\theta = \text{Position angle of major axis}$$

$$\theta_k = \text{Position angle of measurement}$$

$$R_k = \text{Projected radius of measurement}$$

The measured velocities are given by:

$$v_k^2 = \left(\frac{GM}{R_k}\right)\frac{\sin^2 i \cos^3 i}{\cos(\theta+\theta_k)[\cos^2 i + \tan^2(\theta+\theta_k)]^{3/2}}$$

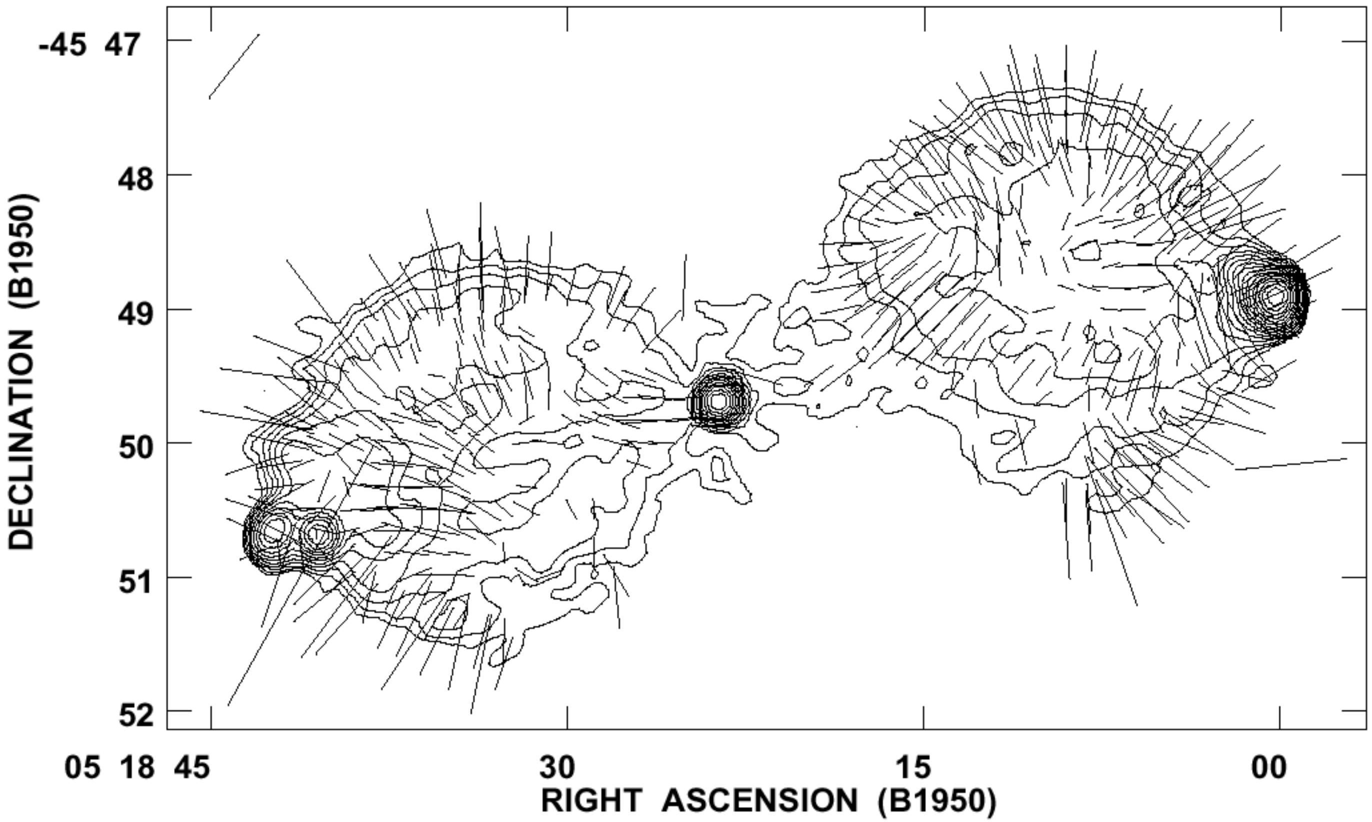
This model was used by Ford et al. (ApJ, **435**, L35) to estimate a black hole mass

$$M_{\mathrm{bh}} = (2.4 \pm 0.7) \times 10^9 \text{ solar masses}$$

6 Information gained from polarisation

6.1 Example from Pictor A

The following image is typical of the sort of image that radio astronomers produce for a polarised source.



Radio image of Pictor A showing the total intensity contours and the direction and magnitude of the polarisation. (Perley et al, A&A, **328**, 12)

The polarization structure in the lobes of Pictor A, at 6 cm wavelength and 1000 resolution. The contours are drawn at 0.4 to 72.4% of the peak brightness of 3.21 Jy/beam with a spacing ratio of $2^{1/2}$. The dashes show the direction of the observed E-vector, corrected for a foreground RM of 45 rad/ square metre. The projected B-vectors are normal to the dashes. The length of the dash is proportional to the degree of polarization, a length of 1 arcsecond indicates a polarization of 1%. The

This image of Pictor A shows a typical way of representing polarisation information. The contours represent the total intensity and the lines show the direction and magnitude of the linear polarisation.

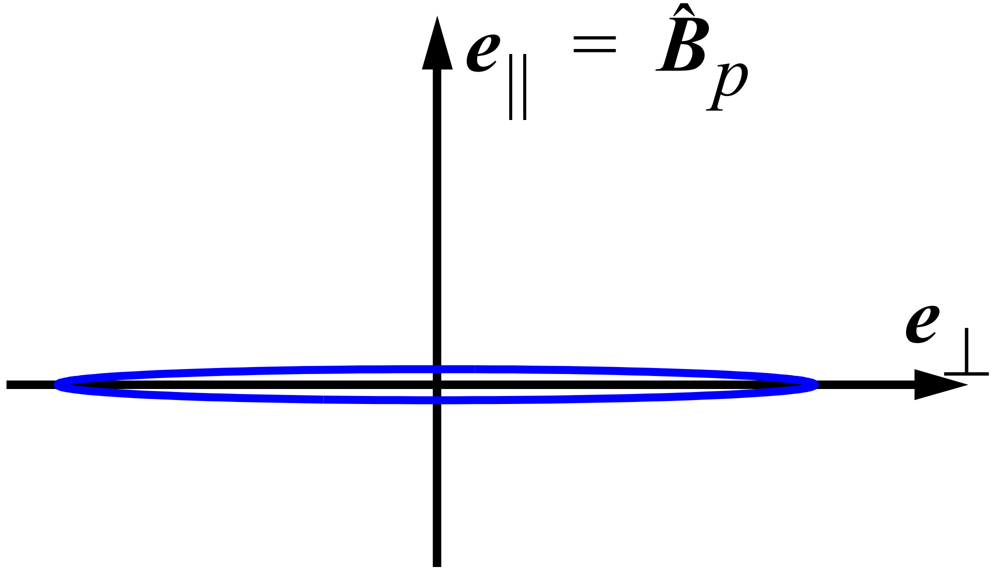
One of the motivations for understanding the theory for the polarisation of synchrotron radiation is to use the information gained from polarisation to infer properties of the source. We utilise the main property of synchrotron radiation:

$$\begin{array}{c}\text{Direction of polarisation} \\ \text{from emissivity}\end{array} \perp \begin{array}{c}\text{Projection of } \boldsymbol{B} \text{ onto the} \\ \text{plane of propagation}\end{array}$$

Let us look at polarised emission in some detail.

6.2 The Stokes parameters from a synchrotron emitting region

In the coordinate system shown we know that for synchrotron



radiation

$$j_I(\omega) \neq 0 \qquad j_Q(\omega) \neq 0$$

$$j_U(\omega) = 0 \qquad j_V(\omega) \approx 0$$

What do we take for the emissivities in a general coordinate system (e.g. Right ascension and declination). The best way to look at this is to go back and look at the power in a single pulse.

$$\frac{dW_{\alpha\beta}}{d\Omega d\omega} = \left(\frac{c\varepsilon_0}{\pi}\right) r^2 E_\alpha(\omega) E_\beta^*(\omega)$$

After convolving this expression with the particle distribution we obtain the emissivities in the various Stokes parameters so that in an arbitrary coordinate system:

$$\frac{1}{2}(j_I(\omega) + j_Q(\omega)) \propto E_x(\omega)E_x^*(\omega)$$

$$\frac{1}{2}(j_U(\omega) - ij_V(\omega)) \propto E_x(\omega)E_y^*(\omega)$$

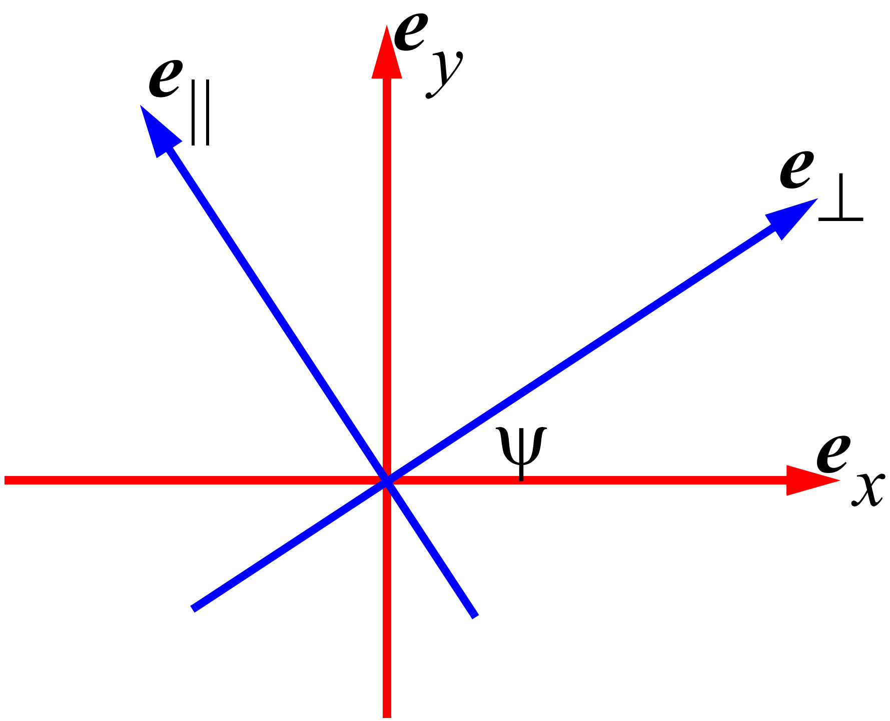
$$\frac{1}{2}(j_U(\omega) + ij_V(\omega)) \propto E_x^*(\omega)E_y(\omega)$$

$$\frac{1}{2}(j_I(\omega) - j_Q(\omega)) \propto E_y(\omega)E_y^*(\omega)$$

In the expressions for synchrotron emission, we have calculated the emissivity in a particular coordinate system, in which

$$j_I(\omega) \neq 0 \qquad j_Q(\omega) \neq 0 \qquad j_U(\omega) = 0 \qquad j_V(\omega) \approx 0$$

In order to calculate the emissivities in an arbitrary system we need to determine the transformation properties of $E_\alpha(\omega)E^*_\beta(\omega)$. We therefore consider an arbitrary coordinate system as shown:



The magnetic field coordinate system is related to the arbitrary system by:

$$\begin{bmatrix} \boldsymbol{e}_\perp \\ \boldsymbol{e}_{||} \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \boldsymbol{e}_x \\ \boldsymbol{e}_y \end{bmatrix}$$

with the components of the electric field related by:

$$\begin{bmatrix} E_\perp \\ E_{||} \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix}$$

Let

$$R_\psi = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \qquad R_\psi^t = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix}$$

The reverse transformation is

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = R_\psi^t \begin{bmatrix} E_\perp \\ E_{||} \end{bmatrix}$$

Now,

$$\begin{bmatrix} E_x E_x^* & E_x E_y^* \\ E_x^* E_y & E_y E_y^* \end{bmatrix} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} \begin{bmatrix} E_x^* & E_y^* \end{bmatrix} = R_\psi^t \begin{bmatrix} E_\perp \\ E_\parallel \end{bmatrix} \begin{bmatrix} E_\perp^* & E_\parallel^* \end{bmatrix} R_\psi$$

$$= R_\psi^t \begin{bmatrix} E_\perp E_\perp^* & E_\perp E_\parallel^* \\ E_\perp^* E_\parallel & E_\parallel E_\parallel^* \end{bmatrix} R_\psi$$

It just remains to multiply out the matrices. The result is:

$$\begin{bmatrix} E_x E_x^* & E_x E_y^* \\ E_x^* E_y & E_y E_y^* \end{bmatrix} =$$

$$\begin{bmatrix} \cos^2\psi E_\perp E_\perp^* + \sin^2\psi E_\parallel E_\parallel^* & \cos^2\psi E_\perp E_\parallel^* - \sin^2\psi E_\perp^* E_\parallel \\ -\sin\psi\cos\psi(E_\perp E_\parallel^* + E_\perp^* E_\parallel) & + \sin\psi\cos\psi(E_\perp E_\perp^* - E_\parallel E_\parallel^*) \\ \cos^2\psi E_\perp^* E_\parallel - \sin^2\psi E_\perp E_\parallel^* & \sin^2\psi E_\perp E_\perp^* + \cos^2\psi E_\parallel E_\parallel^* \\ + \sin\psi\cos\psi(E_\perp E_\perp^* - E_\parallel E_\parallel^*) & + \sin\psi\cos\psi(E_\perp E_\parallel^* + E_\perp^* E_\parallel) \end{bmatrix}$$

We then use

$$\frac{1}{2}[j_I(\omega) + j_Q(\omega)] \propto E_x(\omega)E_x^*(\omega)$$

$$\frac{1}{2}[j_U(\omega) - ij_V(\omega)] \propto E_x(\omega)E_y^*(\omega)$$

$$\frac{1}{2}[j_U(\omega) + ij_V(\omega)] \propto E_x^*(\omega)E_y(\omega)$$

$$\frac{1}{2}[j_I(\omega) - j_Q(\omega)] \propto E_y(\omega)E_y^*(\omega)$$

with primes to denote the emissivities in the magnetic field frame.

The result of combining the various terms is

$$\begin{bmatrix} j_I(\omega)+j_Q(\omega) & j_U(\omega)-ij_V(\omega) \\ j_U(\omega)+ij_V(\omega) & j_I(\omega)-j_Q(\omega) \end{bmatrix} =$$

$$\begin{bmatrix} j_I(\omega)' & \sin 2\psi j_Q'(\omega)+\cos 2\psi j_U'(\omega) \\ +\cos 2\psi j_Q'(\omega)-\sin 2\psi j_U'(\omega) & -ij_V'(\omega) \\ \sin 2\psi j_Q'(\omega)+\cos 2\psi j_U'(\omega) & j_I'(\omega) \\ +ij_V'(\omega) & -\cos 2\psi j_Q'(\omega)+\sin 2\psi j_U'(\omega) \end{bmatrix}$$

The transformation laws for the emissivities are therefore:

$$j_I(\omega) = j_I'(\omega)$$

$$j_Q(\omega) = \cos 2\psi j_Q'(\omega) - \sin 2\psi j_U'(\omega)$$

$$j_U(\omega) = \sin 2\psi j_Q'(\omega) + \cos 2\psi j_U'(\omega)$$

$$j_V(\omega) = j_V'(\omega)$$

In matrix form

$$\begin{bmatrix} j_I(\omega) \\ j_Q(\omega) \\ j_U(\omega) \\ j_V(\omega) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\psi & -\sin 2\psi & 0 \\ 0 & \sin 2\psi & \cos 2\psi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} j_I'(\omega) \\ j_Q'(\omega) \\ j_U'(\omega) \\ j_V'(\omega) \end{bmatrix}$$

Note that the transformation for Q and U involves a rotation through 2ψ.

6.3 The special case of synchrotron emission

We know that for synchrotron emission

$$j_{\omega}^{U'} = 0$$

Hence,

$$j_Q(\omega) = \cos 2\psi j_Q'(\omega) - \sin 2\psi j_U'(\omega) = \cos 2\psi j_Q'(\omega)$$

$$j_U(\omega) = \sin 2\psi j_Q'(\omega) + \cos 2\psi j_U'(\omega) = \sin 2\psi j_Q'(\omega)$$

For optically thin emission:

$$I_Q(\omega) = \int j_Q(\omega) ds = \int \cos 2\psi j_Q'(\omega) ds$$

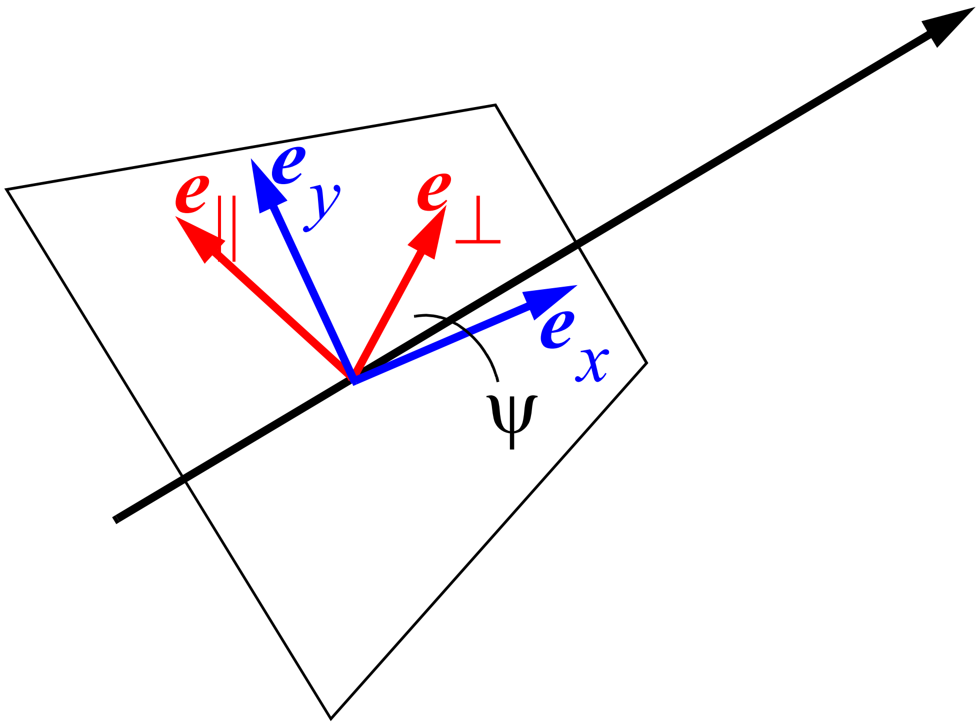
$$I_U(\omega) = \int j_U(\omega) ds = \int \sin 2\psi j_Q'(\omega) ds$$

where $j_Q'(\omega)$ is, for a power-law distribution, the polarised emissivity (See Synchrotron Radiation II)

$$j_Q'(\omega) = \frac{a+1}{a+7/3} j_I(\omega)$$

$$= \frac{3^{a/2}}{32\pi^3} \frac{\Gamma\left(\frac{a}{4}+\frac{19}{12}\right)\Gamma\left(\frac{a}{4}-\frac{1}{12}\right)}{a+7/3}$$

$$\times \left(\frac{e^2}{\varepsilon_0 c}\right) K(\Omega_0 \sin\vartheta)\left(\frac{\omega}{\Omega_0 \sin\vartheta}\right)^{-\frac{(a-1)}{2}}$$



When the angle ψ between the projected magnetic field and the adopted coordinate system is constant, then:

$$I_Q(\omega) = \int \cos 2\psi j_Q'(\omega) ds = \cos 2\psi \left[\frac{a+1}{a+7/3}\right] I(\omega)$$

$$I_U(\omega) = \int \sin 2\psi j_Q'(\omega) ds = \sin 2\psi \left[\frac{a+1}{a+7/3}\right] I(\omega)$$

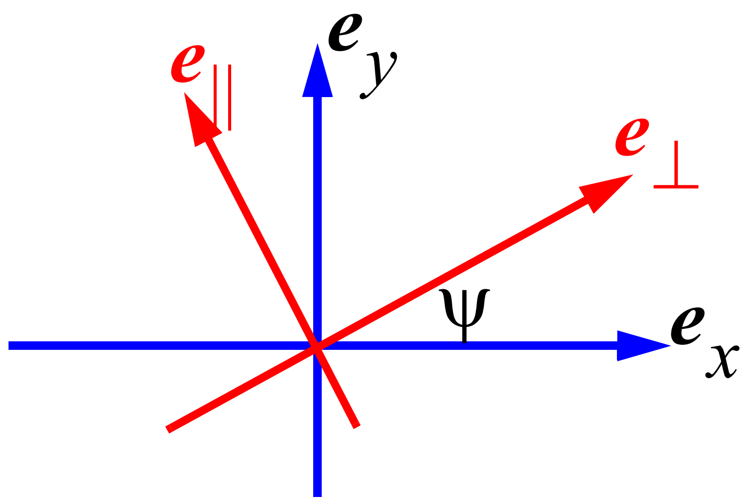
The degree of polarisation can be determined from:

$$[I_Q(\omega)]^2 + [I_U(\omega)]^2 = \left[\frac{a+1}{a+7/3}\right]^2 [I(\omega)]^2$$

$$\Rightarrow p = \frac{([I_Q(\omega)]^2 + [I_U(\omega)]^2)^{1/2}}{I(\omega)} = \left[\frac{a+1}{a+7/3}\right]$$

The angle ψ is given by:

$$\tan 2\psi = \frac{I_U(\omega)}{I_Q(\omega)}$$



The direction determined from ψ gives the direction of the axis perpendicular to the magnetic field. The magnetic field.

If the angle ψ varies through the source, then the degree of polarisation is less than the maximum value given above.

Also the direction of the magnetic field is an emission weighted direction. To see how this occurs consider the following expressions for $I_Q(\omega)$ and $I_U(\omega)$.

$$I_Q(\omega) = \int \cos 2\psi j_Q'(\omega) ds = \int \cos 2\psi(s) \left[\frac{a+1}{a+7/3}\right] j_I(\omega) ds$$

$$= \left[\frac{a+1}{a+7/3}\right] I(\omega) \frac{\int \cos 2\psi(s) j_I(\omega) ds}{\int j_I(\omega) ds}$$

$$I_U(\omega) = \int \sin 2\psi j_Q'(\omega) ds = \int \sin 2\psi(s) \left[\frac{a+1}{a+7/3}\right] j_I(\omega) ds$$

$$= \left[\frac{a+1}{a+7/3}\right] I(\omega) \frac{\int \sin 2\psi(s) j_I(\omega) ds}{\int j_I(\omega) ds}$$

Thus,

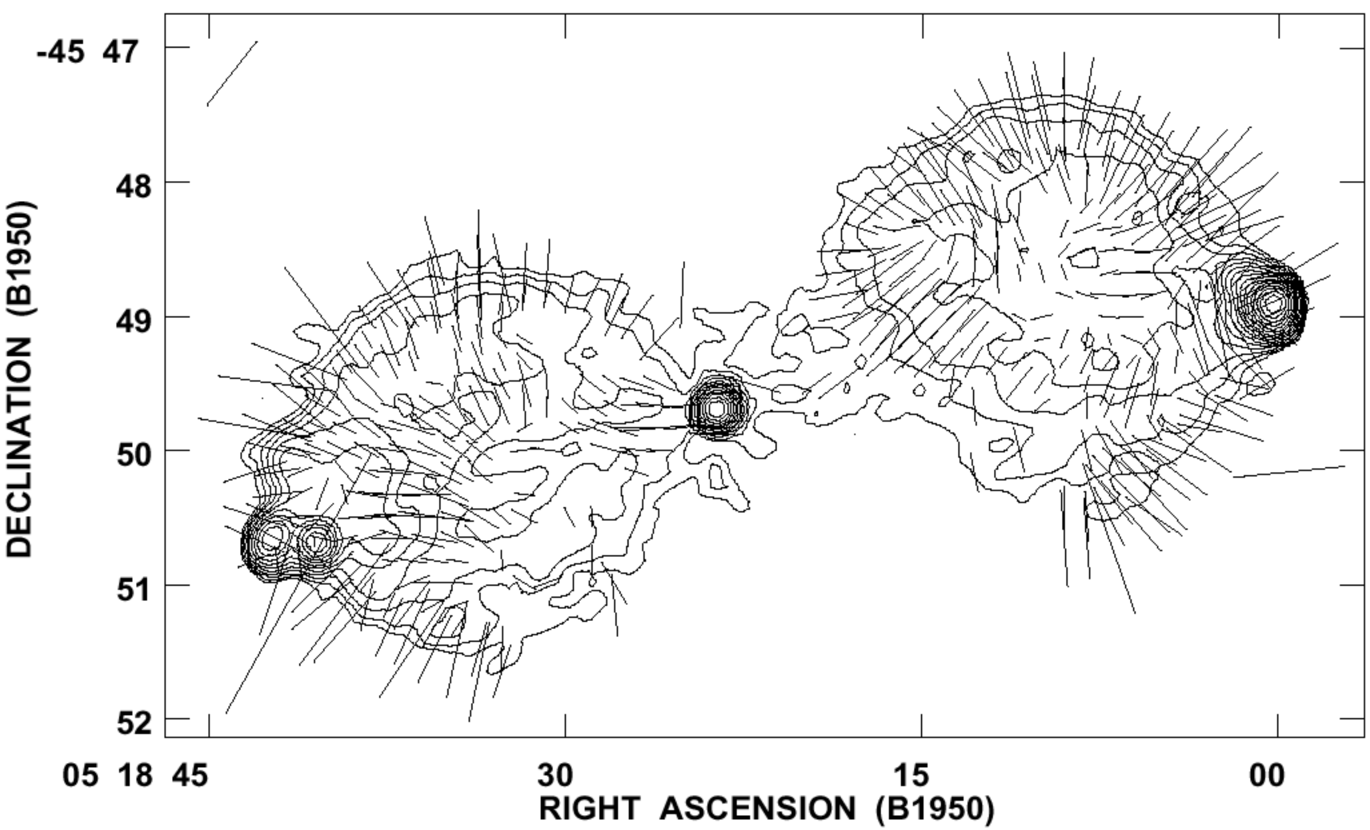
$$\frac{I_Q(\omega)}{I(\omega)} = \frac{a+1}{a+7/3}\langle\cos 2\psi\rangle$$

$$\frac{I_U(\omega)}{I(\omega)} = \frac{a+1}{a+7/3}\langle\sin 2\psi\rangle$$

where the <> indicate an emission-weighted mean.

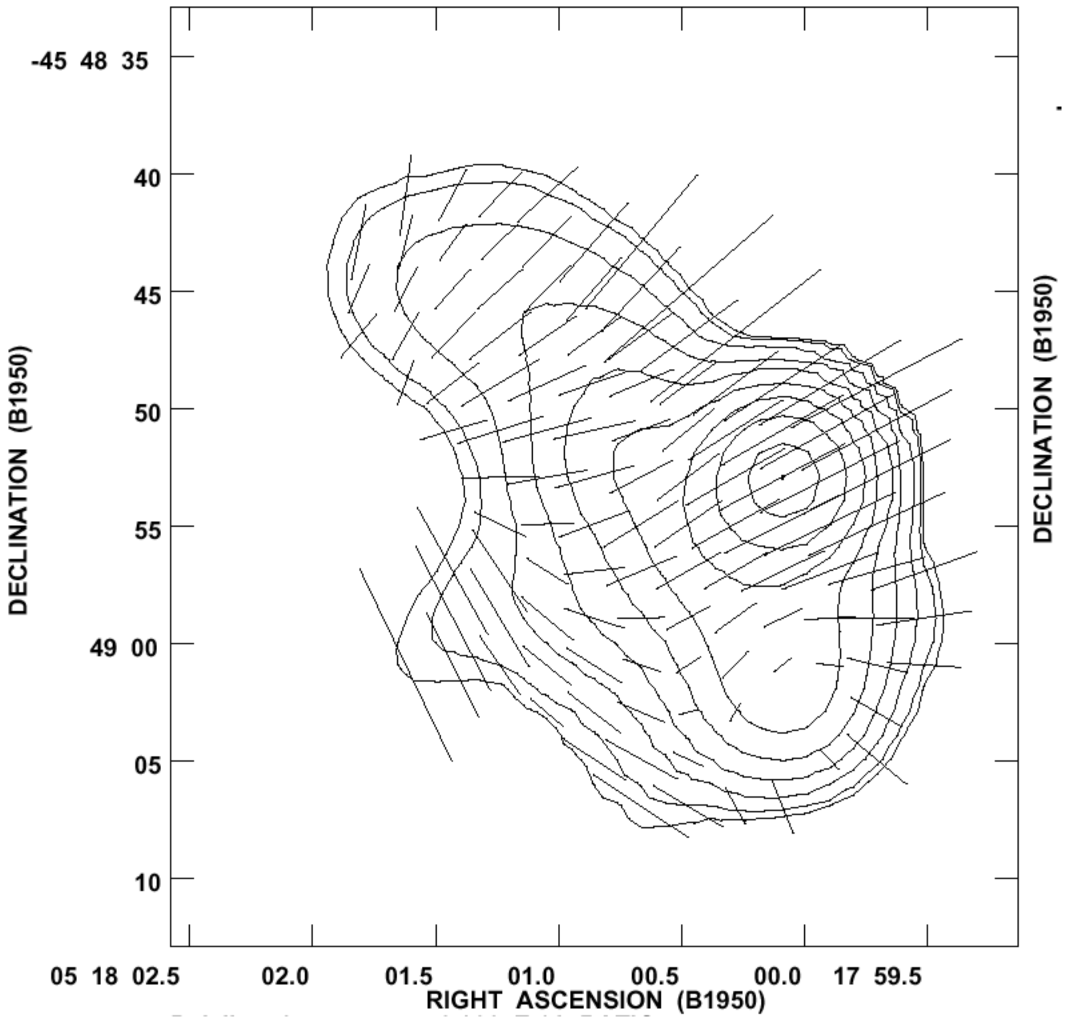
We define the intensity weighted direction of the magnetically oriented coordinates by:

$$\tan 2\psi = \frac{I_U(\omega)}{I_Q(\omega)}$$



The implied direction of the magnetic field in this image is perpendicular to the straight lines. That is, the magnetic field has a circumferential direction with respect to the plasma in the lobe.

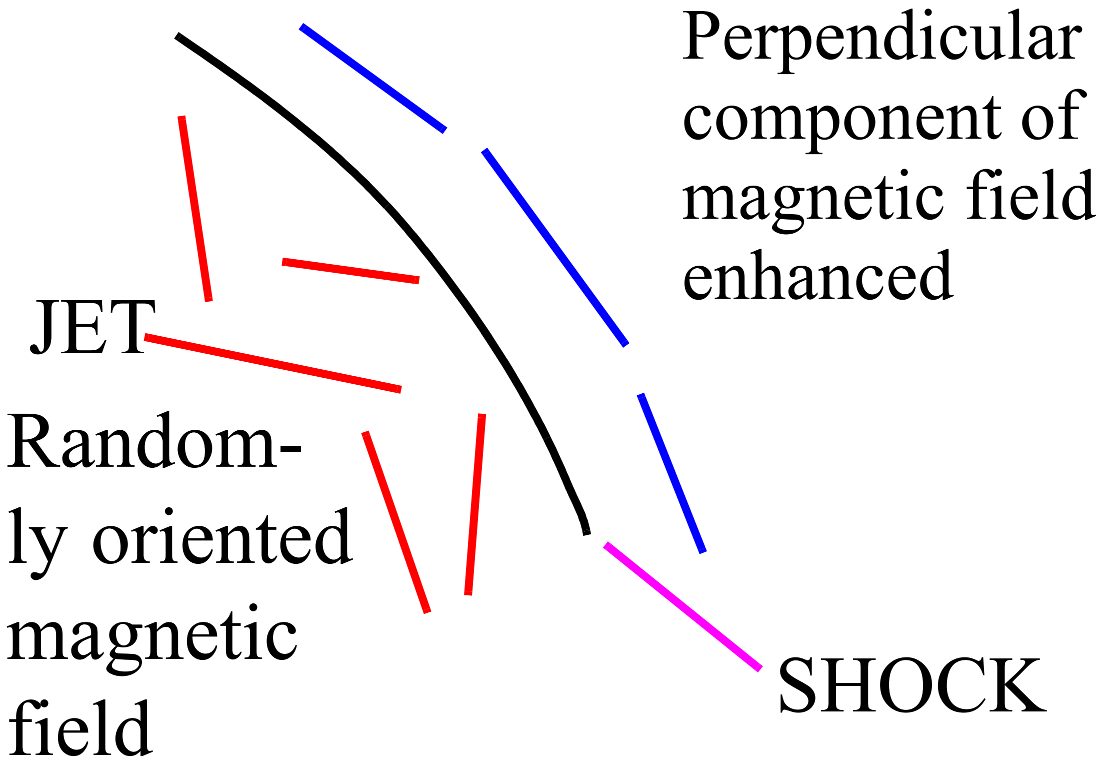
6.4 Polarisation of hot spots



Polarization of the western hot spot of Pictor A, at 3.6 cm wavelength with 400 resolution (left), and at 0.77 by 0.17 resolution (right). The lower resolution map shows the general features of this region, and is contoured at 0.391% and then with a spacing of a factor of 2 between 0.552 and 70.71% of the maximum intensity of 1.55 Jy/beam. The dashed lines again indicate the plane of the electric vector. Their lengths are proportional to the degree of polarization, with 100 equal to 6.67%.

The western hot spot of Pictor A

The polarisation of the hot spot in Pictor A reveals magnetic field structure that is consistent with that produced by a shock wave.



At the terminal shock of the jet, the component of the magnetic field perpendicular to the shock is amplified, whilst leaving the parallel component unchanged. This lines the field up with the shock as shown