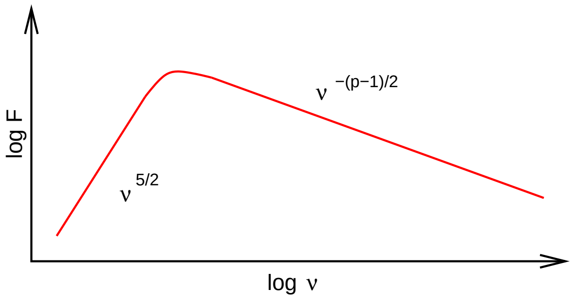
Synchrotron Self-Absorption



after Shu, Fig. 18.6

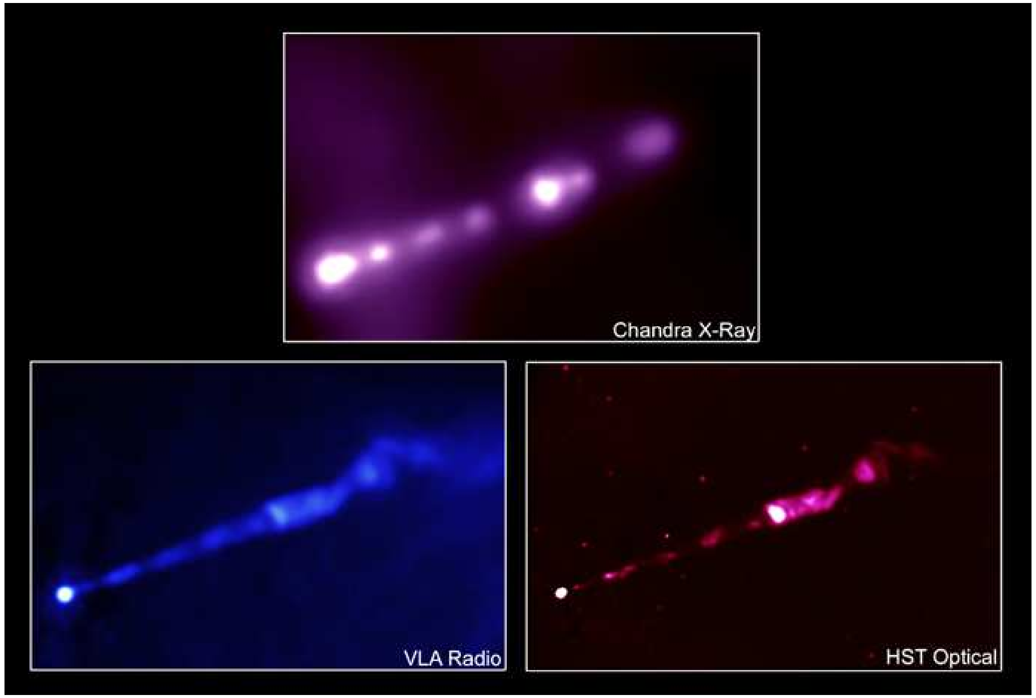
At low ν: synchrotron emitting electrons can absorb synchrotron photons: synchrotron self-absorption.

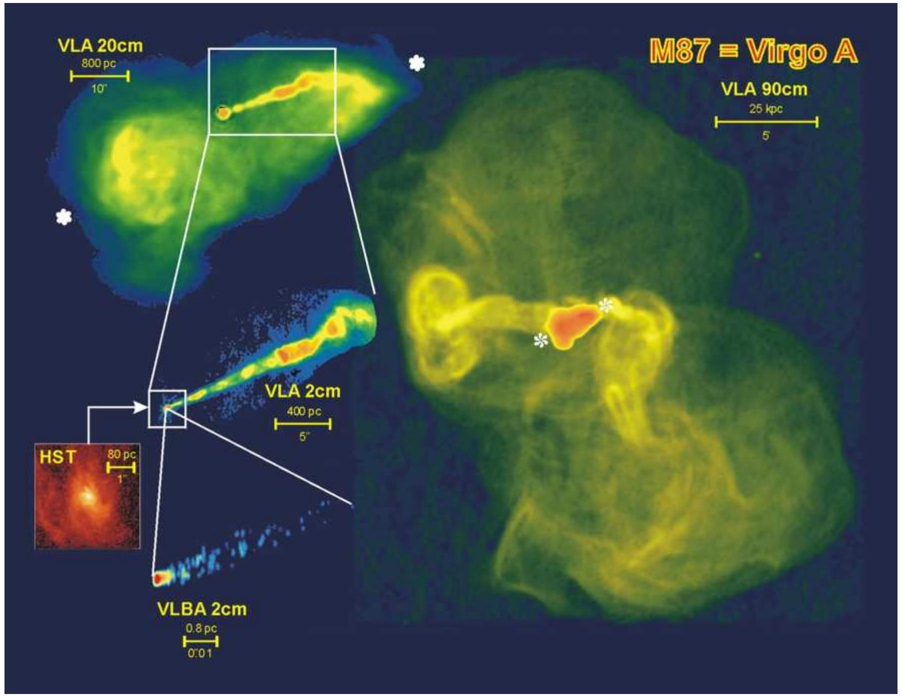
For a power law electron distribution $\propto E^{-p}$, total spectral shape is:

For low frequencies: $P_\nu \propto B^{-1/2}\nu^{5/2}$ (independent of p!)

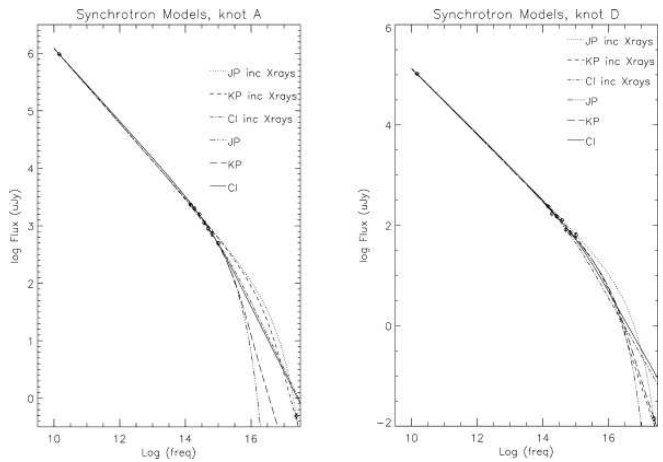
For large frequencies: $P_\nu \propto \nu^{-(p-1)/2}$

At very high frequencies, additional break due to electron energy losses. The transition frequency can be used to measure the strength of the B-Field. See text-books on radio astronomy.





Jet Spectrum

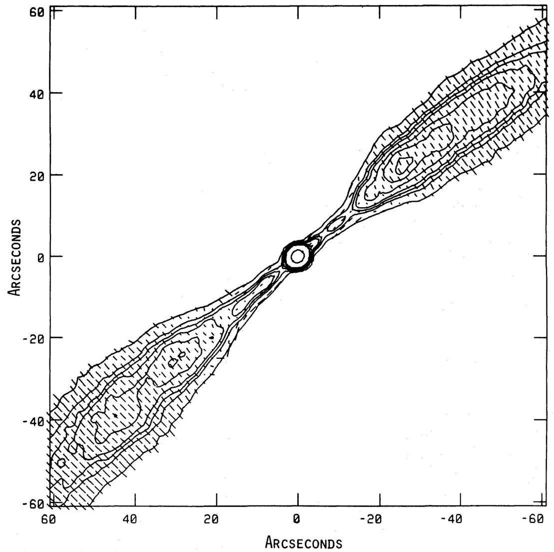


(M87; Perlman et al., 2002)

Spectral shape of jet emission is a power law $\Longrightarrow$ synchrotron radiation

Typical power law index: $\alpha \sim 0.65$ between radio and optical.

Jet Polarization



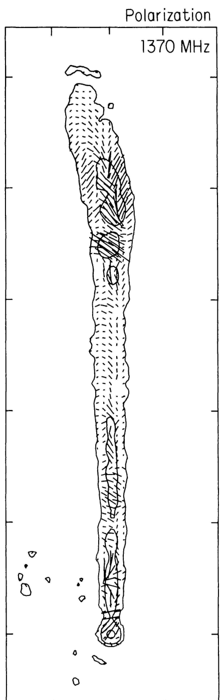
polarization in two-sided jet sources (FR 1): up to 40%

B-field orientation:

- close to core: $B \parallel$ jet axis
- away from core ($\sim$10% jet length): $B \perp$ jet axis

B-field can change orientation again in knots

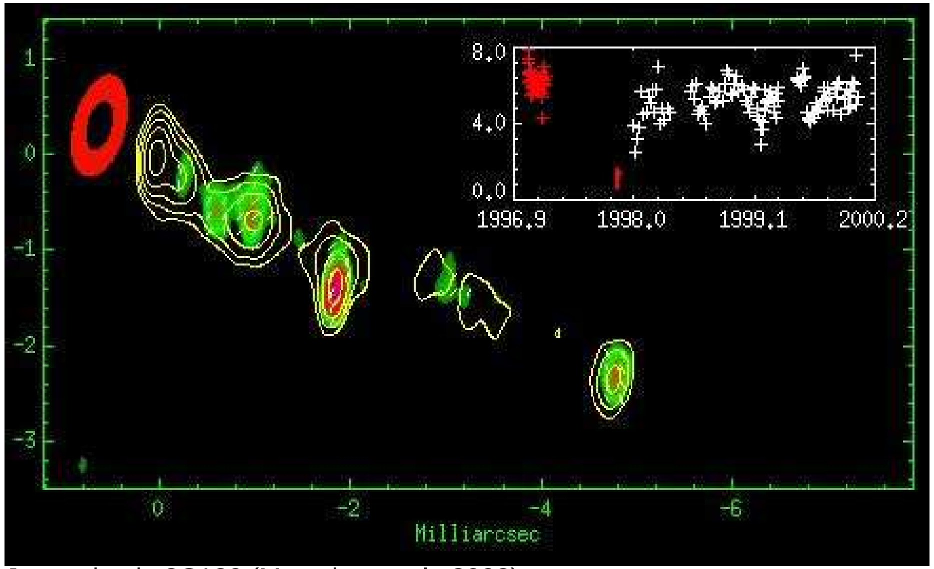
(B-field configuration in IC 4296; Killeen, Bicknell & Ekers, 1986, Fig. 25b)



polarization in one-sided jet sources (FR 2): similar to FR 1, i.e., 40% and higher

B-field orientation in FR 2: parallel to jet axis throughout the jet

(E-field configuration in NGC 6251, note: B-field is perpendicular to E-field!; Perley, Bridle & Willis, 1984, Fig. 17)

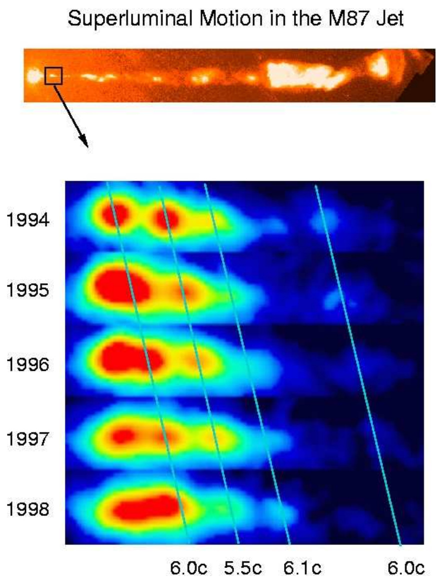


Jet motion in 3C120 (Marscher et al., 2002)

3C120: Sy 1, $M_{\mathrm{BH}} = 3 \times 10^7\,M_\odot$ from reverberation mapping

MOVIE TIME: `jetmovies/3c120rx.avi`

Superluminal Motion, II



3C120: Apparent speed of jet: $\sim 5c$

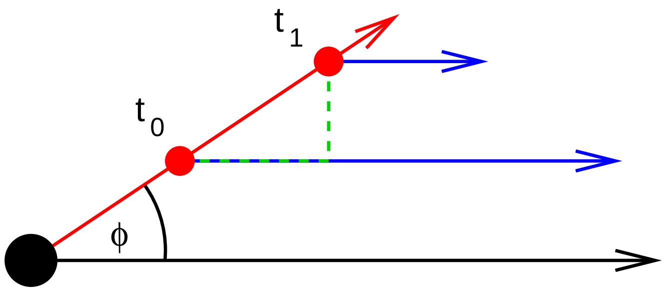
M87: Apparent speed of jet: $\sim 6c$

Superluminal motion: The apparent velocities measured in many AGN jets are $v > c$.

First discovered in 1971 in 3C273.

Biretta/STScI

Superluminal Motion, III



Consider blob moving towards us with speed v and angle ϕ with respect to line of sight, emitting light signals at t_0 and $t_1 = t_0 + \Delta t_e$

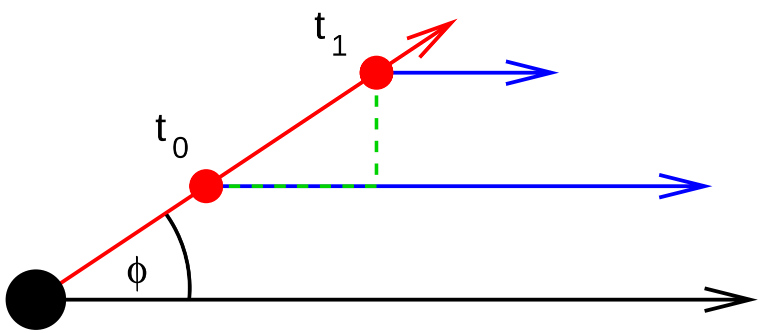
Light travel time: Observer sees signals separated by

$$\Delta t_o = \Delta t_e - \Delta t_e \frac{v}{c}\cos\phi = \left(1 - \frac{v}{c}\cos\phi\right)\Delta t_e \tag{10.36}$$

Observed distance traveled in plane of sky:

$$\Delta \ell_\perp = v \Delta t_e \sin\phi \tag{10.37}$$

Superluminal Motion, IV

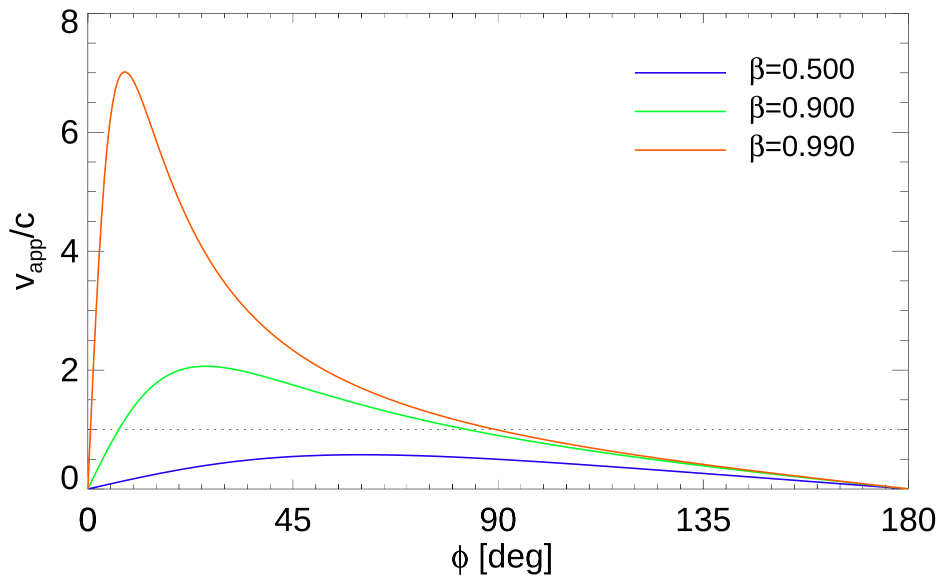


Apparent velocity deduced from observations:

$$v_{app} = \frac{\Delta \ell_\perp}{\Delta t_o} = \frac{v \Delta t_e \sin\phi}{\left(1 - \frac{v}{c}\cos\phi\right)\Delta t_e} = \frac{v\sin\phi}{\left(1 - \frac{v}{c}\cos\phi\right)} \tag{10.38}$$

$\Longrightarrow$ For v/c large and ϕ small: $v_{app} > c$

Superluminal Motion, V



A relativistic invariant, I

So, if ϕ is known, we can determine real speed.

In order to determine ϕ, we have to make use of an useful relativistic invariant:

$$\frac{I_{nu}}{\nu^3} = \text{const.} \tag{10.39}$$

in all frames of reference.

Proof: The number of photons with momentum in interval $\boldsymbol{p}, \boldsymbol{p} + d^3$ is given by

$$dN = 2n\left(\frac{V\,d^3p}{h^3}\right) \tag{10.40}$$

where n: photon number, $V\,d^3p$: phase volume, h^3: volume of phase space cell.

$\Longrightarrow$ Energy flowing through volume element $d^3x = dA(c\,dt)$:

$$dE = h\nu\,dN = 2nh\nu\,dA(c\,dt)\left(\frac{d^3p}{h^3}\right) \tag{10.41}$$

A relativistic invariant, II

Since $p = h\nu/c$:

$$d^3p = p^2\,dp\,d\Omega = \left(\frac{h\nu}{c}\right)^2 h\frac{d\nu}{c}\,d\Omega = \left(\frac{h}{c}\right)^3 \nu^2\,d\nu\,d\Omega \qquad (10.42)$$

Therefore

$$dE = 2nh\nu c\,dA\,dt\left(\frac{d^3p}{h^3}\right) = \frac{2h\nu^3}{c^2}n\,dA\,dt\,d\Omega\,d\nu \qquad (10.43)$$

or

$$\frac{dE}{dA\,dt\,d\Omega\,d\nu} = I = \frac{2h\nu^3}{c^2}n \qquad (10.44)$$

Therefore

$$\frac{I}{\nu^3} = \frac{2h}{c^2}n \qquad (10.45)$$

and since n is just a number, I/ν^3 is Lorentz-invariant.

Relativistic Aberration

Relativistic invariance: $I_\nu/\nu^3 = \text{const.}$ where I_ν is the intensity.

Therefore, observed intensity of a moving blob:

$$\frac{I(\nu_{\text{obs}})}{\nu^3_{\text{obs}}} = \frac{I(\nu_{\text{em}})}{\nu^3_{\text{em}}} \qquad (10.46)$$

Because of the relativistic Doppler effect:

$$\nu_{\text{obs}} = \frac{\nu_{\text{em}}}{\gamma(1-\beta\cos\phi)} \qquad (10.47)$$

($\beta = v/c$) and thus

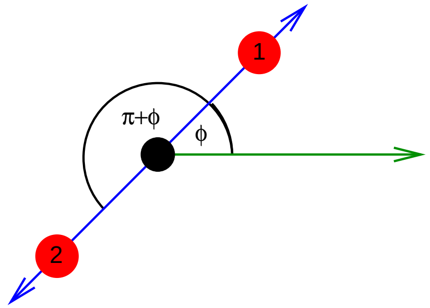
$$I(\nu_{\text{obs}}) = \nu^3_{\text{obs}}\frac{I(\nu_{\text{em}})}{\nu^3_{\text{em}}} = \frac{I(\nu_{\text{em}})}{(\gamma(1-\beta\cos\phi))^3} \qquad (10.48)$$

Specifically, for a blob with a power law spectrum:

$$I(\nu_{\text{obs}}) = \frac{A\nu_{\text{em}}^{-\alpha}}{(\gamma(1-\beta\cos\phi))^3} = \frac{A\,(\gamma(1-\beta\cos\phi))^{-\alpha}\,\nu_{\text{obs}}^{-\alpha}}{(\gamma(1-\beta\cos\phi))^3} = \frac{A\nu_{\text{obs}}^{-\alpha}}{(\gamma(1-\beta\cos\phi))^{3+\alpha}} \qquad (10.49)$$

(where A is the normalization constant of the power law).

Relativistic Aberration



Now take a source emitting blobs symmetrically in two directions.

From Eq. (10.49) the ratio of fluxes from the blobs is

$$\frac{F_1}{F_2} = \left(\frac{1+\beta\cos\phi}{1-\beta\cos\phi}\right)^{3+\alpha} \qquad (10.50)$$

Radiation from a blob moving towards observer is strongly boosted.

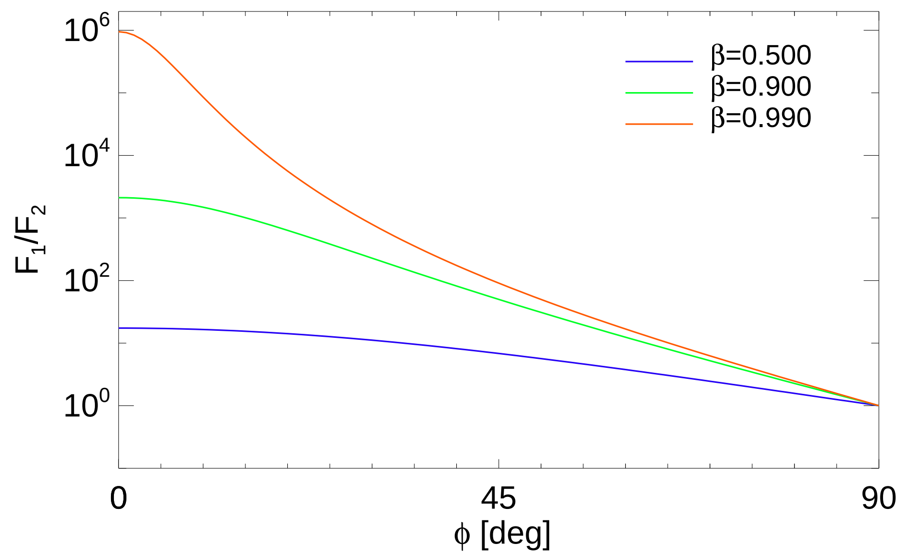
Jet can be expressed as a series of blobs. But the number of blobs observed scales as $(\gamma(1-v\cos\phi))^{-1}$, such that for jets:

$$\frac{F_1}{F_2} = \left(\frac{1+\beta\cos\phi}{1-\beta\cos\phi}\right)^{2+\alpha} \qquad (10.51)$$

One sidedness of jets is a relativistic effect.

From measuring F_1/F_2, we can in principle determine ϕ.

Relativistic Aberration

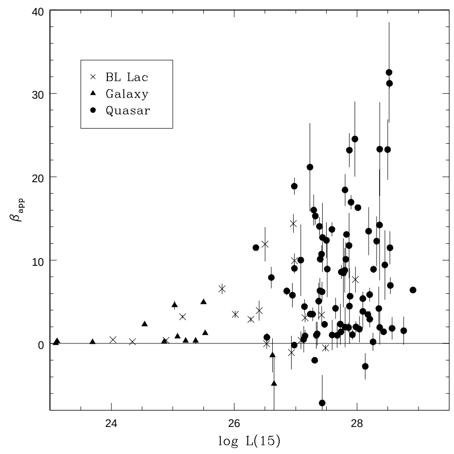


Jet Statistics, I

Kellermann et al. (2004): Largest survey of jets performed so far.

- Wavelength 2 cm (15 GHz)
- All AGN with flat spectra ($\alpha < 0.5$ for $S_\nu \propto \nu^{-\alpha}$) and fluxes above 1.5 Jy at 15 GHz
- Survey started in 1994, ended in 2001, typically 7 observations per source
- 208 features in 110 AGN (Seyfert, BL Lac, Quasars).
- movies and images at `http://www.nrao.edu/2cmsurvey` (recommended!)

Jet Statistics, III



(Kellermann et al., 2004, Fig. 6)

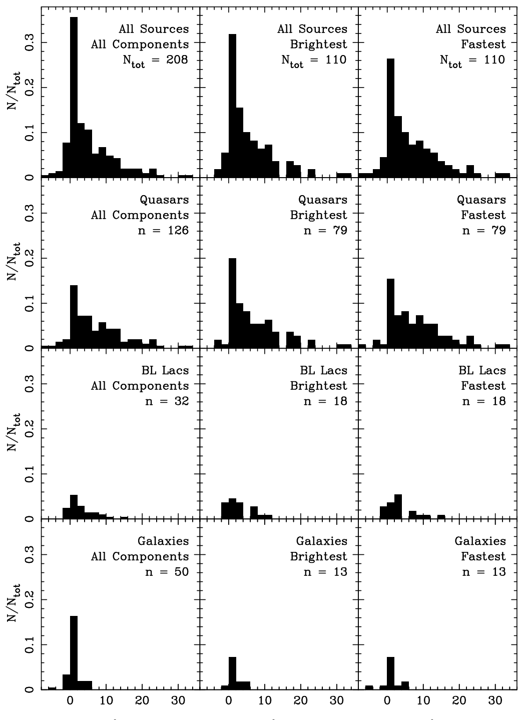
Relation between β and luminosity: larger scatter at higher L

This does *not* mean that lower L sources have lower speeds, since observational effects also play a role:

sample is flux limited

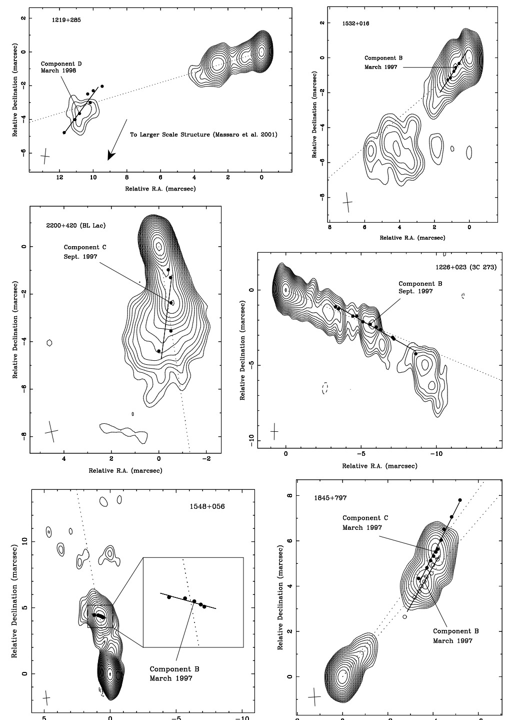
$\Longrightarrow$ faintest sources are close, and probably represent the most normal sources

$\Longrightarrow$ probability that high Lorentz factor jets point in our direction grows with sampled volume, so perhaps the distribution is a selection effect.



Distribution of observed velocities:

- apparent velocity range: $\beta \leq 15$
- Quasars: tail up to $\beta \sim 34$
- others: mainly $\beta \lesssim 6$

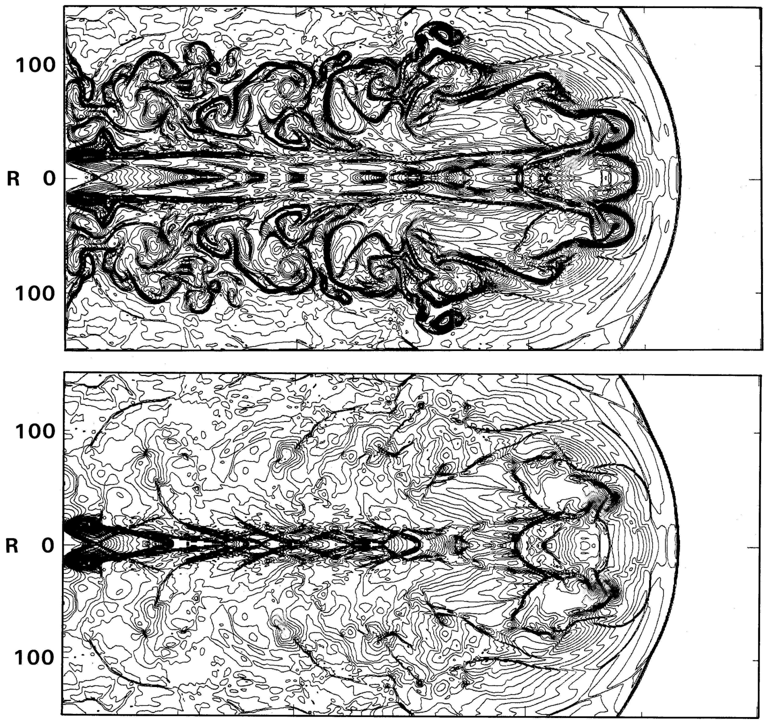


In many sources, bent trajectories are observed, which do not follow jet axis

$\Longrightarrow$ do blobs follow pre-existing channel?

$\Longrightarrow$ nonballistic motion?

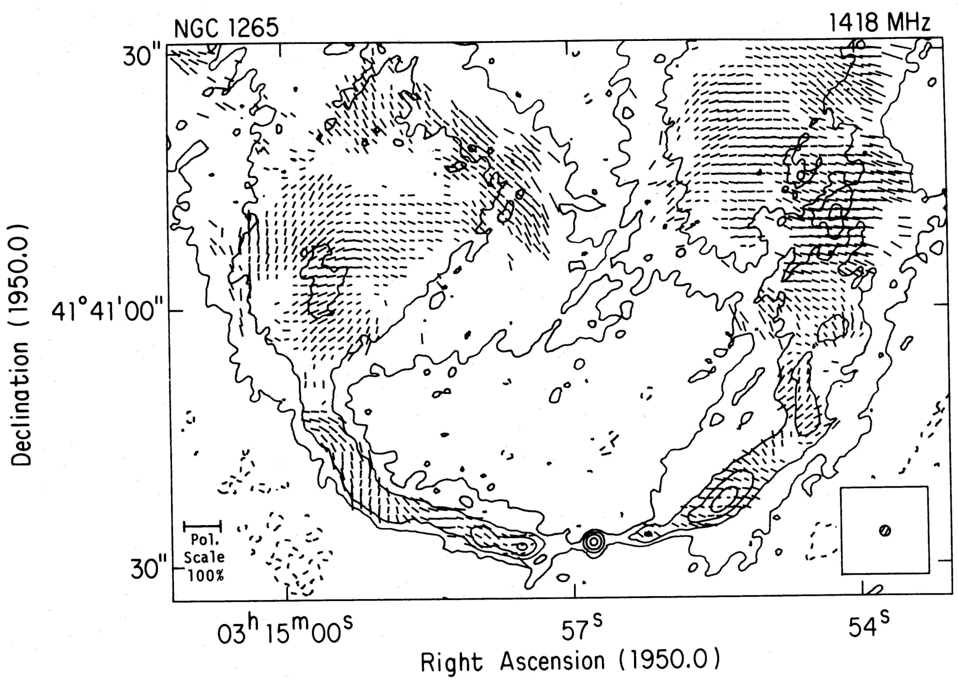
$\Longrightarrow$ difference between bulk motion and pattern motion?



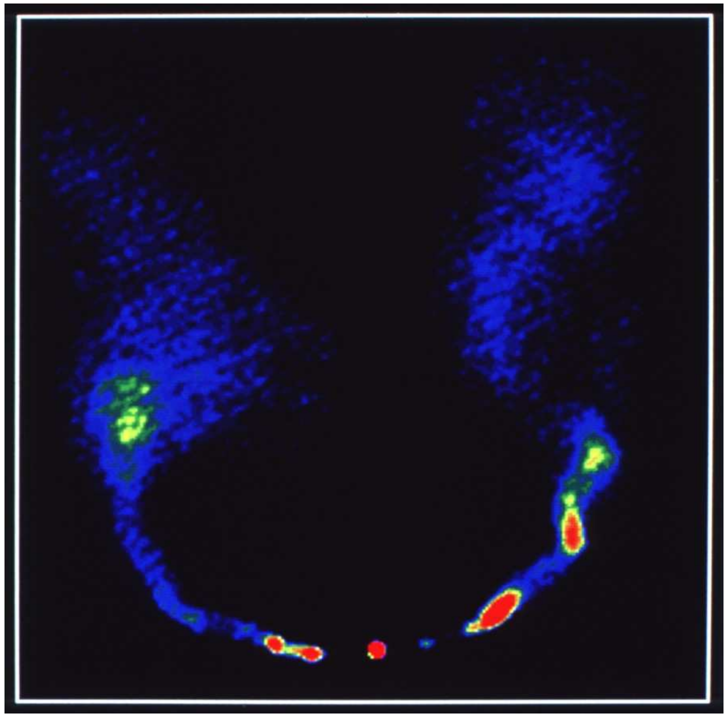
Jet propagation is very hydrodynamics: generally solved numerically

Numerical simulation of a Mach=6 jet (Top: density, bottom: pressure Lind et al., 1989).

Turbulent structure due to Kelvin-Helmholtz instability (hydrodynamical instability in shear flows)

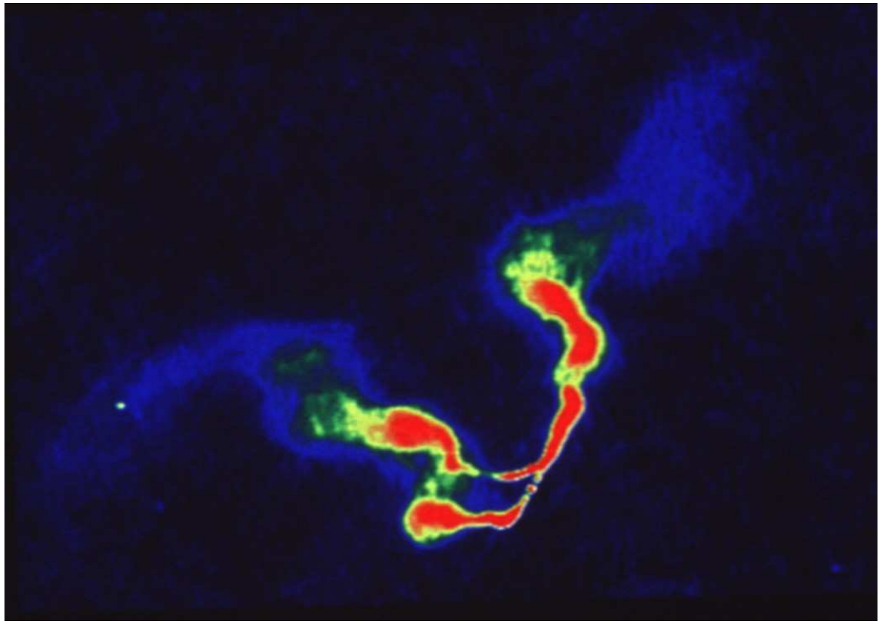


E-field structure of NGC 1265 (O'dea & Owen, 1986)



NGC 1265: radio galaxy in Perseus cluster, moving with 2000 km s^{-1} through intergalactic medium.

(NRAO/AUI; O'dea & Owen, 1986)



(NRAO/AUI/Owen et al.)

3C75 in Abell 400 at $\lambda = 20$ cm: twin radio jets from double core.

Jets and IGM, IV

Radio lobe physics:

Total energy content of lobe for a power law distribution of electrons, $n(E) = n_0 E^{-p}$:

$$U_\mathrm{e} = V \int_{E_1}^{E_2} n(E)\, E\, dE = \frac{V n_0}{2-p}\left(E_2^{2-p} - E_1^{2-p}\right) \qquad (10.52)$$

Integrating over the synchrotron spectrum (Eq. (10.26)) gives the total synchrotron luminosity produced by this electron population:

$$L = \frac{4\sigma_\mathrm{T} U_B V n_0}{3 m_\mathrm{e}^2 c^4}\left(\frac{E_2^{3-p} - E_1^{3-p}}{3-p}\right) \qquad (10.53)$$

Using the characteristic frequency

$$\omega_\mathrm{c} = \gamma^2 \omega_\mathrm{L} = \frac{eB}{m_\mathrm{e} c}\left(\frac{E}{m_\mathrm{e} c^2}\right)^2 \qquad (10.18)$$

E_1 and E_2 can be expressed in terms of the frequency band over which the power law is observed, ν_1, ν_2. After some messy calculation one obtains:

$$\frac{U_\mathrm{e}}{L} = \frac{A}{B^{3/2}} \qquad (10.54)$$

where A is some constant.

Jets and IGM, V

The total kinetic energy in particles is

$$U_\mathrm{particles} = aU_\mathrm{e} = aAB^{-3/2}L \qquad (10.55)$$

where $a > 1$ (since there are other particles than electrons in the lobe).

Therefore the total energy of the radio lobe is

$$U_\mathrm{tot} = U_\mathrm{particles} + U_B = \frac{aAL}{B^{3/2}} + \frac{VB^2}{8\pi} \qquad (10.56)$$

The minimum of U_tot is reached for

$$B_\mathrm{min} = \left(\frac{6\pi aAL}{V}\right)^{2/7} \qquad (10.57)$$

while the equipartition B-field, for which $U_\mathrm{particles} = U_B$ is

$$B_\mathrm{eq} = \left(\frac{8\pi aAL}{V}\right)^{2/7} \qquad (10.58)$$

Since the total energy for equipartition is $1.01 U_\mathrm{min}$, one often assumes synchrotron sources are in equipartition.

First noticed by Burbidge (1959).

Jets and IGM, VI

Radio lobes:

- Typical luminosity is a few times $L = 10^{44}\,\mathrm{erg\,s^{-1}}$
- Typical B-fields are $\sim 10^{-4}\,\mathrm{G}$

Assuming equipartition: typical energy content of a radio lobe: $E \sim 10^{60}\,\mathrm{erg}$

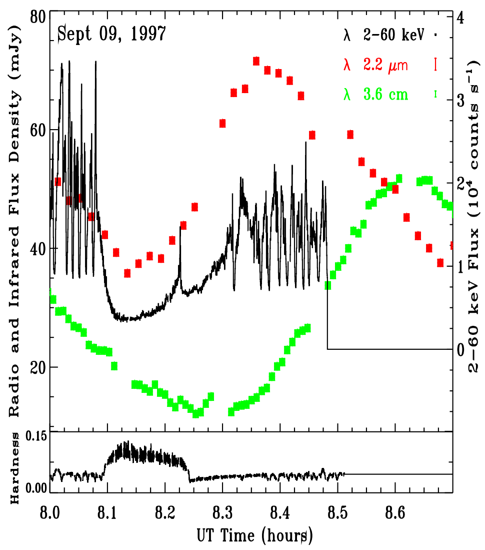
corresponding to 10^7 supernovae

$\Longrightarrow$ lobe lifetime $t \sim E/L \sim 10^8\,\mathrm{yr}$

$\Longrightarrow$ jets and lobes are rather long lived phenomena

Equipartition holds only approximately true for jets and lobes (see, e.g., Heinz & Begelman 1997).

Jet Formation



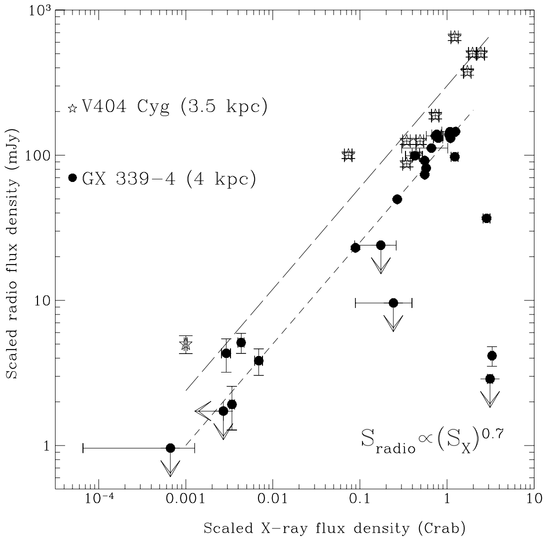
Dynamics of jet formation are better studied in Galactic black holes with jets ("microquasars") because of shorter timescales.

Find clear X-ray–radio correlation (similar also seen in some AGN such as 3C120)

$\Longrightarrow$ "universal disk-jet-connection"

(GRS 1915+105; Mirabel et al., 1998)

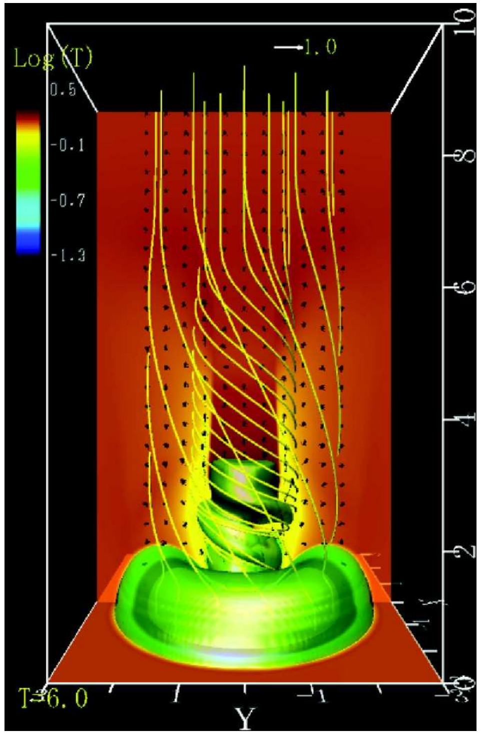
Jet Formation



X-ray binaries: $S_{\text{radio}} \propto S_X^{0.7}$

$\Longrightarrow$ Radio and X-ray fluxes are correlated: evidence for interaction between disk and jet!

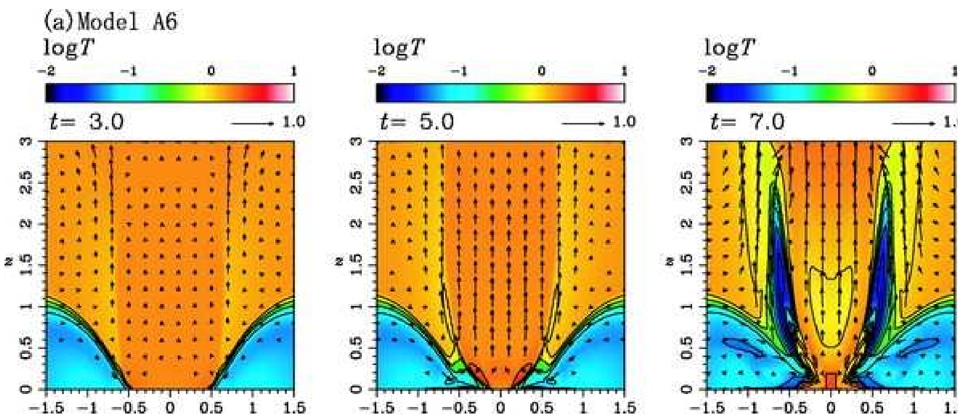
(Gallo, Fender & Pooley, 2003)



Temperature profile and B-field configuration of a MHD-jet

(Kigure & Shibata, 2005, Fig. 6)

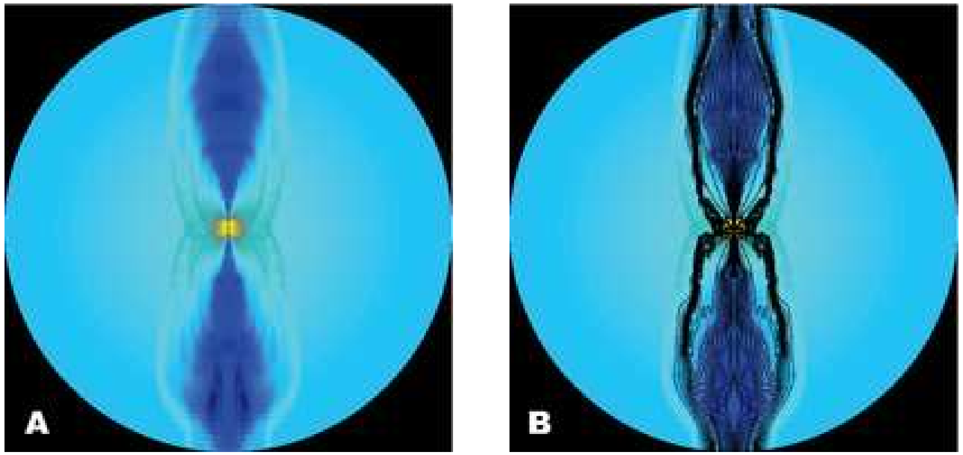
Jet Formation



Evolution of a newly launched jet (Kigure & Shibata, 2005)

To study jet confinement and propagation: use magnetohydrodynamical simulations

Jet Formation



(McKinney, 2006, Fig. 1)

$\log\rho$ (left) and $\log\rho$ and B for a jet launched via a disk. Outer radius is $10^4 GM/c^2$.