Fanaroff-Riley Classes

- **Morphological classification**
- **FRI**: brightest close to galaxy nucleus
- **FRII**: brightest at outer extremities

Classification correlates strongly with luminosity (also with galactic environment).

Local space densities:
- FRI: $3 \times 10^{-4}$ Mpc$^{-3}$
- FRII: $1 \times 10^{-6}$ Mpc$^{-3}$
  (cf. Normal spirals: $3 \times 10^{-2}$ Mpc$^{-3}$)

**Ingredients (FRII) - Cygnus A, the nearest very powerful radio source**

- External pressure: $10^{-11}$ Pa, $c_s \sim 1000$ km s$^{-1}$
- Jet momentum flux: $10^{30}$ N
- Hot-spot pressure: $2 \times 10^{-10}$ Pa; $B \sim 20$ nT (inverse Compton + synchrotron)
- Advance speed: $3000$ km s$^{-1}$ (0.01c), $M \sim 3$ (ram pressure) => supersonic forward expansion (N.B. uncertainties in ram-pressure and spectral 'ages').
- Age: $40$ Myr, total energy supply: $3 \times 10^{53}$ J
- Compare minimum energy in the lobes from synchrotron emission: $10^{53}$ J

**Cygnus A: some numbers**

- External pressure: $10^{-11}$ to $10^{-10}$ Pa
- Jet energy flux: $10^{37}$ W; momentum flux: $3 \times 10^{28}$ N
- Jet flow velocities: $0.9c$ at 1 kpc, $0.2c$ at 10 kpc.
- Internal jet density: $10^{-27}$ kg m$^{-3}$

**More ingredients (FRI)**

- External pressure: $3 \times 10^{-12}$ to $10^{-10}$ Pa
- Jet energy flux: $10^{37}$ W; momentum flux: $3 \times 10^{28}$ N
- Jet flow velocities: $0.9c$ at 1 kpc, $0.2c$ at 10 kpc.
- Internal jet density: $10^{-27}$ kg m$^{-3}$
Same ingredients; different recipe (FRI)

Images of M87

Ingredients

- Central component or core (actually the optically-thick, parsec-scale jet base)
- Jet
  - Strong-flavour
  - Weak-flavour
- Hot-spot (termination or major disruption of a jet)
- Lobe
  - Bridge (majority of emission between end of jet / hot-spot and nucleus) or
  - Tail (emission mostly further from the nucleus than the end of the jet)

Weak -flavour jets

- Common in weak FRI ($P_{1.4} < 10^{24.5}$ WHz$^{-1}$) sources.
- Two-sided (<4:1)
- Perpendicular apparent field in centre
- Opening angle $> 8^\circ$
- Centre-brightened
- Smooth
- Decelerating, trans/subsonic flows

N.B. $P_{\nu} dv$ is the power emitted in the frequency range $\nu$ to $\nu + dv$

Weak-flavour jets in M84

Strong-flavour jets

- Most jets in powerful FRII ($P_{1.4} > 10^{25}$ WHz$^{-1}$) sources are of this type.
- Also found in FRI jet bases.
- Usually one-sided (>4:1) - some exceptions
- Parallel apparent B-field (transverse or oblique at bright knots)
- Opening angle <4$^\circ$, limb-brightened, knotty
- Supersonic, relativistic flows
- Jets in both weak and powerful sources start off as strong-flavour jets.
Strong-flavour jets in a radio galaxy

Strong-flavour jet in a quasar

Types of radio source

Host galaxies

- Almost all powerful radio sources live in massive elliptical galaxies (there are small, jet-powered sources in spirals).
- Hence very massive ($10^8$ to $10^{10}$ solar mass) black holes (next lecture).
- Surrounding hot plasma with temperature ~ $10^7$ to $10^8$ K. Components associated with the host galaxy and/or group/cluster.
- Hence radial fall-off of pressure and density, with a range of characteristic radii from 1 - 100 kpc.

Environment and the FR division

FRI sources: jet deceleration

- There is good evidence that FRI jets are highly relativistic on pc scales (and direct measurement of motions at >5c in M 87 on kpc scales).
- They appear to decelerate to sub-relativistic speeds on scales ~1 - 30 kpc.
- Kinetic energy is dissipated near the nucleus
- Jet deceleration counteracts adiabatic losses (lecture 5) so the jet remains a strong synchrotron emitter despite rapid expansion.
FRII sources: supersonic flow

- Basic picture due to Blandford & Rees: jets remain supersonic (and relativistic) until they terminate in strong shocks (hot-spots).
- Synchrotron-emitting plasma escapes from the hot-spots to form the extended bridges.
- Jets remain well-collimated, so adiabatic losses are minimised.
- Shock at hot-spot can re-accelerate electrons by the Fermi process (lecture 6).

Why are jets narrow?

- If a jet has a constant opening angle, then it need not necessarily be confined by an external pressure (a free jet).
- Sideways expansion is at the local sound speed, \( c_s \), so the half-opening angle is \( \theta = \arctan \left( \frac{c_s}{v} \right) = \arctan \left( \frac{1}{M} \right) \)
  where \( v \) is the flow speed and \( M \) is the Mach number.
- Still valid in the relativistic case, but with
  \[
  M = \gamma \frac{v}{\gamma s c_s} \\
  (\gamma_s = \left(1 - c_s^2/c^2\right)^{-1/2})
  \]

If not free, then what provides the confining pressure

- Compare the internal pressure \( p = u/3 \) from synchrotron-emitting particles with external pressure \( p_{ext} = nkT \) of surrounding thermal plasma.
- How to estimate \( p \)?
  Comparison of synchrotron and inverse Compton emission (but there may be other sources of pressure).
  Minimum energy argument (lecture 4).
- Both methods have significant uncertainties because we do not know the form of the electron energy spectrum at all energies.

Static pressure confinement

- Jet pressure is balanced by the thermal pressure of the surrounding plasma: \( p < p_{ext} = nkT \).
- This definitely works for weak-flavour jets in FRI sources on kpc scales, but not for (at least some) strong-flavour jets.
- Cannot work in the region where the jets are collimated: the bremsstrahlung emission from the high-pressure gas cloud required is >> observed.

Mass, momentum and energy transport

- Jet speed \( v \) (non-relativistic), area \( A \), internal energy \( e \) per unit mass, density \( \rho \), pressure \( p \):
  Mass flux = \( \rho v A \) (N.B. entrainment of matter)
  Momentum flux = \( A (\rho v^2 + p) \)
  Energy flux = \( \rho v A (\rho v^2/2 + e + p/\rho) \)
- Relativistic generalization: subscript 0 denotes fluid rest frame and \( e_0 \) includes the rest mass:
  Mass flux = \( \gamma^2 \rho_0 v A \)
  Momentum flux = \( A \gamma^2 \left( e_0 + p_0 \right) v^2/c^2 + A p_0 \)
  Energy flux = \( A \gamma^2 \left( e_0 + p_0 \right) v \)

An example of the application of conservation laws: deceleration of an FRI jet.
Internal and external pressures

- FRI jet: initially over-pressured, then reaches equilibrium.

Internal density

- Synchrotron min.

Entrainment rate

- Stellar mass loss.

Mach number

Stellar mass loss is inadequate to slow the jet.

What are jets made of?

- Possibilities: UR electron-positron, UR electron/cold proton; UR electron-proton; also entrained thermal material.
- UR electron-proton very unlikely (energetics).
- Possible discriminants:
  - Annihilation line (too tenuous)
  - Dynamics
  - Low-energy electron spectrum from circular polarization transport or inverse Compton scattering.
  - Faraday rotation to detect thermal material.

Interaction of lobes with the external environment

- Radio (synchrotron) emission is anticorrelated with X-ray (bremsstrahlung) emission from hot plasma around the host galaxies.
- Hence the relativistic plasma has pushed the surrounding medium aside (thereby doing pdV work; lecture 5) rather than mixing with it.
Environmental impact (FRI)
3C84 (NGC1275): X-ray false colour on radio contours

Environmental impact (FRII)
Cygnus A: Chandra image showing cluster gas, cavity around radio source and SSC emission from the radio hot-spots

FRII schematic

FRII physics
- Jet terminates in a strong shock (the hot-spot). Compression, field amplification and in some cases Fermi acceleration give enhanced emission. X-rays from SSC or synchrotron.
- Flow around the hot-spot is complex and 3-dimensional. Post-shock flow speeds may still be relativistic.
- Particles escape from the hot-spot and flow back towards the nucleus. The external medium is pushed out of the way, leaving a cavity (the lobe).
- Advance speed \( < 0.1c \) (i.e. \( << \) jet speed) but supersonic -> bow shock in IGM.

Expansion speed and ram-pressure balance
- Speed of advance \( V \) of the contact discontinuity immediately behind the bow-shock of a propagating jet. Momentum balance in the frame of the discontinuity in 1D:
  \[
  \rho_j v_j^2 = \rho_{ext} V^2
  \]
  where \( \rho_j \) and \( v_j \) are the jet density and velocity, \( \rho_{ext} \) is the external density and \( V \) is the advance speed.
- \( V = \eta^{1/2} v_j/(1 + \eta^{1/2}) \)
  where \( \eta = \rho_j/\rho_{ext} \) is the density contrast.
- If the jet is very light, then \( V \ll v \)

3D simulation of FRII jet
Simulation of a $\gamma = 5$ relativistic jet

Pressure  Velocity  Lorentz factor

Evolution of FRII sources

- Youngest FRII sources observed so far (compact symmetric objects or CSOs) are 10 - 30 pc long and have measured advance speeds of 0.2c, so are inferred to be a few hundred years old.
- Advance speeds are statistically <0.05 - 0.1c in larger FRII sources from light-travel arguments.
- Models suggest that the advance speed falls and the radio luminosity decreases with time.
- Typical ages inferred for FRII sources are $10^7$ - $10^8$ years (N.B. possible inconsistencies between spectral and dynamical ages).

Measuring the advance speed in a young FRII radio source

Separation velocity = 0.35c
Age = 770 years

Radio sources in clusters of galaxies

- Higher densities and pressures in the external environment.
- Motion of a radio jet with respect to the intracluster medium (either because the host galaxy is moving or as a result of bulk gas motions in the cluster) causes bending of the structure by ram pressure.
- Buoyancy effects are important if $\rho < \rho_{\text{ext}}$.

3C75: FRI sources in both nuclei of a double galaxy in a cluster

The effects of motion and buoyancy in a galaxy cluster
How are jets collimated?

Not:
- **Twin exhaust** (collimation by a flattened gas cloud) -> too much thermal X-ray emission.
- **Funnel** (thick accretion disk) -> radiation drag.
- **Radiation pressure** -> Lorentz factors too low.

This leaves:
- **Magnetic collimation** - a natural mechanism, as toroidal field is expected from a spinning system, and this provides a confining force.

-> black holes in AGN (next lecture)