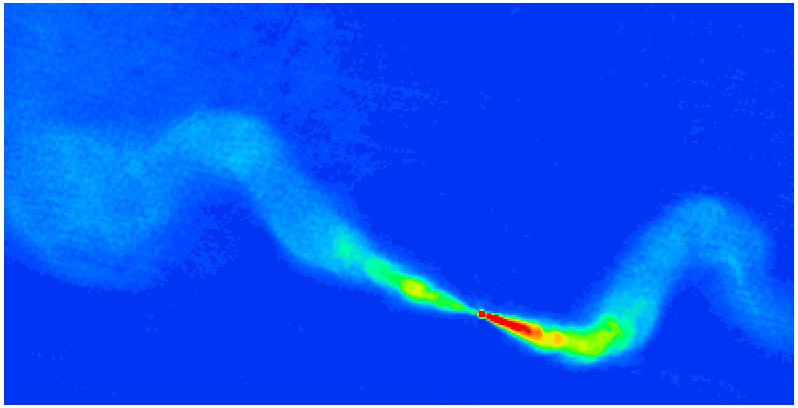
Observations of jet dissipation

Robert Laing (ESO/Oxford)



Overview

- X-ray – radio connections in radio galaxies and quasars:
  - High-energy emission from non-thermal electrons.
  - The interaction of radio galaxies with external hot plasma.
- Deceleration of relativistic jets in FRI radio galaxies:
  - Models of synchrotron emission → 3D velocity field, emissivity, field structure.
  - Velocity + external p, ρ, T → energy flux, p, ρ, Mach number, entrainment rate.
  - Where are energetic particles accelerated?

X-ray – radio connections

- X-ray emission from the non-thermal electron population:

  synchrotron - same population?

  inverse Compton – source of photons, B

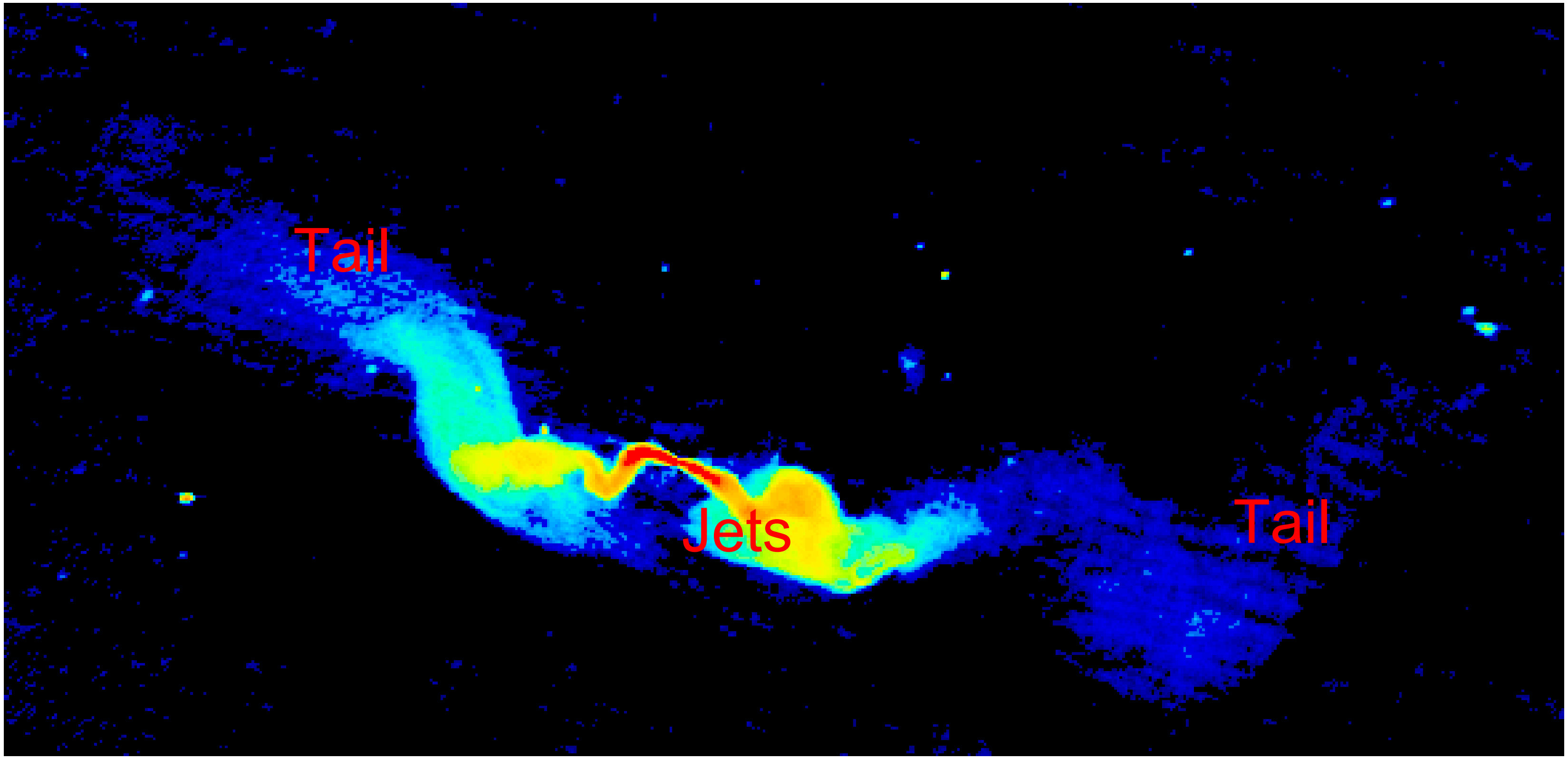
- X-ray observations of the surrounding hot plasma

  cavities

  external pressure and density

  entrainment and mixing

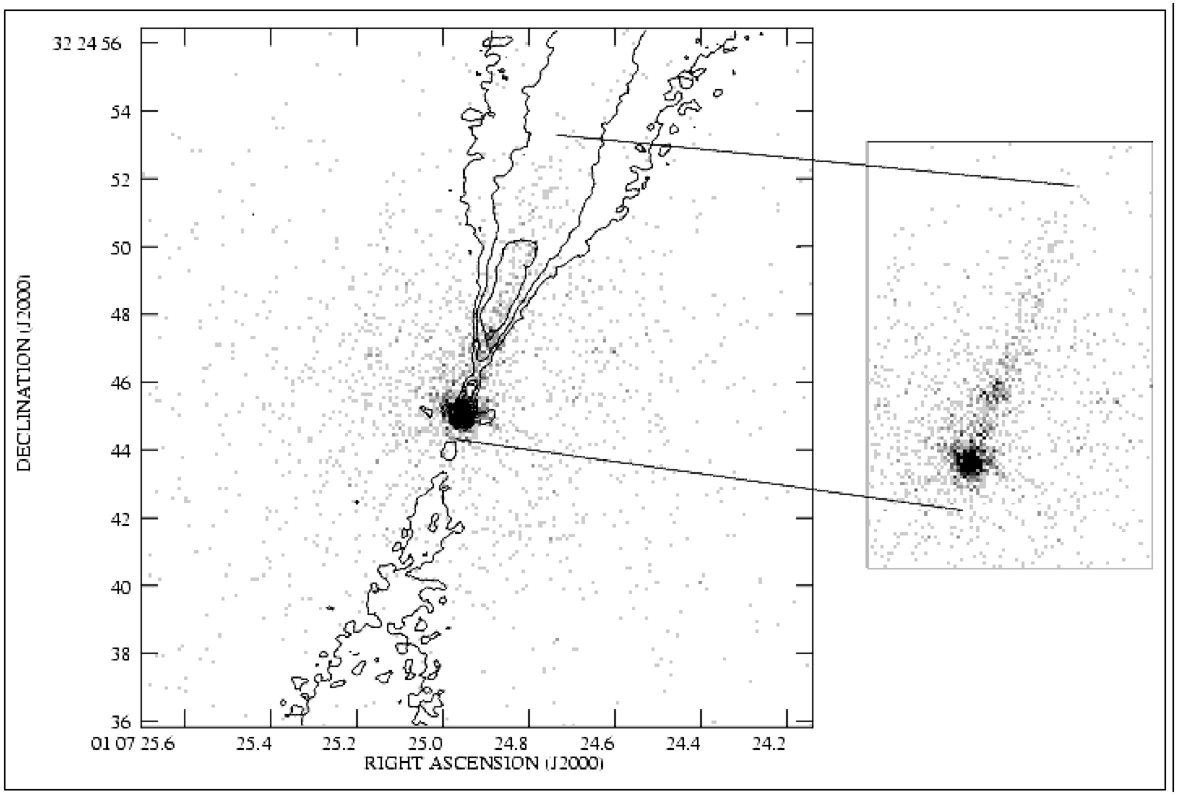
A weak (FRI) radio galaxy



3C 31 (VLA 1.4GHz; 5.5 arcsec FWHM)

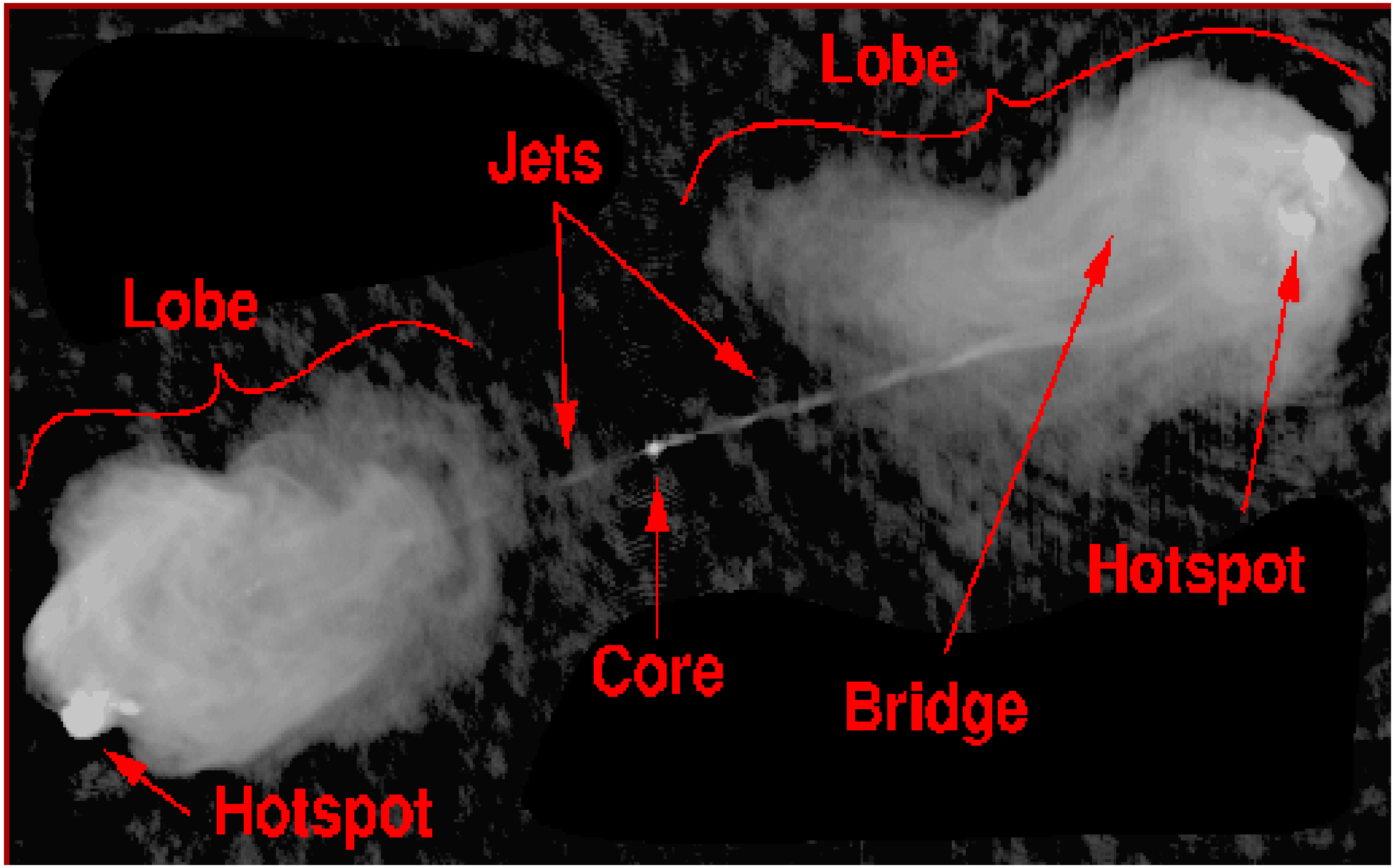
Jets in FRI sources decelerate, becoming trans- or subsonic and produce much of their radiation close to the nucleus – see later.

X-ray synchrotron emission from FRI jets [Hardcastle]



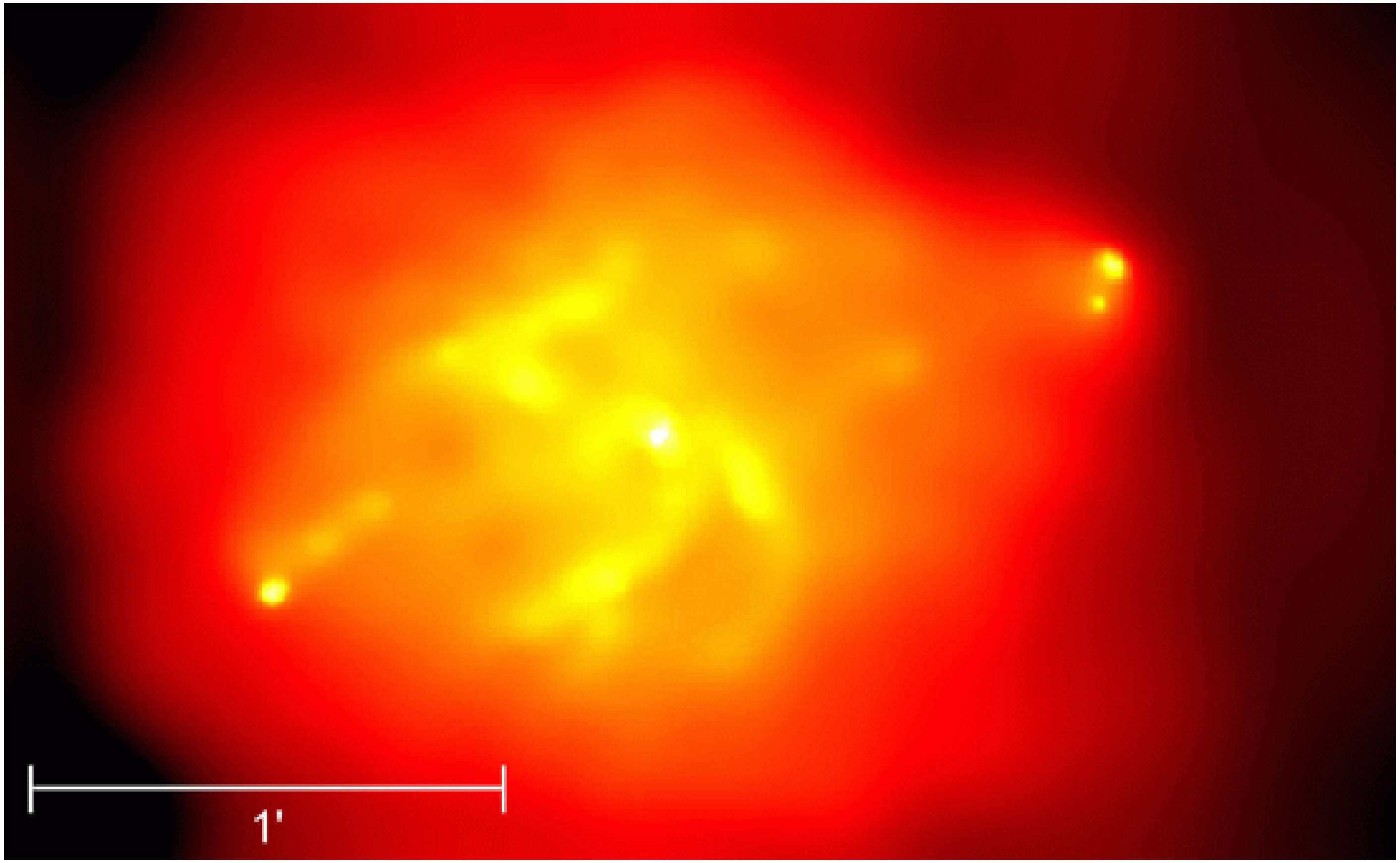
3C 31 (Hardcastle et al. 2002)

A powerful (FRII) radio galaxy



Jets in FRII sources remain supersonic (and relativistic) until they terminate in hot-spots.

Cygnus A (FRII)

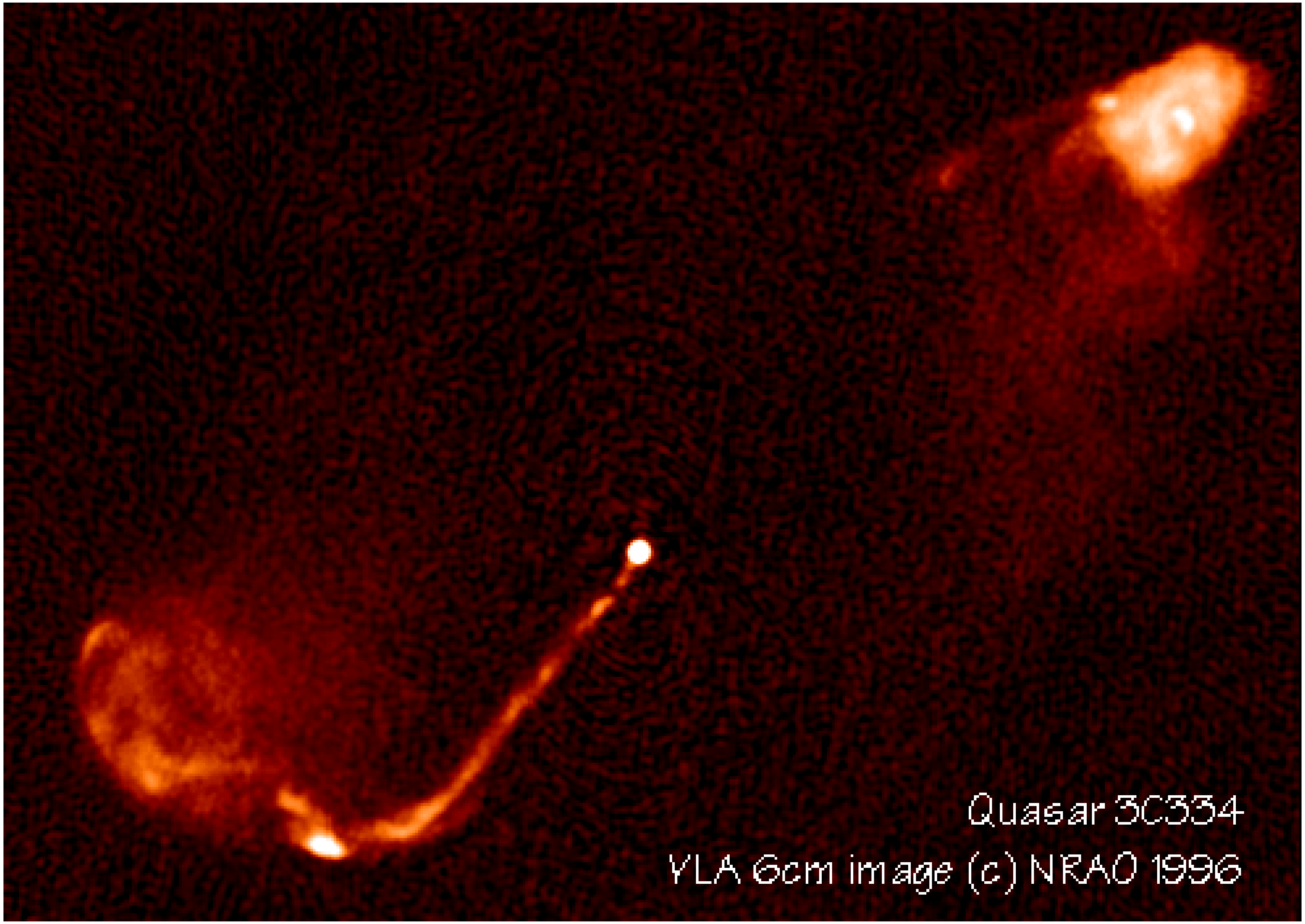


Hot-spot X-rays from SSC with B close to equipartition in this and other cases …….

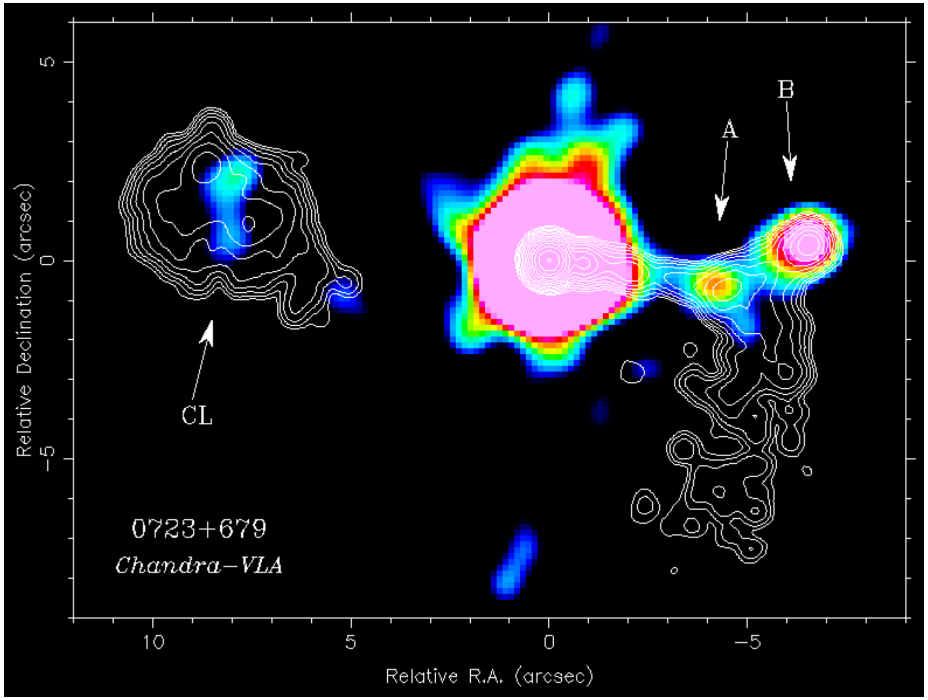
but synchrotron and iC emission suggested for some hot-spots.

Cygnus A: Chandra image showing cluster gas, cavity around radio source and emission from the radio hot-spots (Wilson, Young & Shopbell (2000)

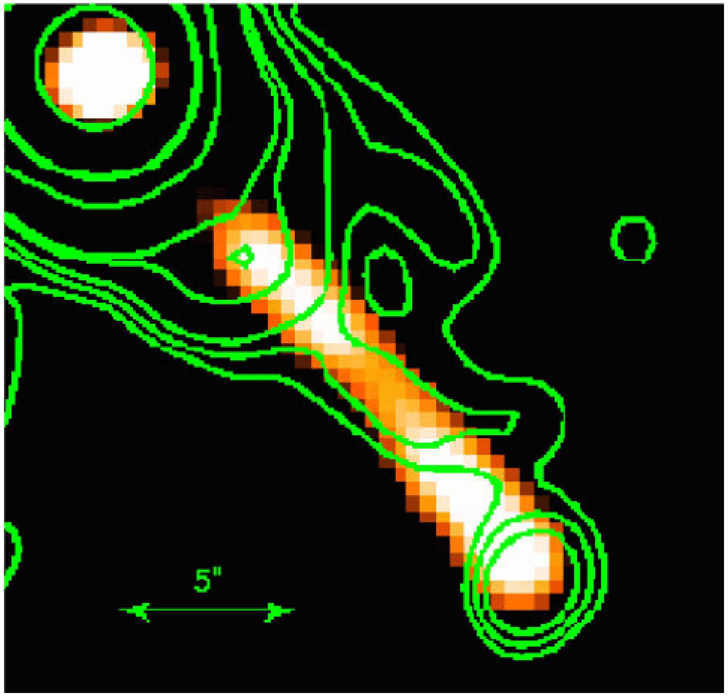
A powerful FRII quasar



Powerful jets [Georganopoulos, Harris, Jester]



3C179 (Sambruna et al. 2002)



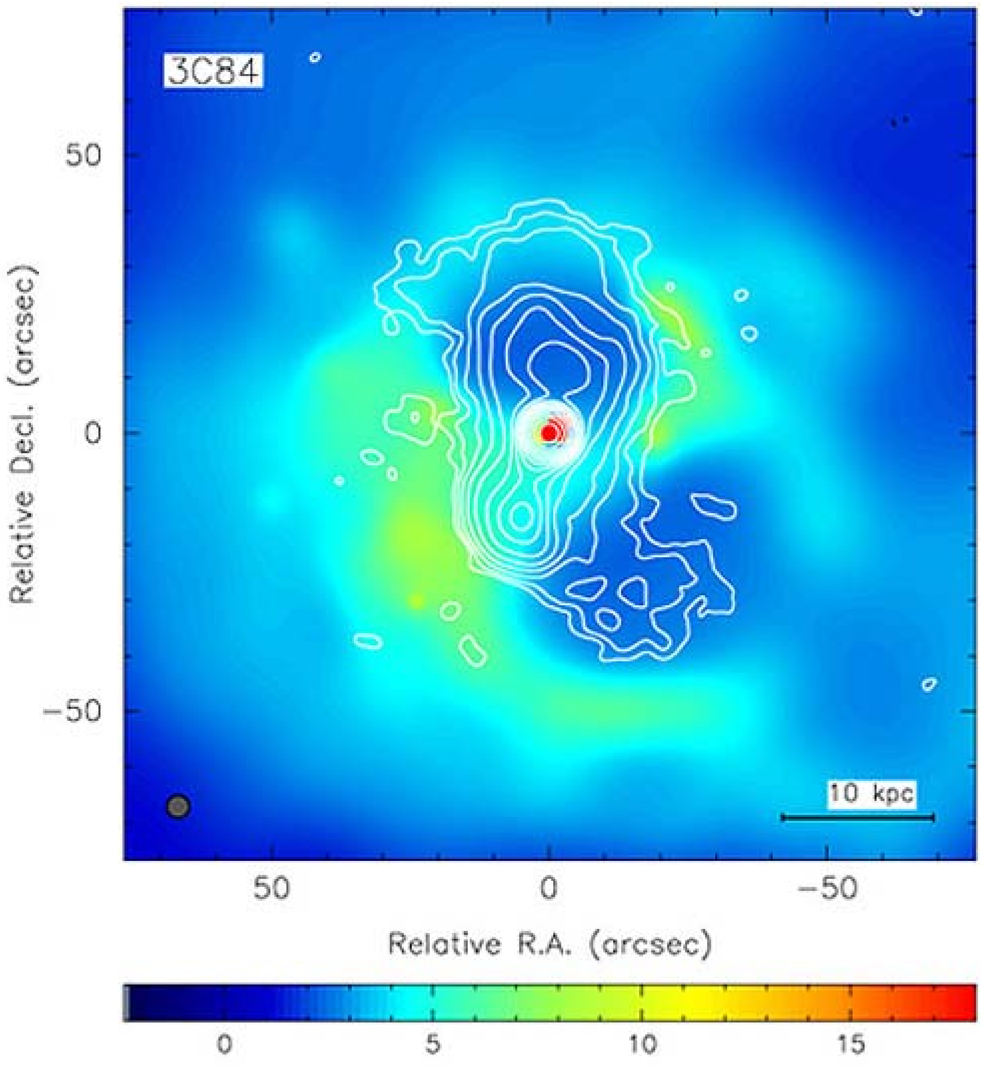
3C219 (Comastri et al. 2003)

Synchrotron?

Beamed inverse Compton - CMB photons?

- Photons from slower regions of the jet?

X-ray cavities around radio lobes [Croston, Kraft et al., Clarke]



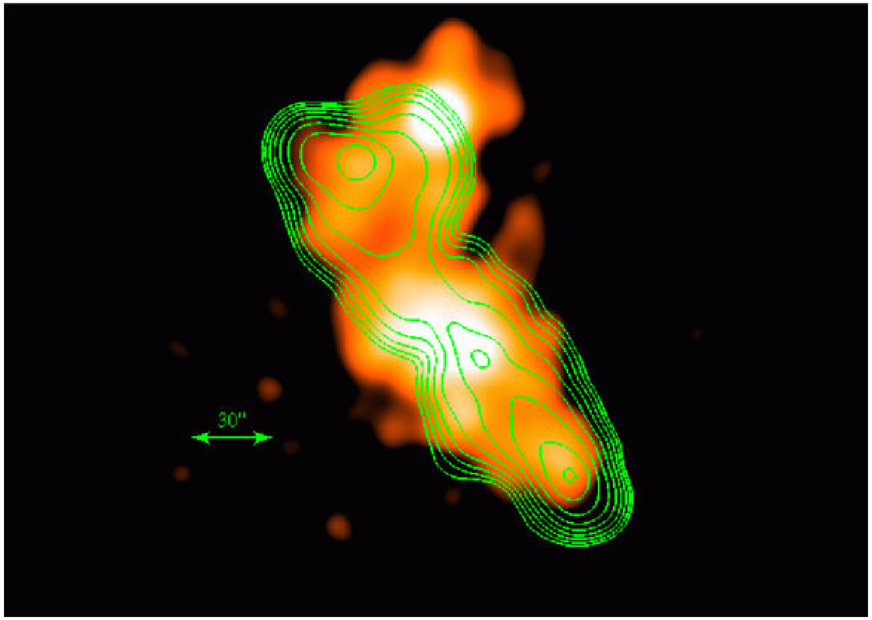
3C84 (NGC1275): X-ray false colour on radio contours

Radio and X-ray emission anticorrelate: radio lobes displace X-ray emitting plasma.

Gas surrounding the cavities in low-power sources often at or below ambient temperature, but….

Evidence for heating in some sources (Cen A, Cyg A) – expected for supersonic expansion in powerful FRII's.

Lobes [Croston, Isobe, Belsole]



3C219 (Comastri et al. 2003)

Inverse Compton scattering of IR photons from an obscured AGN?

If so, a probe of the low-energy part of the electron spectrum.

X-ray emission from lobes expected from inverse Compton scattering of CMB photons.

Current results suggest that B is usually close to equipartion.

Modelling of FRI jets

- Model FRI jets as intrinsically symmetrical, axisymmetric, relativistic flows **[free models].** Derive 3D velocity, emissivity and field geometry. [Deep, high-resolution radio images. Linear polarization essential.]
- Apply conservation of mass, momentum and energy to infer the variations of pressure, density, entrainment rate and Mach number. [External density and pressure from X-ray observations.]
- Model the acceleration and energy-loss processes, starting with **adiabatic models**. [Images at mm, IR, optical, X-ray wavelengths.]

Progress so far

- B2 sample statistics (Laing et al. 1999)
- Free models of 3C31 (Laing & Bridle 2002a)
- Conservation-law analysis of 3C 31 (Laing & Bridle 2002b)
- Adiabatic models of 3C 31 (Laing & Bridle 2004)
- Free models of B2 0326+39 and 1553+24 (Canvin & Laing, MNRAS submitted)
- Free model of NGC 315

Alan Bridle, James Canvin – models

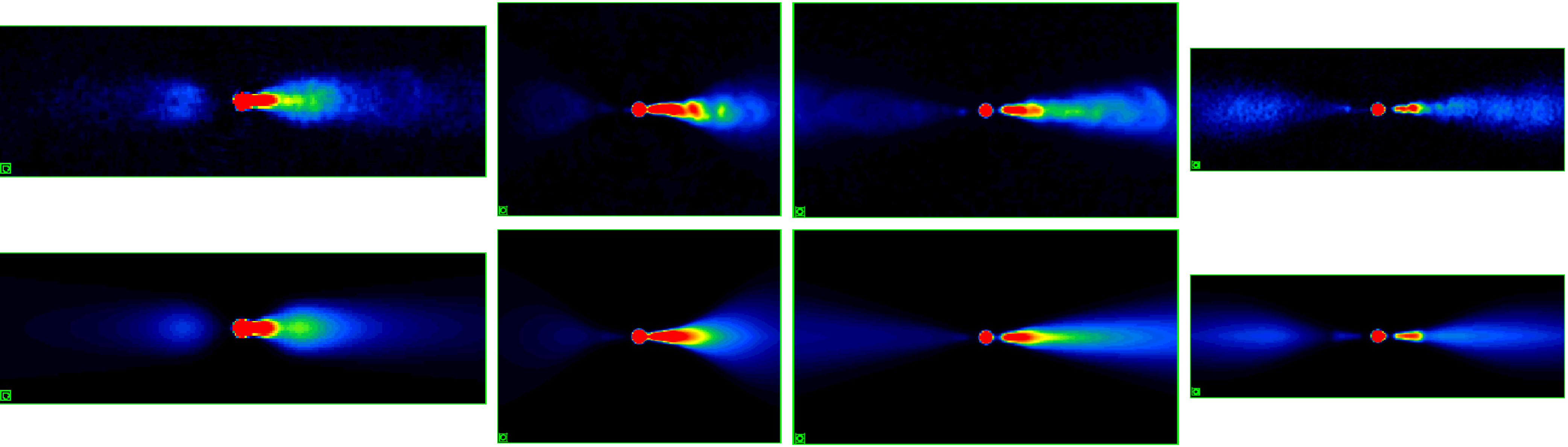
Diana Worrall, Martin Hardcastle, Mark Birkinshaw (Bristol) – X-ray

Bill Cotton, Paola Parma, Gabriele Giovannini, … - radio

Free models – basic principles

- Model jets as intrinsically symmetrical, axisymmetric, relativistic, stationary flows. Fields are disordered, but anisotropic.
- Parameterize geometry, velocity, emissivity and field structure.
- Optimize model parameters by fitting to IQU images.
- Derive model IQU by integration along the line of sight, taking account of anisotropy of synchrotron emission in the rest frame, aberration and beaming.
- Linear polarization is essential to break the degeneracy between angle and velocity.

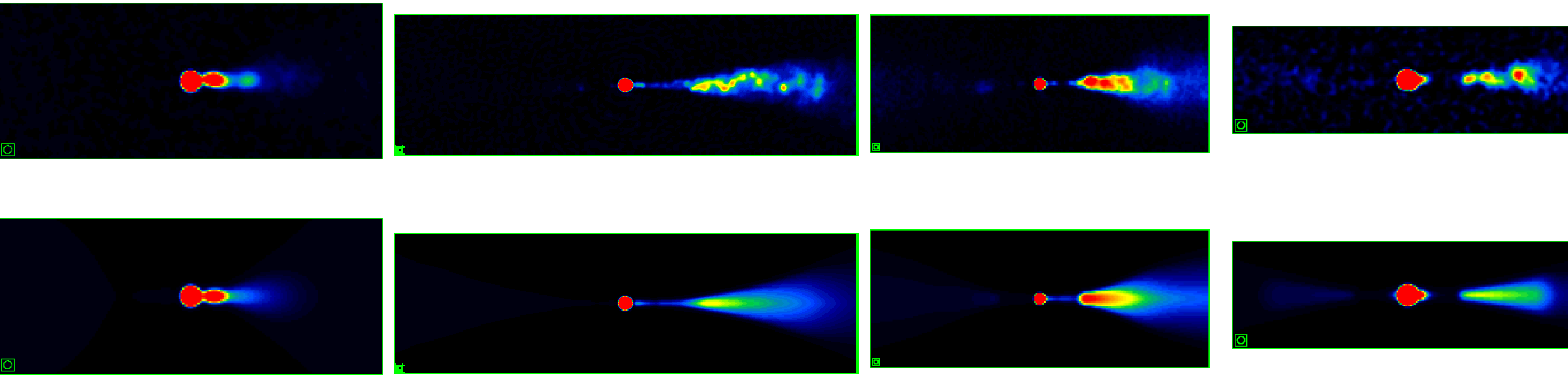
Total Intensity



θ 8° 37° 52° 64°

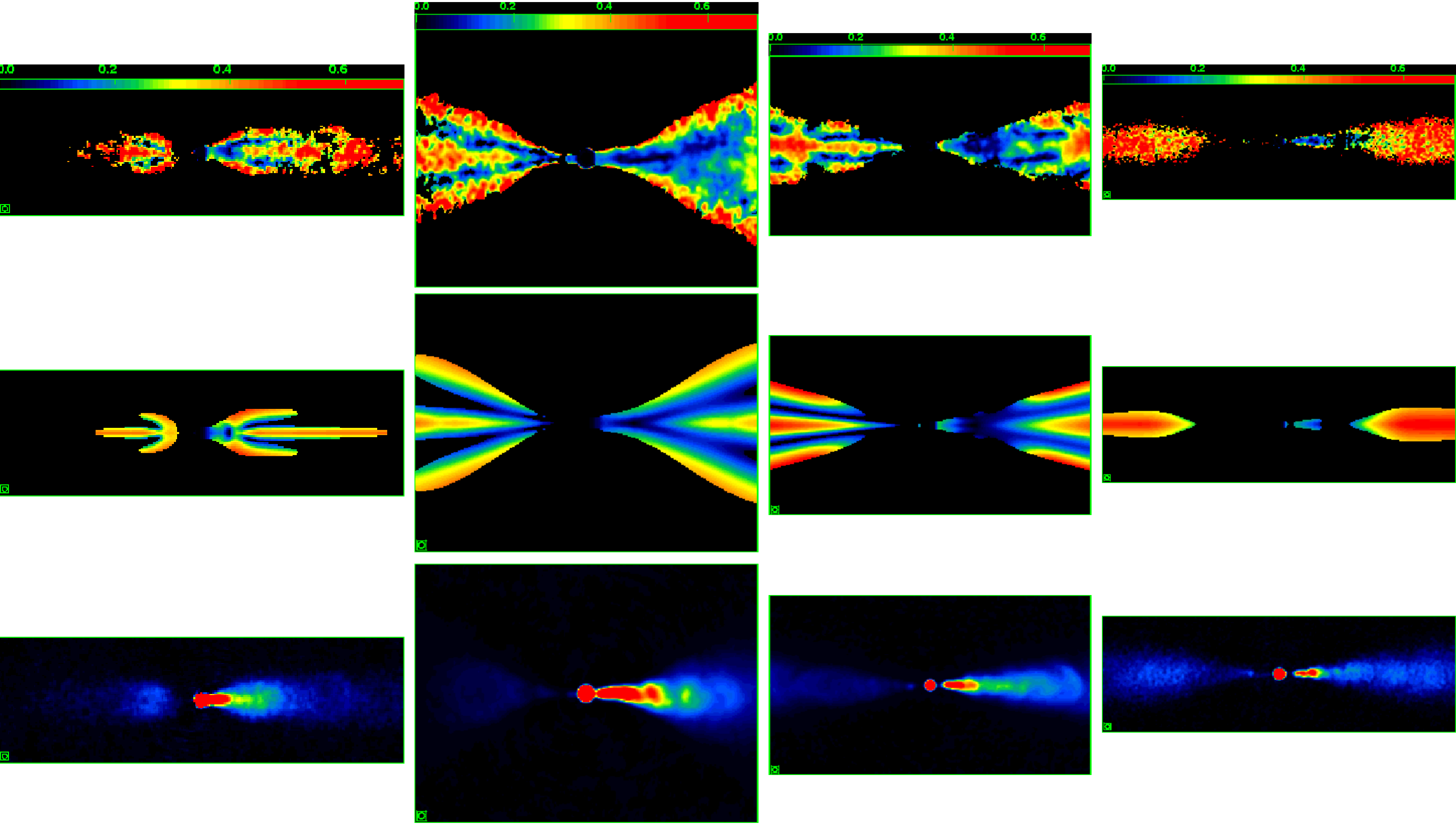
B2 1553+24 NGC 315 3C 31 B2 0326+39

Total Intensity (high resolution)



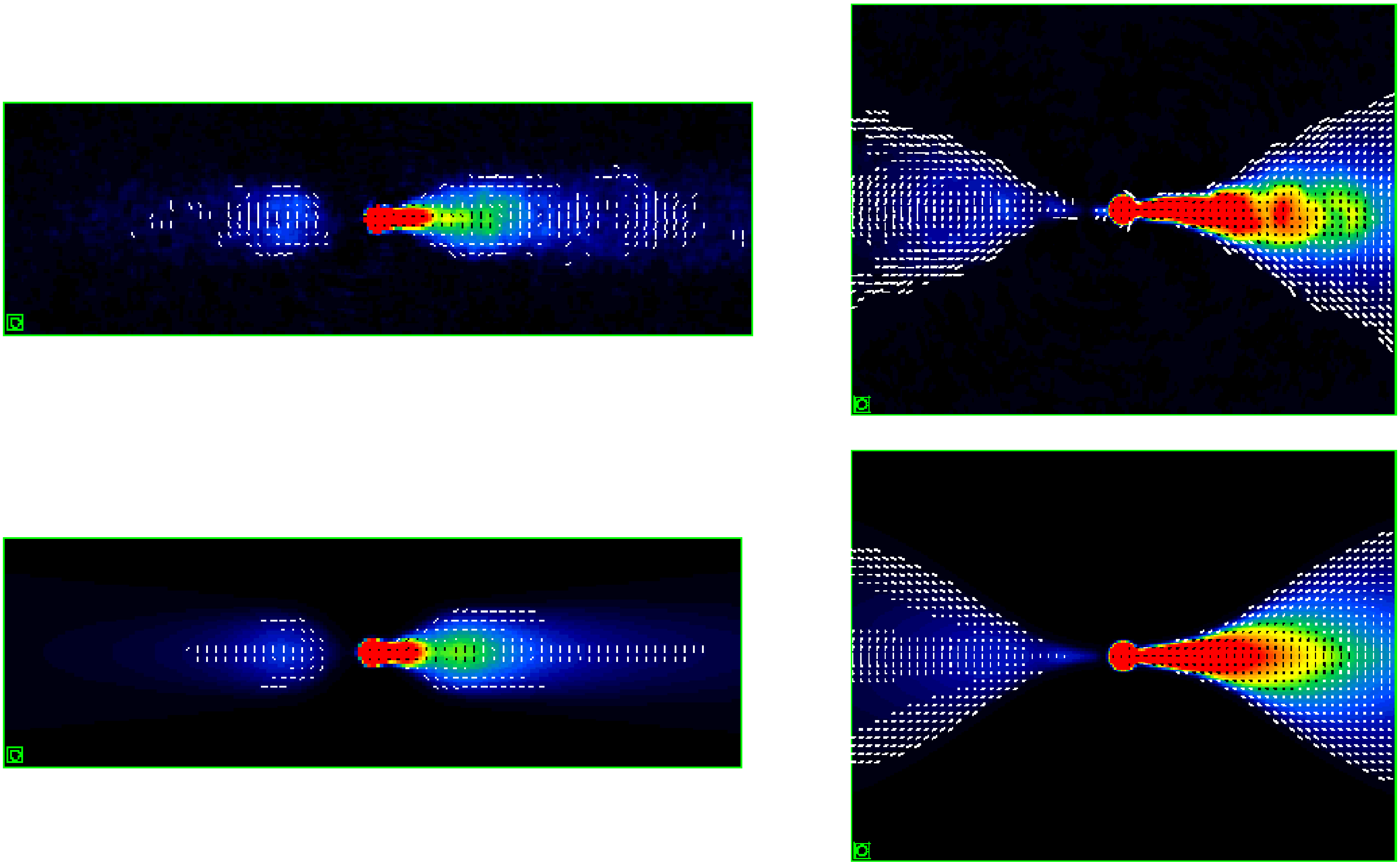
$\theta =$ 8^{o} 37^{o} 52^{o} 64^{o}

Degree of polarization



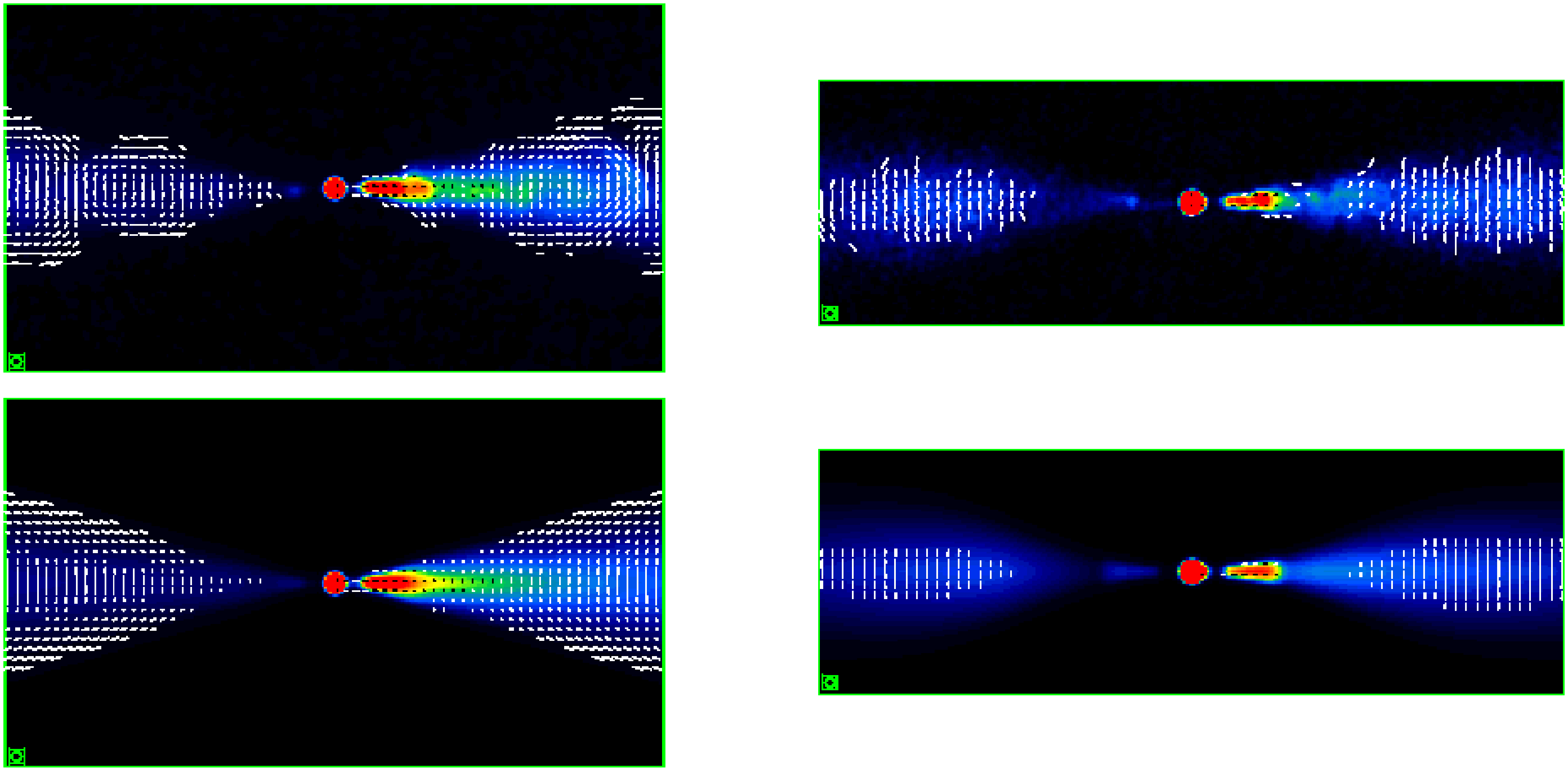
θ 8° 37° 52° 64°

Apparent magnetic field (1)



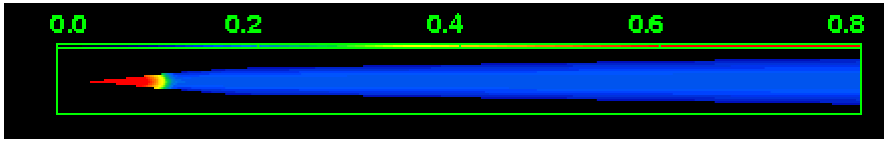
θ = 8° 37°

Apparent magnetic field (2)

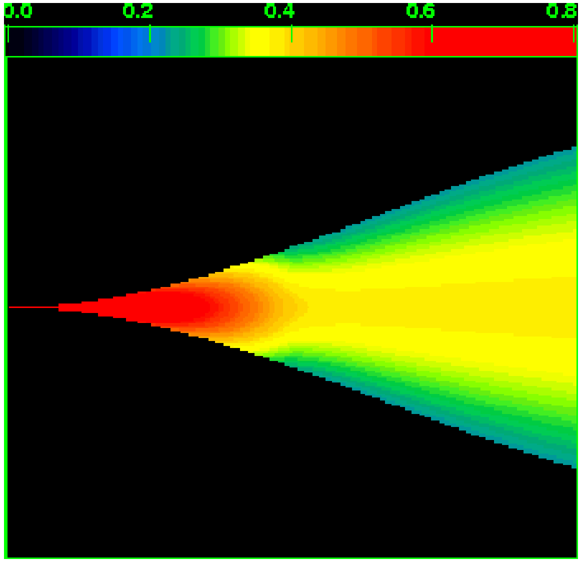


$\theta =$ 52^{o} 64^{o}

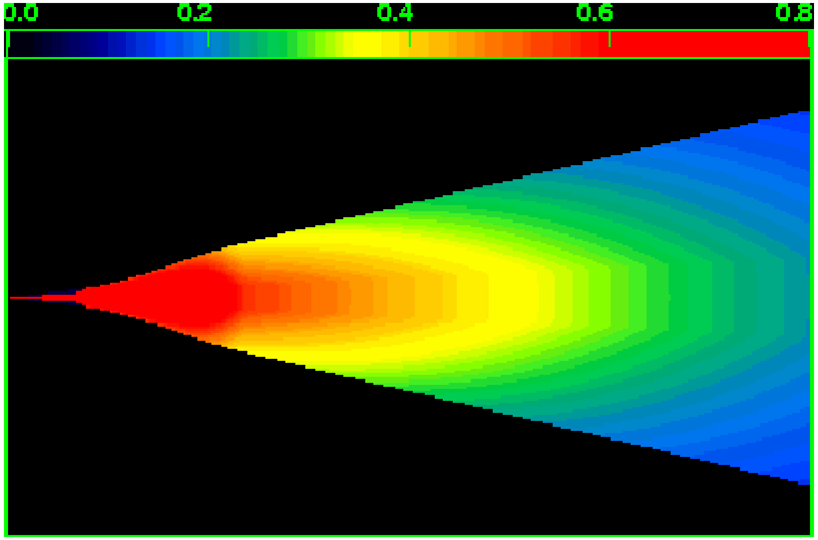
Velocity β = v/c



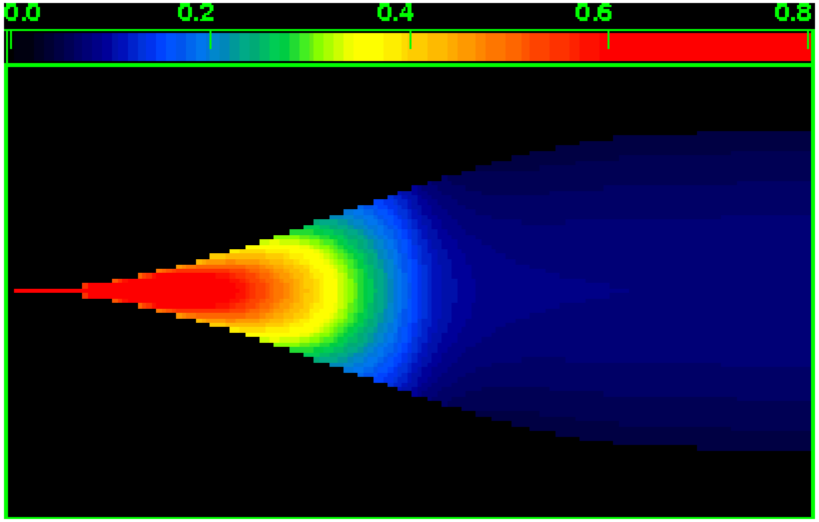
B2 1553+24



NGC 315



3C 31



B2 0326+39

Geometry and velocity

- FRI jets are initially narrow, flare abruptly and then recollimate to form conical (often almost cylindrical) outer regions.
- Their velocities are $\beta \approx 0.8$ at the start of the model.
- All of the jets decelerate abruptly in the flaring region, but at different distances from the nucleus.
- At larger distances, they have roughly constant velocities in the range $\beta \approx 0.1 – 0.2$.
- They have transverse velocity gradients, with edge/on-axis velocity consistent with 0.7 everywhere. There are no obvious low-velocity wings.

Emissivity and field

- Emissivity profile tends to flatten at large distances from the nucleus (compare with adiabatic models – later).
- FRI jets are intrinsically centre-brightened.
- Dominant field component at large distances is **toroidal**.
- The longitudinal component can be signficant close to the nucleus, but decreases further out.
- Radial component behaviour is peculiar.
- Qualitatively consistent with flux freezing, but laminar-flow models, even including shear, do not fit.

FRI deceleration physics

- Jets have (at least) two regions, differentiated by collimation and kinematic properties – flaring and outer.
- The onset of jet deceleration is within the flaring region, and is sudden.

  Reconfinement shock (Sanders 1983)?

  Non-linear K-H instabilities (Rosen et al. 1999) or transition to fully-developed turbulence?
- There is evidence from the field structure of 3C 31 for interaction with the external medium where the jet flares.

Conservation law analysis

- We now know the velocity and area of the jet.
- The external density and pressure come from Chandra observations.
- Solve for conservation of momentum, matter and energy.
- Well-constrained solutions exist.
- Key assumptions:

  Energy flux = momentum flux x c

  Pressure balance in outer region

Mass, energy and momentum flux conservation

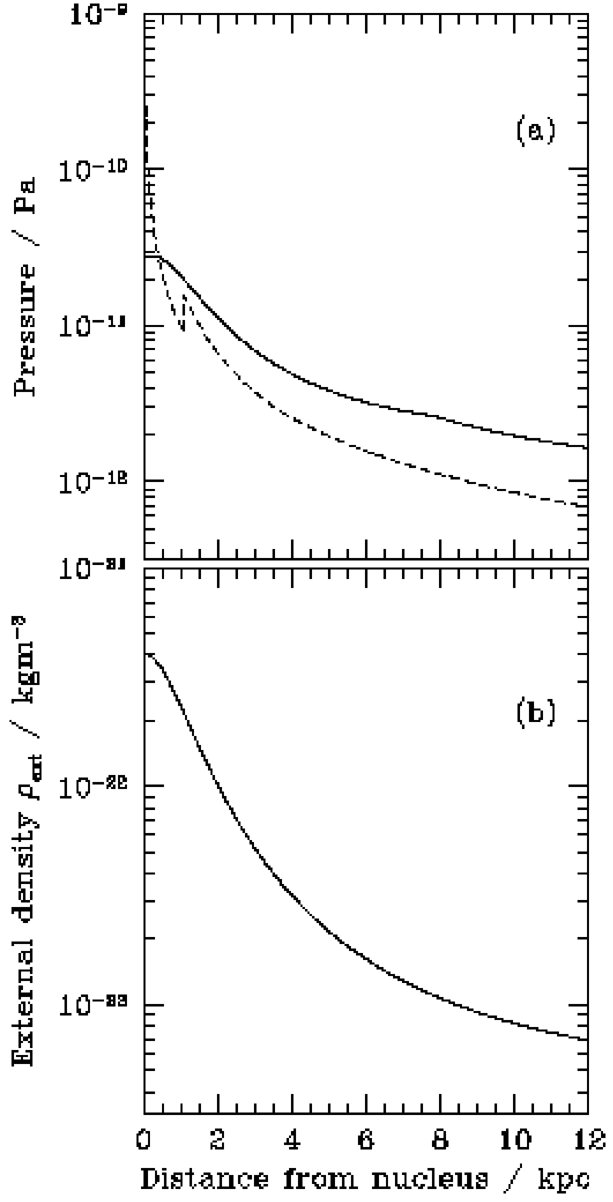
$$\Phi = [(\Gamma^2 - \Gamma)\rho c^2 + 4\Gamma^2 p]\beta c A \quad (1)$$

$$\Pi = [\Gamma^2\beta^2(\rho c^2 + 4p) + p - p_{\rm ext}]A + \int_{r_1}^{r} A \frac{dp_{ext}}{dr}\left[1 - \frac{\Gamma^2(\rho c^2 + 4p)}{c^2(1+\beta^2)\rho_{\rm ext}}\right] dr \quad (2)$$

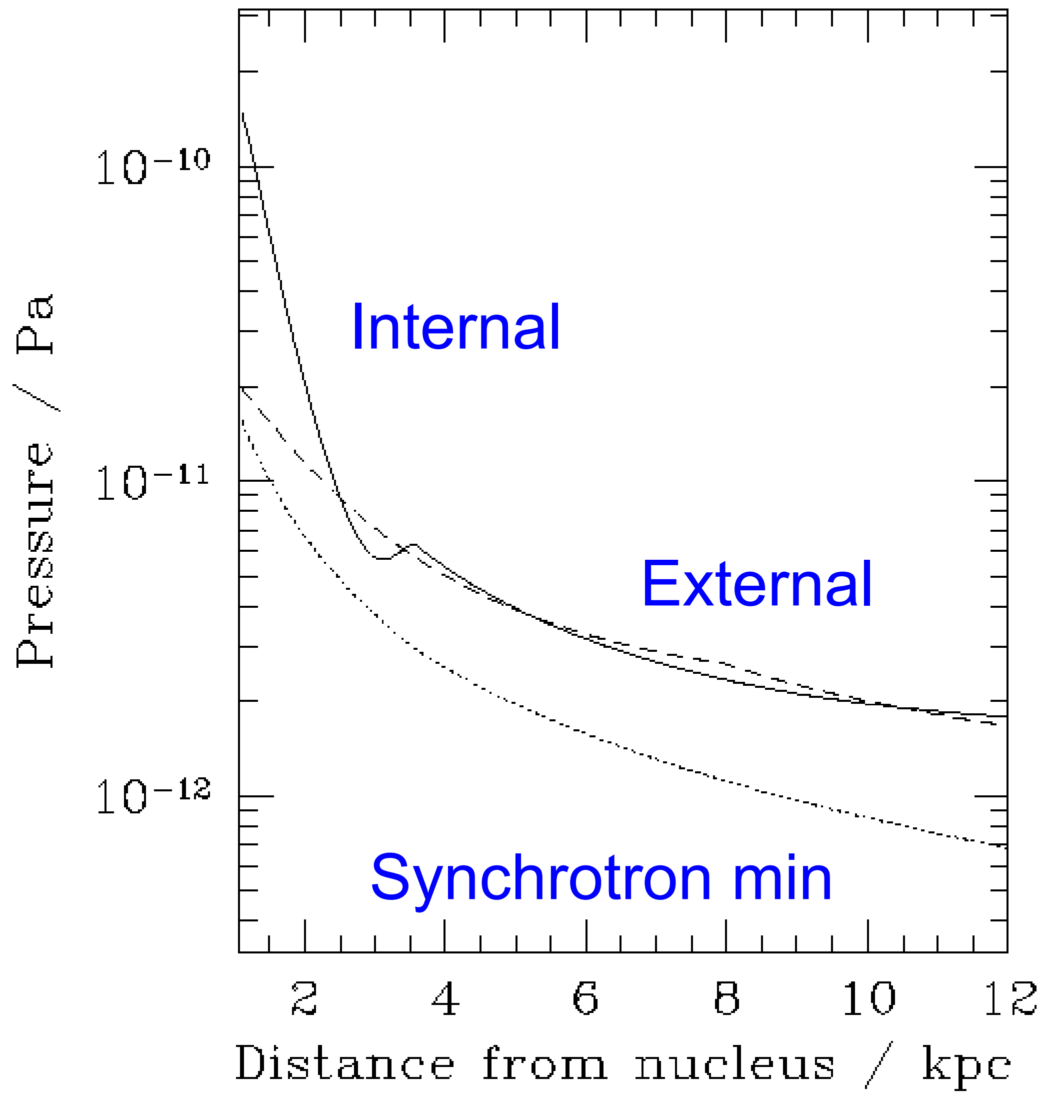
Conservation-law analysis: fiducial numbers at the jet flaring point

- Mass flux 3×10^{19} kgs^{-1} (0.0005 solar masses/yr)
- Energy flux 1.1×10^{37} W
- Pressure 1.5×10^{-10} Pa
- Density 2×10^{-27} kgm^{-3}
- Mach number 1.5
- Entrainment rate 1.2×10^{10} $kgkpc^{-1}s^{-1}$

External pressure and density

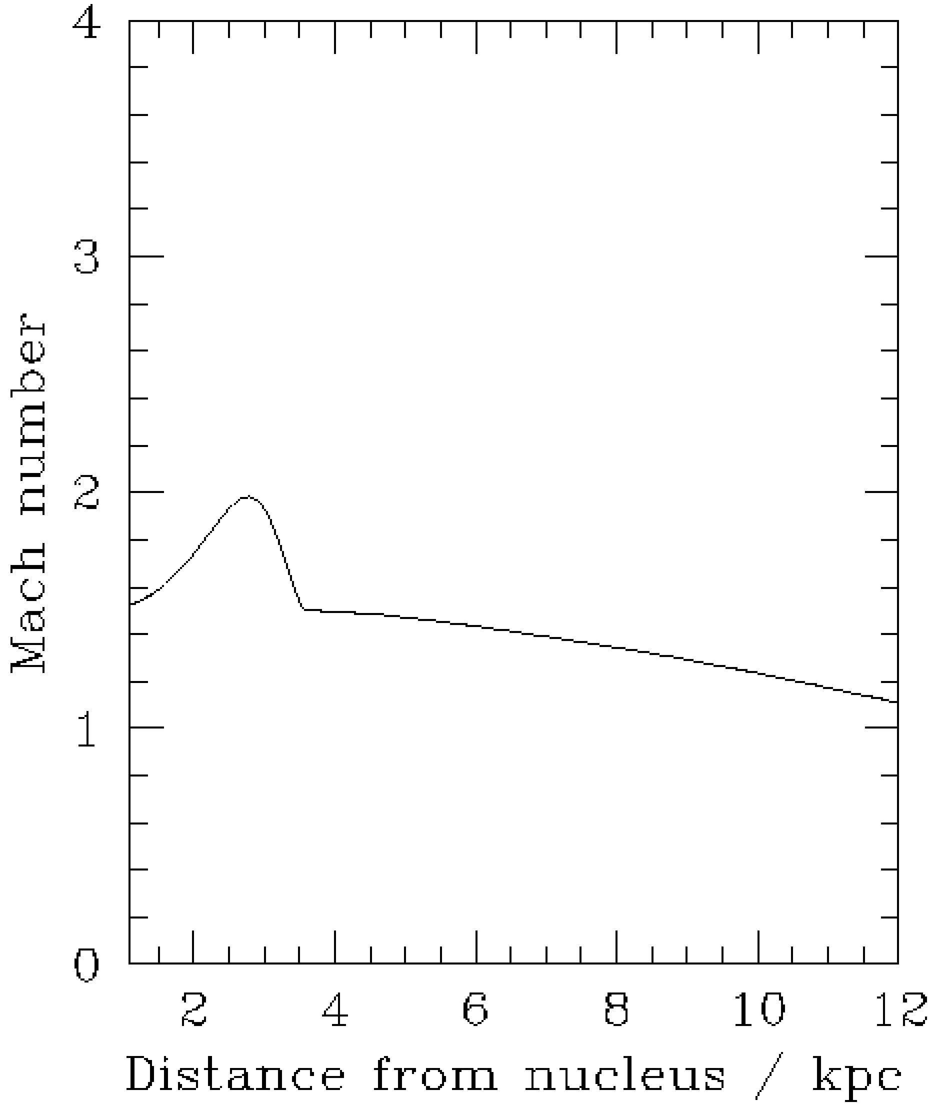


Internal and external pressures

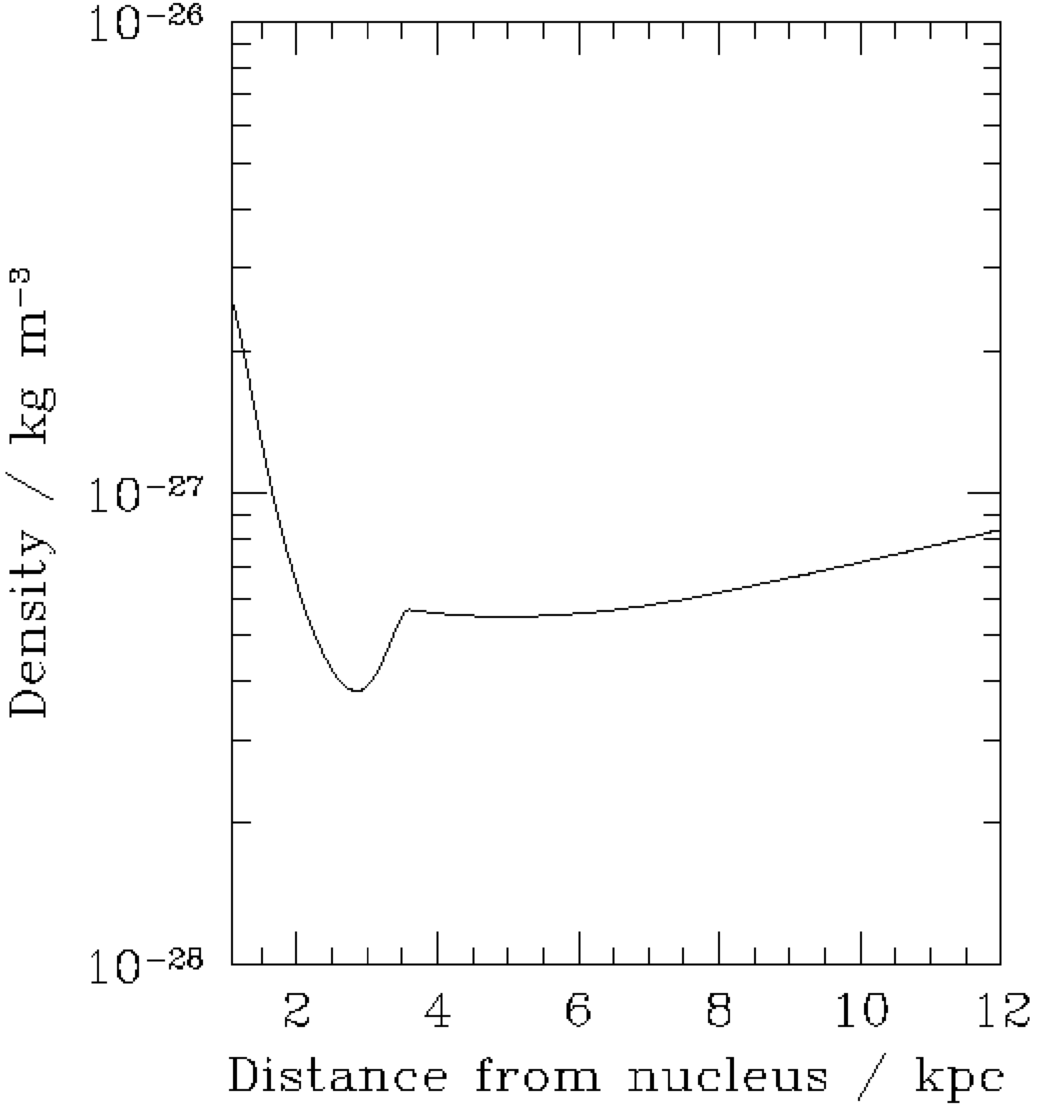


The jet is initially over-pressured, then reaches equilibrium

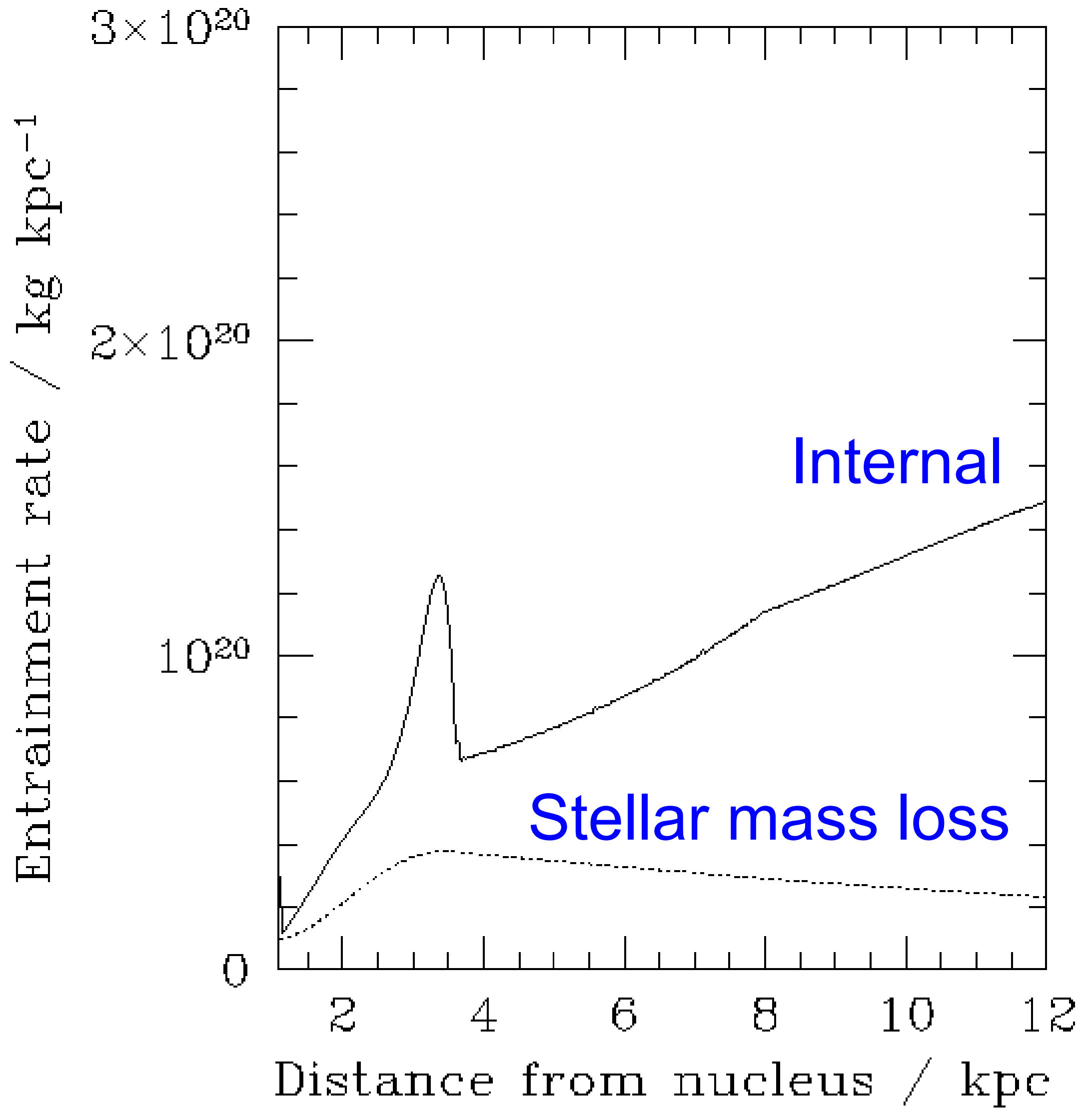
Mach number



Internal density



Entrainment rate

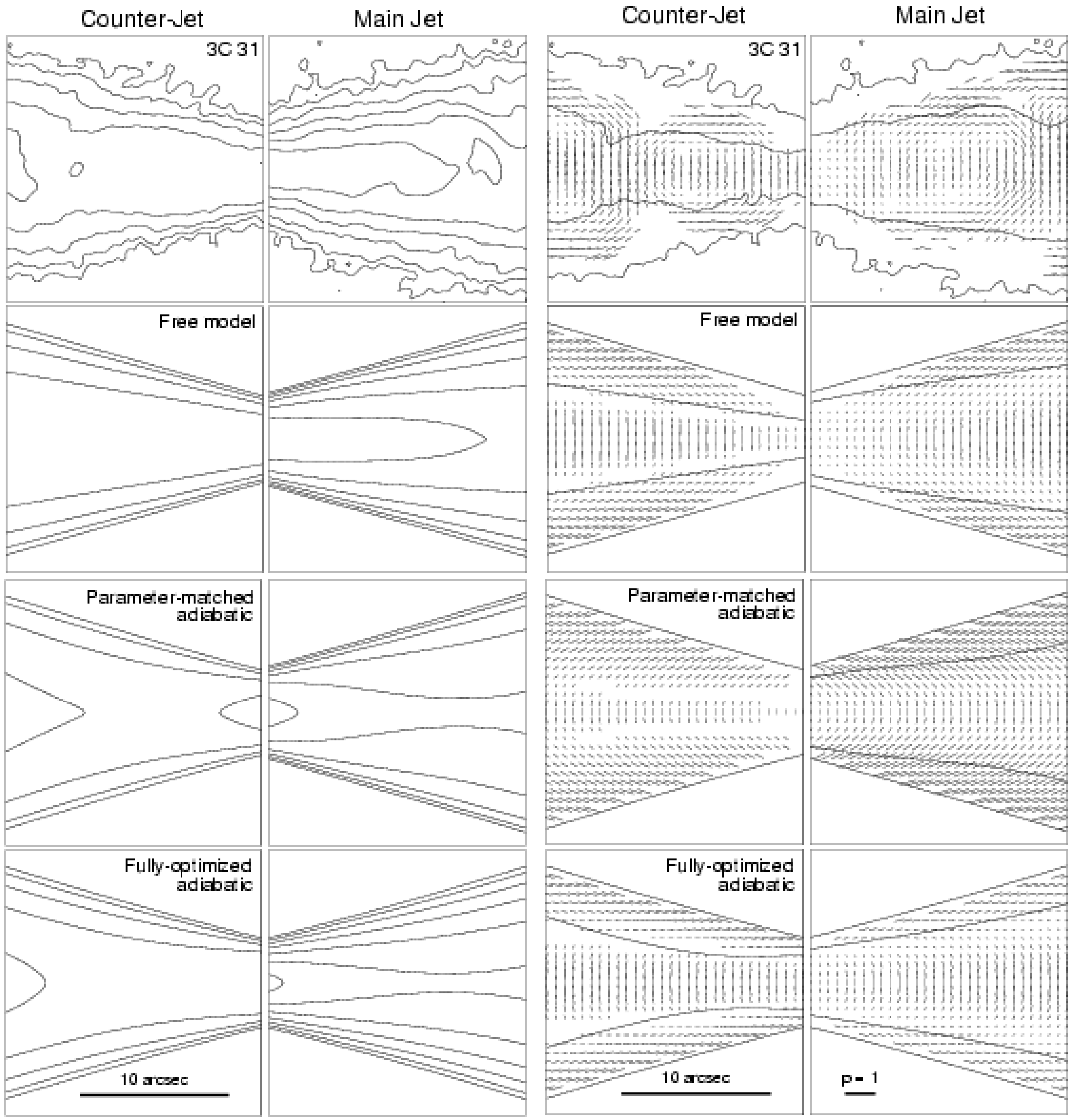


Stellar mass loss is inadequate to slow the jet at large distances, but could provide all of the mass required for distances <1 kpc

What are the jets made of?

- $\rho = 2.3 \times 10^{-27}$ kg m^{-3} (equivalent to 1.4 protons m^{-3}) at the flaring point.
- For a power-law energy distribution of radiating electrons, $n = 60\ \gamma_{min}^{-1.1}$ m^{-3} ($\sim 10^{-28}\ \gamma_{min}^{-1.1}$ kg m^{-3}).
- Possibilities include:
  - Pure e^+e^- plasma with an excess of particles over a power law at low energies.
  - e^+e^- plasma with a small amount of thermal plasma.
  - Cold protons in equal numbers with radiating electrons and γ_{min} = 20 - 50 (not observable).

Adiabatic models



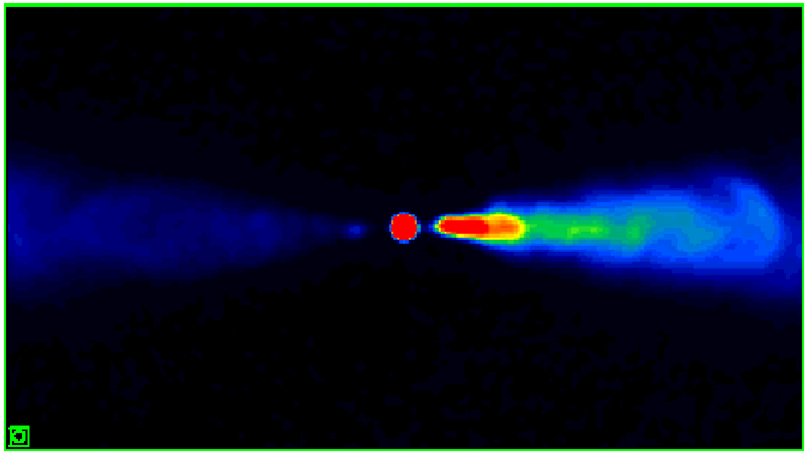
Set initial conditions at start of outer region.

Calculate evolution of particle density and field assuming adiabatic/flux-freezing in a laminar flow.

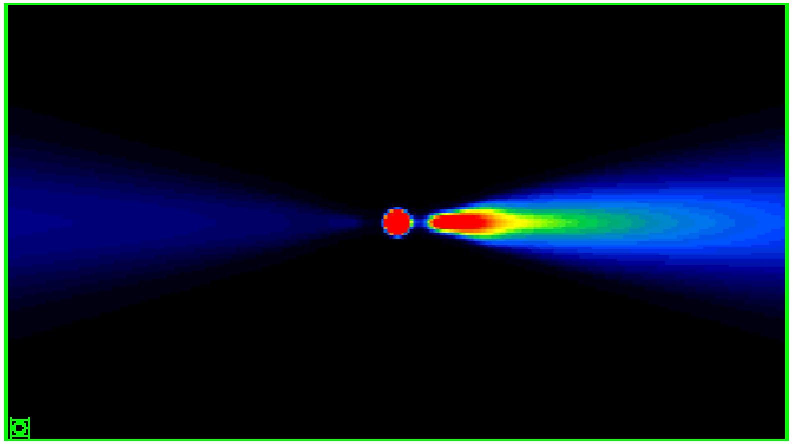
Adiabatic models give a reasonable fit, but do not get either the intensity or polarization quite right.

Not surprising if the flow is turbulent?

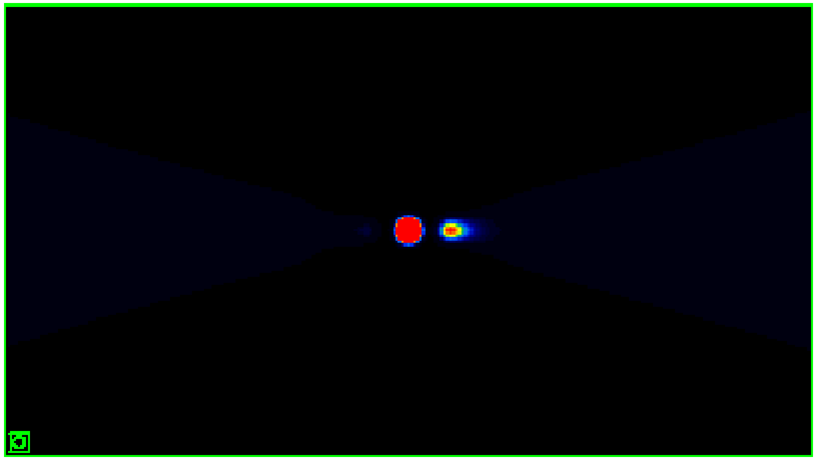
Adiabatic models



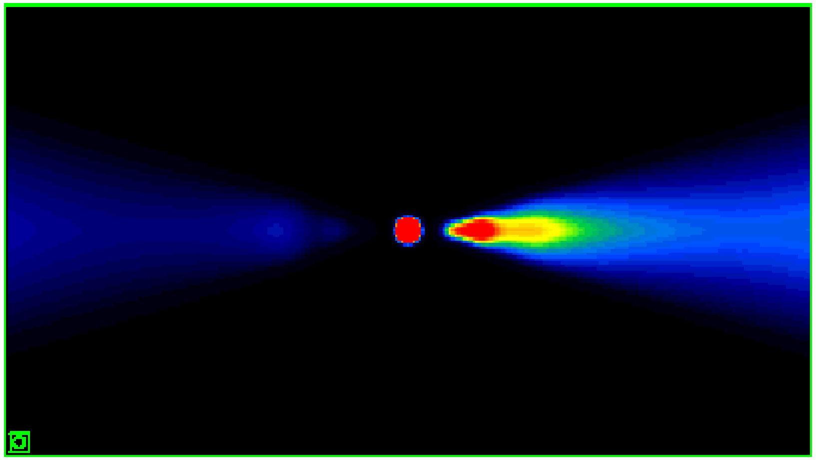
3C 31 I



Free model

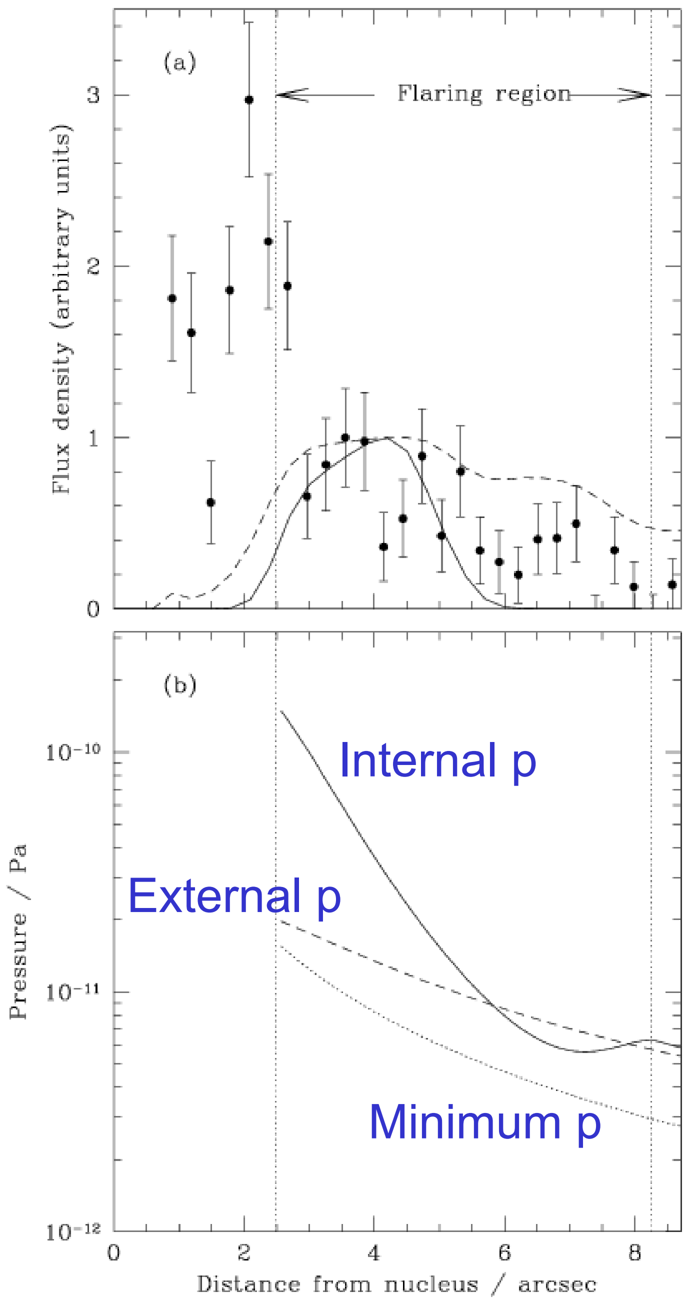


Adiabatic, with same velocity and initial conditions.



Adiabatic model with distributed particle injection.

Where are particles injected?

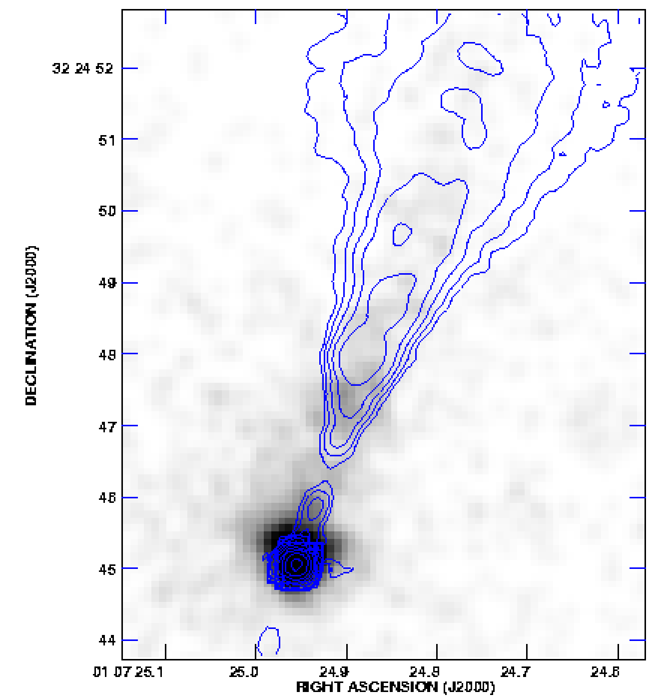


Points – X-ray

Full line – particle injection function

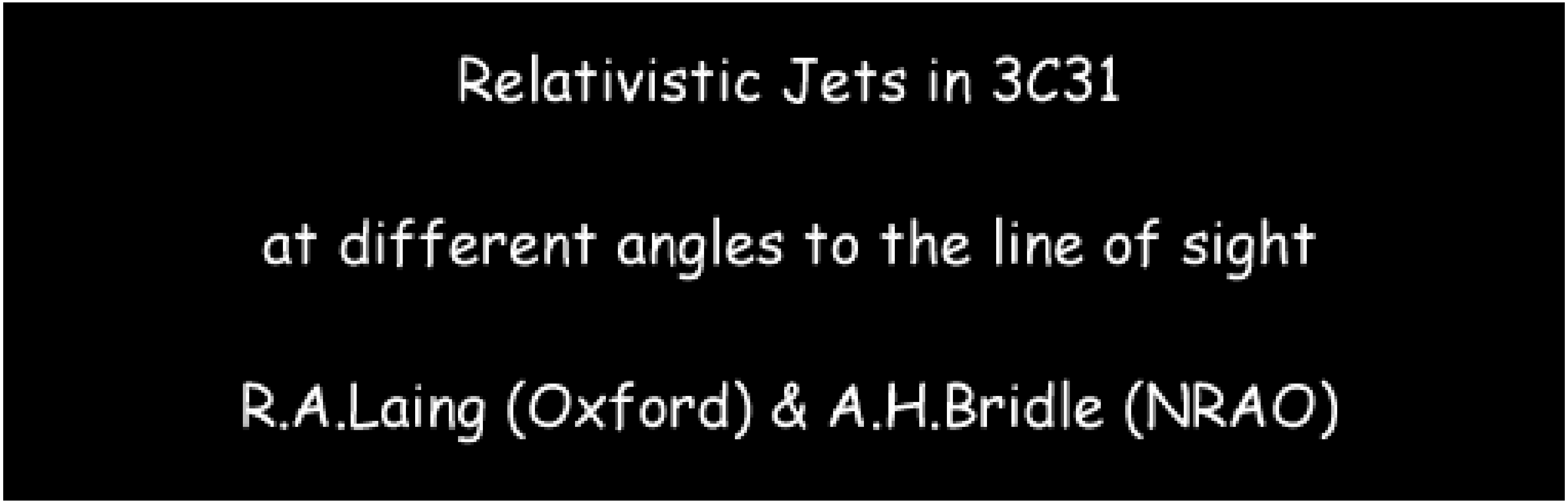
Dashed line - radio

Pressures from conservation-law analysis



VLA + Chandra

Changing the angle to the line of sight: Unified models



Conclusions

- FRI jets are decelerating relativistic flows, which we can now model quantitatively.
- The 3D distributions of velocity, emissivity and field ordering can be inferred by fitting to radio images in total intensity and linear polarization.
- Application of conservation of energy and momentum allows us to deduce the variation of density, pressure and entrainment rate along the jet.
- Boundary layer entrainment and mass input from stars are probably both important in slowing the jet.
- Adiabatic models and flux freezing do not work, although they are closer to observations at large distances.
- Particles must be injected where the jets are fast.