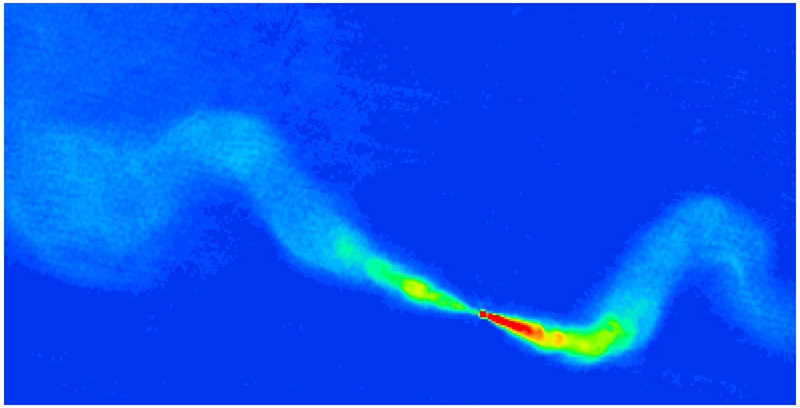
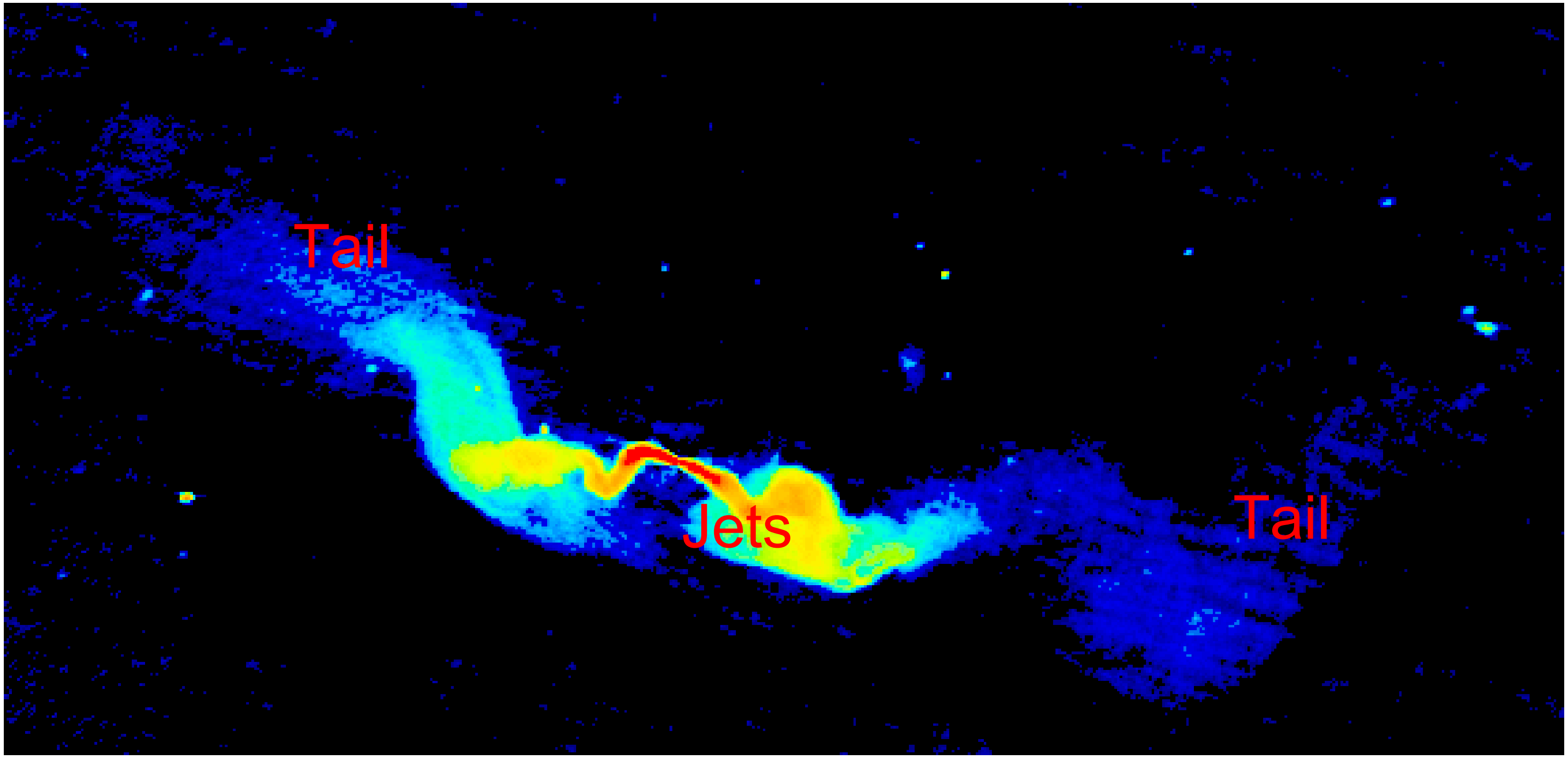
Radio jets as decelerating relativistic flows

Robert Laing (ESO)



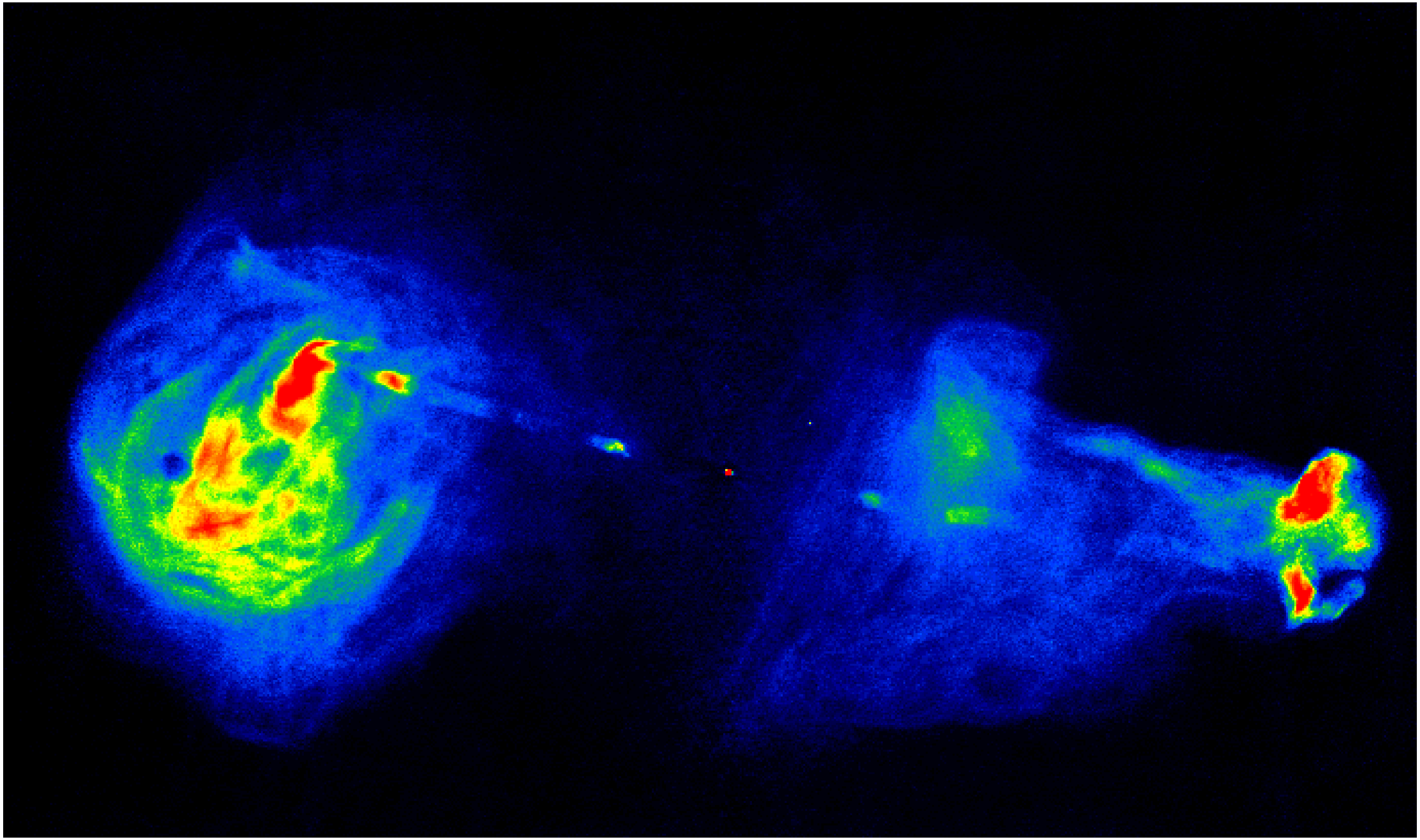
A weak (FRI) radio galaxy



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

FRII radio galaxy



3C 353 (VLA, 8.4 GHz, 0.44 arcsec)
FRII jets remain supersonic (and relativistic) until the hot-spots

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 2004)

Free model of NGC 315 (Canvin et al., MNRAS, nearly)

Alan Bridle, James Canvin – models

Diana Worrall, Martin Hardcastle, Mark Birkinshaw (Bristol UH) – 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 (see later)

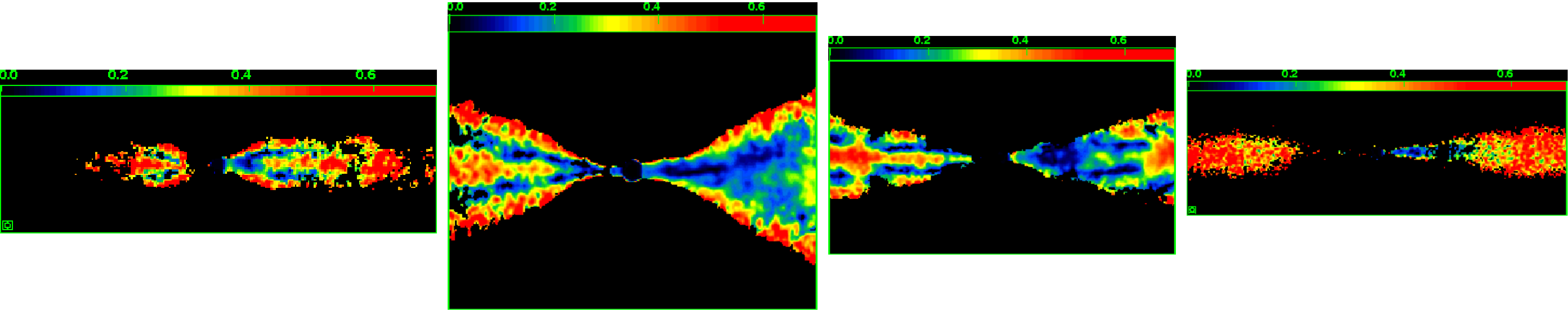
Parameterize geometry, velocity, emissivity and field structure.

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.

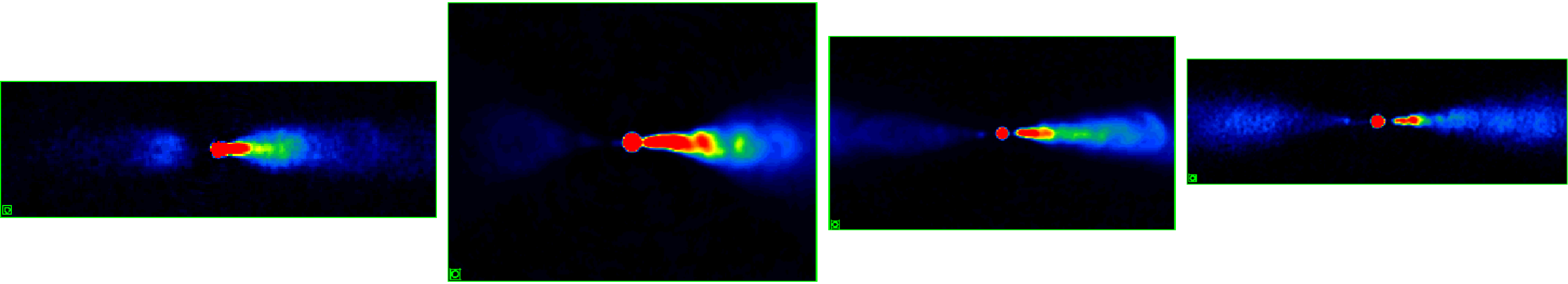
Linear polarization is essential to break the degeneracy between angle and velocity.

Degree of polarization



B2 1553+24 NGC 315 3C 31 B2 0326+29

Correlated asymmetry between I sidedness and polarization



Breaking the $\beta - \theta$ degeneracy

For isotropic emission in the rest frame, jet/counter-jet ratio depends on $\beta\cos\theta$ – how to separate?

But B is not isotropic, so rest-frame emission (IQU) depends on angle to line of sight in that frame θ'

$\sin\theta' = D \sin\theta$ and $D = [\Gamma(1 \pm \beta\cos\theta)]^{-1}$ is different for the main and counter-jets

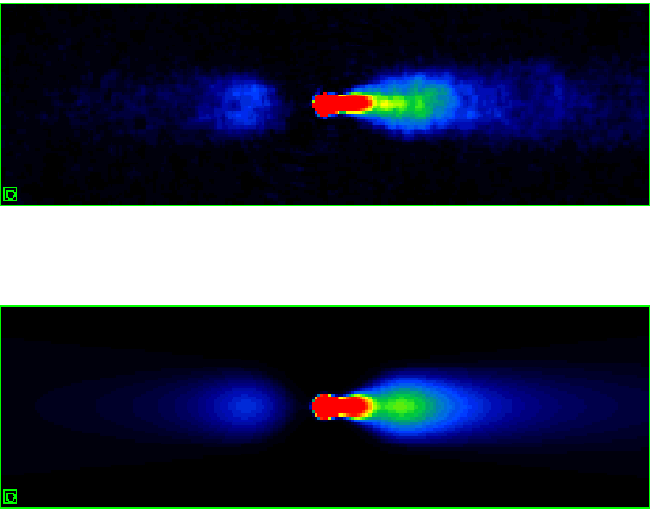
So the polarization is different for the two jets

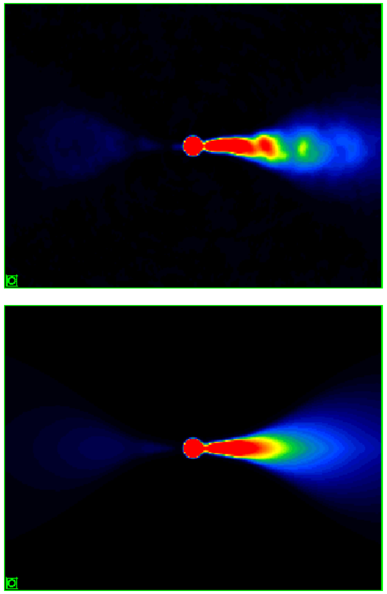
If we knew the field, we could separate β and θ

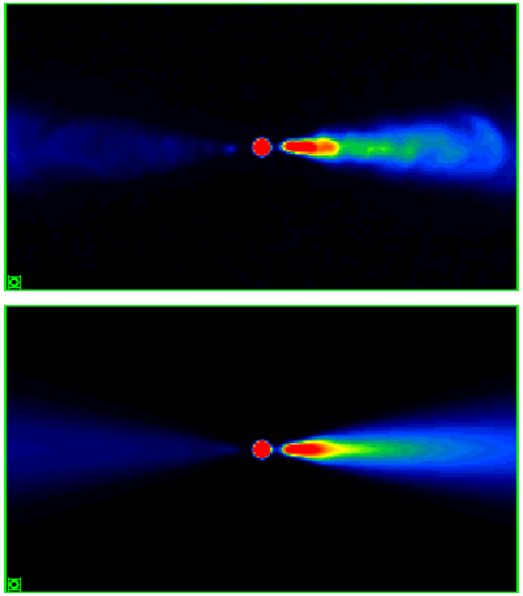
We don’t, but we can fit the transverse variation of polarization and determine field component ratios

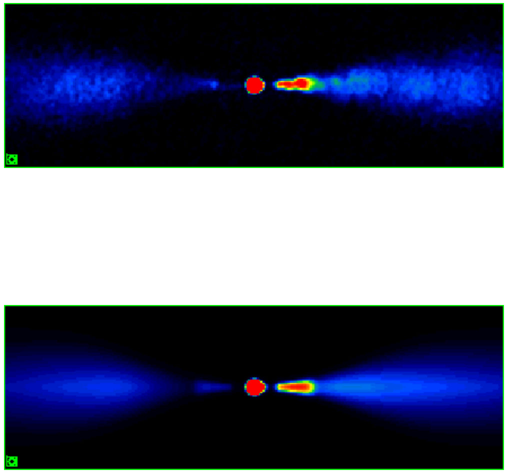
Need good transverse resolution and polarization

Total Intensity





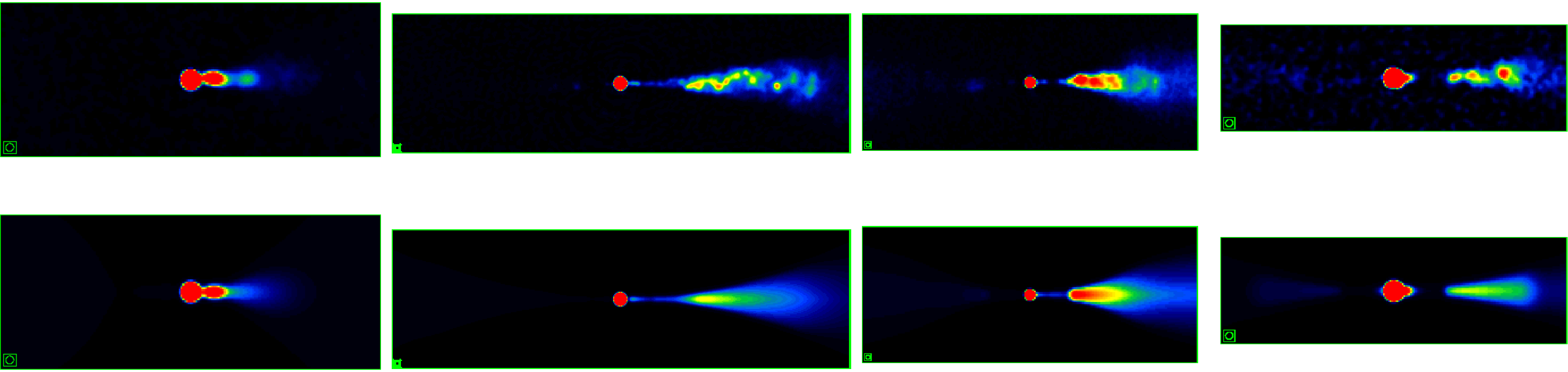




θ 8° 37° 52° 64°

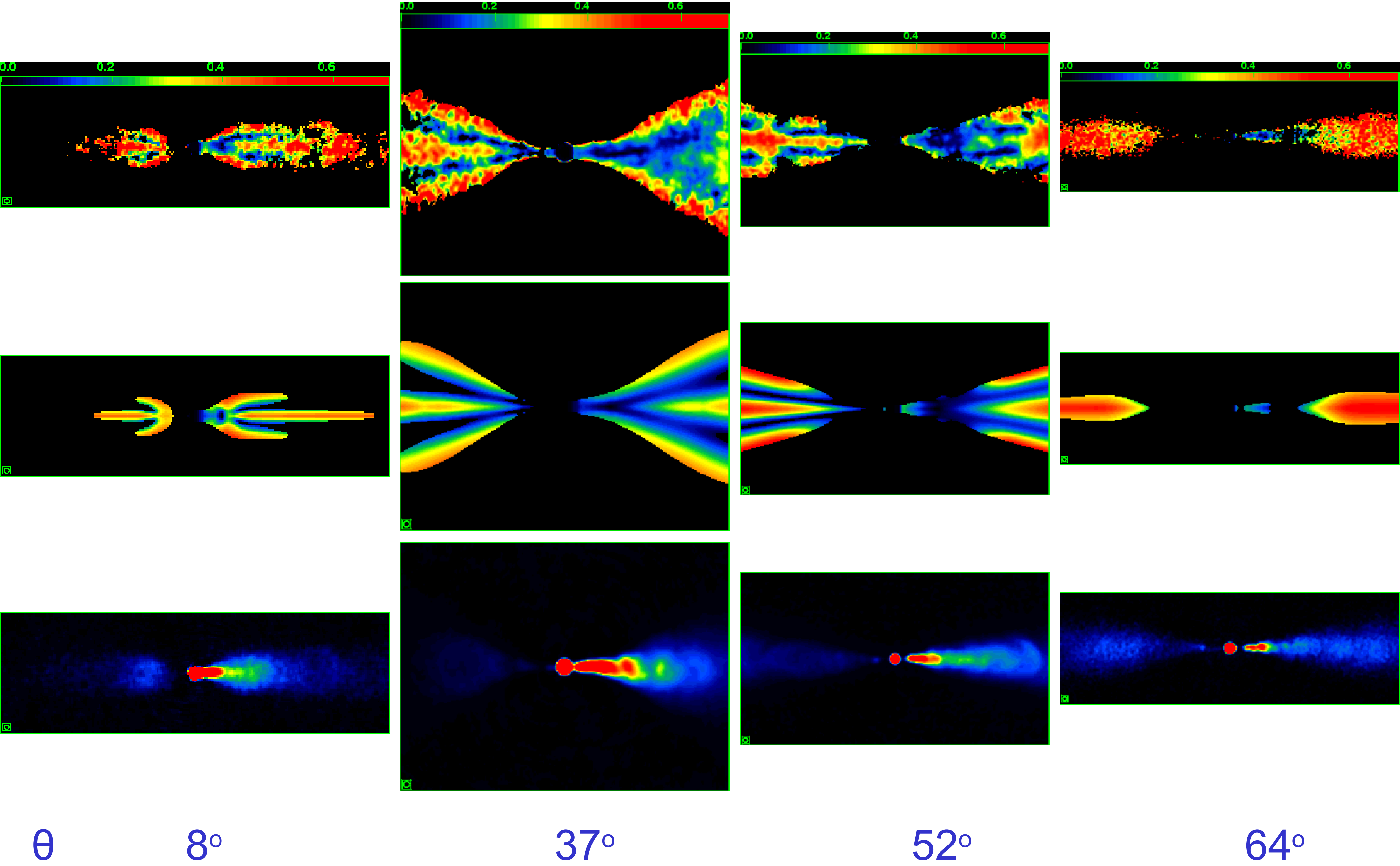
B2 1553+24 NGC 315 3C 31 B2 0326+39

Total Intensity (high resolution)

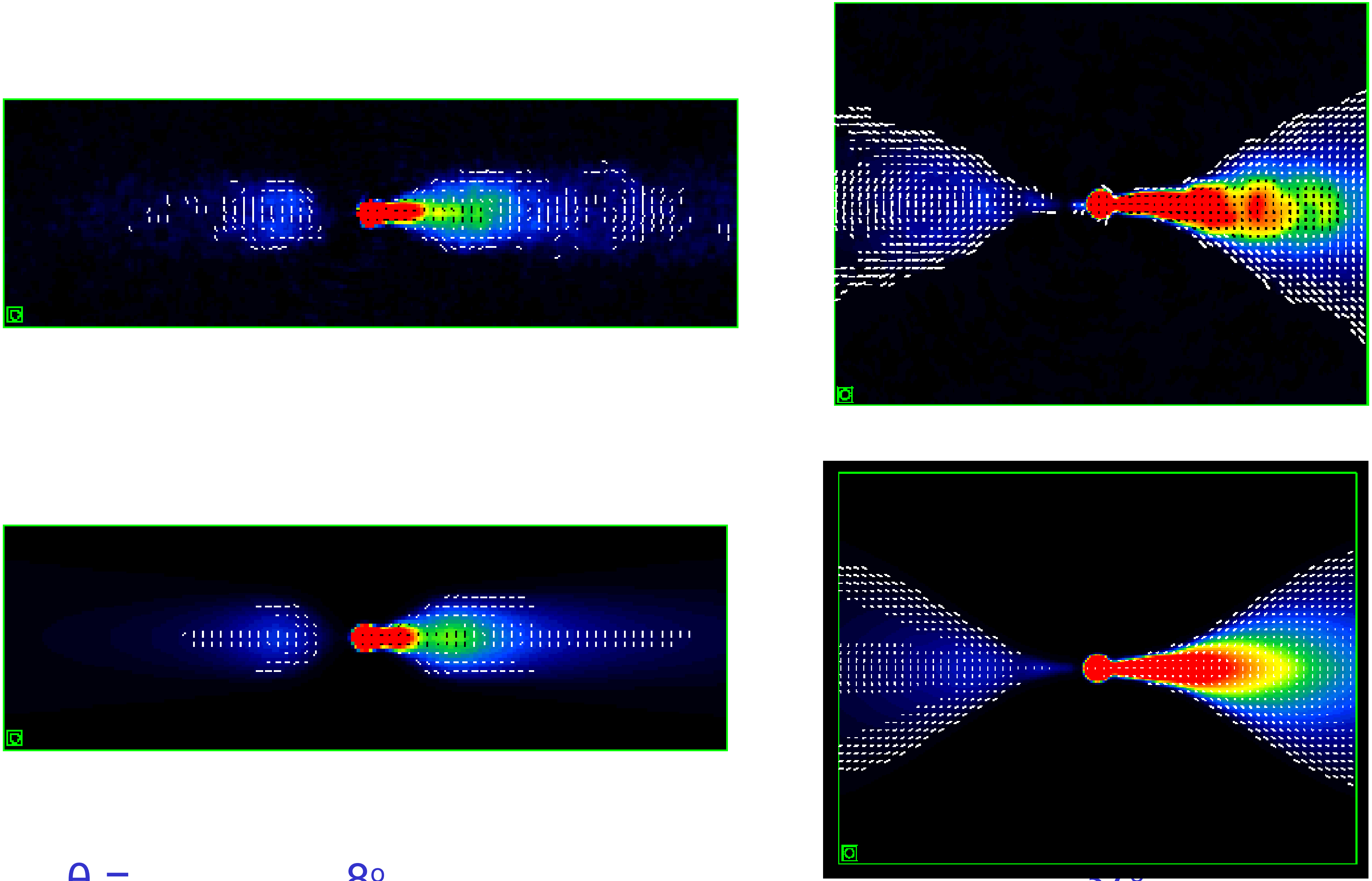


θ = 8° 37° 52° 64°

Degree of polarization



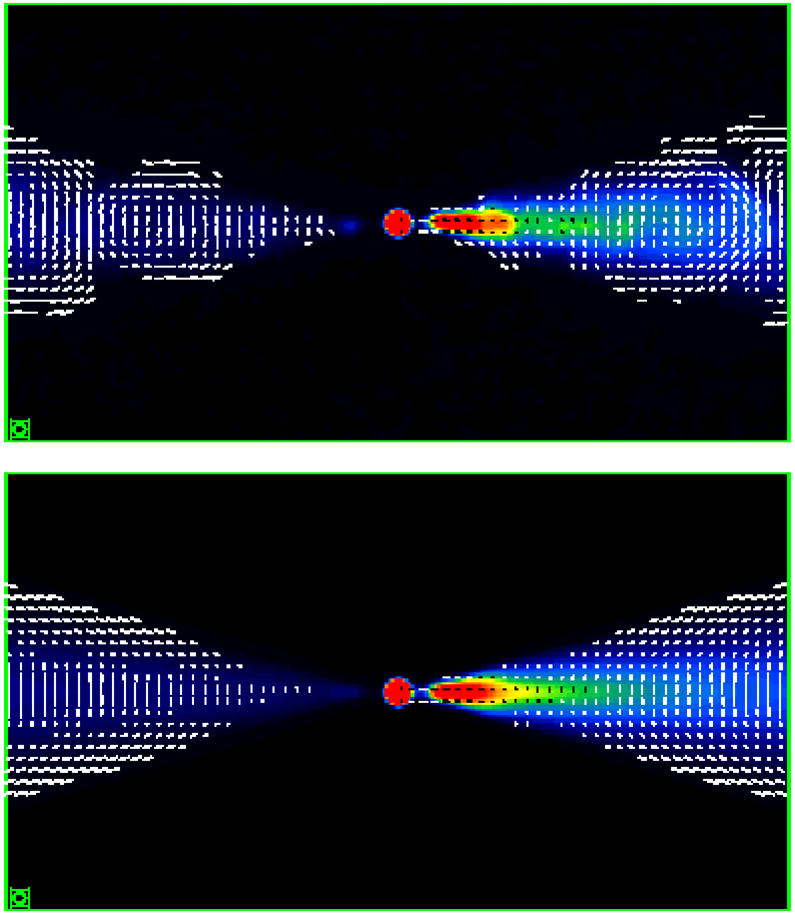
Apparent magnetic field (1)

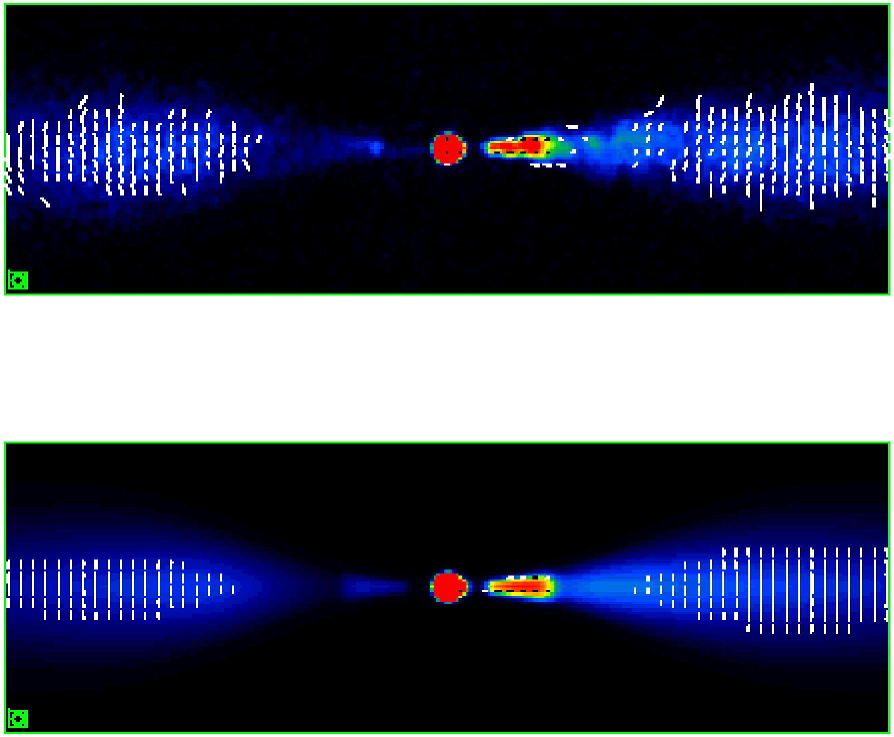


θ = 8°

37°

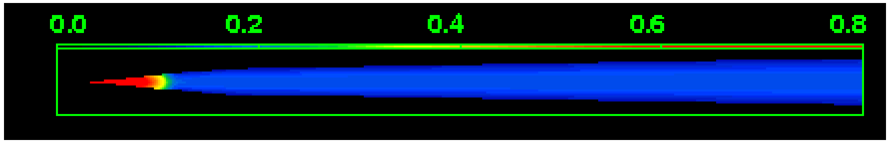
Apparent magnetic field (2)



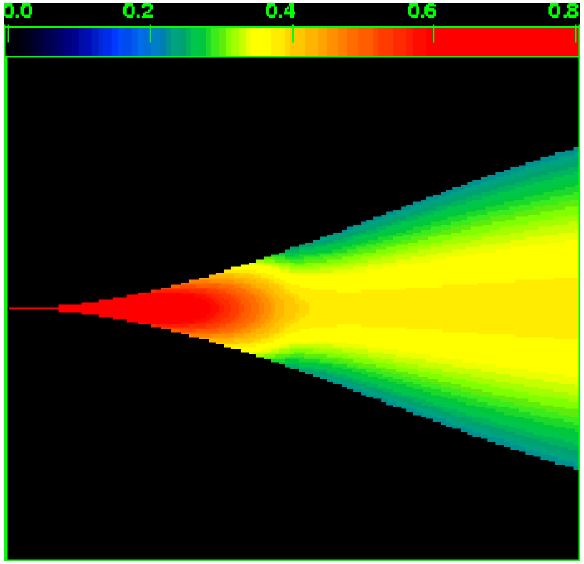


θ =   52°   64°

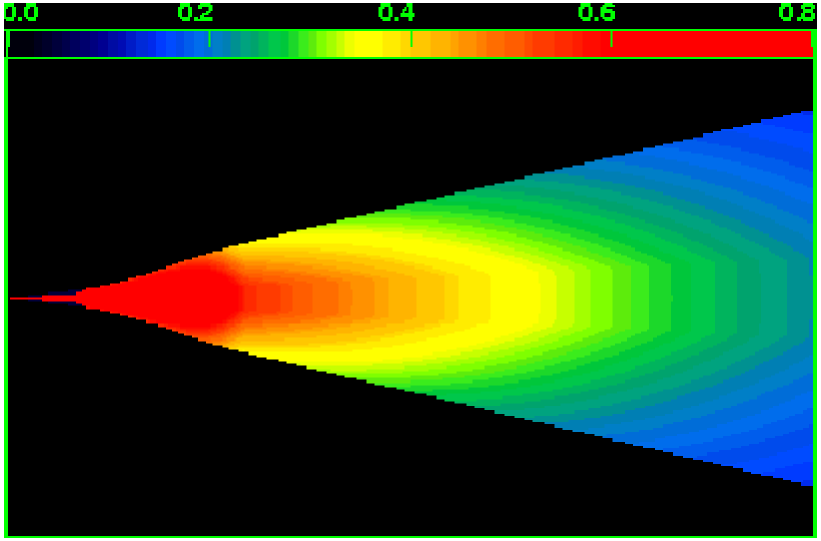
Velocity $\beta = v/c$



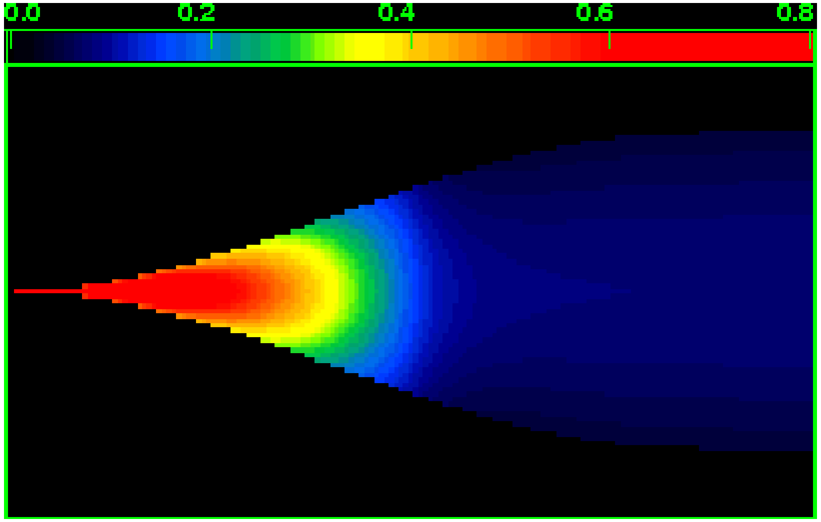
B2 1553+24



NGC 315



3C 31



B2 0326+39

Velocity, spines and shear layers

$\beta \approx 0.8$-0.9 where the jets first brighten

All of the jets decelerate abruptly in the flaring region, but at different distances from the nucleus.

At larger distances, three have roughly constant velocities in the range $\beta \approx 0.1 – 0.4$ and one (3C 31) decelerates slowly

They have transverse velocity gradients, with edge/on-axis velocity consistent with 0.7 everywhere.

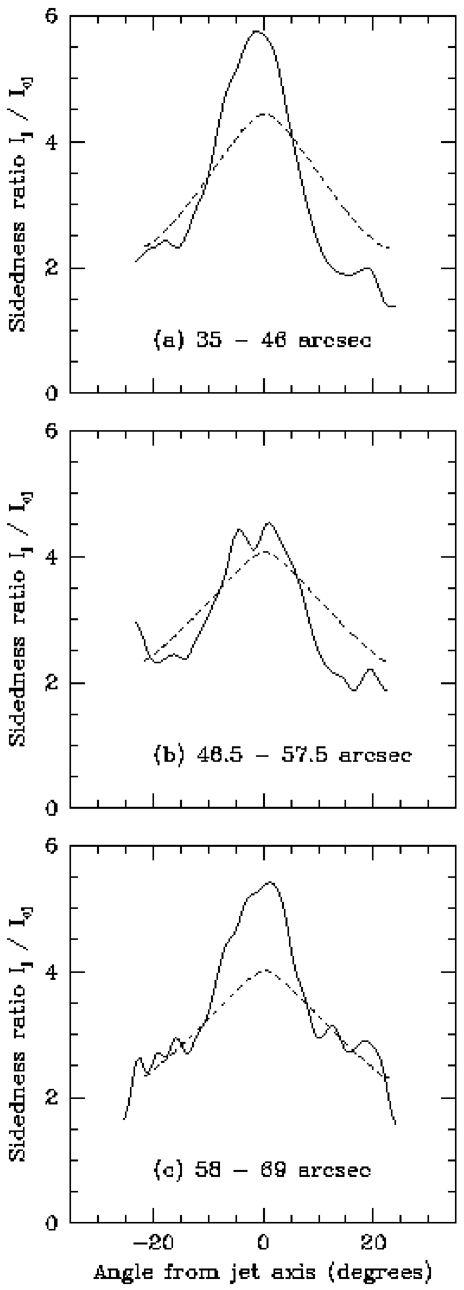
No obvious low-velocity wings.

No large differences in Γ or narrow shear layers

We no longer favour a separate spine – transverse profiles are as well fit by a single truncated Gaussian (but see next slide)

Large uncertainties where jets are slow or poorly resolved

Transverse velocity profile may be more complex



NGC 315 (best resolved case)

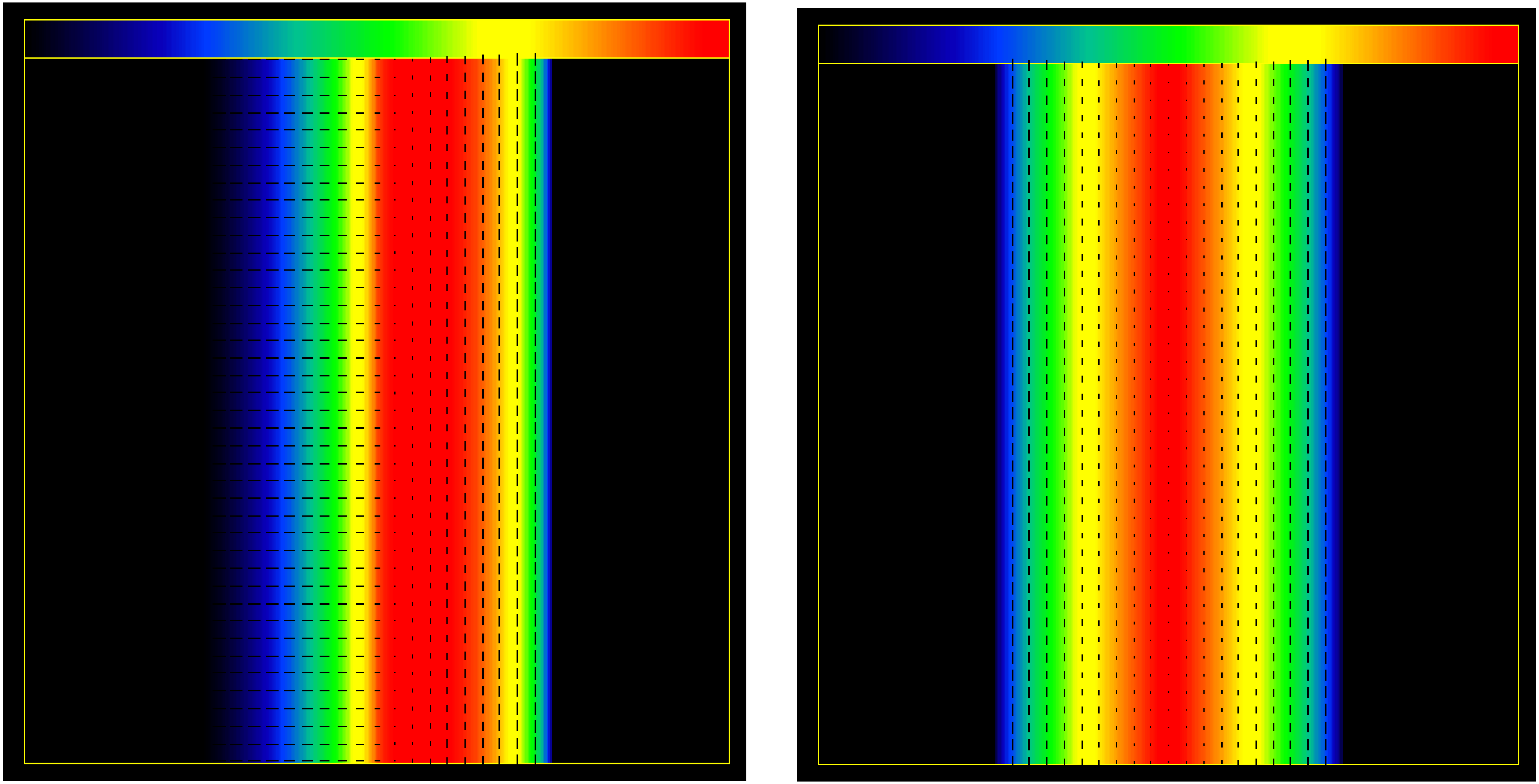
Full line = measured sidedness ratio
Dashed = model (truncated Gaussian velocity profile)

Shear at intermediate radii?

Helical Fields?

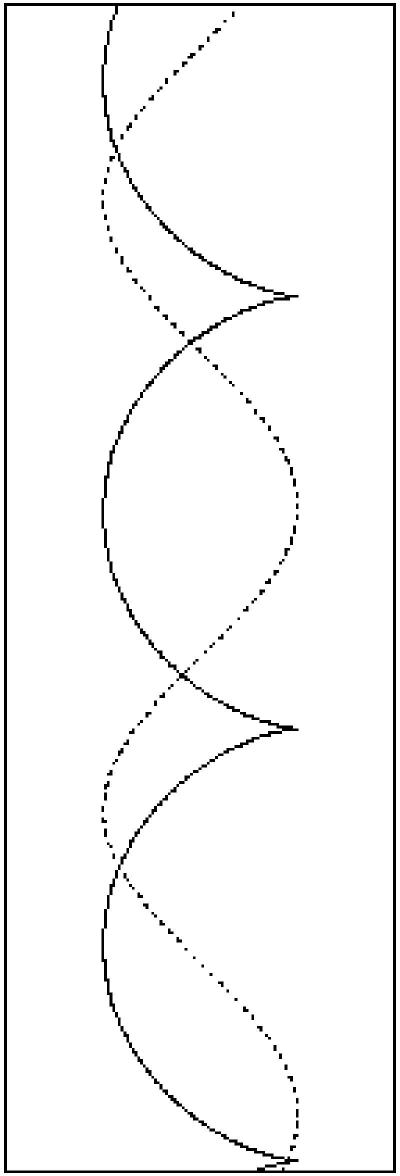
$\theta = 45^o$

$\theta = 90^o$



Synchrotron emission from a helical field with pitch angle 45^o

Helical Fields?



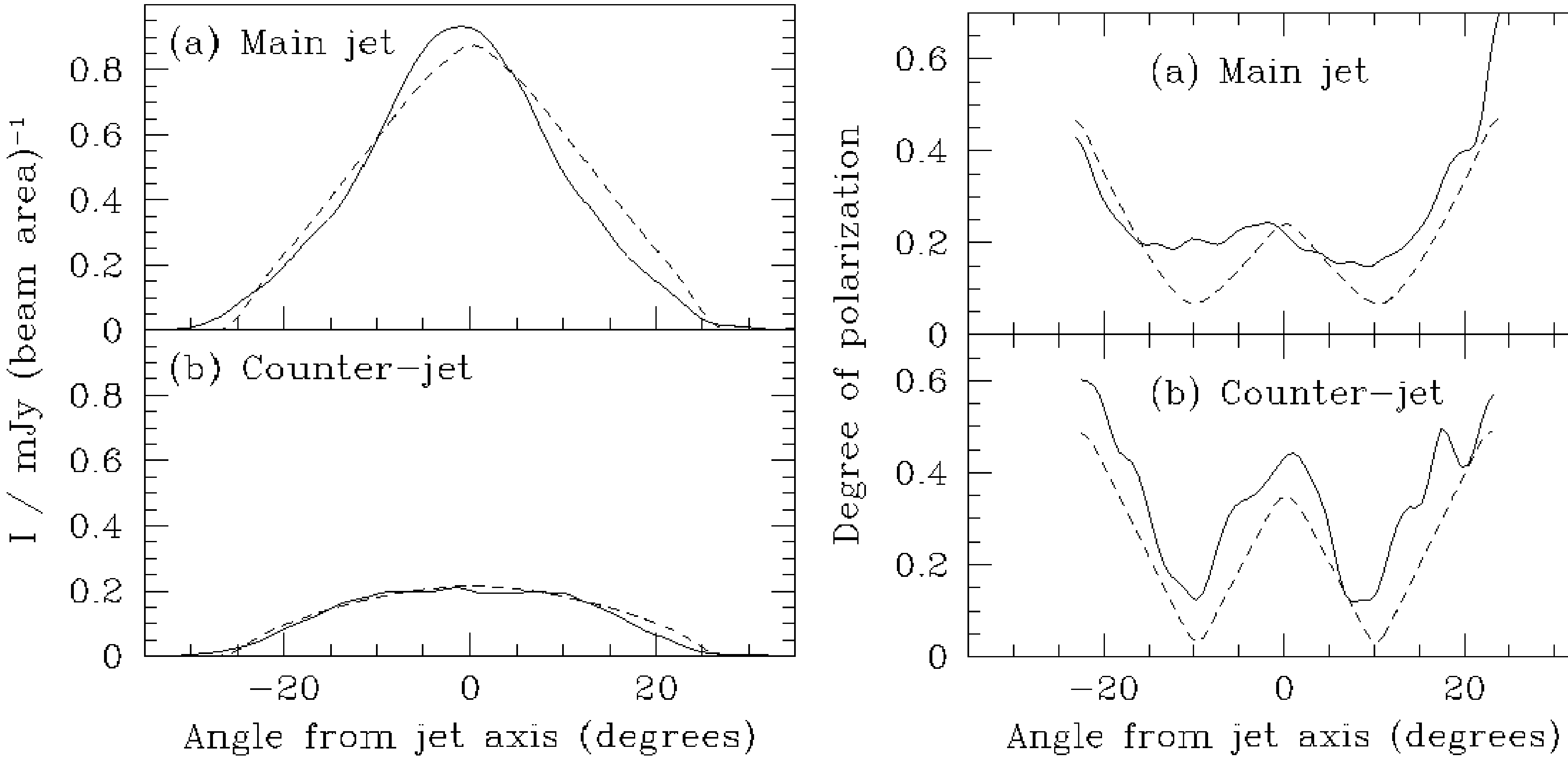
Helical fields generally produce brightness and polarization distributions which have asymmetric transverse profiles

The profiles are symmetrical only if:
- there is no longitudinal component or
- the jet is at 90° to the line of sight in the rest frame of the emitting material

The condition for the approaching jet to be observed side-on in the rest frame is $\beta = \cos\theta$ - also the condition for maximum Doppler boost: hence a selection effect in favour for blazar jets

Never true in counter-jet unless $\beta = 0$ or $\theta = 90^{o}$

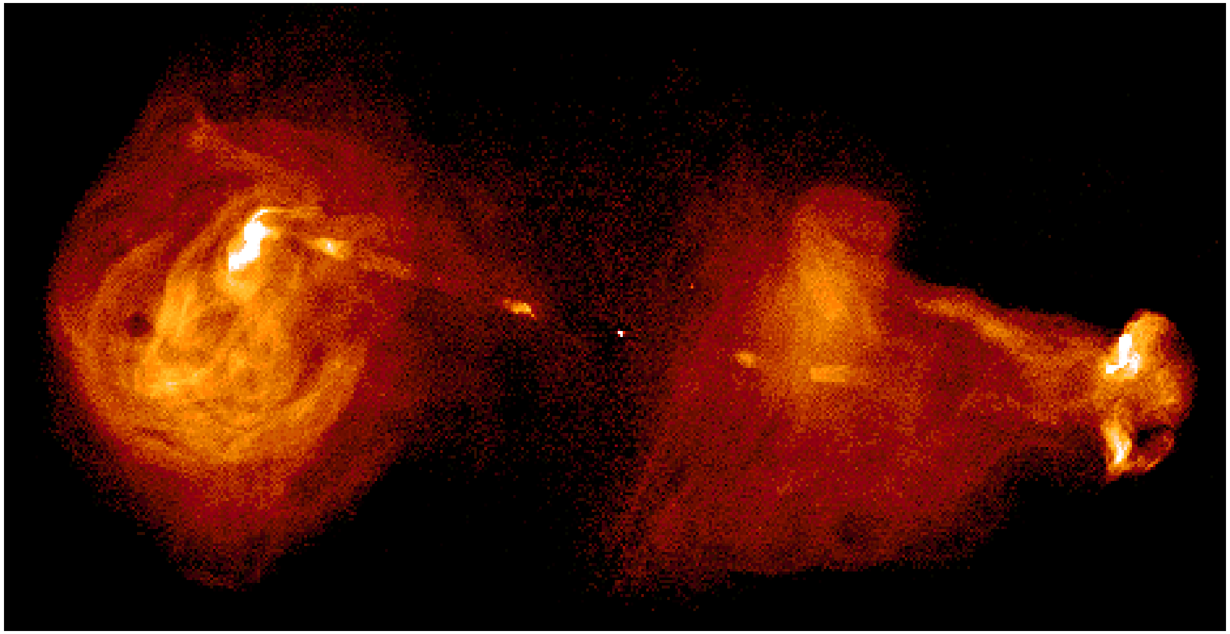
Helical Fields in FRI jets?



Transverse profiles of I and p for NGC315 – symmetrical, especially in counter-jet

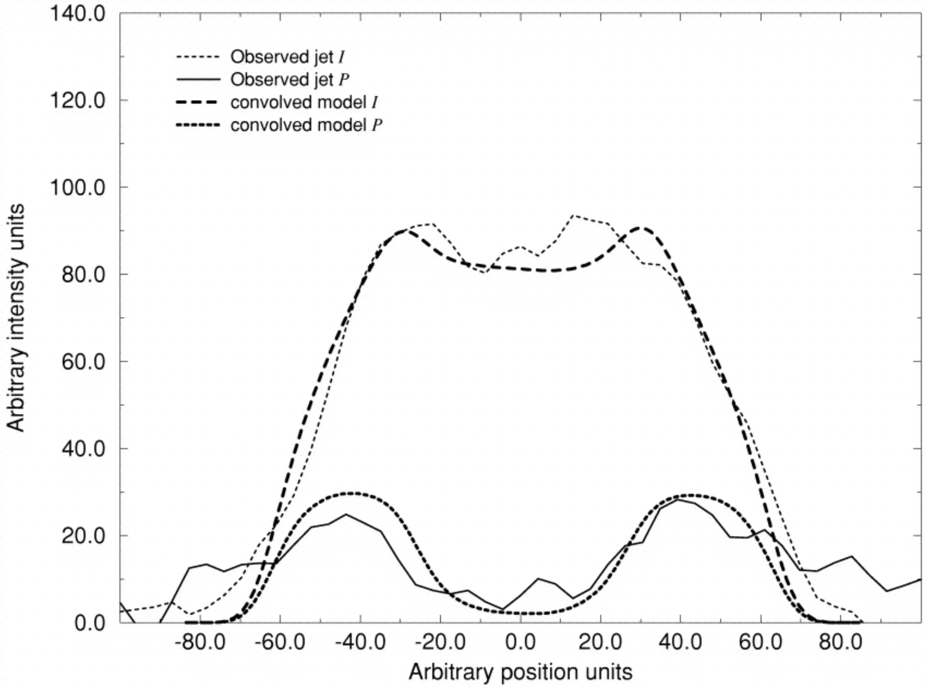
Not a helical field (but could be ordered toroidal + longitudinal with reversals)

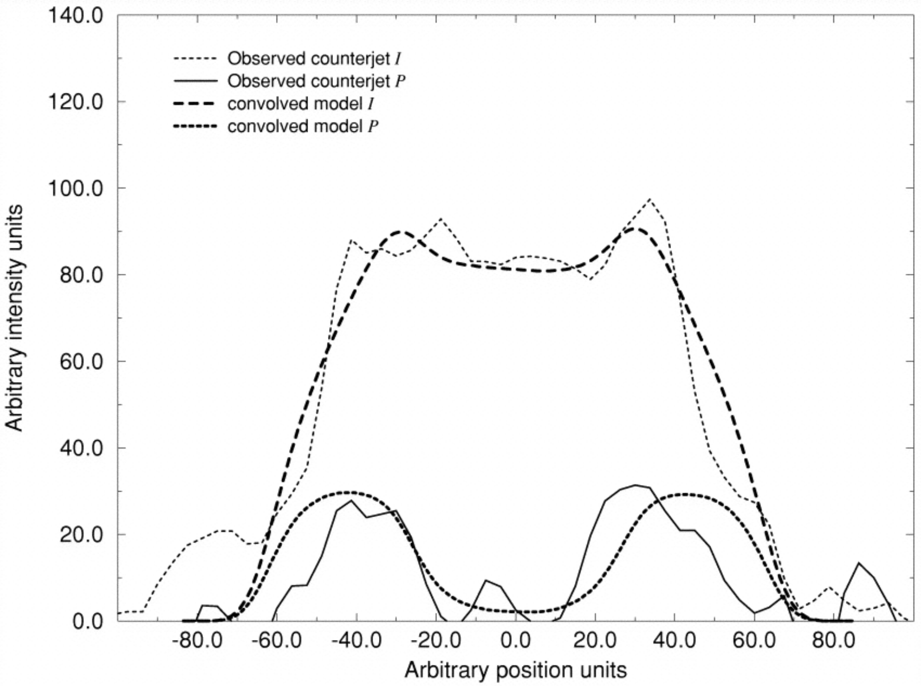
Helical Fields in FRII jets?



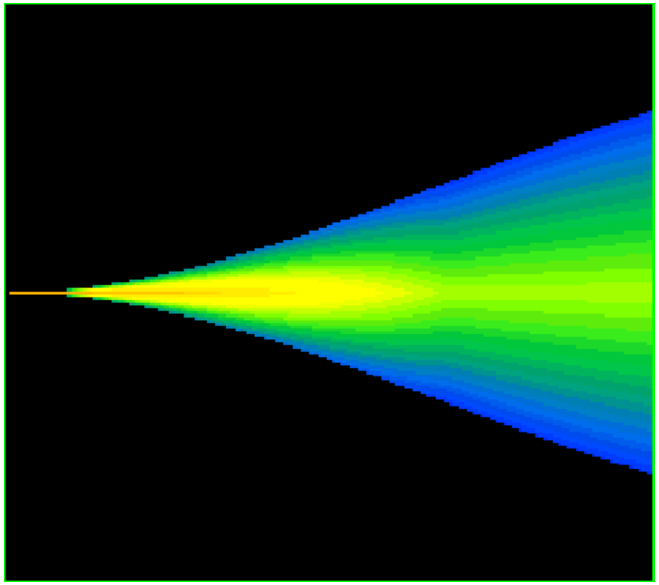
3C353
(Swain, Bridle & Baum 1998)

Profiles are very symmetrical – field probably not helical

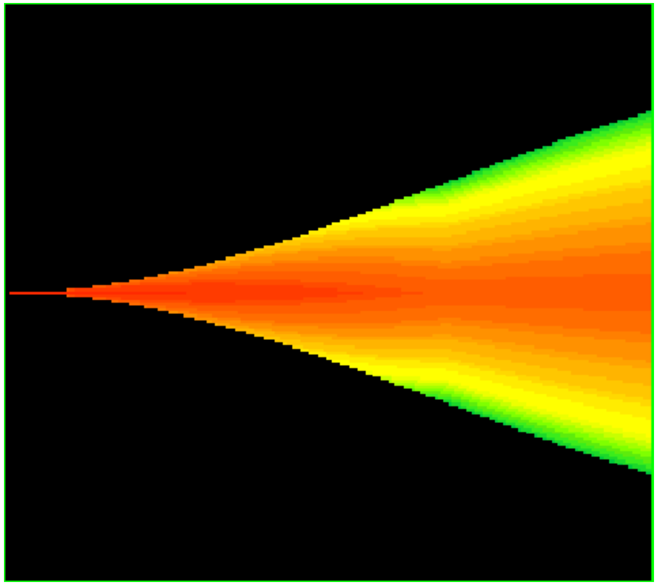




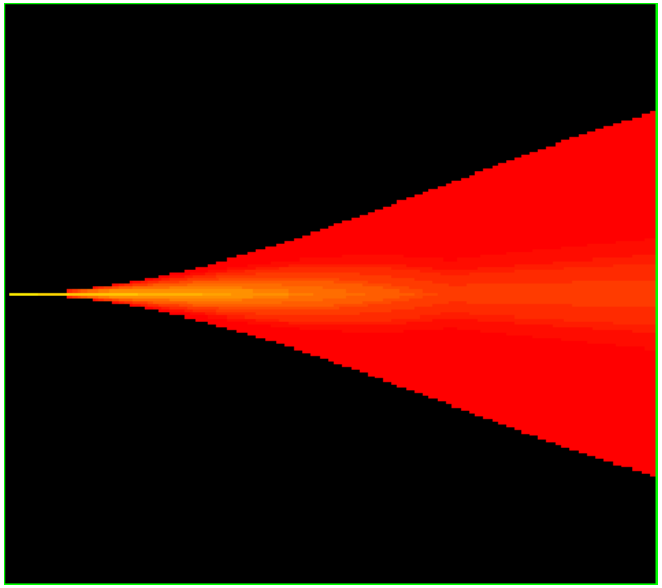
Field component evolution in NGC 315



Radial



Longitudinal



Toroidal

Field structure

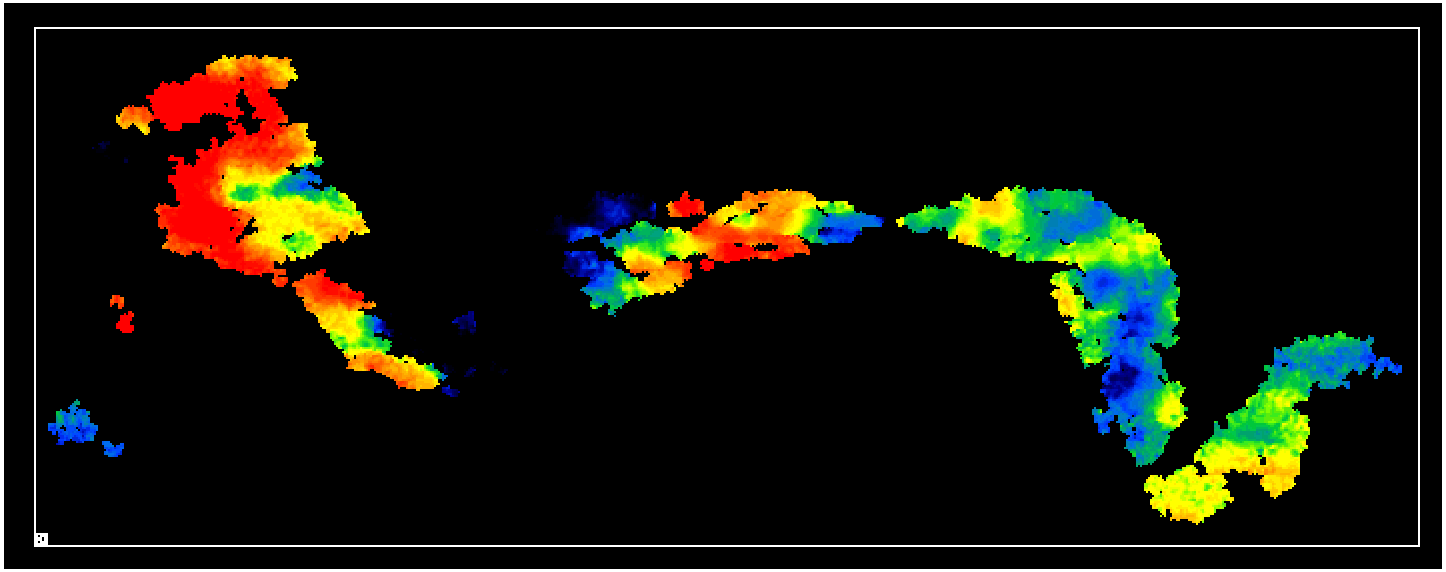
Fields on kpc scales are not vector-ordered helices. Nor should they be (poloidal flux proportional to r^{-2})

Transverse (i.e. radial+toroidal) field spine + longitudinal-field shear layer predicts field transition closer to the nucleus in the main jet – not observed.

Field is primarily toroidal + longitudinal, with smaller radial component.

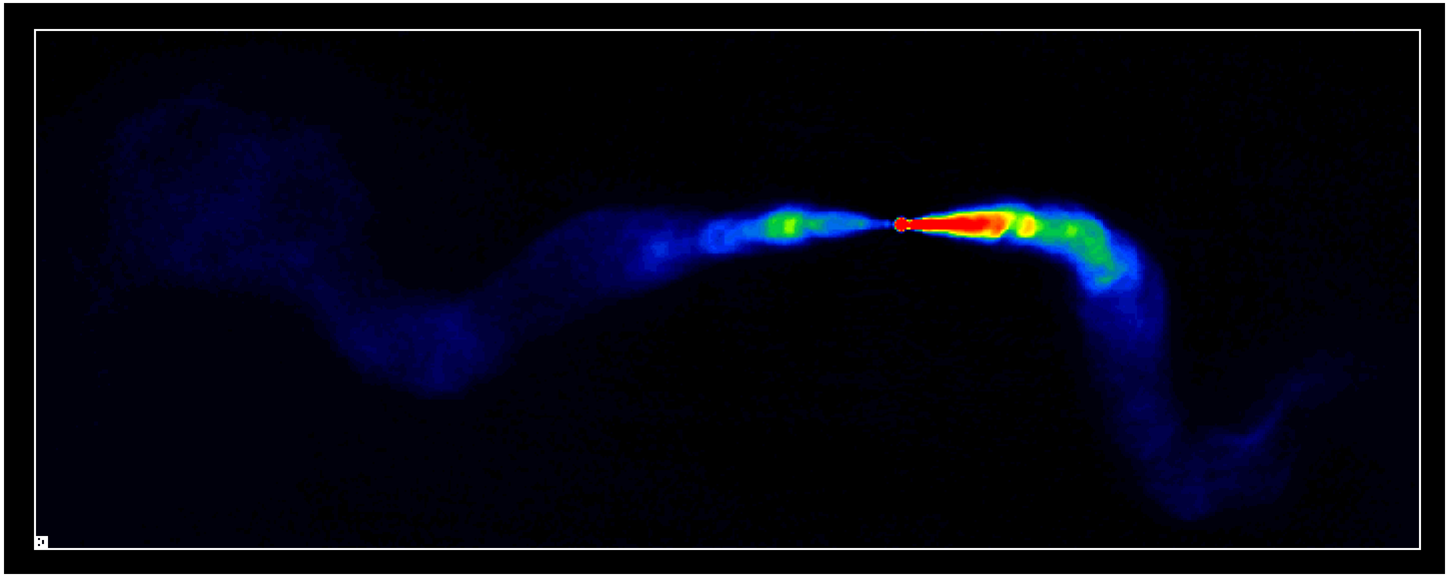
Toroidal component could be ordered, provided that the longitudinal field has many reversals.

Digression: rotation measure gradients



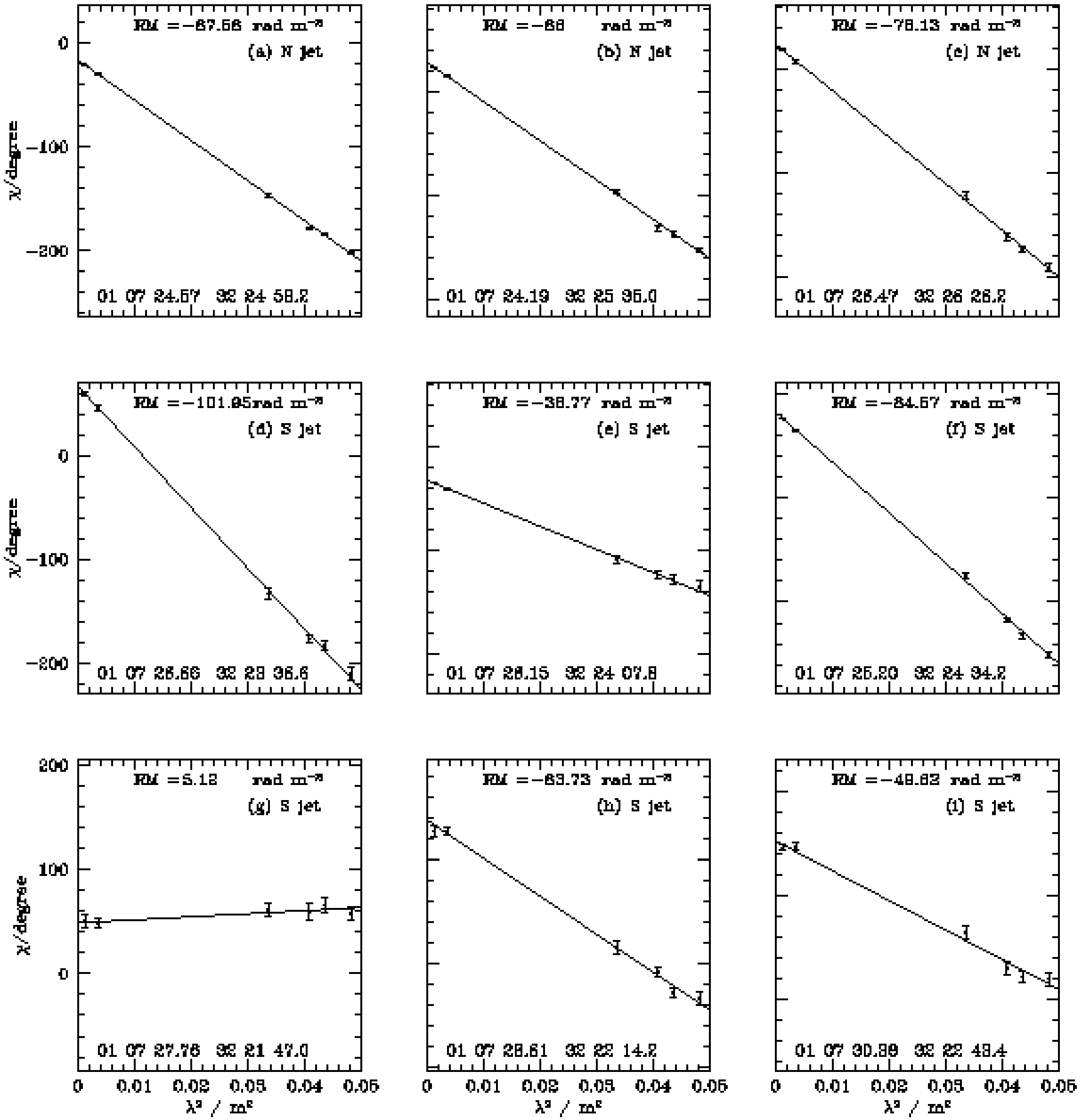
3C 31
Rotation
measure

Counter-jet Main jet



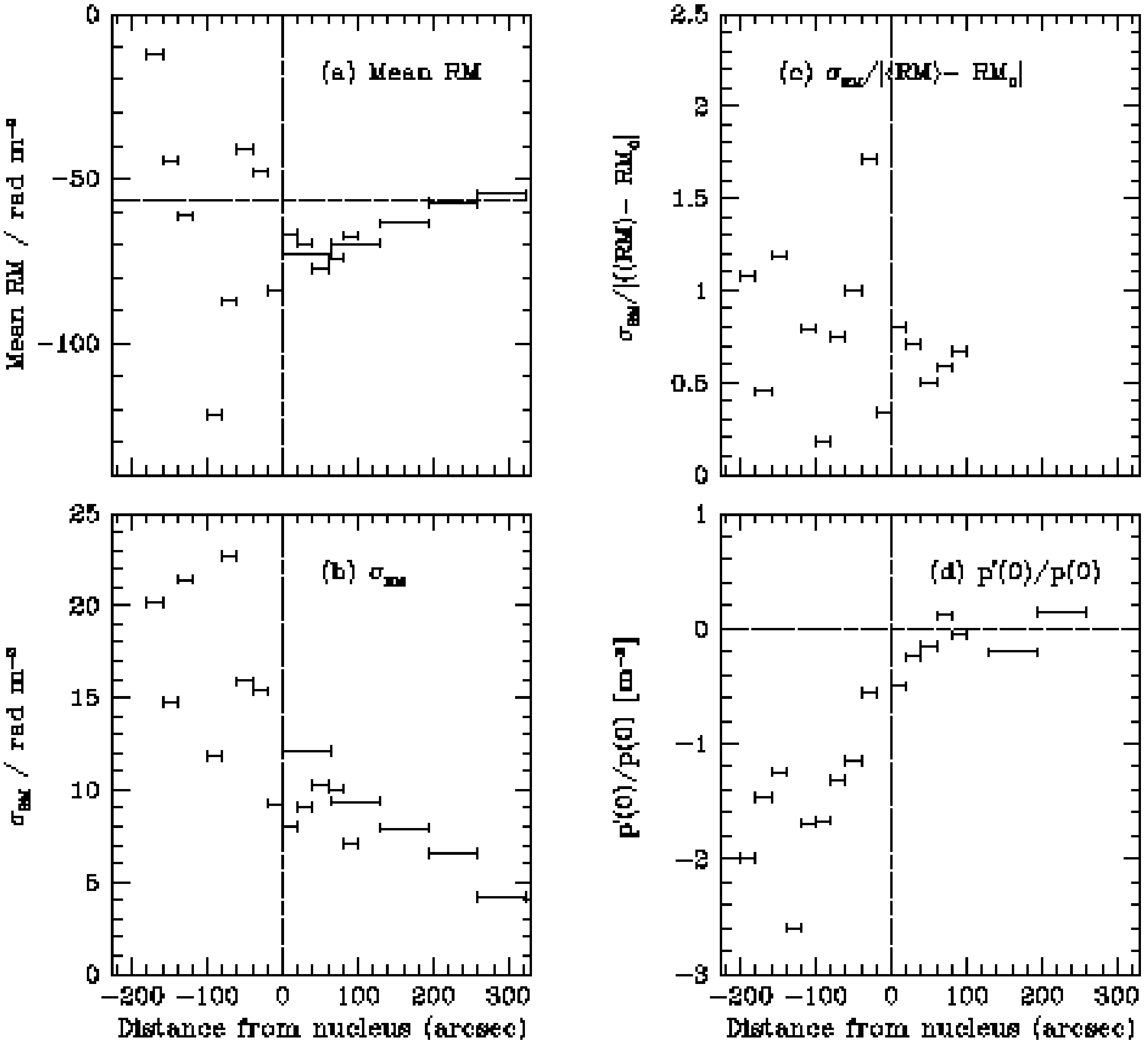
Total
intensity

Linearity of χ – λ² relation

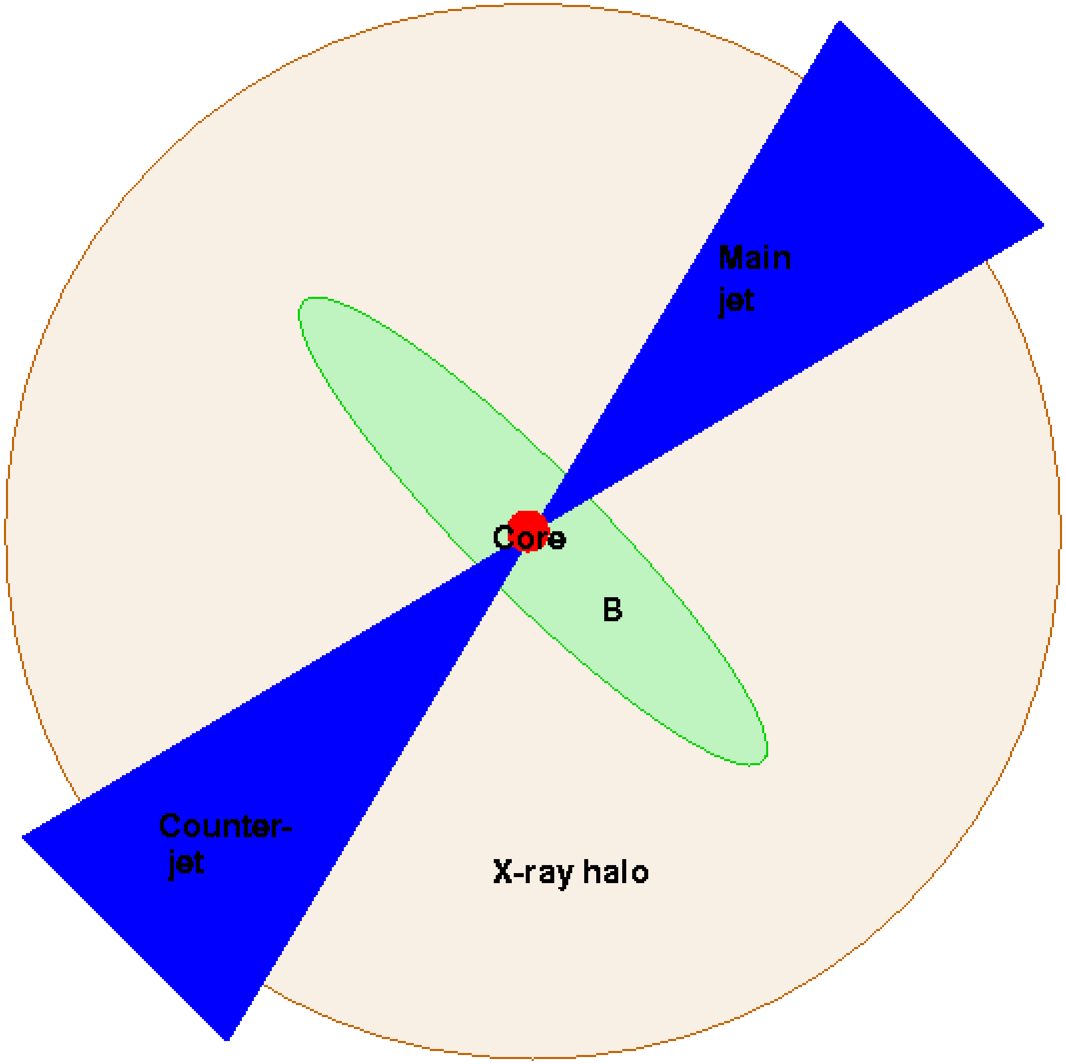


Linearity of χ - λ² relation and very small depolarization requires foreground Faraday rotation

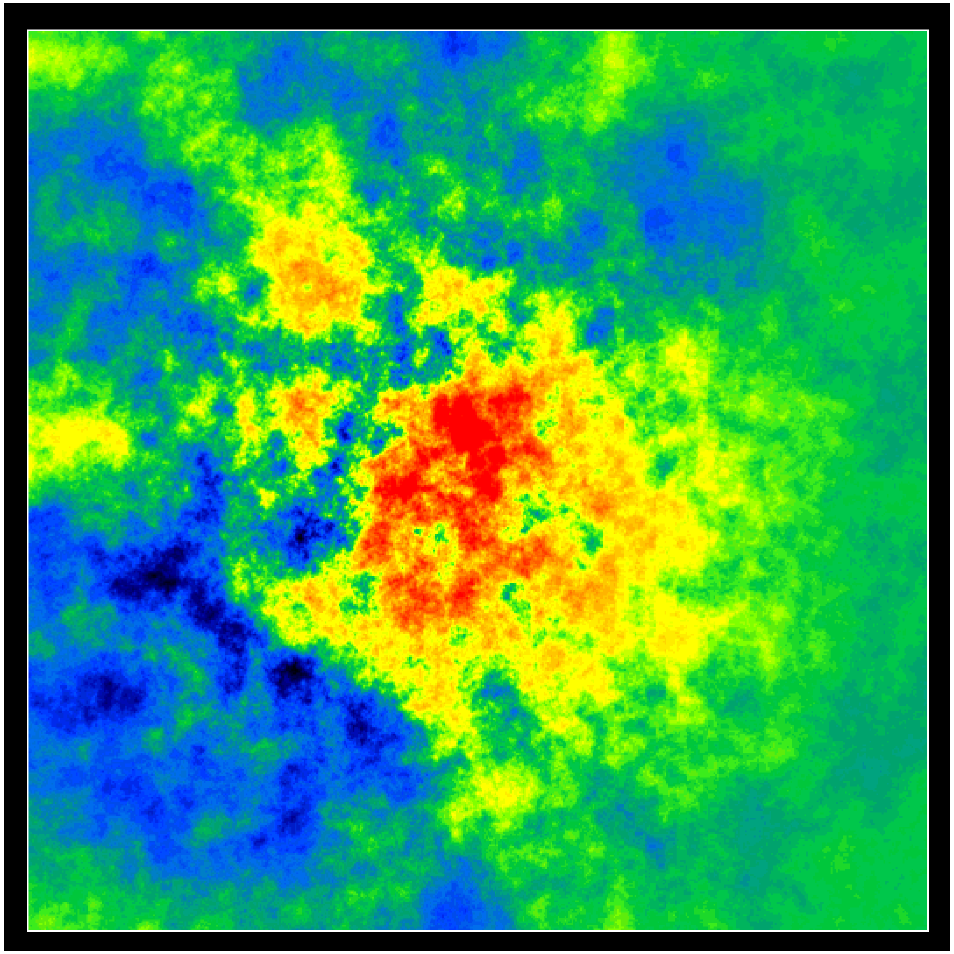
Variation of RM and depolarization along jets



Geometry for RM asymmetries



Modelling RM variations



Realisation of a random magnetic field with a power-law energy spectrum in the group gas associated with 3C 31

RM calculated for a plane at 52° to the line of sight, as for the jet model (near side on the right)

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**.

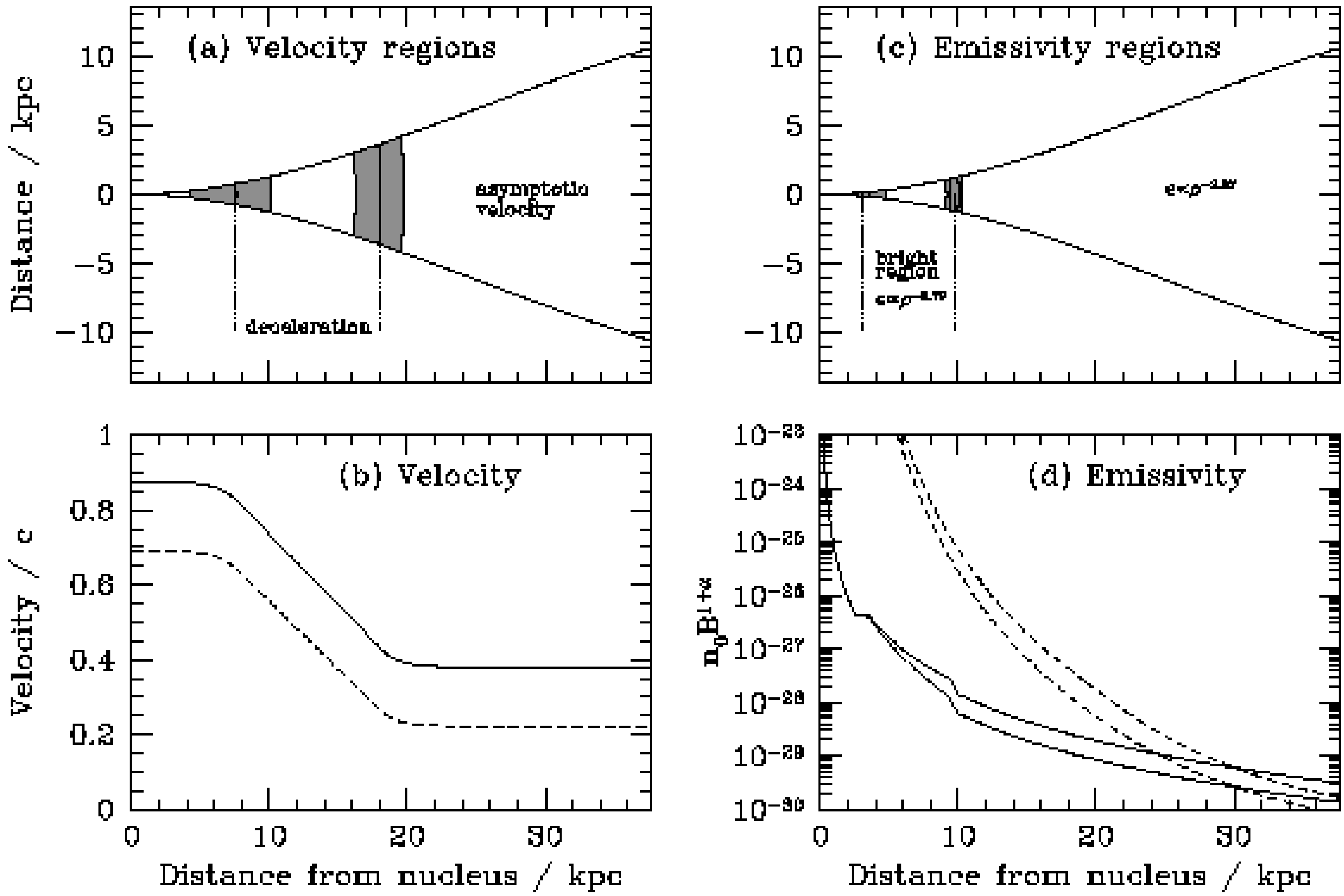
Dominant field component at large distances is **toroidal**.

The longitudinal component can be significant 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.

Geometry, velocity and emissivity



NGC 315

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.

Include buoyancy

Well-constrained solutions exist.

Key assumptions:

Energy flux = momentum flux x c

Pressure balance in outer region

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

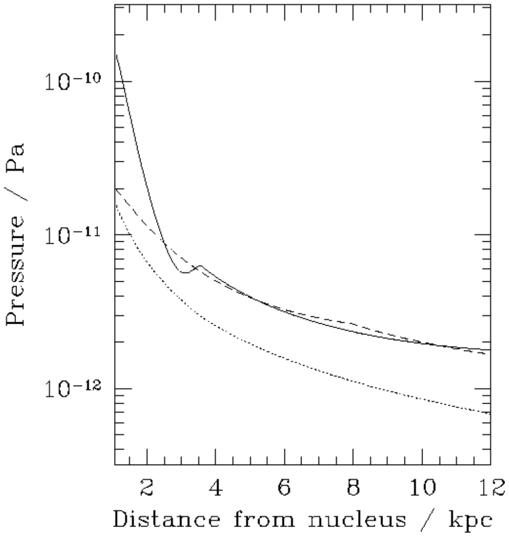
Density 2×10^{-27} kgm^{-3}

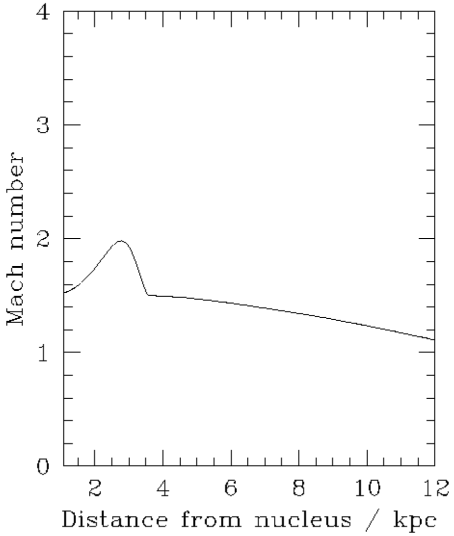
Mach number 1.5

Entrainment rate 1.2×10^{10} $kgkpc^{-1}s^{-1}$

Presssure, density, Mach number, entrainment

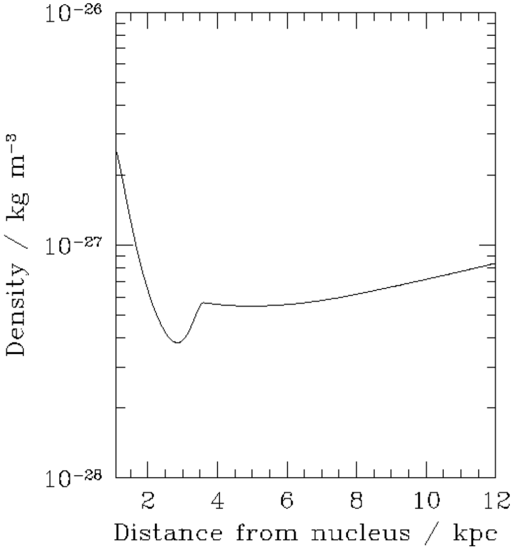
Pressure

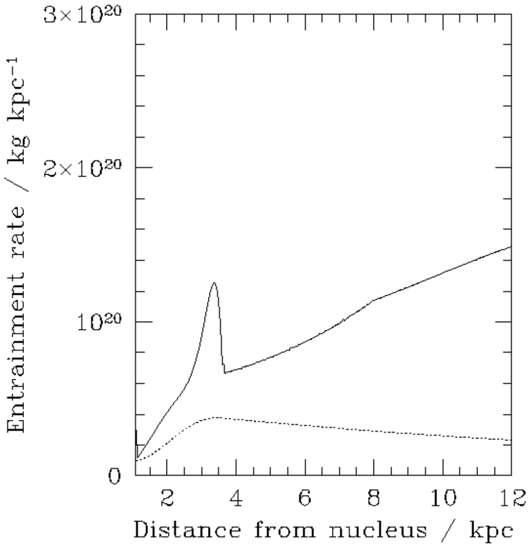




Mach number (transonic)

Density





Entrainment rate

What are the jets made of?

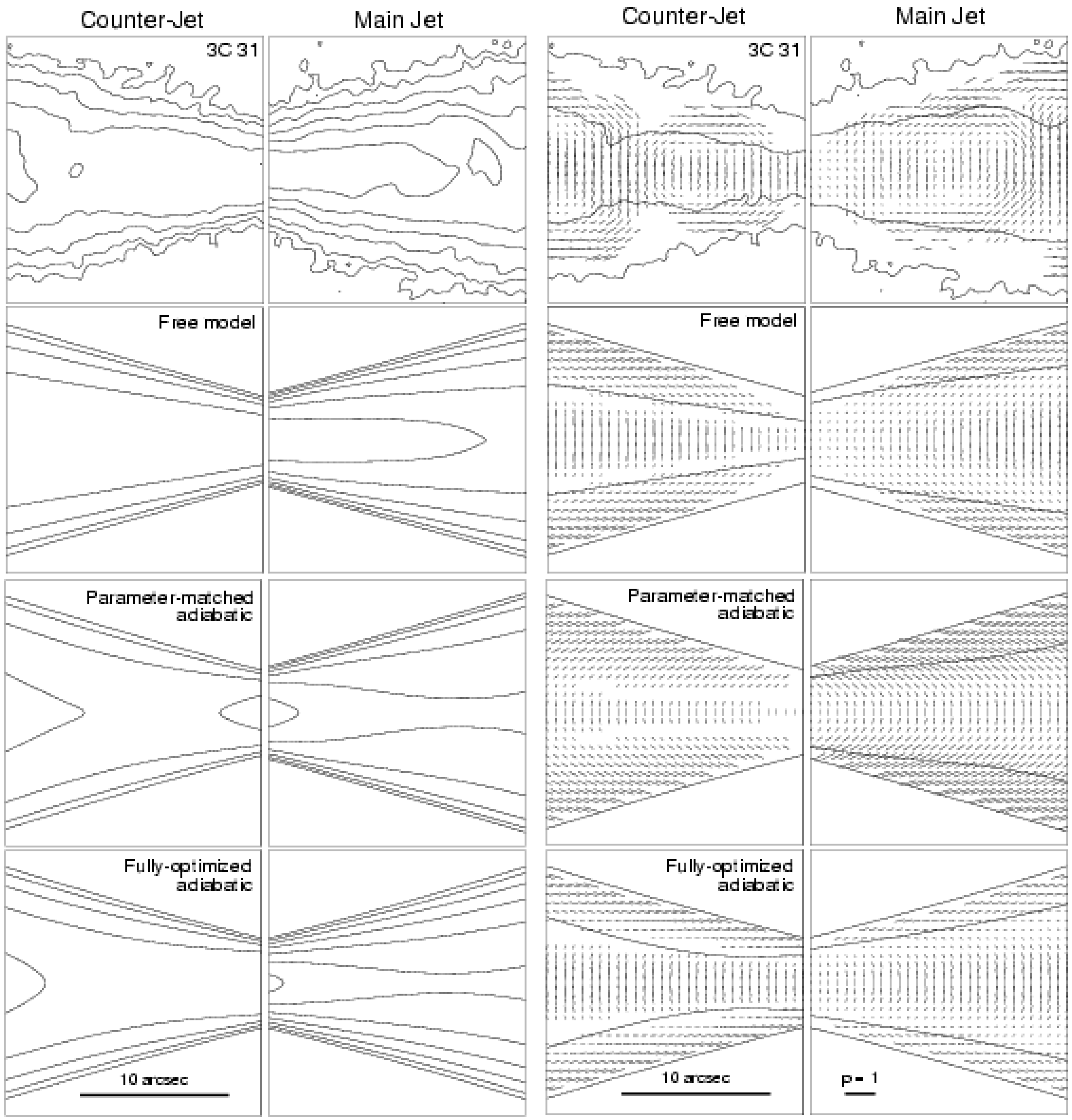
$\rho = 2.3 \times 10^{-27}$ kg m^{-3} (equivalent to 1.4 protons m^{-3}) at the flaring point.

For a power-law energy distribution of radiating electrons, $n = 60\,\gamma_{\rm min}^{-1.1}$ m^{-3} ($\sim 10^{-28}\,\gamma_{\rm min}^{-1.1}$ 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 $\gamma_{\rm min} = 20 - 50$ (not observable).

Adiabatic models



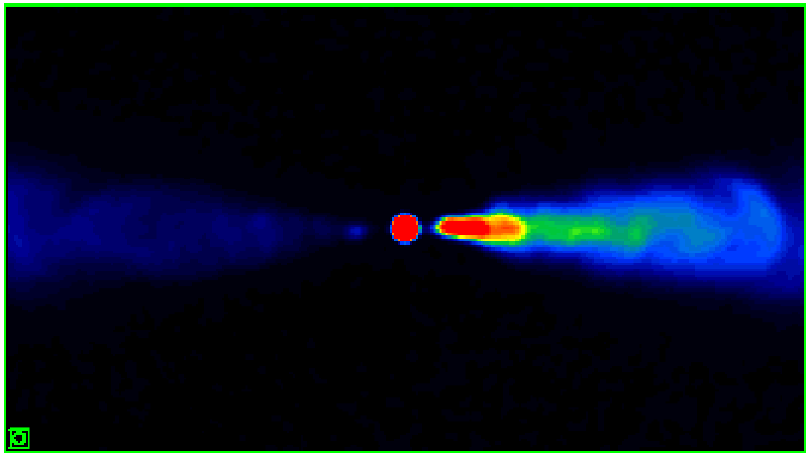
Set initial conditions at start of outer region.

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

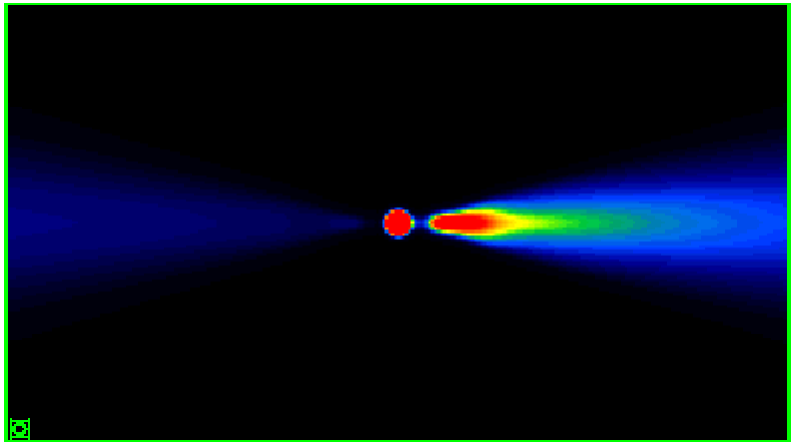
Adiabatic models give a reasonable fit, but do not get either the intensity or polarization quite right.

Not surprising if the flow is turbulent?

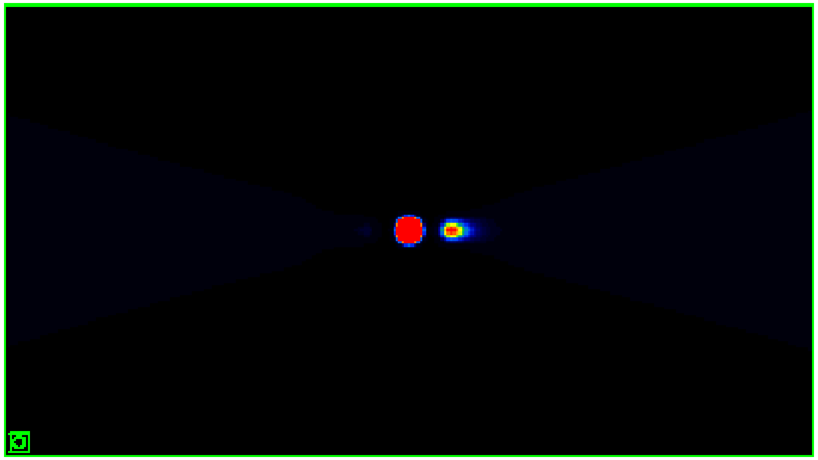
Adiabatic models



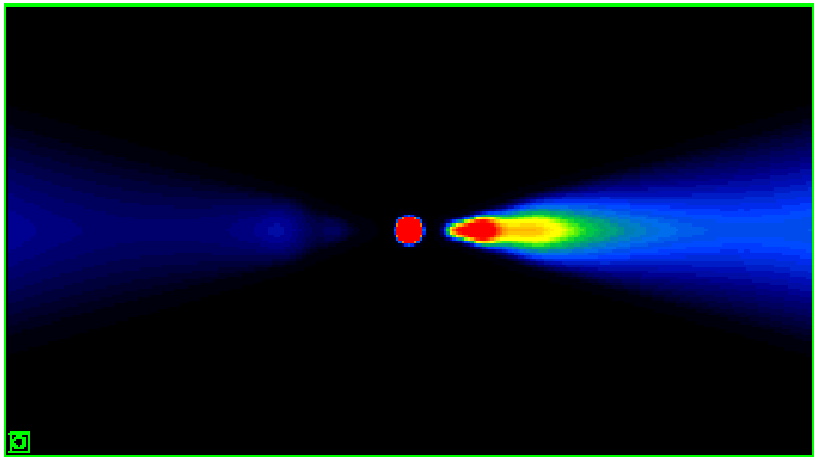
3C 31 I



Free model

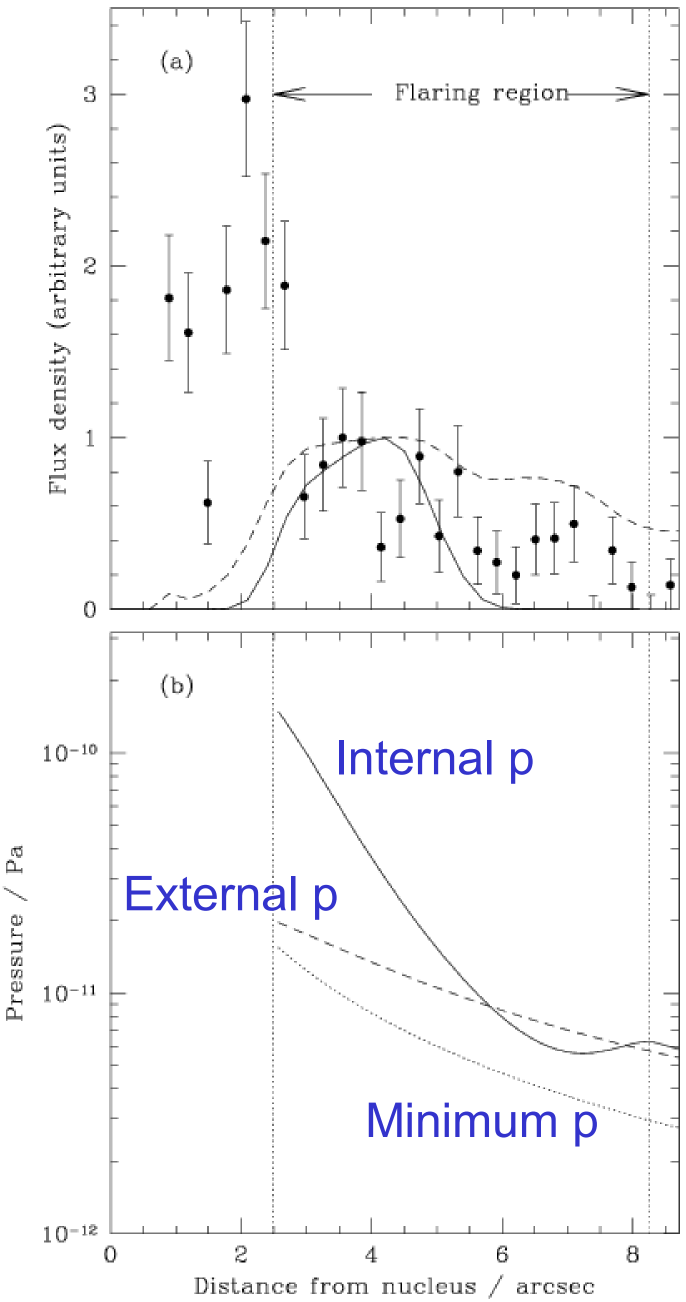


Adiabatic, with same velocity and initial conditions.



Adiabatic model with distributed particle injection.

Where are particles injected?

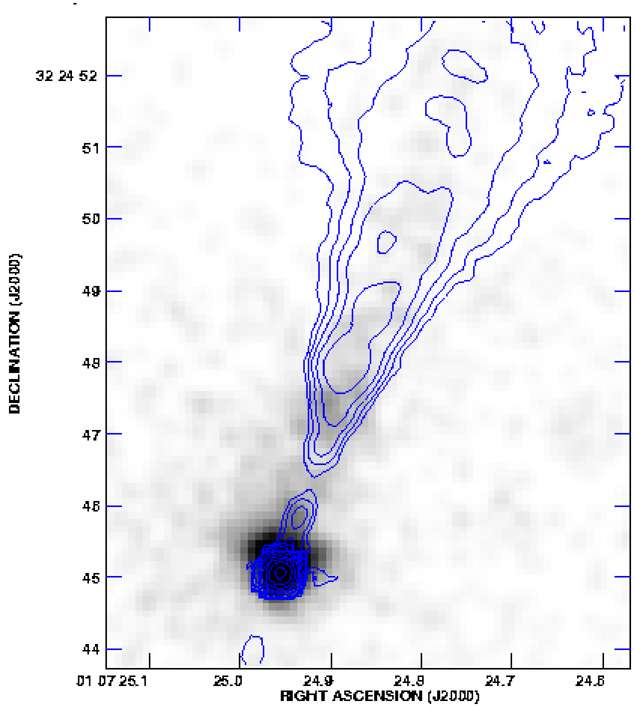


Points – X-ray

Full line – particle injection function

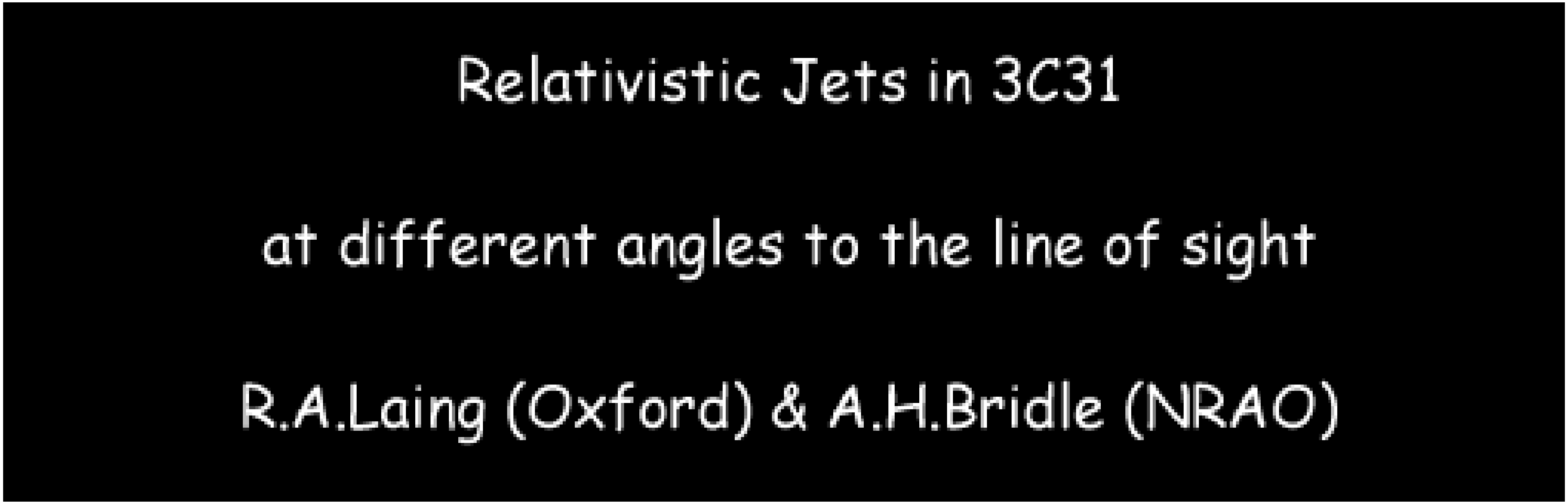
Dashed line - radio

Pressures from conservation-law analysis



VLA + Chandra

Changing the angle to the line of sight: Unified models



Relativistic Jets in 3C31

at different angles to the line of sight

R.A.Laing (Oxford) & A.H.Bridle (NRAO)

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.

Where next

FRII jets. Hard because

- counter-jets are faint (faster flow?)
- jets are narrow
- bends and other asymmetric structure
- sub-structure

Micro-quasars

- Different approach: model individual components

EVLA and e-MERLIN