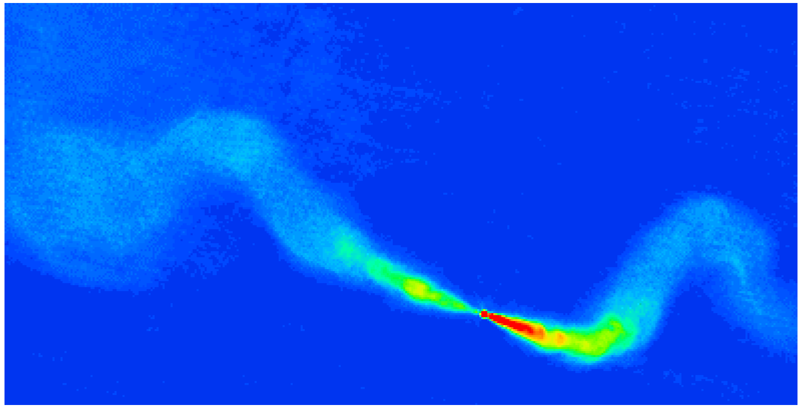
Kinematics and dynamics of relativistic jets on large and small scales

Robert Laing (ESO)



…. or what is someone who works on large-scale jets doing at an EVN Symposium?

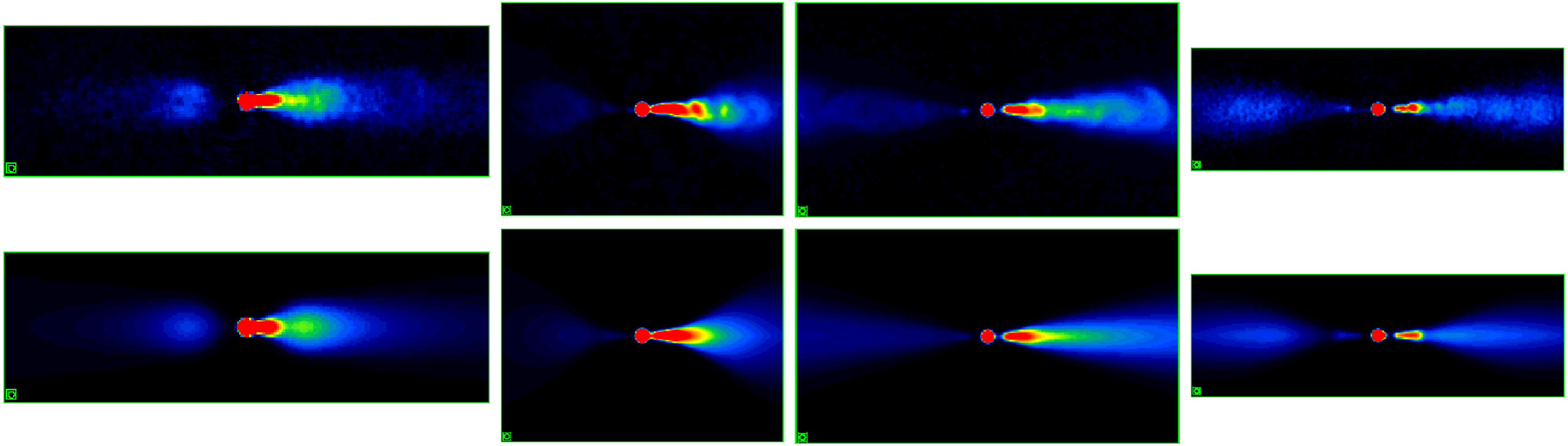
Overview

- Jets on kpc scales 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.
  - Digressions of some relevance to VLBI: helices, (dis)ordered magnetic fields, rotation measures
- Applications on pc scales
  - Observational requirements
  - Assumptions: stationary flows or discrete components
  - Foreground effects

Models – basic principles

- Model jets as intrinsically symmetrical, axisymmetric, relativistic, stationary flows.
- Parameterize geometry, velocity, emissivity and field structure.
- Optimize model parameters by fitting to IQU images.
- Linear polarization is essential to break the degeneracy between angle and velocity. Constraints:
    1. Jet/counter-jet intensity ratio
    2. Differences in polarization because jet and counter-jet are observed at different angles to the line of sight in the rest frame of the emitting plasma.

Total Intensity

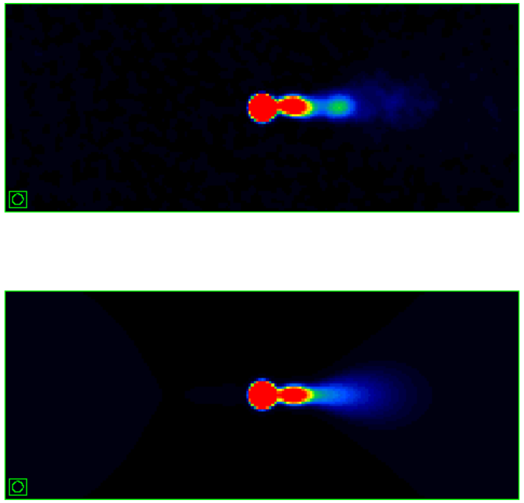


θ 8° 37° 52° 64°

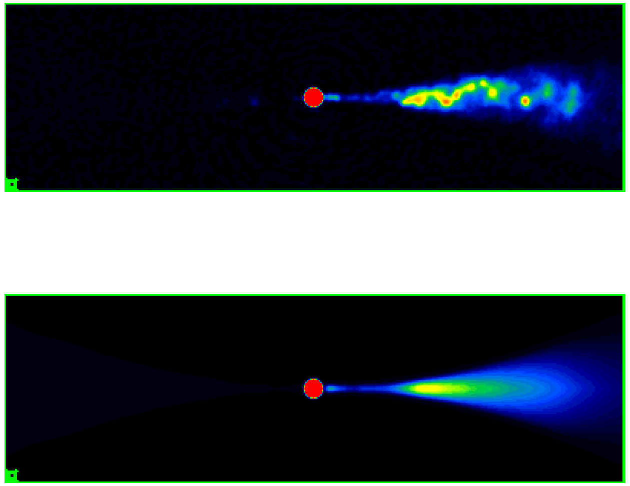
B2 1553+24 NGC 315 3C 31 B2 0326+39

Laing & Bridle (2002), Canvin & Laing (2004), Laing, Canvin & (Bridle 2004)

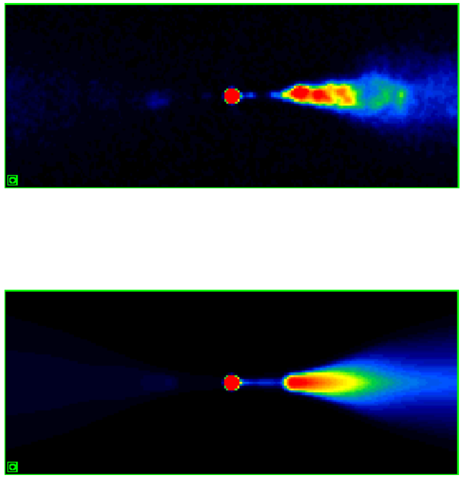
Total Intensity (high resolution)



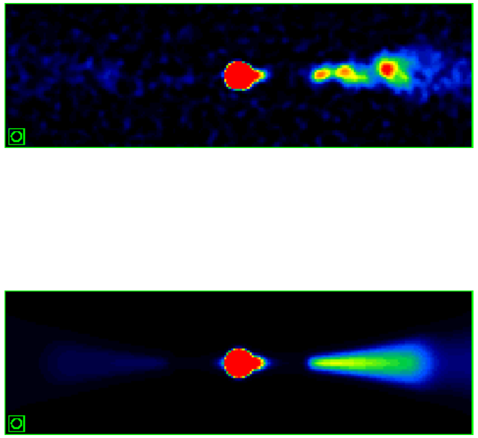
θ = 8°



37°

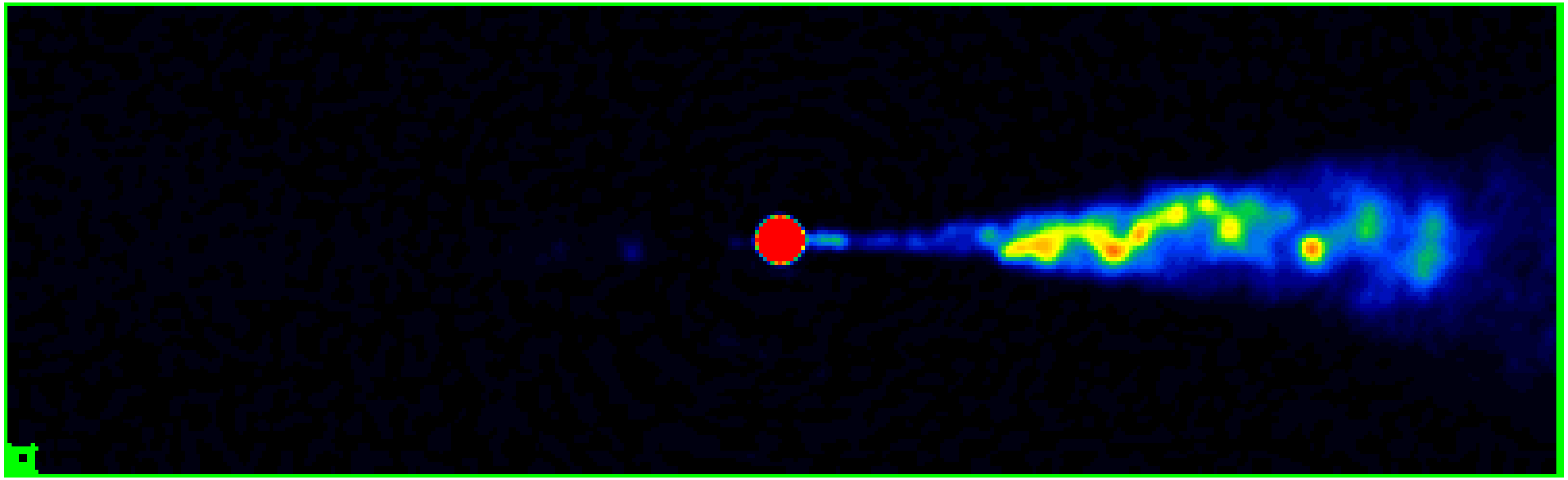


52°



64°

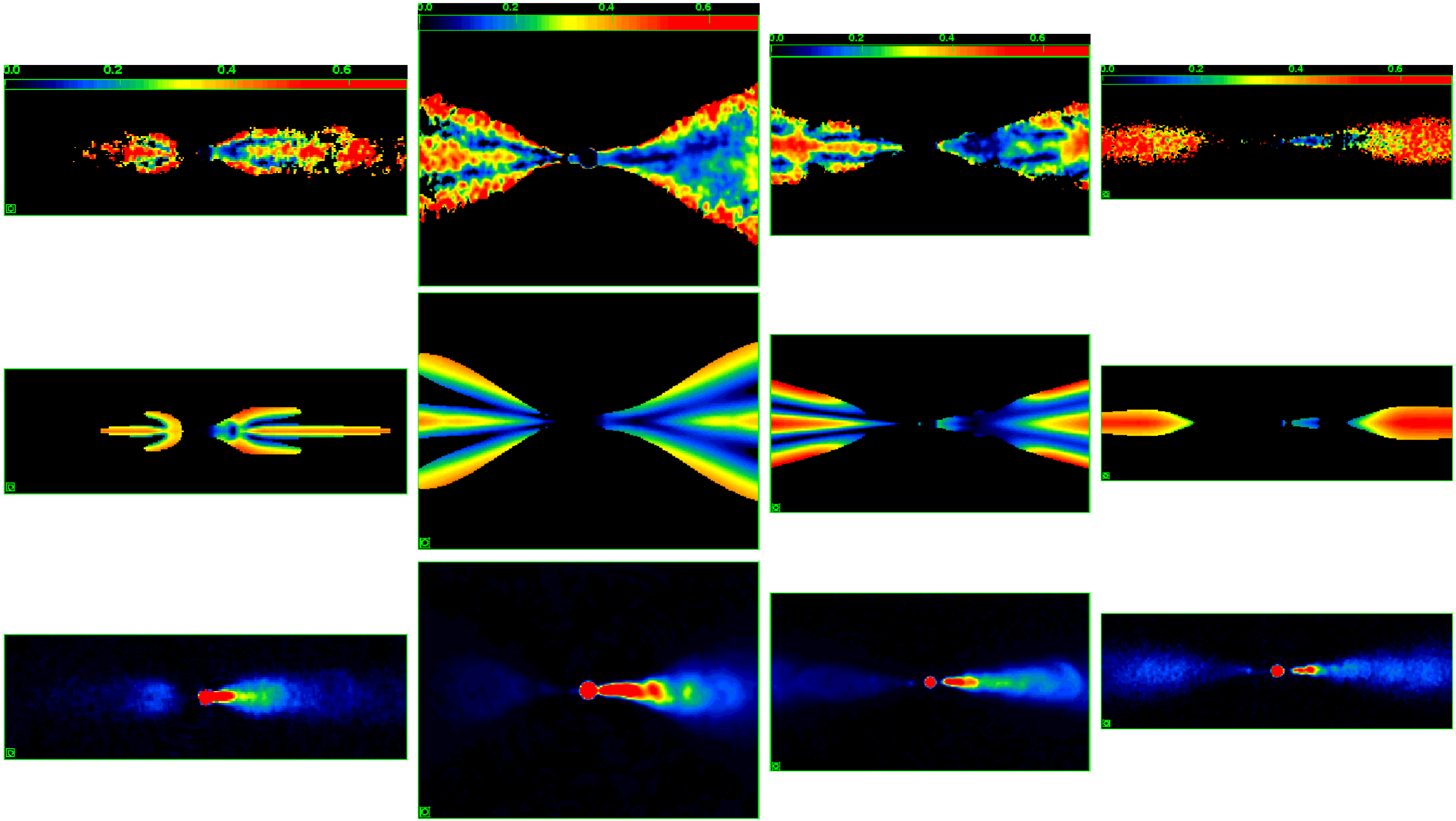
Digression 1: helical structures in jets



NGC 315, 0.4 arcsec FWHM VLA (Bill Cotton et al.)

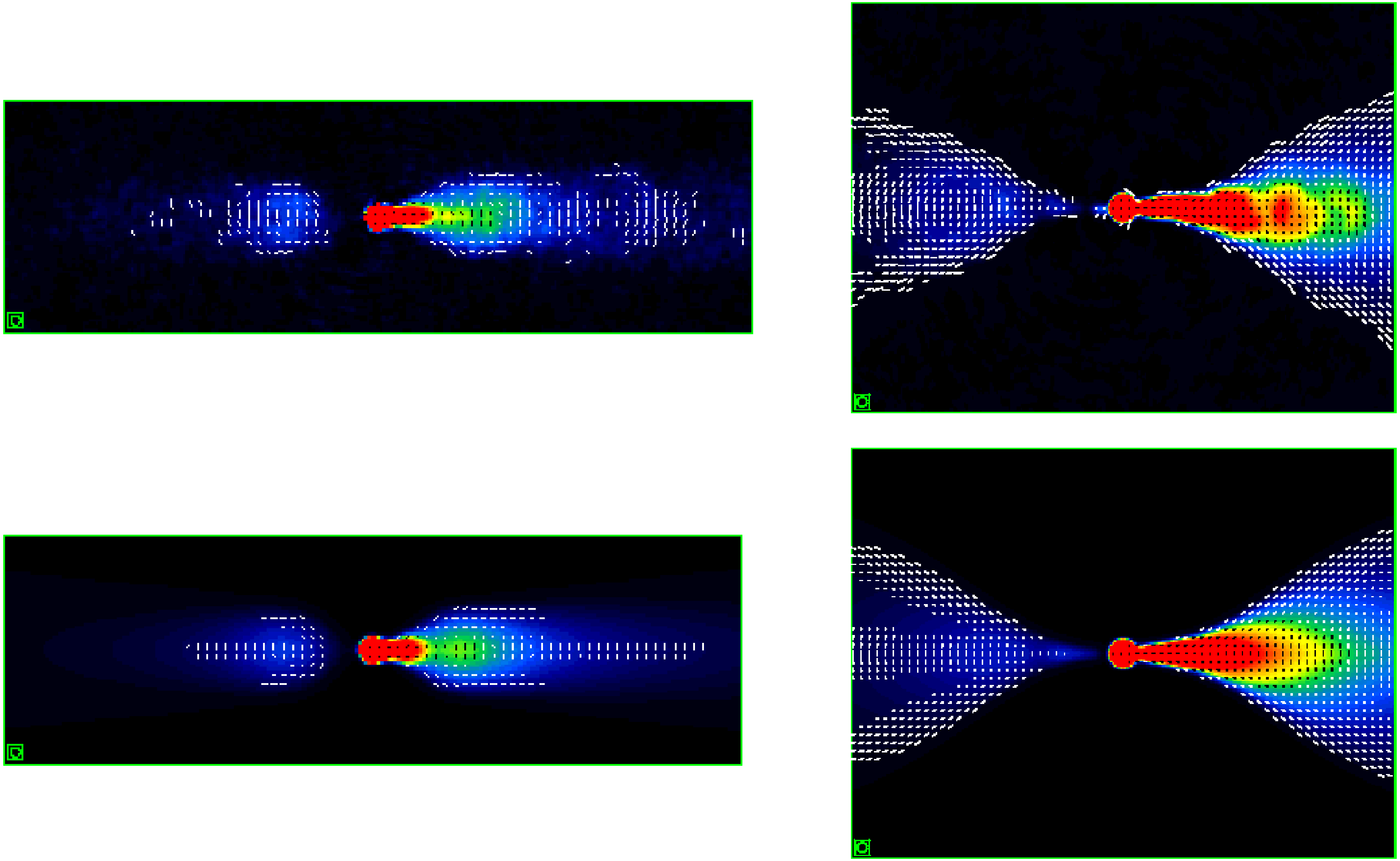
Note the quasi-helical structure (also bright in X-rays) within the envelope of the jet emission.

Degree of polarization



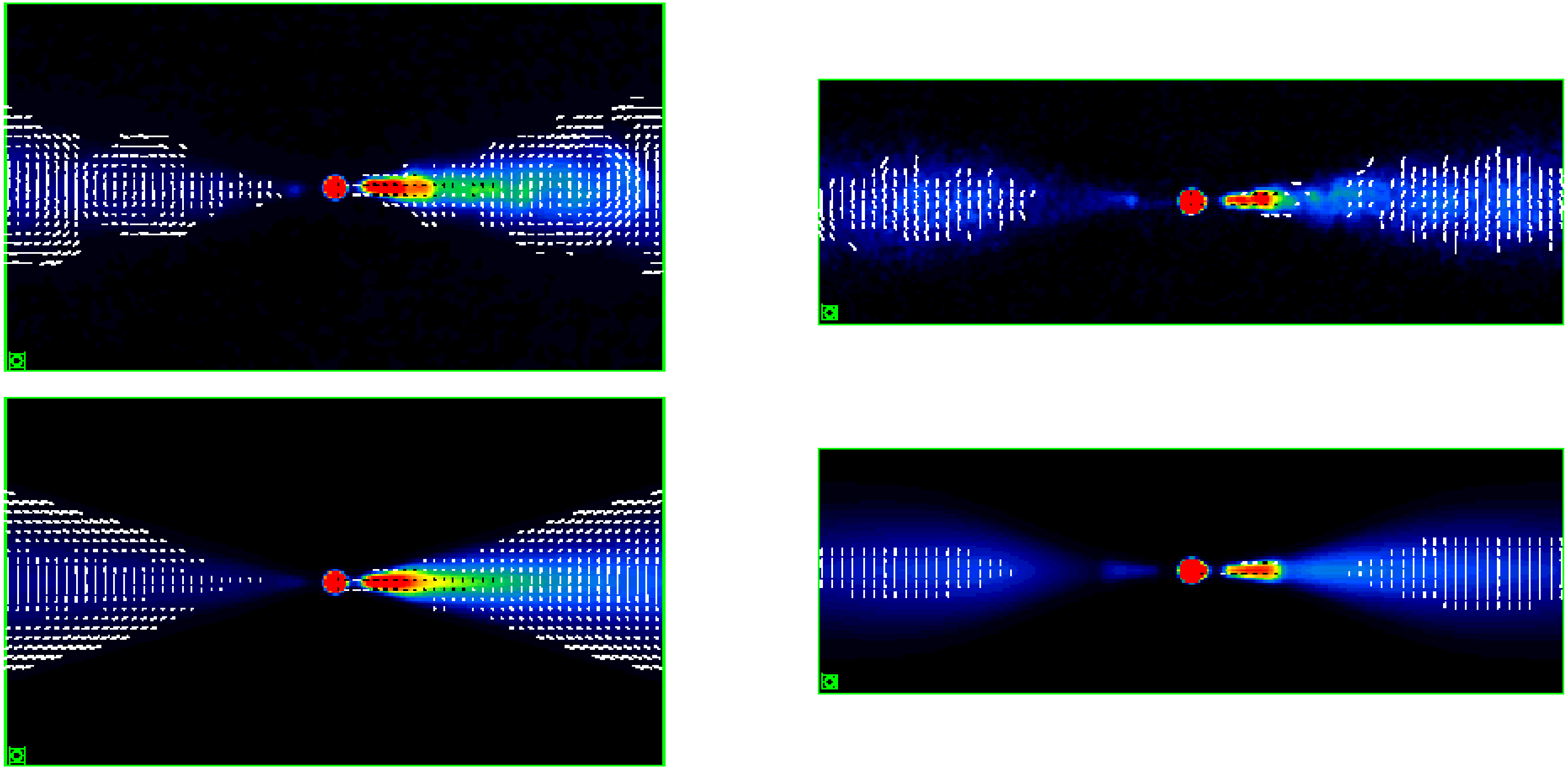
θ 8° 37° 52° 64°

Apparent magnetic field (1)



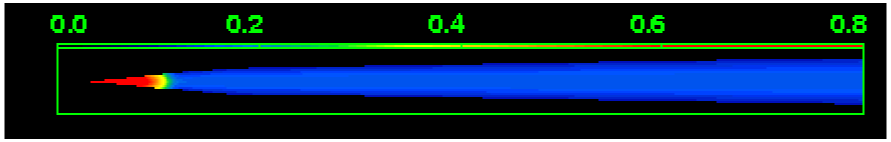
θ = 8° 37°

Apparent magnetic field (2)

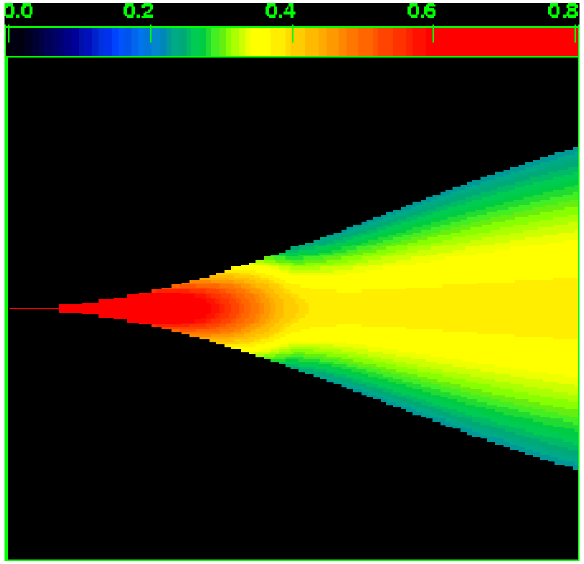


θ = 52° 64°

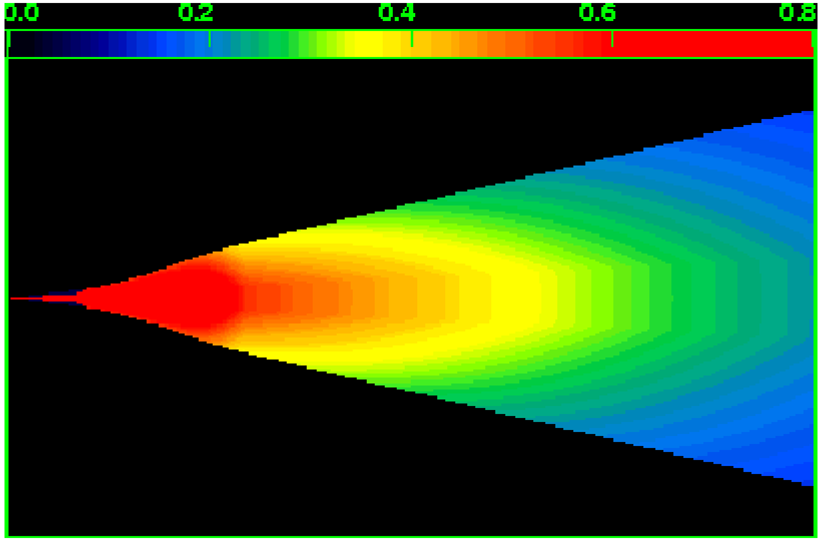
Velocity $\beta = v/c$



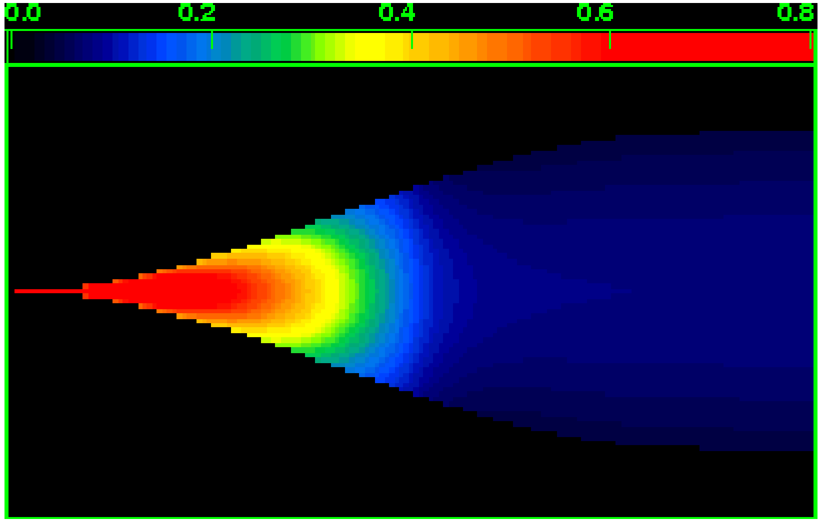
B2 1553+24



NGC 315

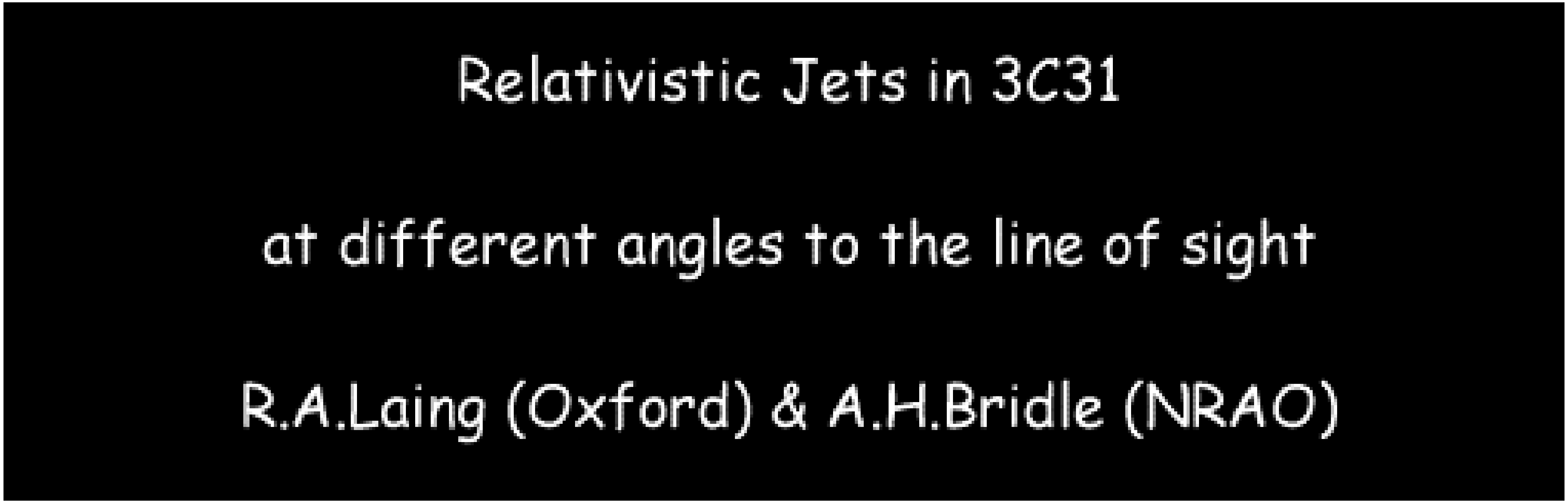


3C 31



B2 0326+39

Changing the angle to the line of sight: Unified models

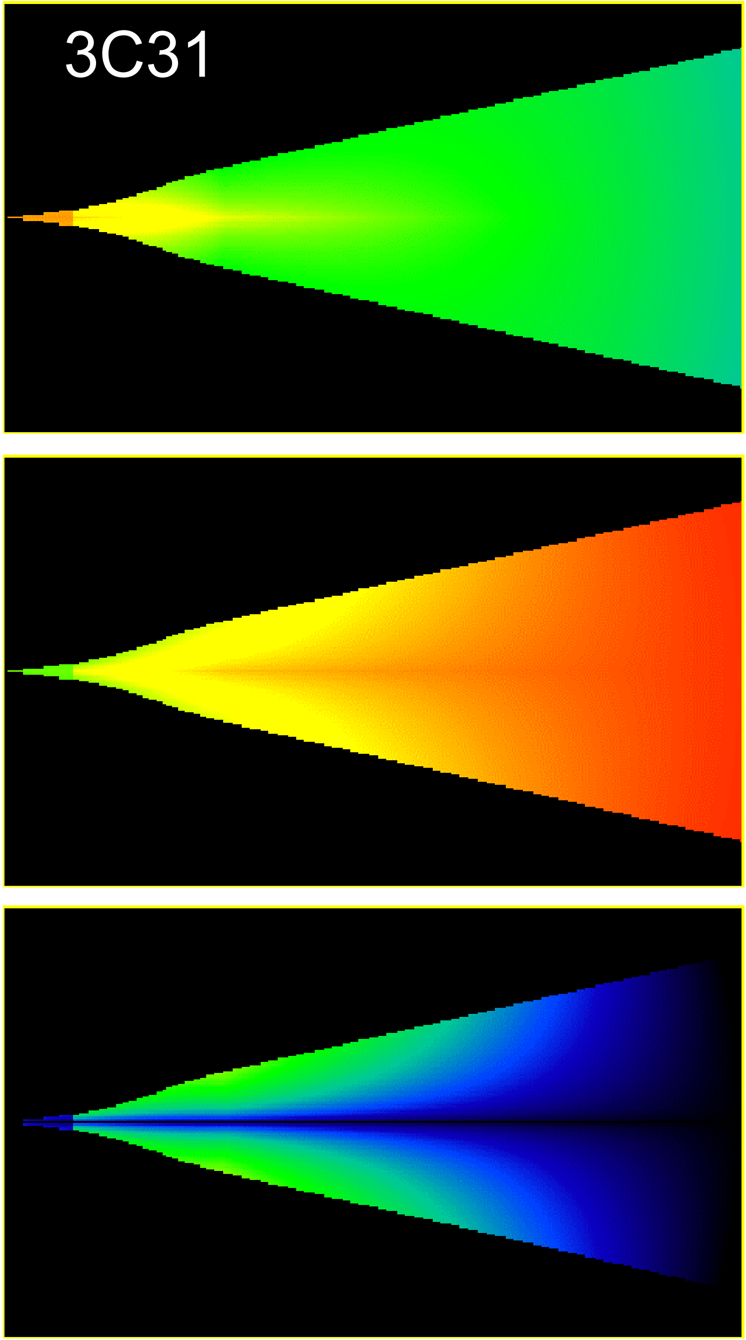


Relativistic Jets in 3C31

at different angles to the line of sight

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

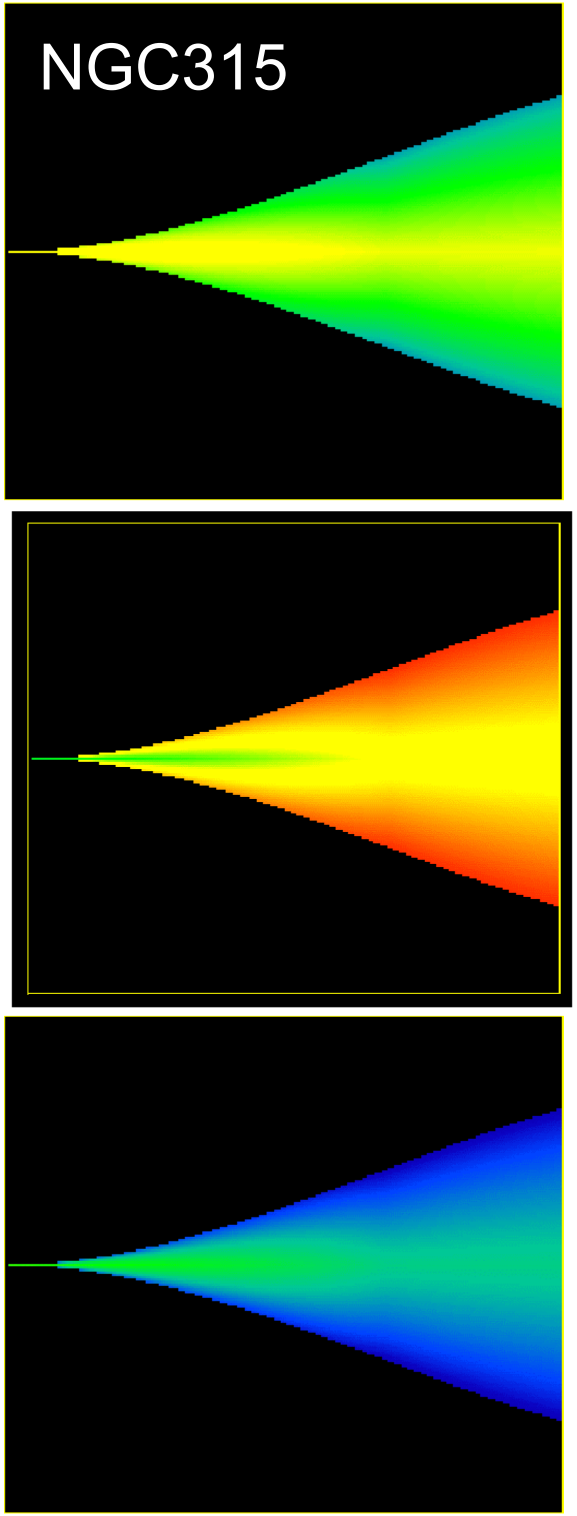
Field component ratios



Longitudinal

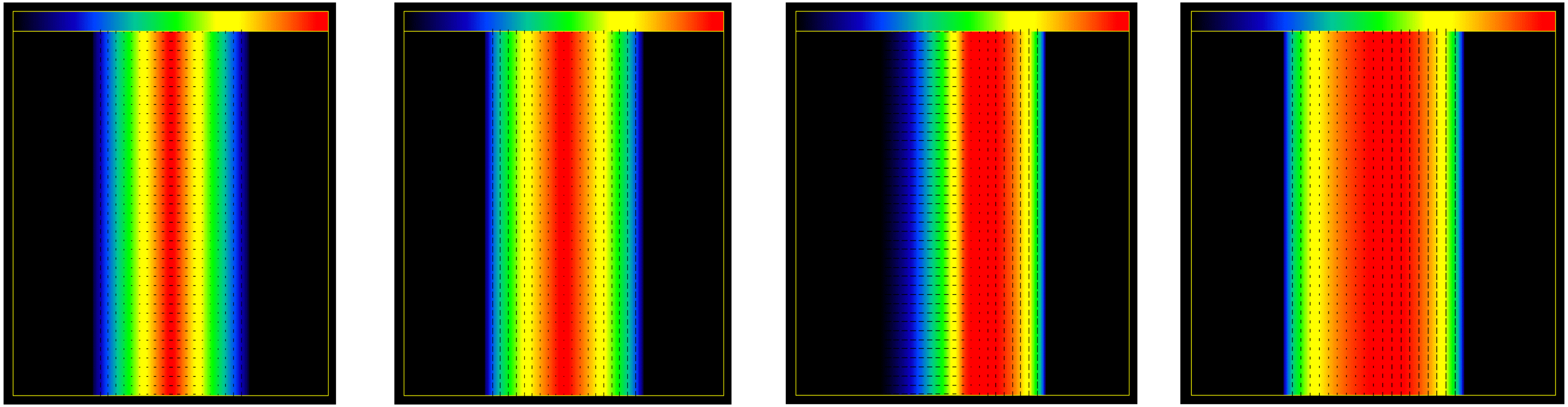
Toroidal

Radial



One component (toroidal?) could be ordered

Digression 2: magnetic fields: vector-ordered or many reversals?

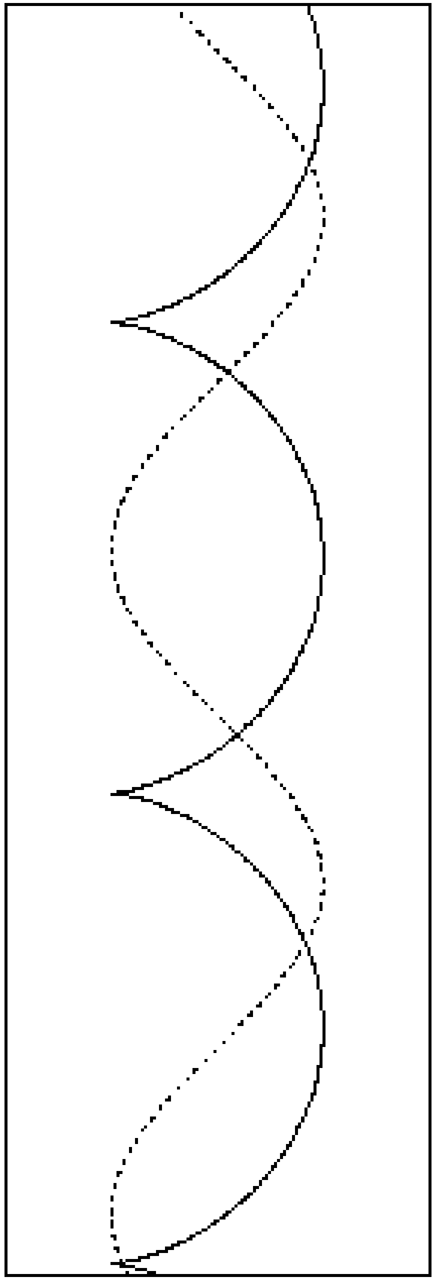


θ =	90	90	45	30
ψ =	60	45	45	20

(θ is the angle to the line of sight (in the fluid rest frame); ψ is the pitch angle)

Axisymmetric helical fields produce asymmetric brightness distributions

Helical field geometries



Total intensity and linear polarization are asymmetric under reflection though the jet axis, because both the angle between the field and the line of sight and its position angle on the sky are different on the two sides.

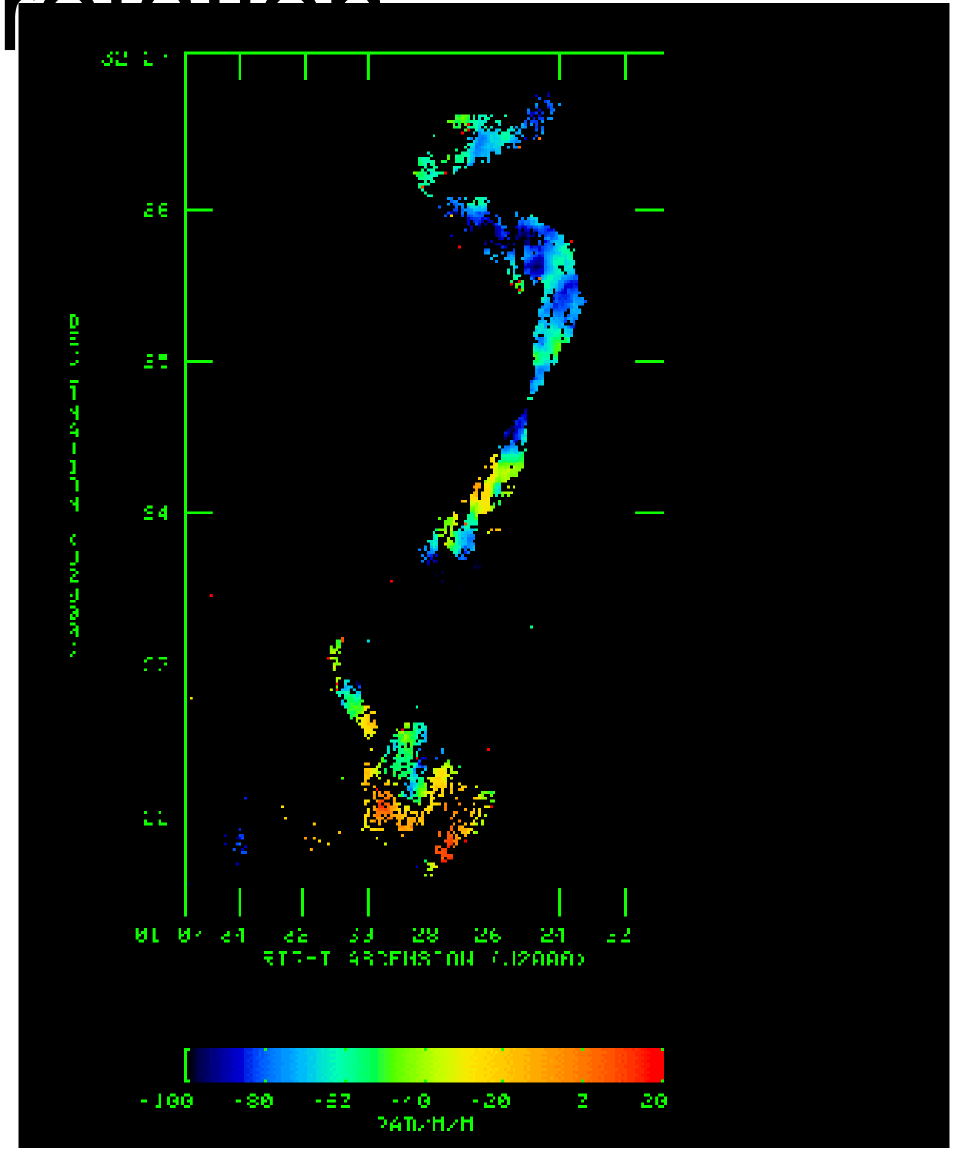
Emission seen side-on in the rest frame is symmetrical – also the maximum boost case.

Helical fields do not fit FRI jets

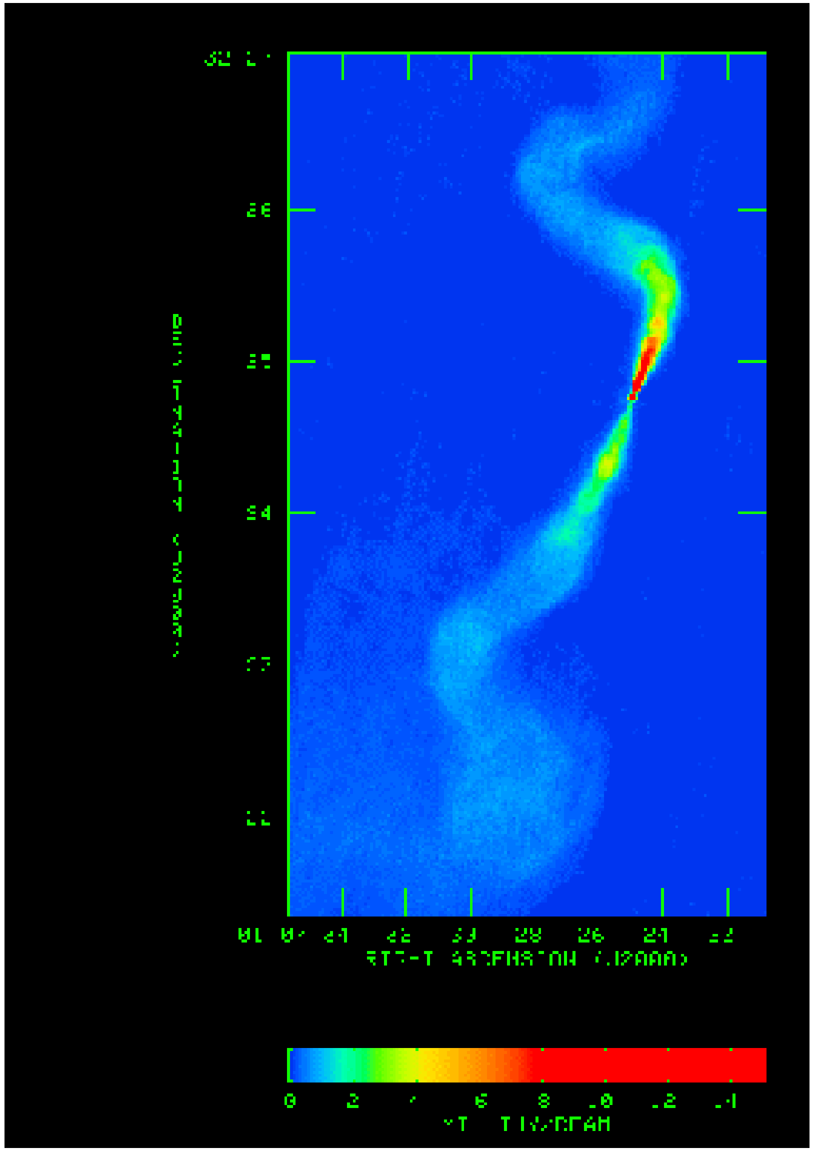
—— $\theta = 45^{o}$, $\psi = 45^{o}$

⋯⋯ $\theta = 90^{o}$, $\psi = 45^{o}$

Digression 3: foreground Faraday rotation

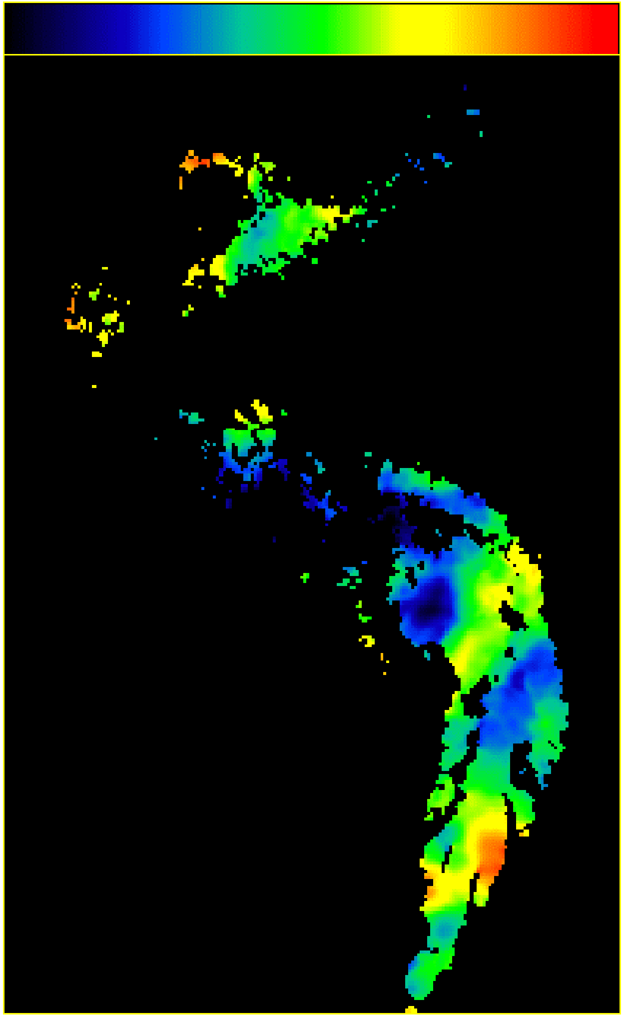


Faraday rotation

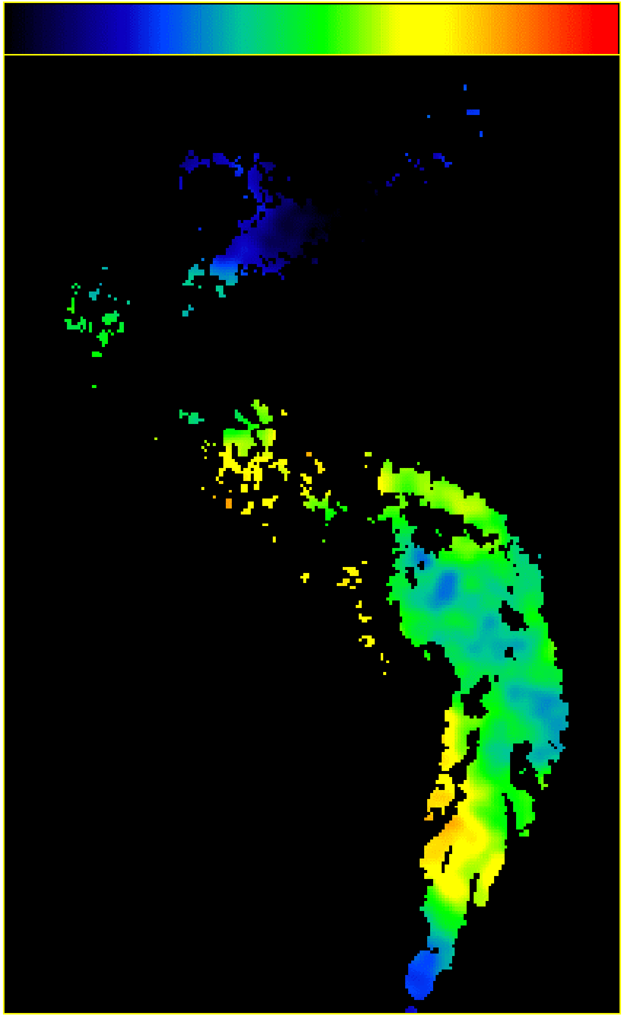


Total intensity

Rotation measure models



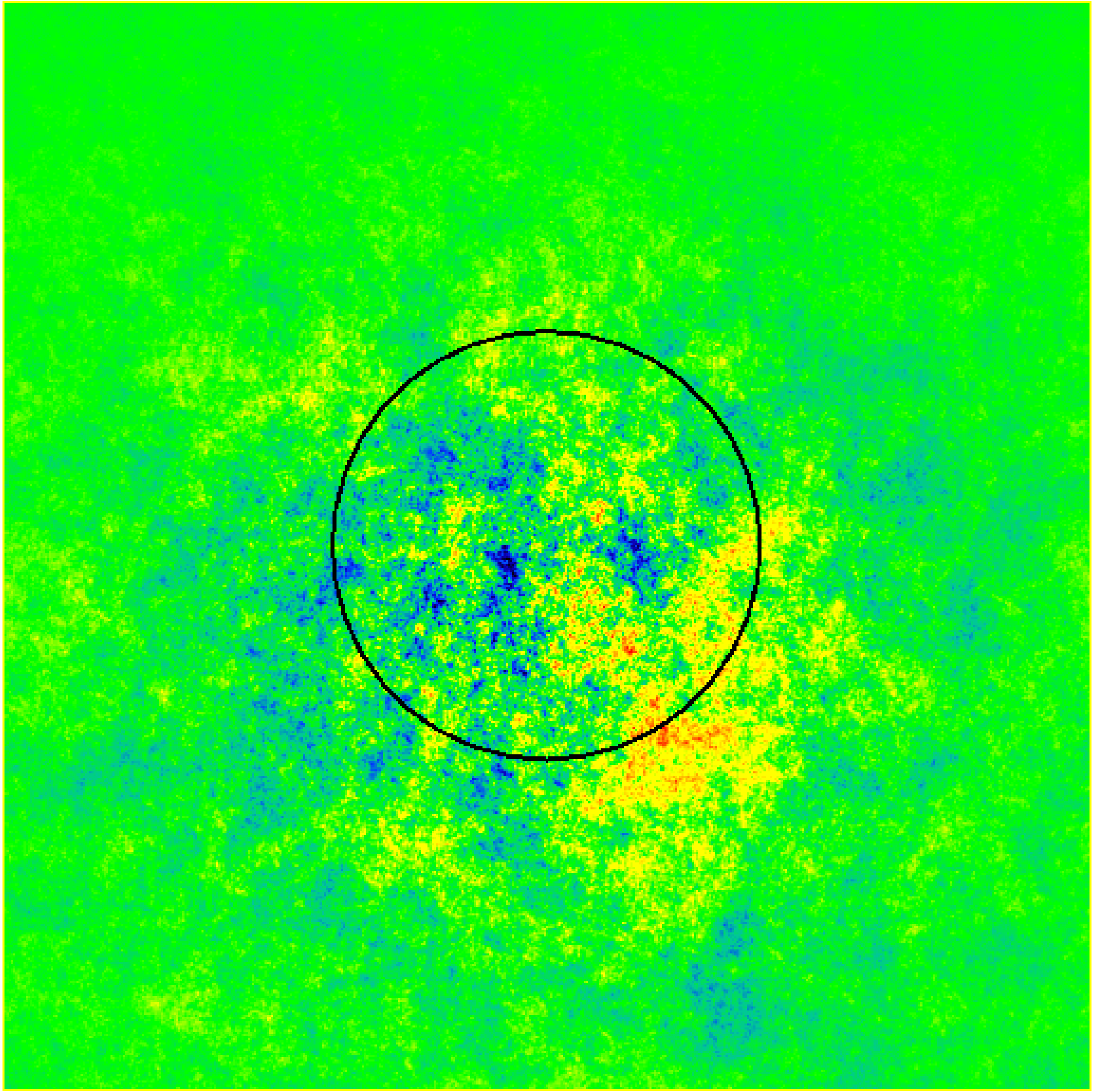
Data



2D model

Power-law power spectrum of foreground RM, matched using a structure-function analysis.

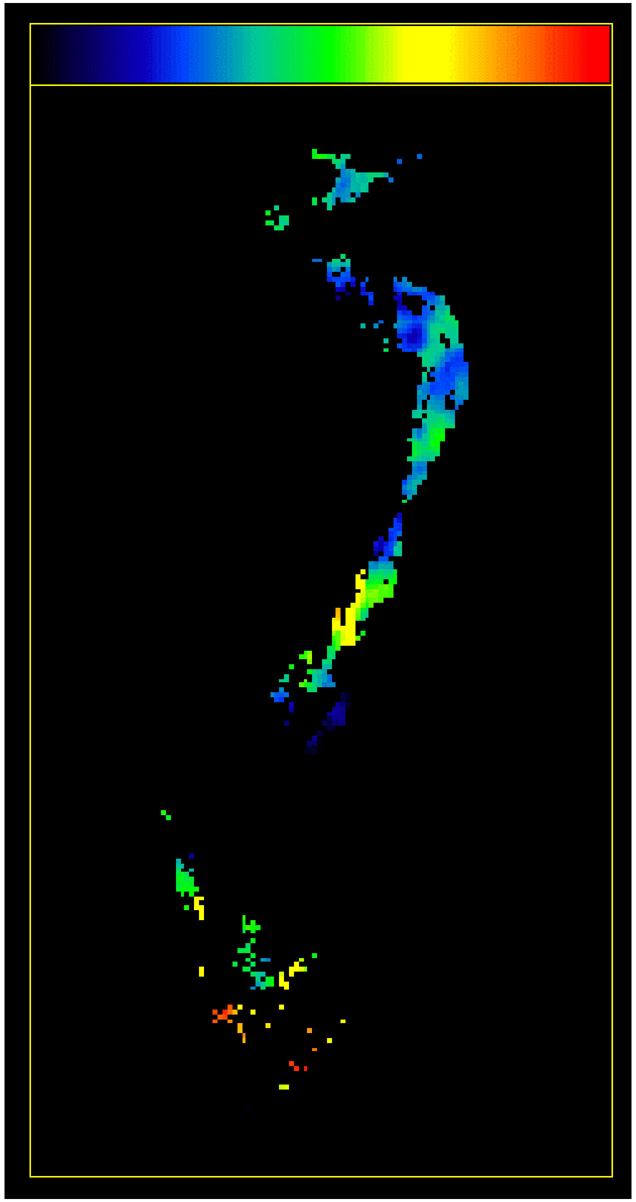
Rotation-measure modelling in 3D



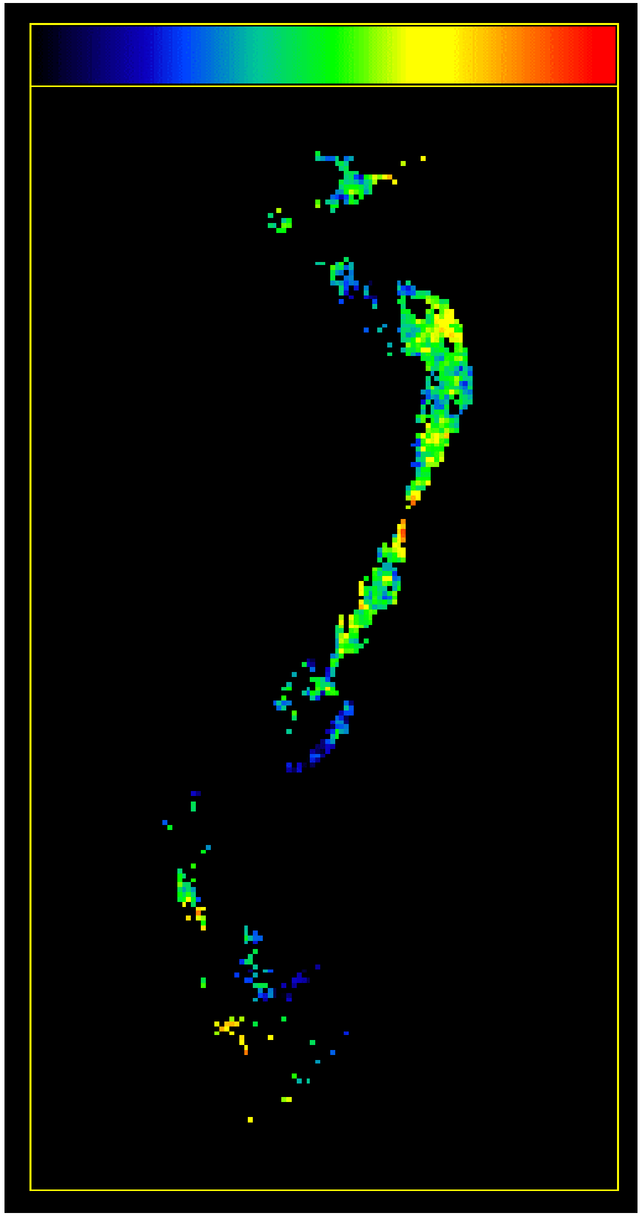
RM simulation using a power-law spectrum of magnetic field fluctuations in the group gas around 3C31

Gas parameters from ROSAT
Inclination from jet models

… and a comparison with observations



Data



Model

Back to the jet models: conservation law analysis

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

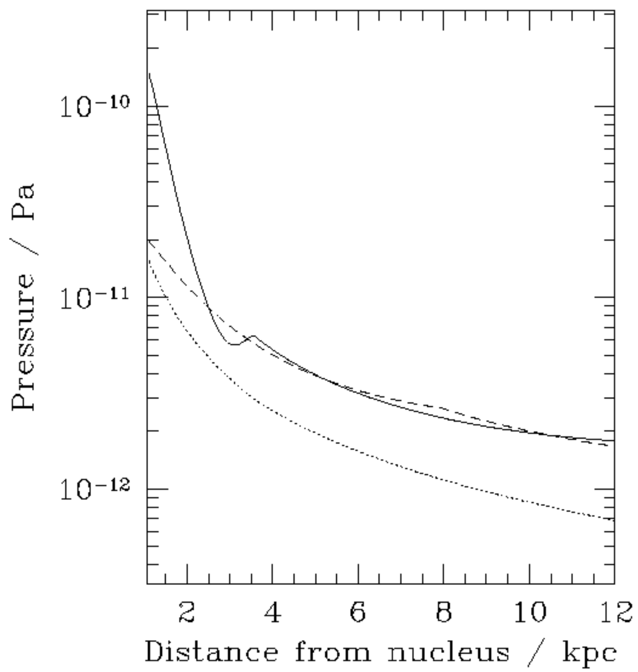
  Energy flux = momentum flux x c

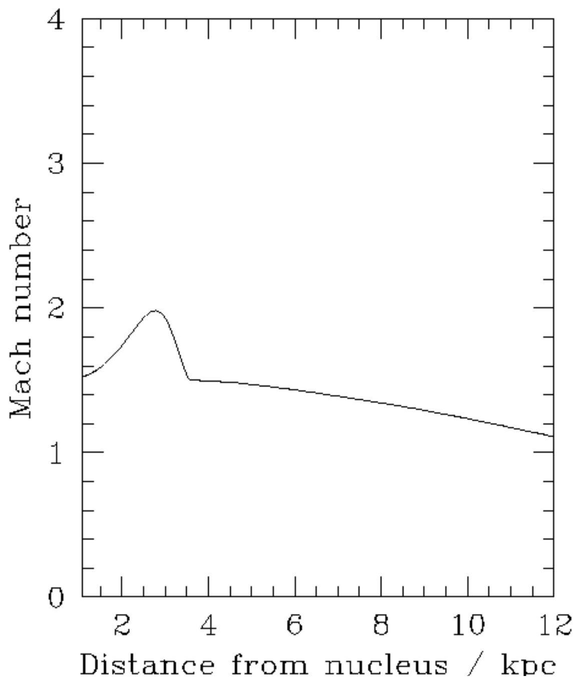
  Pressure balance at large distances

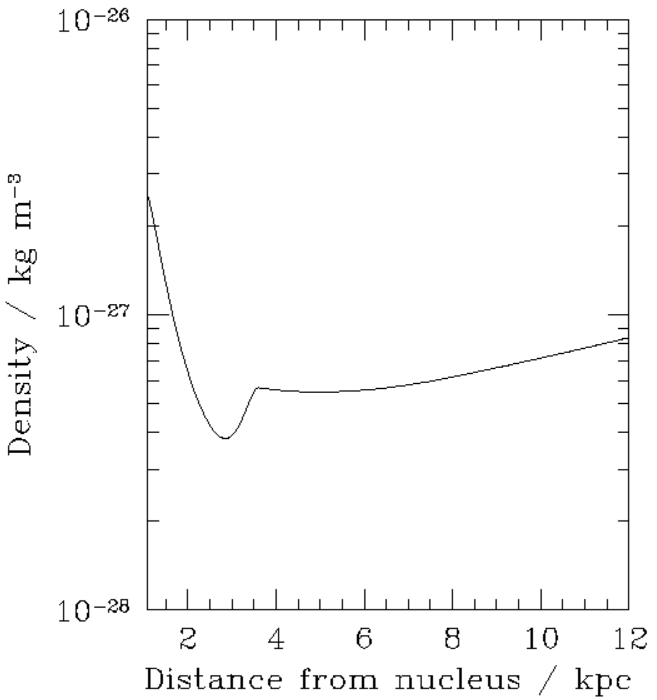
Conservation-law analysis: fiducial numbers at the jet flaring point

- 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}

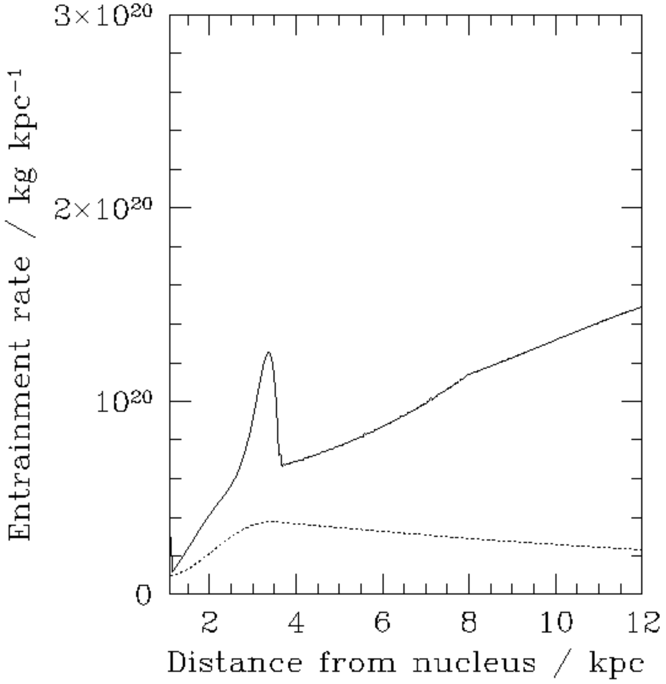
Pressure, Mach number, density and entrainment rate







Laing & Bridle (2002b); Hardcastle et al. (2002)



Applications on parsec scales

- Detect and resolve both jets along and across their axes
- Measure linear polarization, corrected for Faraday rotation
- Remove effects of synchrotron and free-free absorption
- Assumption of intrinsic symmetry must hold, at least on average:

  Quasi-stationary flow?

  Individual components (e.g. microquasars)?
- Not too close to the plane of the sky ($\theta < 70^{\circ}$)

Are there any suitable sources out there?

Conclusions

- Symmetrical, relativistic models can describe FRI radio jets and give a wealth of information about key physical parameters such as velocity, field structure and emissivity.
- Conservation-law analyses can be used to derive energy, mass and momentum fluxes provided that we know external conditions.
- Lessons learnt: fields in jets are not helical (though they may be toroidal), rotation measure is in the foreground and is uncorrelated with source structure and helical intensity structures are within a broader cone of emission …. maybe true on parsec scales too?
- These techniques could be used in principle on VLBI scales: are there suitable targets?