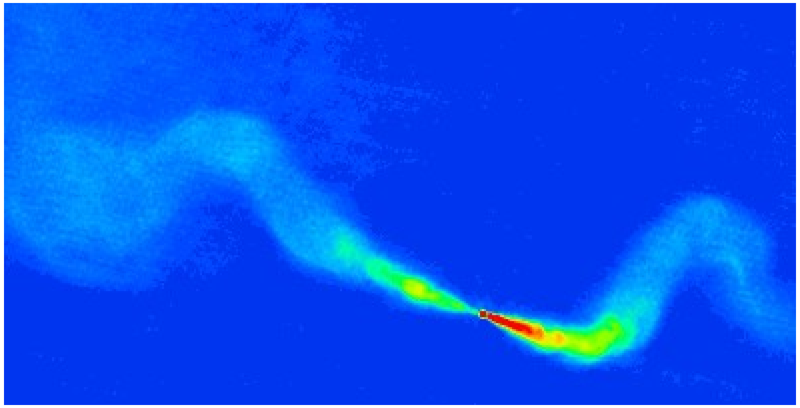
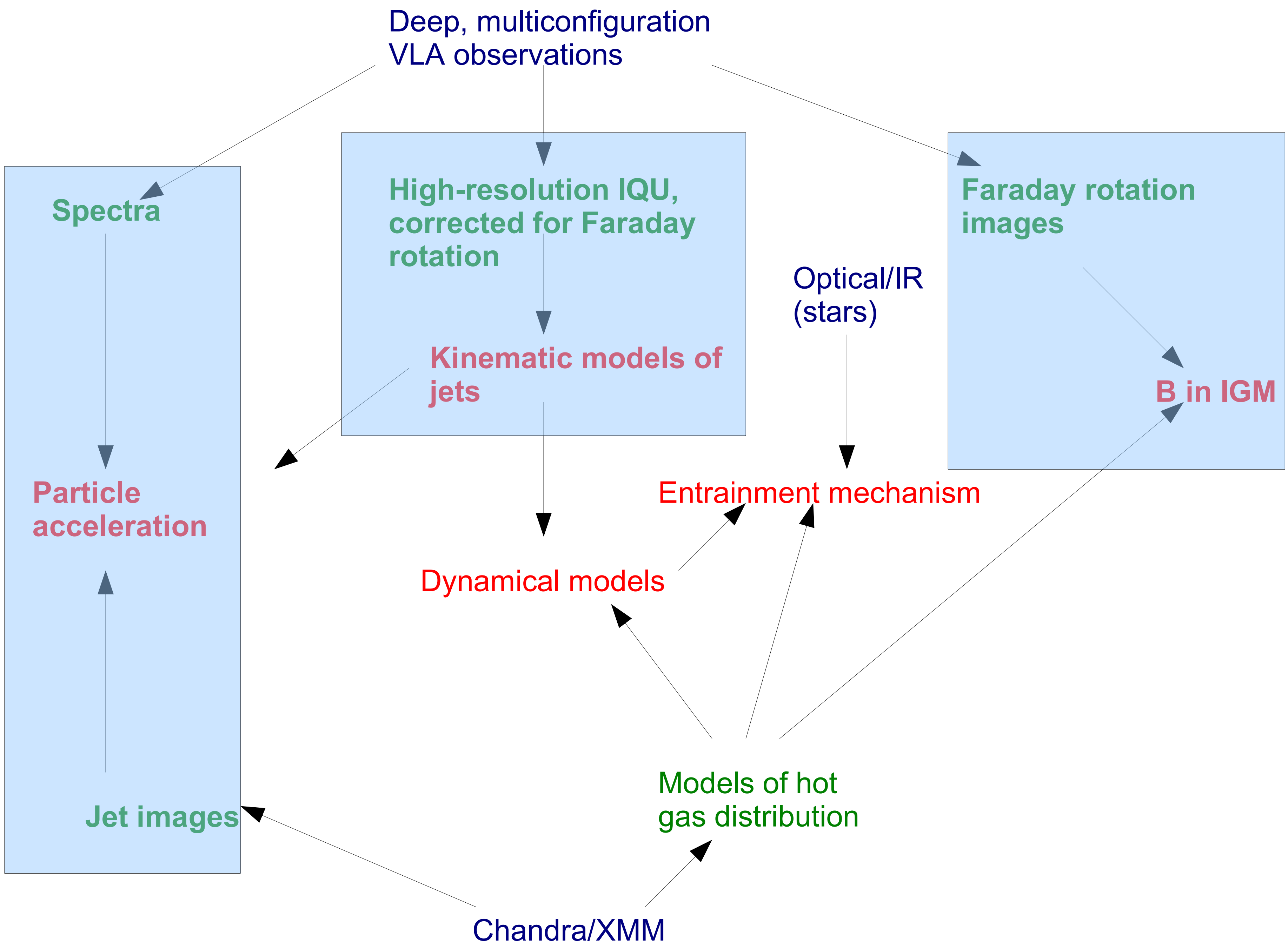
Precision Jet Physics
Low-power radio galaxies and their environments

Robert Laing (ESO)




Deep, multiconfiguration
VLA observations
Spectra
High-resolution IQU,
corrected for Faraday
rotation
Faraday rotation
images
Optical/IR
(stars)
Kinematic models of
jets
B in IGM
Particle
acceleration
Entrainment mechanism
Dynamical models
Models of hot
gas distribution
Jet images
Chandra/XMM

Published so far

- Statistics of B2 sample (Laing et al. 1999)
- Synchrotron formulae (Laing 2002)
- Kinematic models:

  3C31 (Laing & Bridle 2002a), 0326+39, 1553+24 (Canvin & Laing 2004),

  NGC315 (Canvin et al. 2005), 3C296 (Laing et al. 2006a)
- X-ray observations

  3C31 (Hardcastle et al. 2002), 3C296 (Hardcastle et al. 2005),

  NGC315 (Worrall et al. 2007, Croston et al. 2008)
- Conservation law analysis

  3C31 (Laing & Bridle 2002b)
- Adiabatic models

  3C31 (Laing & Bridle 2004)
- Detailed imaging, spectra, polarization

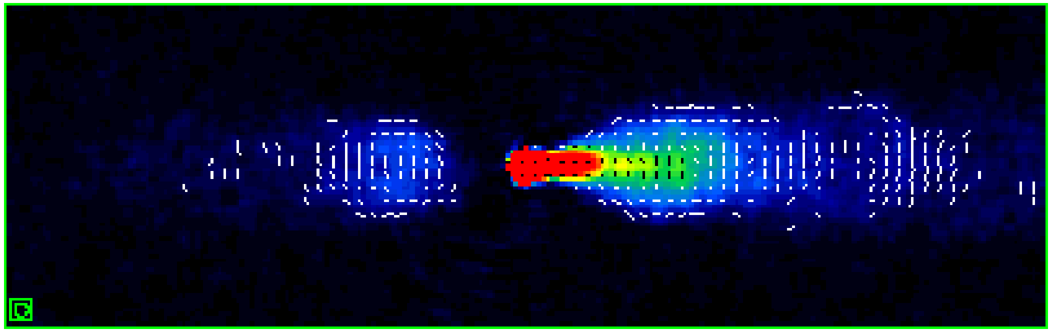
  3C31 (Laing et al. 2008)

  NGC315 (Laing et al. 2006b)

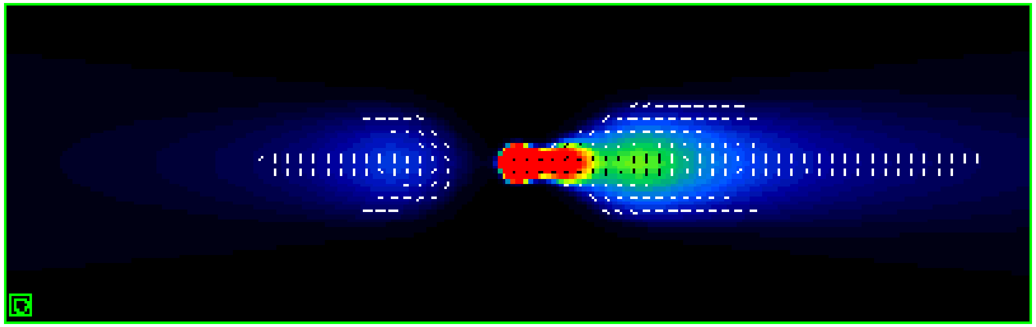
Kinematic models: basic ideas

- Assume that jets are relativistic. intrinsically symmetrical and axisymmetric: we think this is a very good approximation close to the nucleus.
- For isotropic emission in the rest frame, jet/counter-jet ratio depends on $\beta\cos\theta$ – how to separate?
- **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 – decouple β and $\cos\theta$
- Fit models describing geometry, velocity field, emissivity and field ordering to deep radio images in I, Q and U.
- Need good transverse resolution and high sensitivity.

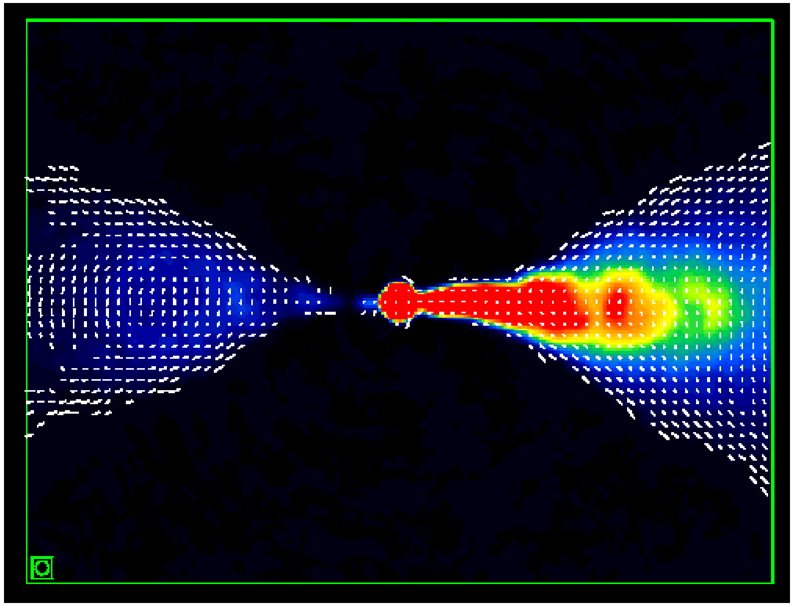
Example fits

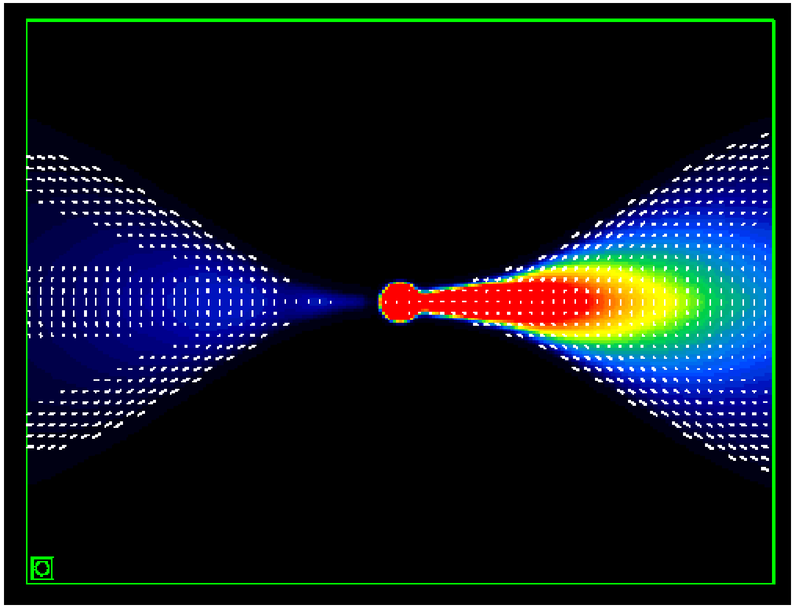


Colour: total intensity
Vector length: fractional polarization
Vector direction: apparent magnetic field



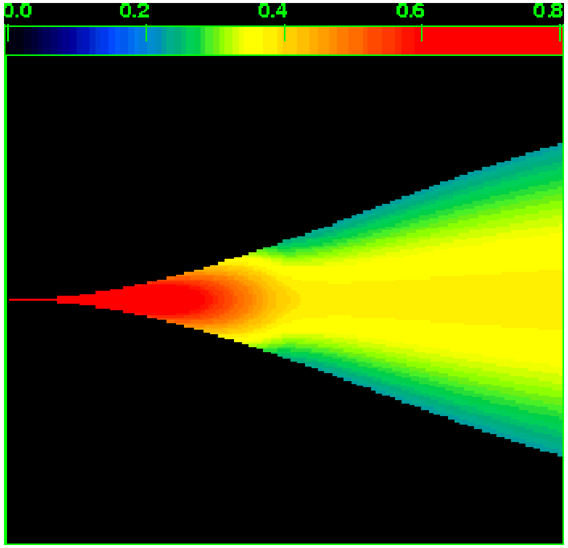
1553+24, $\theta = 8^{o}$



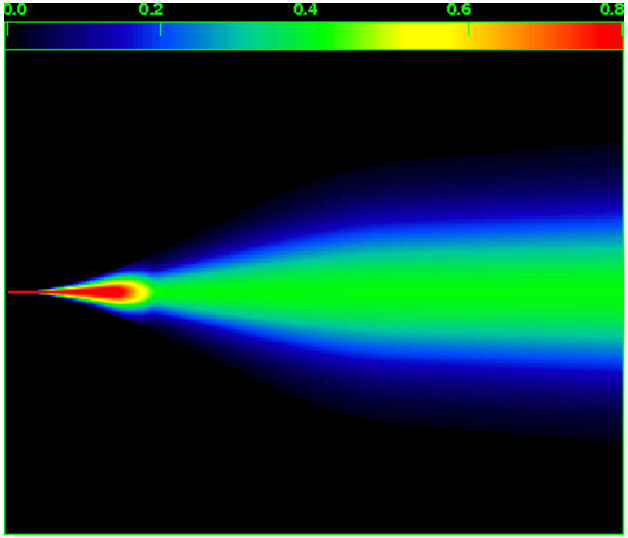


NGC315, $\theta = 38^{o}$

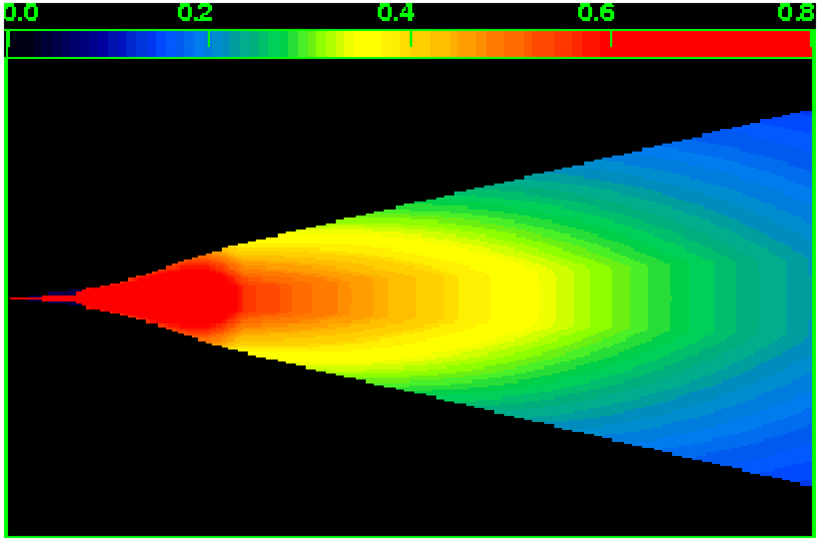
Velocity $\beta = v/c$: deceleration and transverse gradients



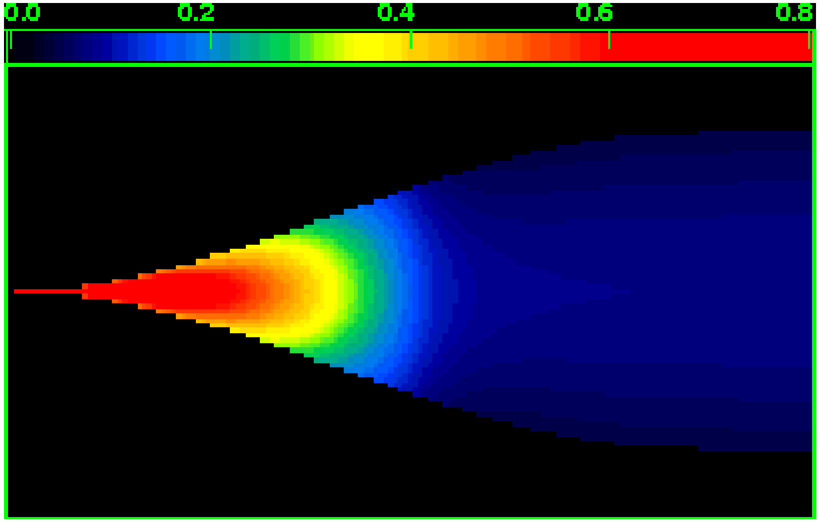
NGC 315



3C296



3C 31

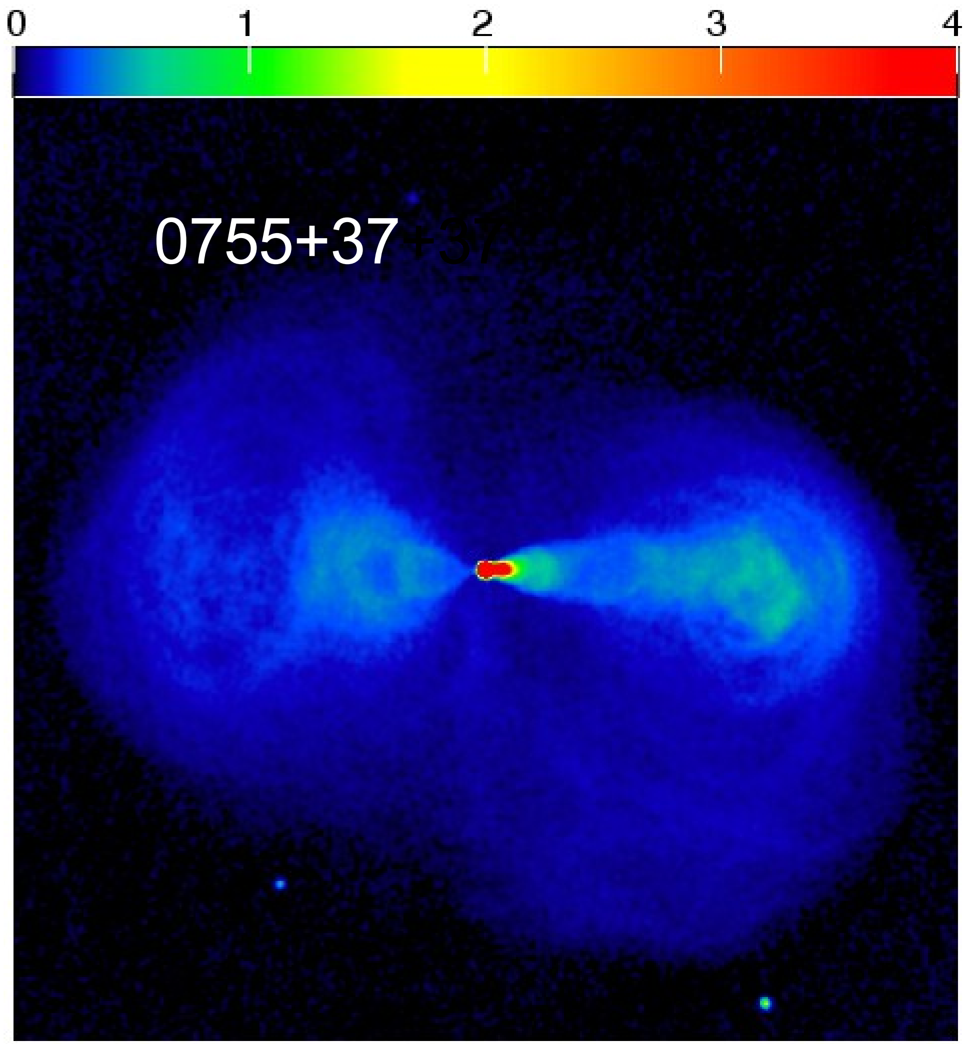


B2 0326+39

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, four 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, except for 3C296, which has a very low fraction edge velocity ≈ 0.1 [something to do with the lobe structure?].
- No narrow shear layers
- Why don’t we see more evolution in the profile, as expected for boundary-layer entrainment?

Backflow?



A minority of FRI sources **with lobes** show counter-jets which are isophotally wider than their main jets

Cannot get this from a symmetrical relativistic outflow

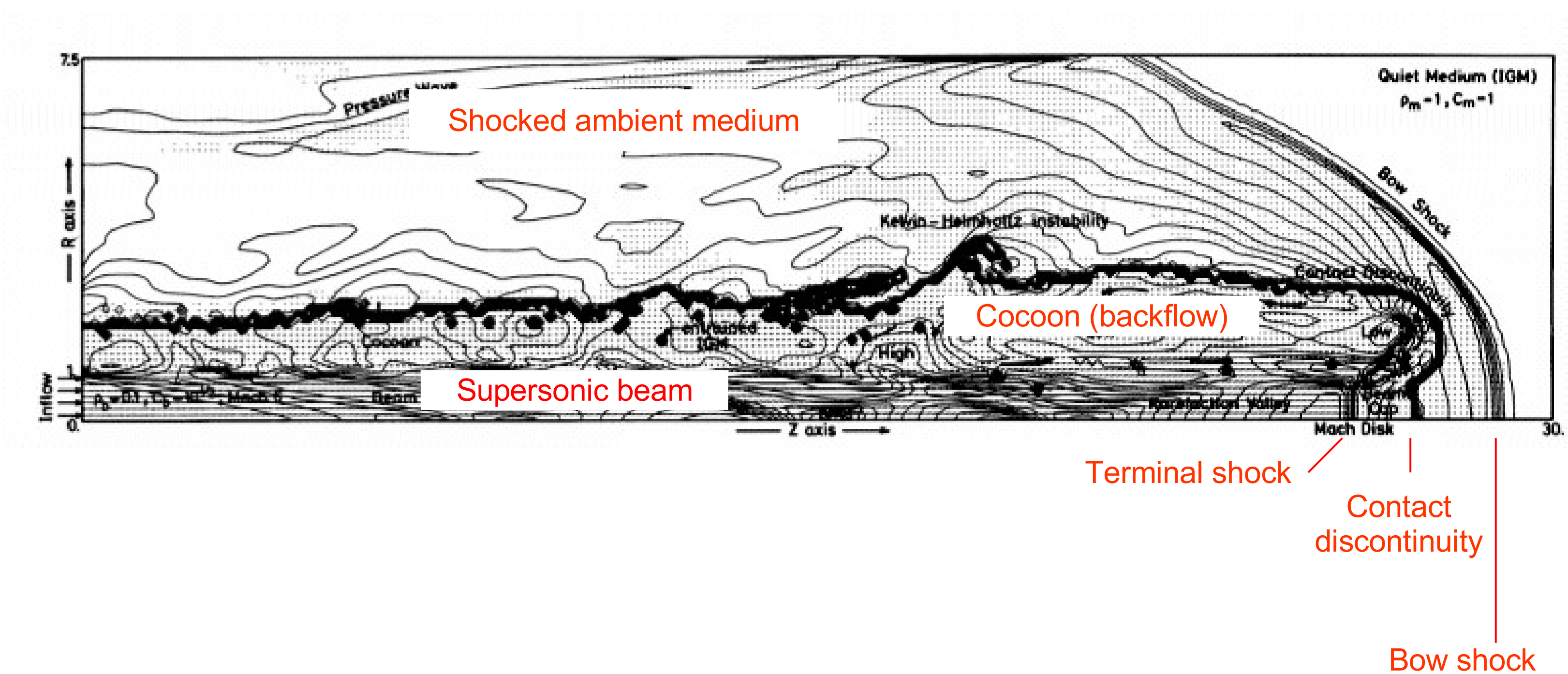
Is there an intrinsic asymmetry?
- We do not know of any sources with main jets much wider than counter-jets

- Hints from 0755+37

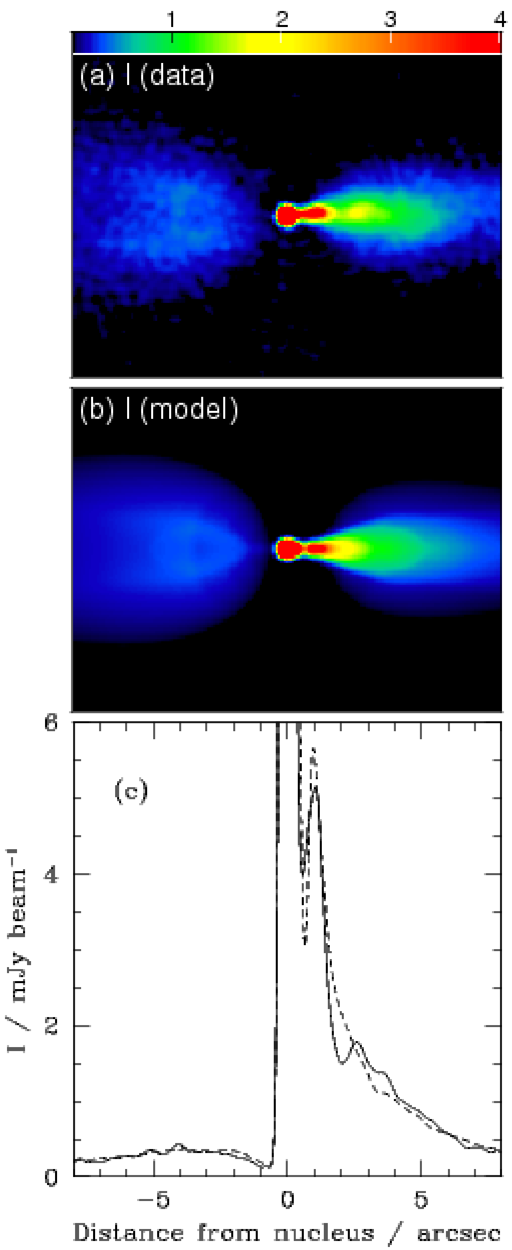
What if there is backflow in the material immediately surrounding the jets?

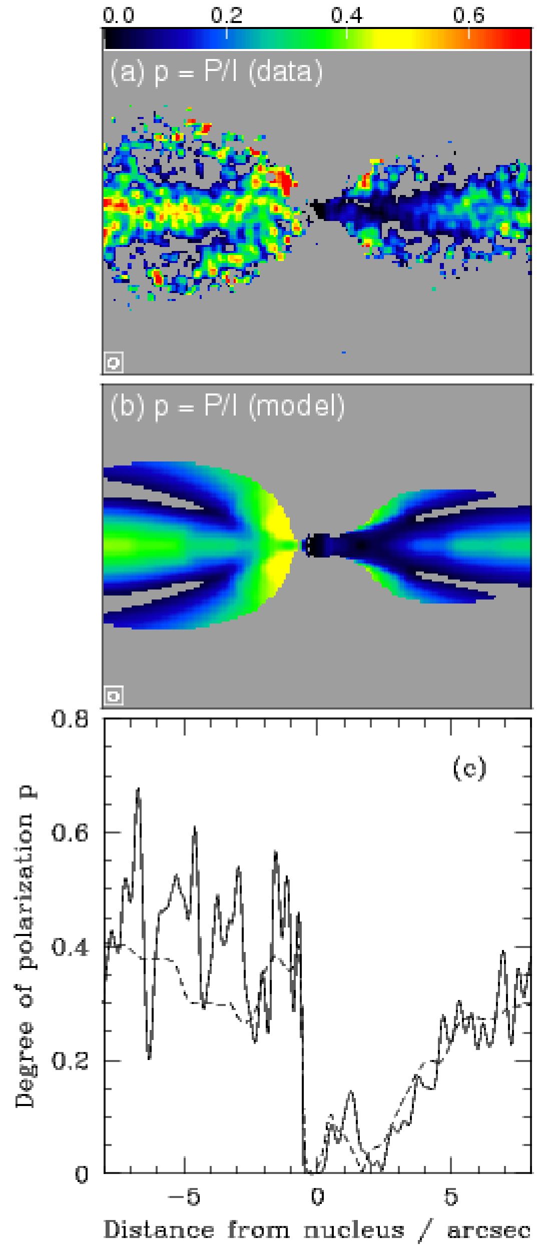
Backflow in theory

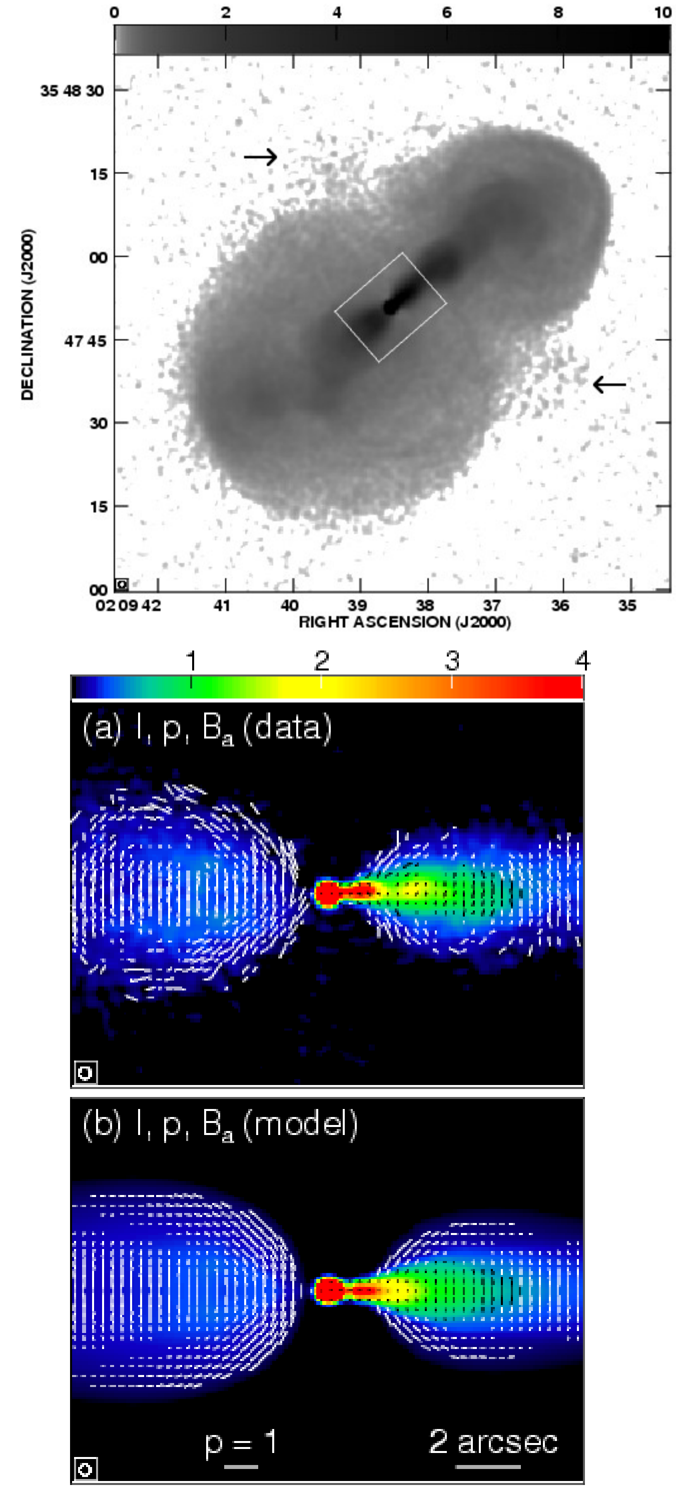
- Backflow from the working surface has been part of the standard model of FRII sources since the earliest simulations (Norman et al. 1982)
- Strongest in highly overpressured, fast, light jets
- Lobed FRI sources should have similar dynamics



Comparisons (0206+35)



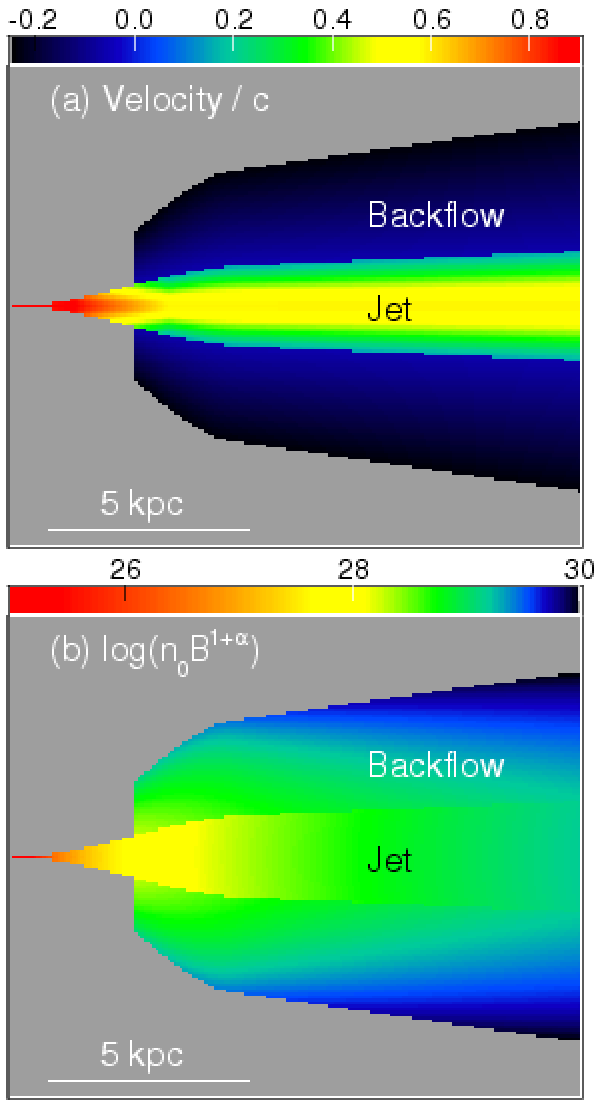




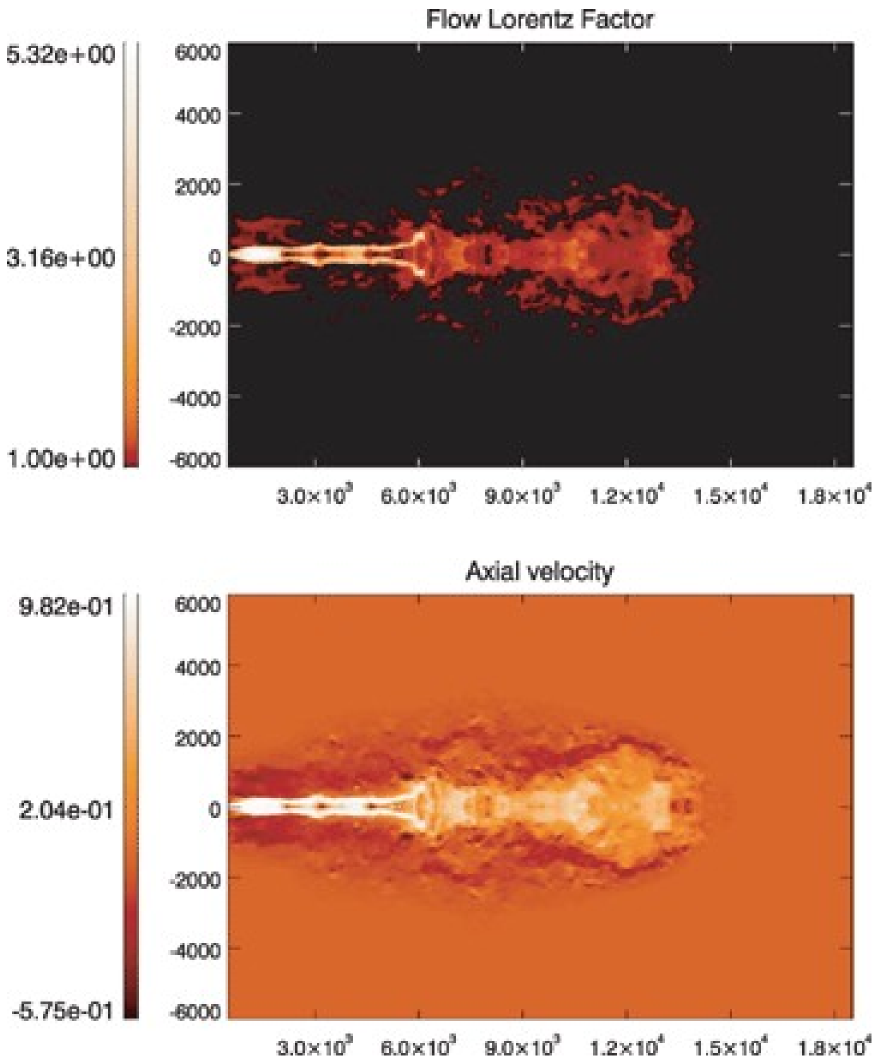
Total intensity

Fractional polarization

Velocity field and emissivity



Inferred from our model

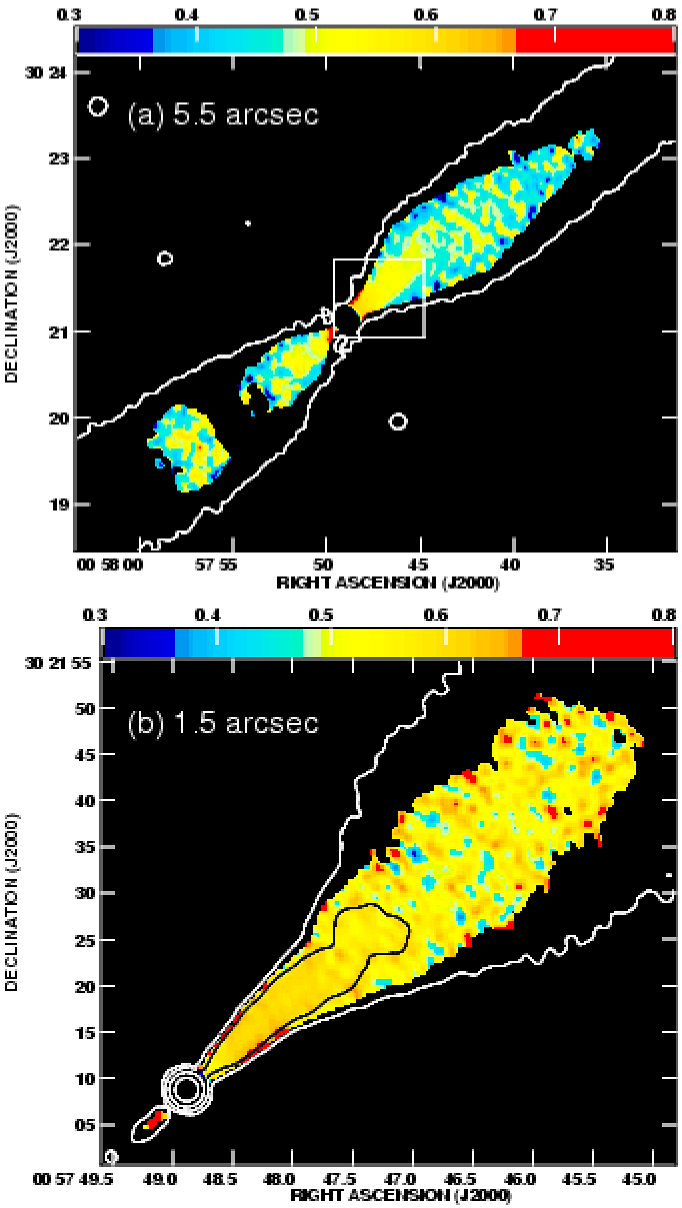


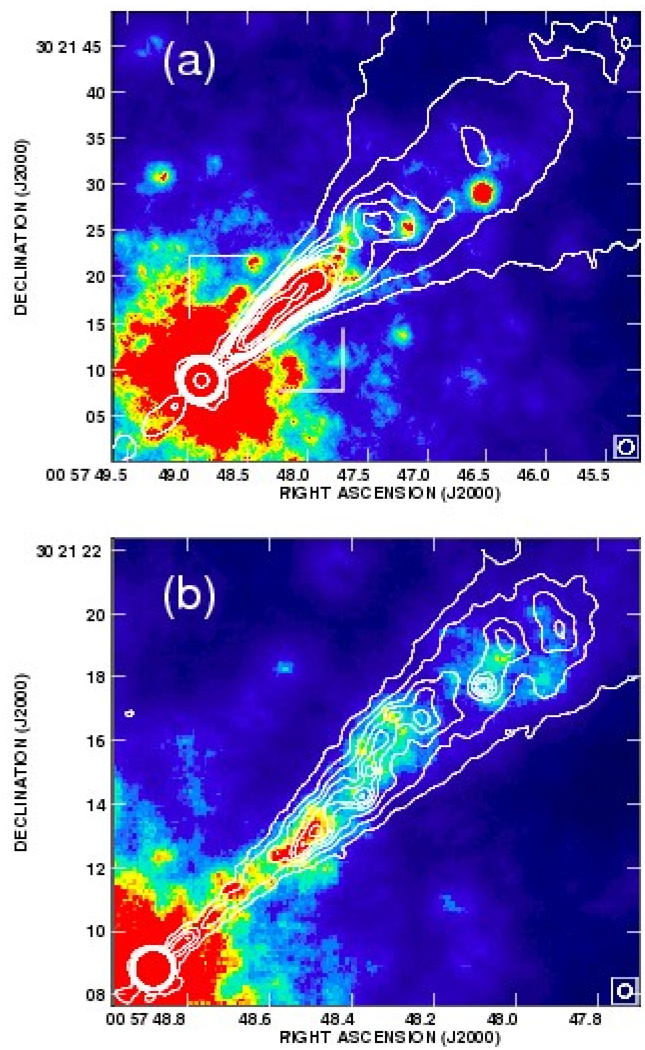
Simulation by Perucho & Marti (2007)

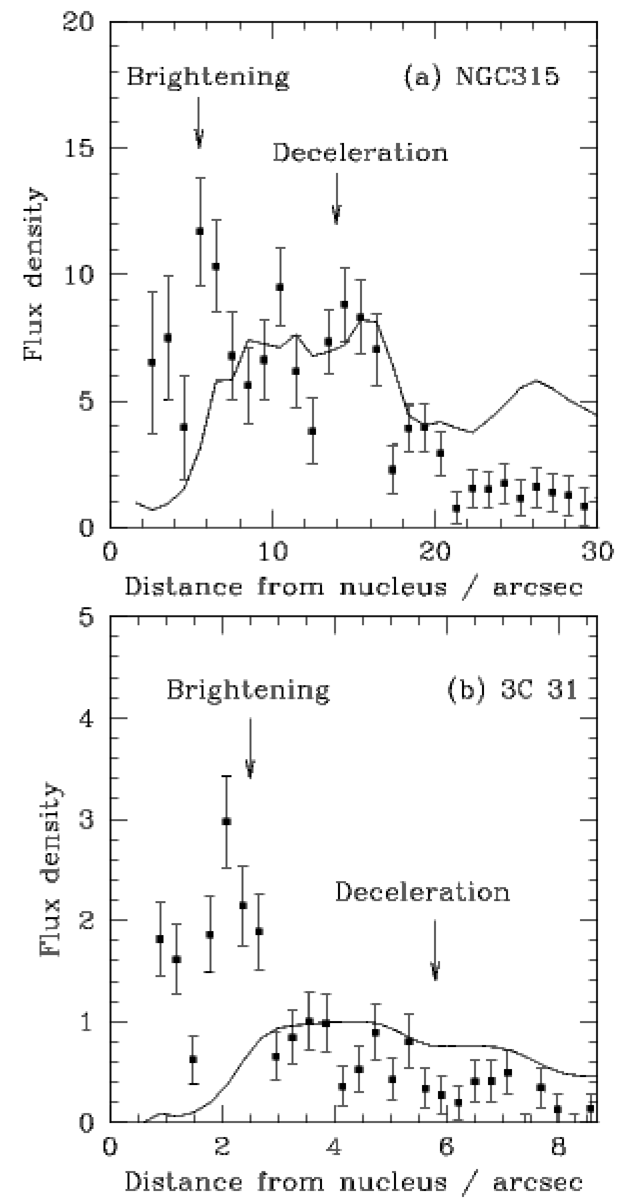
Backflow: conclusions

- Symmetrical backflow model gives a surprisingly good fit to the brightness and polarization of 0206+35.
- We should be able to model one similar source (0755+37) with new high-resolution observations.
- Backflow is expected in lobed FRI sources: the surprise is that it can be described by an axisymmetric, fully symmetrical model.
- The backflow we model must also have enhanced emissivity immediately around the jet outflow.
- Field in backflow consistent with pure toroidal: confining the jet?
- Simulations need to be 3D (very hard for the density contrasts we infer) and two-sided to be fully realistic. Maybe need ordered toroidal field.
- Clear predictions for a larger sample

Particle acceleration in jet bases







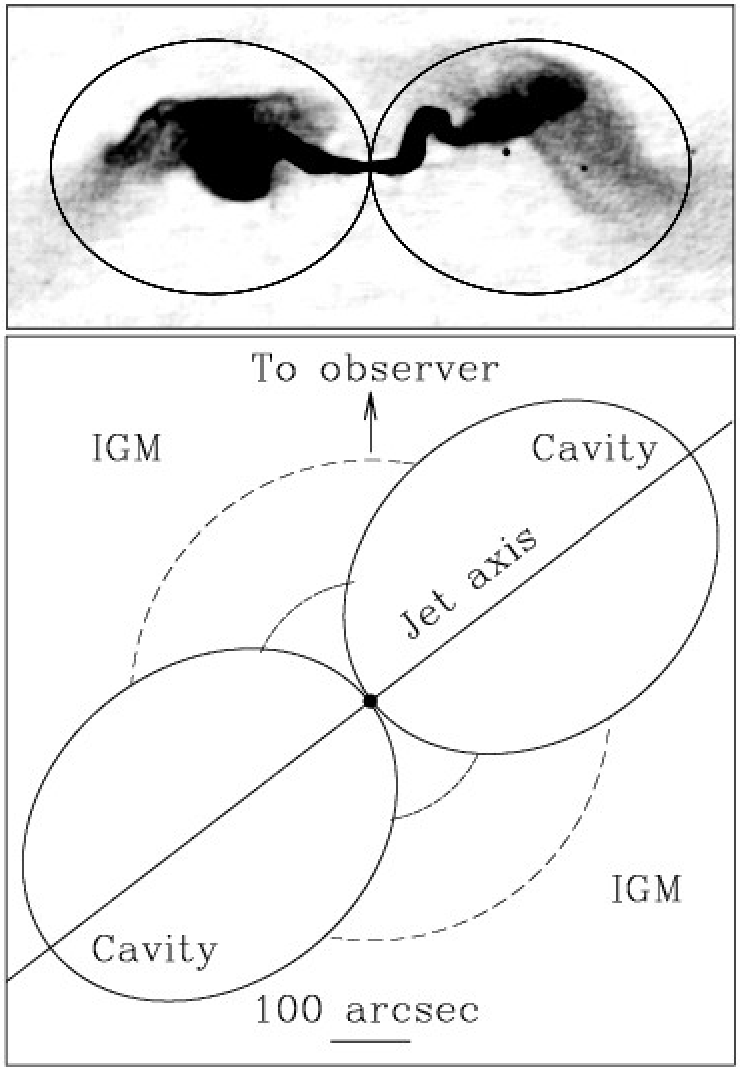
Spectral index

Radio/X-ray

Spectra and particle acceleration

- Jet bases have $\alpha = 0.62$ with a remarkably small dispersion (energy index = 2.24)
- Spectrum flattens with distance from the nucleus and towards the jet edges ($\alpha \approx 0.50 - 0.55$)
- X-ray/radio ratio increases with inferred flow velocity
- Two particle acceleration mechanisms, one associated with shear, the other with X-ray emission?
- Energy index for Fermi I acceleration by ultrarelativistic shocks is 2.23 ($\alpha = 0.615$) – coincidence?

Modelling the magnetic field in groups and clusters



Faraday rotation

$$\Delta\chi = K\lambda^2 \int nB_z dz = \mathrm{RM}\lambda^2$$

Use radio sources in or behind groups and clusters as probes of foreground magnetoionic medium

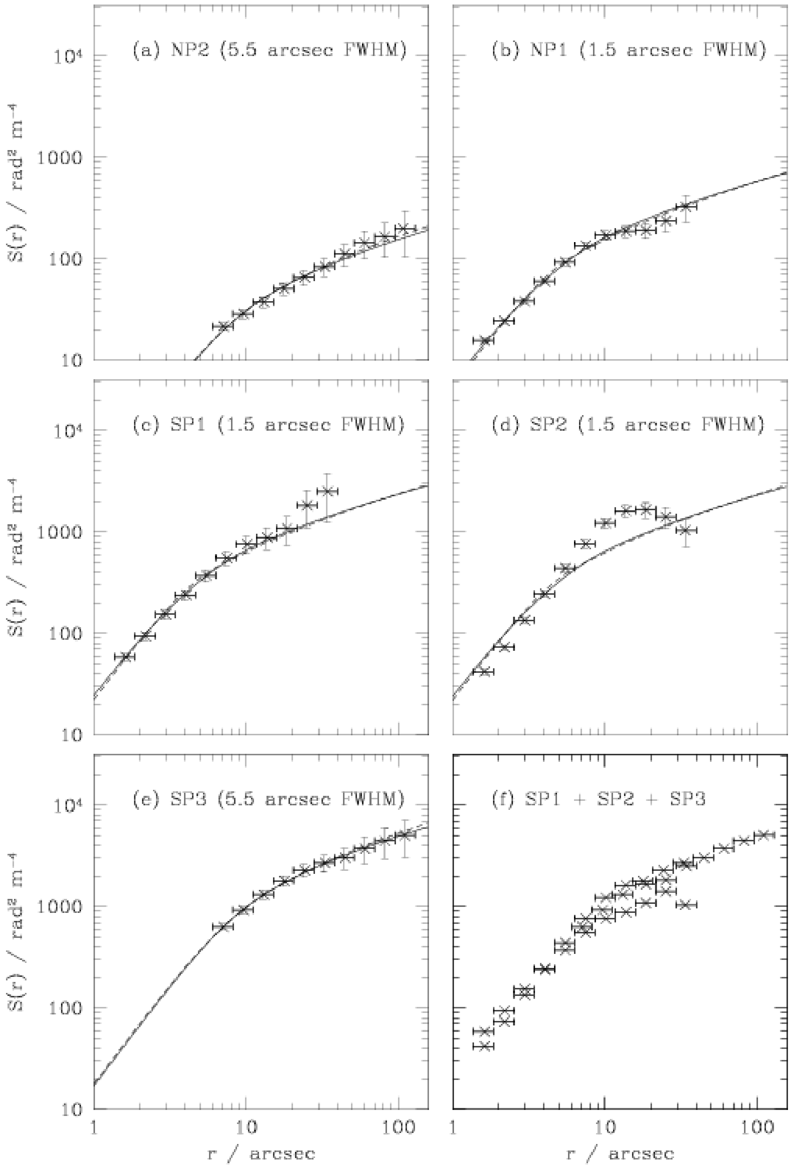
Background sources give few measurements per cluster

Embedded sources have complex geometry

Orientation from jet models

Gas density distribution from X-ray imaging – include cavities

The magnetic power spectrum



Assume that the magnetic field is an isotropic Gaussian random variable

Measure structure function of RM

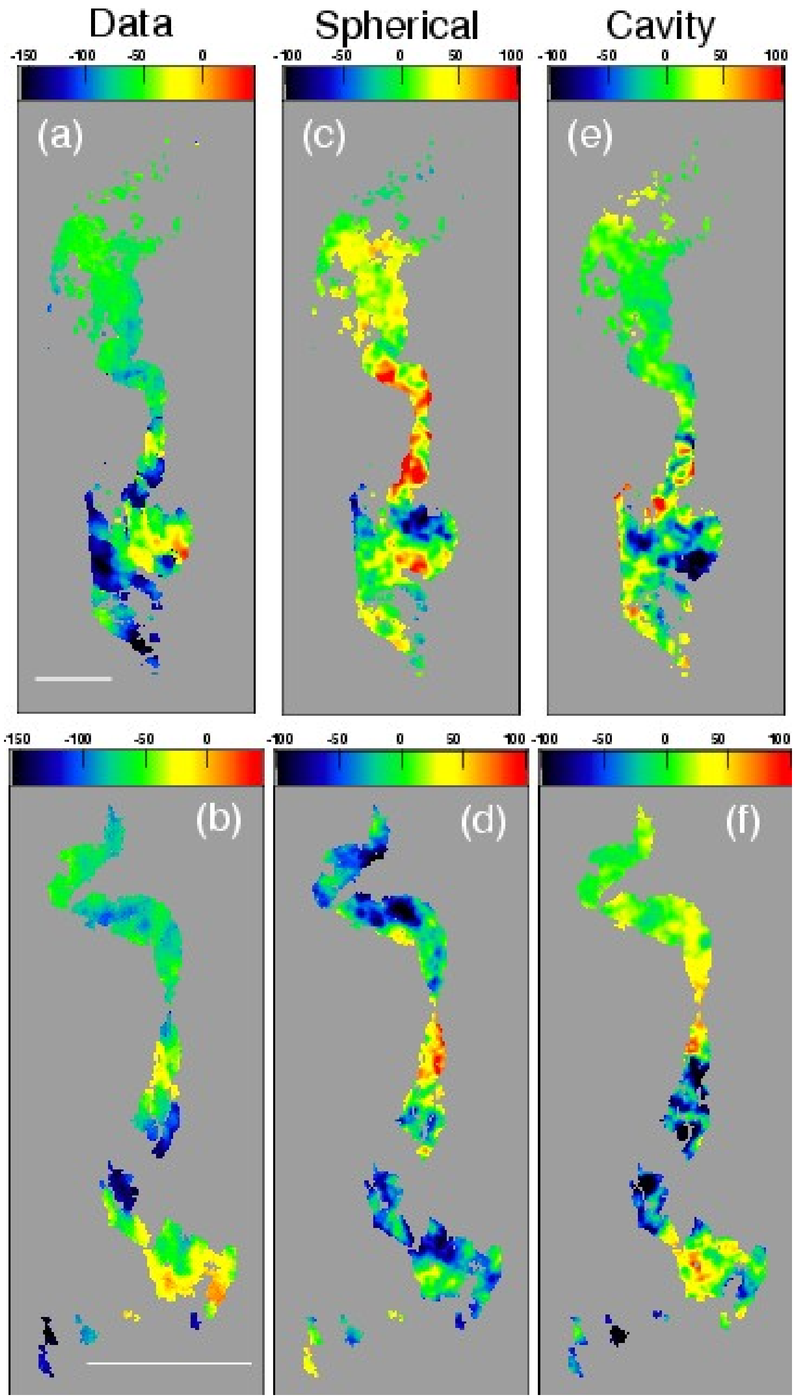
Derive RM (hence magnetic) power spectrum C(f)

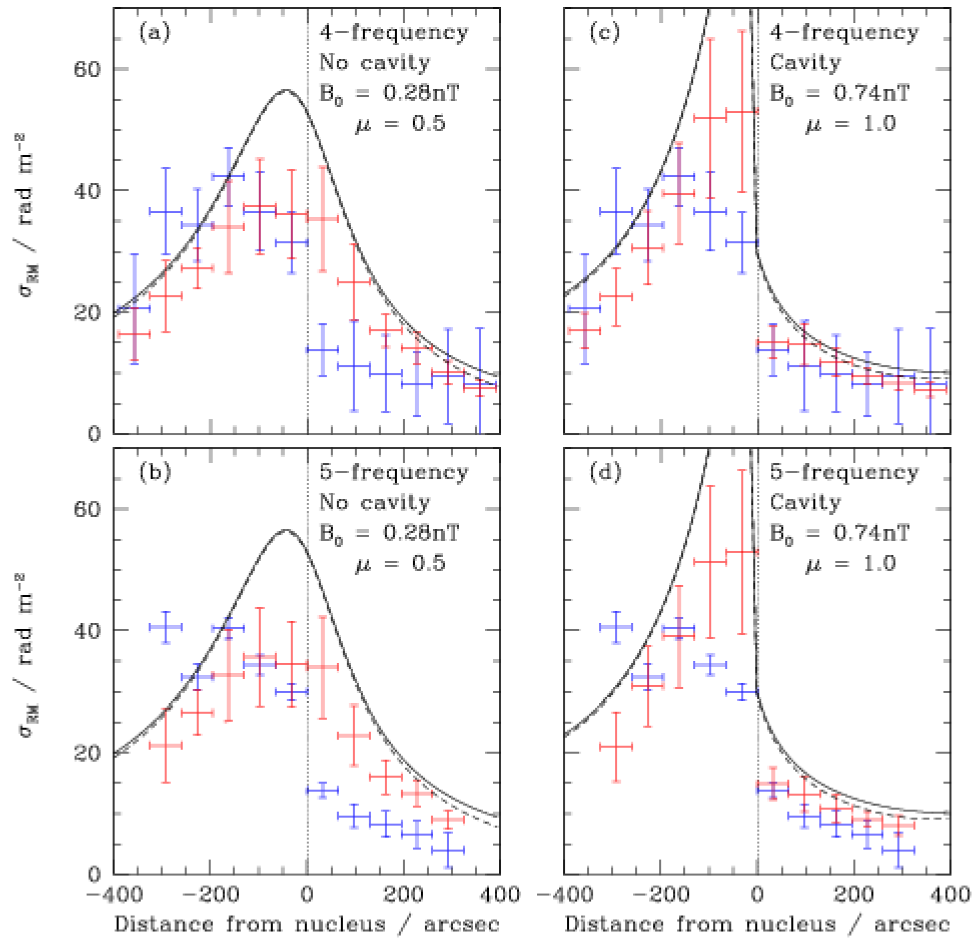
Best models for 3C31 have

$C(f) \propto f^{-2.3}$ for $f < 0.06$ arcsec^{-1}

with either a steeper slope (consistent with Kolmogorov turbulence) or a cut-off at higher frequencies

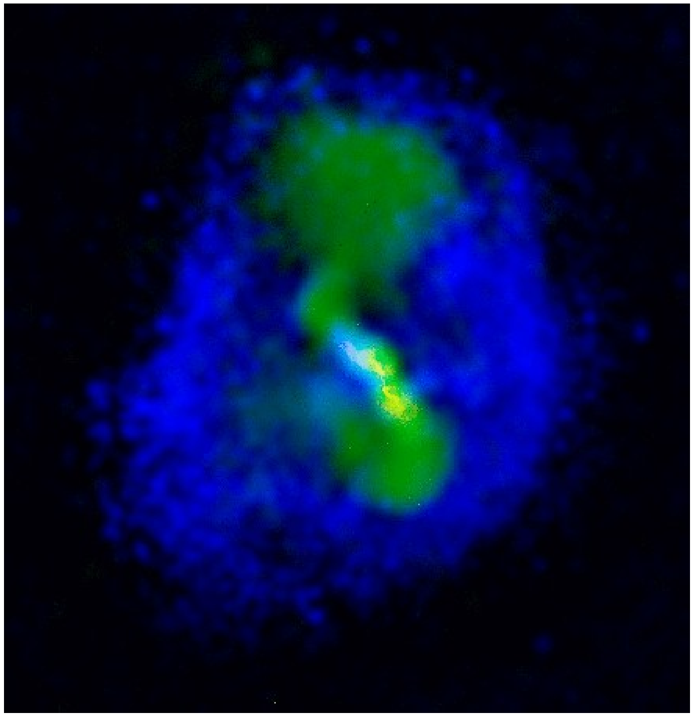
RM images and simulations of 3C31

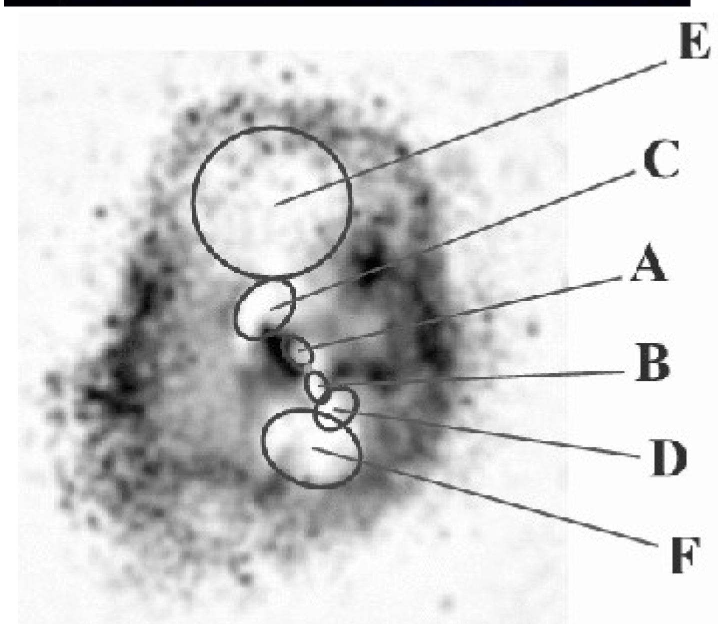


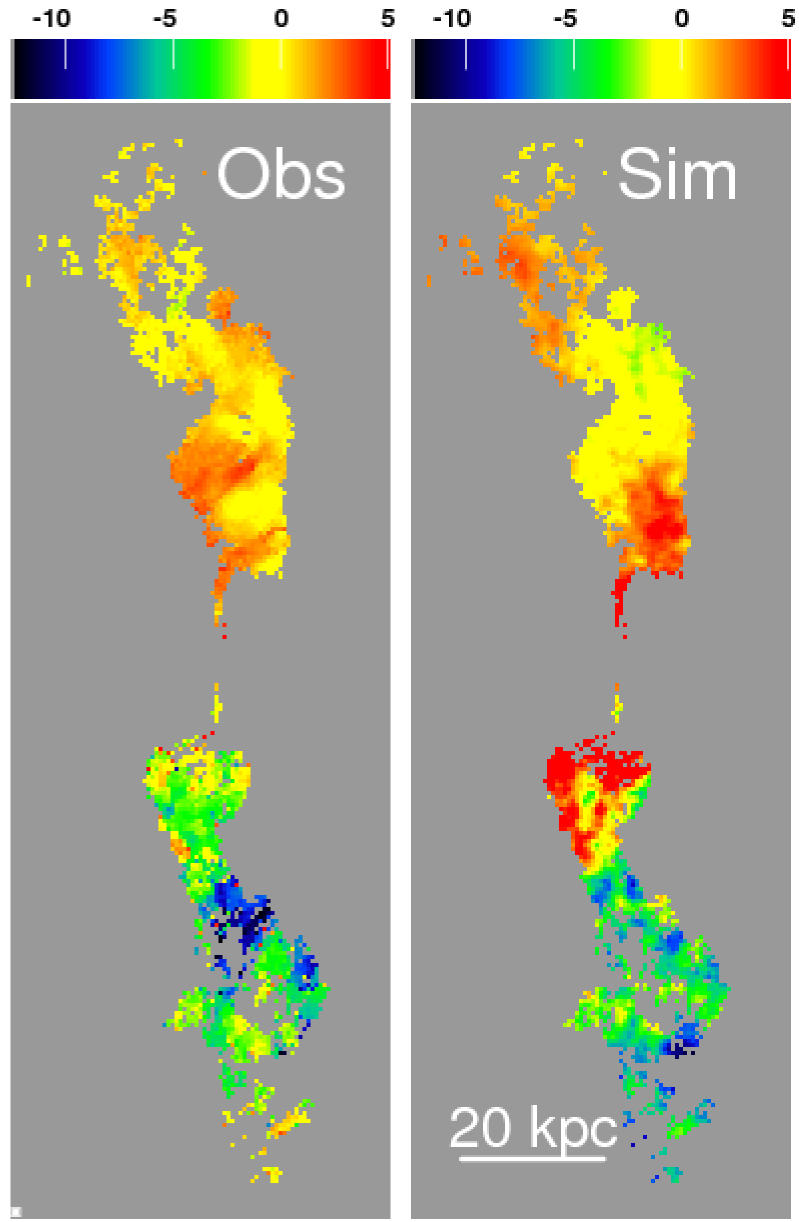


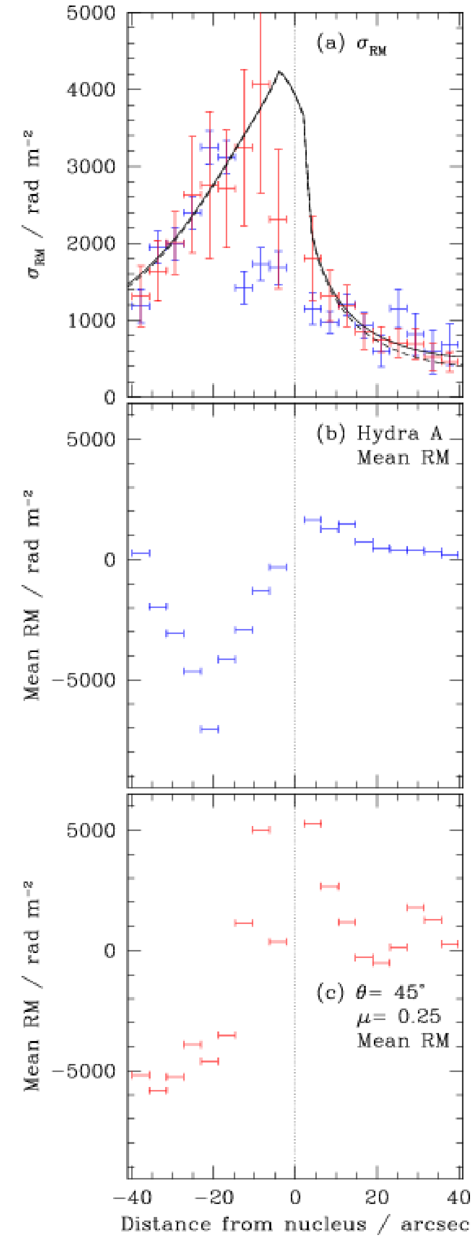
Given C(f), make 3D simulations with gas + cavities. Fit profiles of rms RM.

Rotation measure in Hydra A









RM: conclusions

- Consistent with pure foreground Faraday rotation; field in observed X-ray gas
- Brighter jet has lower path length
- Magnetic-field power law cannot have pure power-law spectrum over the entire observable range of spectral frequencies. Slope is flatter than for Kolmogorov turbulence except at high spatial frequencies.
- Can reproduce variation of RM fluctuation amplitude across a source provided that the effects of cavities are included