Faraday Rotation in and around Radio Galaxies

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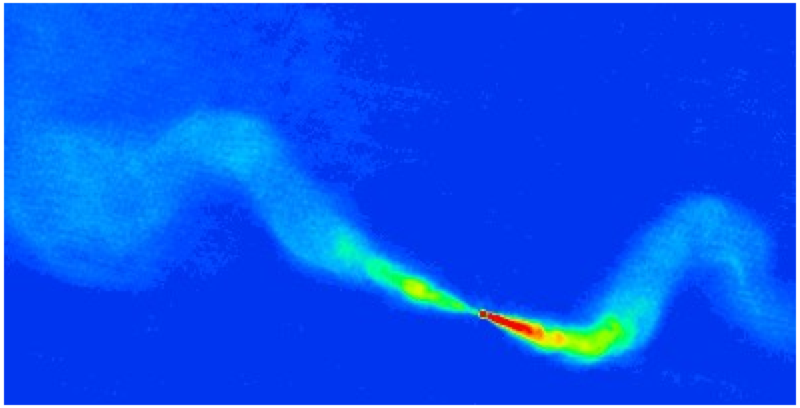


Outline

- Objectives
- Some useful results for foreground rotation in the short-wavelength limit (and where this breaks down)
- Effects of source geometry – compare RM fluctuations in two sources at different angles to the line of sight
- Cavities and their effects on RM distributions
- Modelling VLBI rotation measure images using the same techniques

RL et al. (2008)

Guidetti et al. (2010)

Objectives

- Study the magnetic field in the IGM surrounding radio galaxies by observing Faraday rotation and depolarization in sources whose geometry can be (approximately) determined
- Verify that the correlation between depolarization and jet sidedness observed at low resolution is due to Faraday rotation by a foreground medium
- Determine the spatial statistics of the rotation measure and therefore those of the magnetic field
- Understand the spatial distribution of the Faraday-active medium and its relation to the cluster/group scale IGM and the source

Simple results in the short-wavelength limit

$$\mathbf{p}(\lambda) = |\mathbf{p}(\lambda)| \exp[2i\chi(\lambda^2)]$$

Complex polarization

$$\mathrm{RM} = \frac{\partial \chi}{\partial \lambda^2} = \frac{1}{2}\Im\left(\frac{\partial \ln \mathbf{p}}{\partial \lambda^2}\right)$$

Rotation measure

$$\overline{\mathbf{p}(\mathbf{r}_\perp, \lambda)} = |\mathbf{p}_0| \int W(\mathbf{r}_\perp - \mathbf{r}'_\perp) \exp[2i\mathrm{RM}(\mathbf{r}'_\perp)\lambda^2] d^2\mathbf{r}'_\perp$$

Integrate over a beam

$$\overline{\mathrm{RM}(\mathbf{r}_\perp)} = \int W(\mathbf{r}_\perp - \mathbf{r}'_\perp)\mathrm{RM}(\mathbf{r}'_\perp) d^2\mathbf{r}'_\perp$$

Observed RM for $\lambda \approx 0$

$$\overline{\mathbf{p}(\lambda)} \approx |\mathbf{p}| \exp[2i(\mathrm{RM}(\mathbf{0}) + \mathbf{r}_\perp \cdot \nabla \mathrm{RM}))\lambda^2] \times \exp[-2|\nabla \mathrm{RM}|^2 \sigma^2 \lambda^4]$$

λ^2 rotation and Burn law depolarization

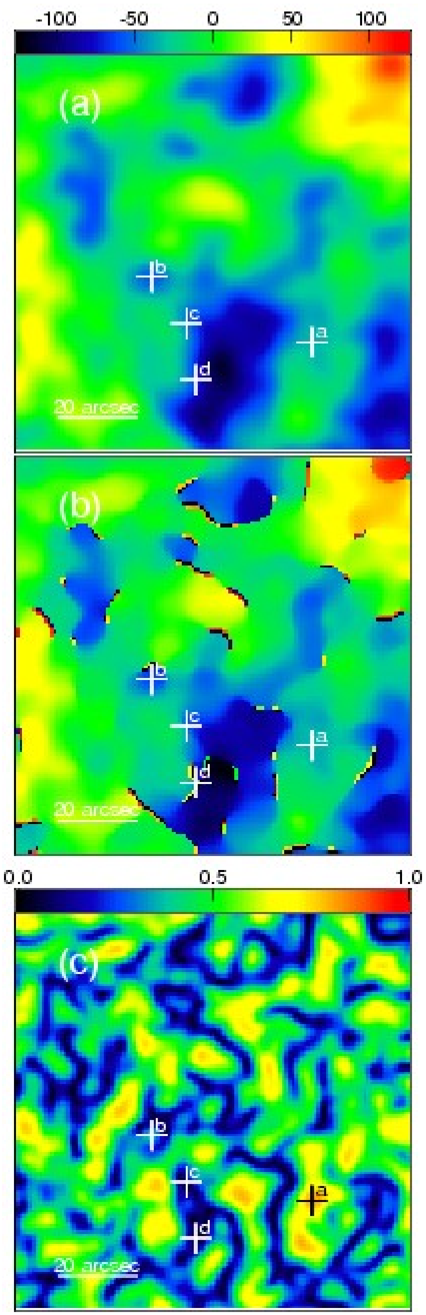
Hankel transforms

- Useful in calculating autocorrelation and structure functions analytically or by simple numerical integration.
- Easy to include the effects of a convolving beam (again in the short-wavelength limit). For a Gaussian beam, FWHM = $2\sigma(\ln 2/\pi)^{1/2}$.

$$C(r_\perp) = 2\pi \int_0^\infty \hat{C}(f_\perp) f_\perp J_0(2\pi f_\perp r_\perp) df_\perp$$

$$\begin{aligned} C(r_\perp) &= 2\pi \int_0^\infty \hat{C}(f_\perp) f_\perp J_0(2\pi f_\perp r_\perp) \\ &\times \exp(-2\pi\sigma^2 f_\perp^2) df_\perp \end{aligned}$$

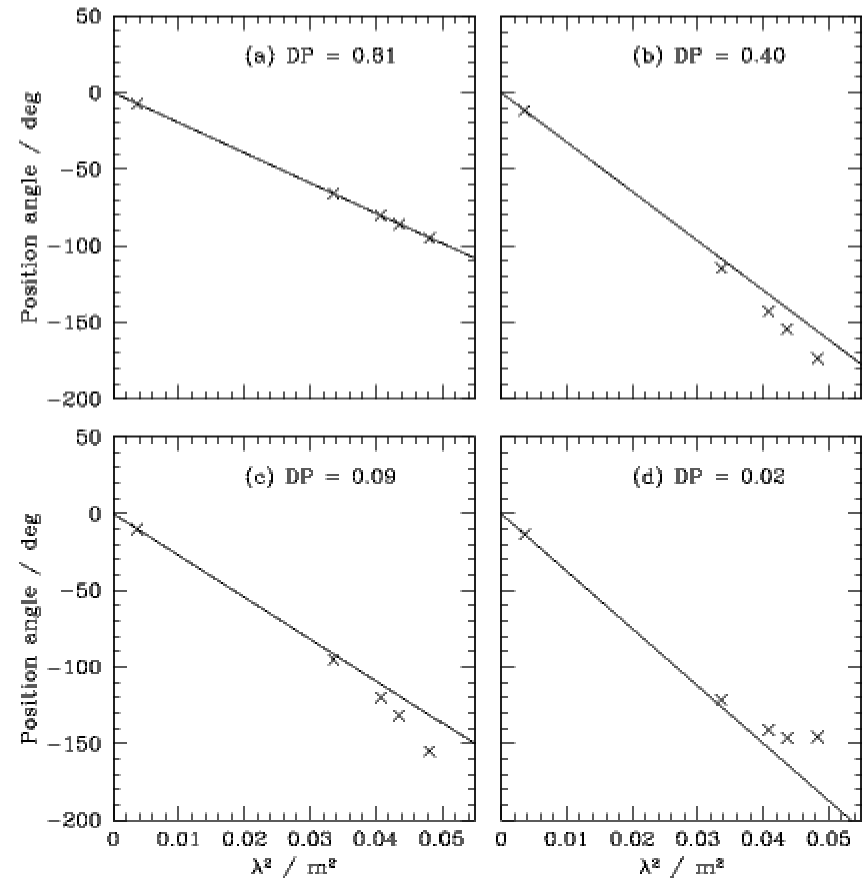
At longer wavelengths, bad things happen



Convolved RM

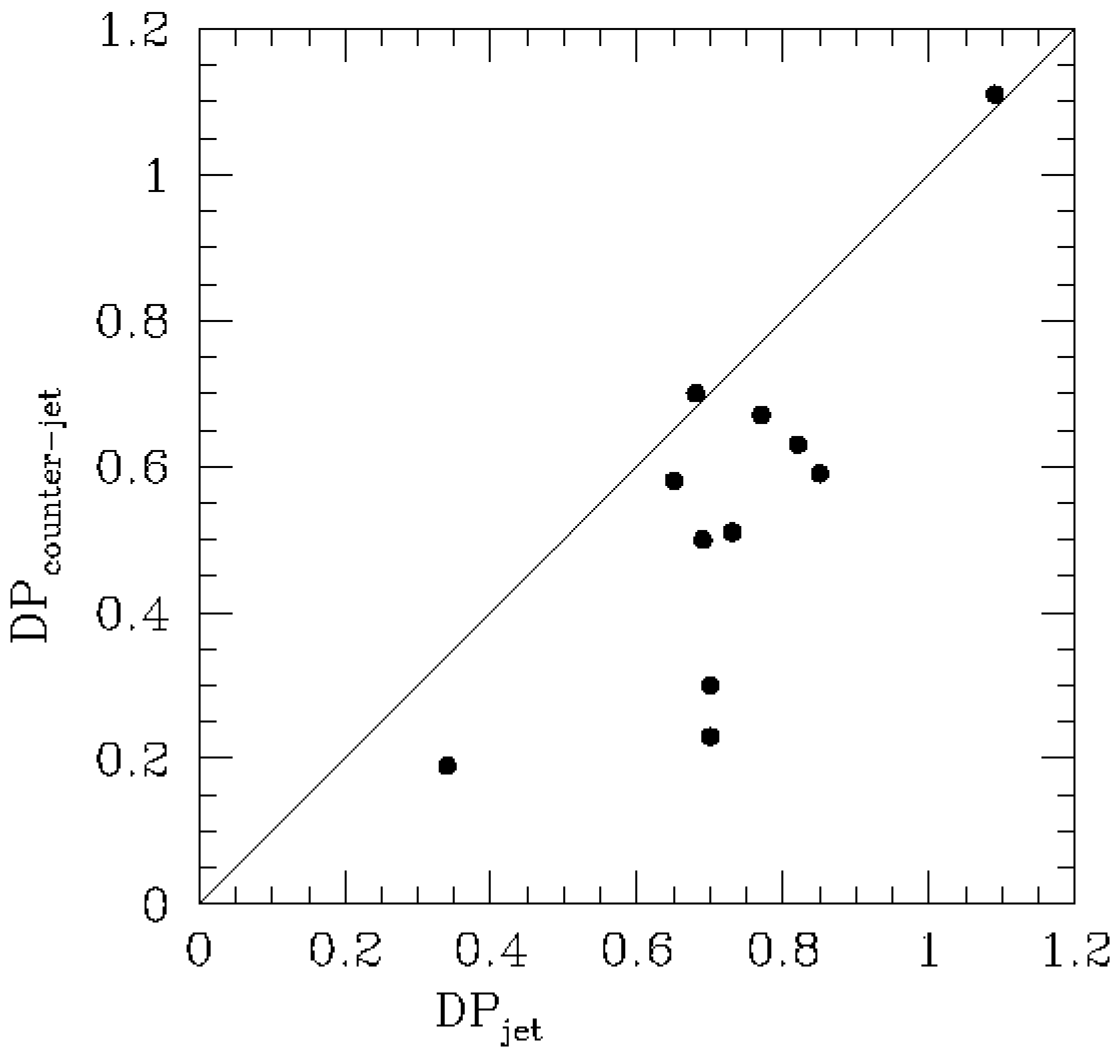
Fitted RM

Depolarization



λ^2 law is surprisingly resilient, but deviations eventually occur at longer wavelengths

Depolarization asymmetry



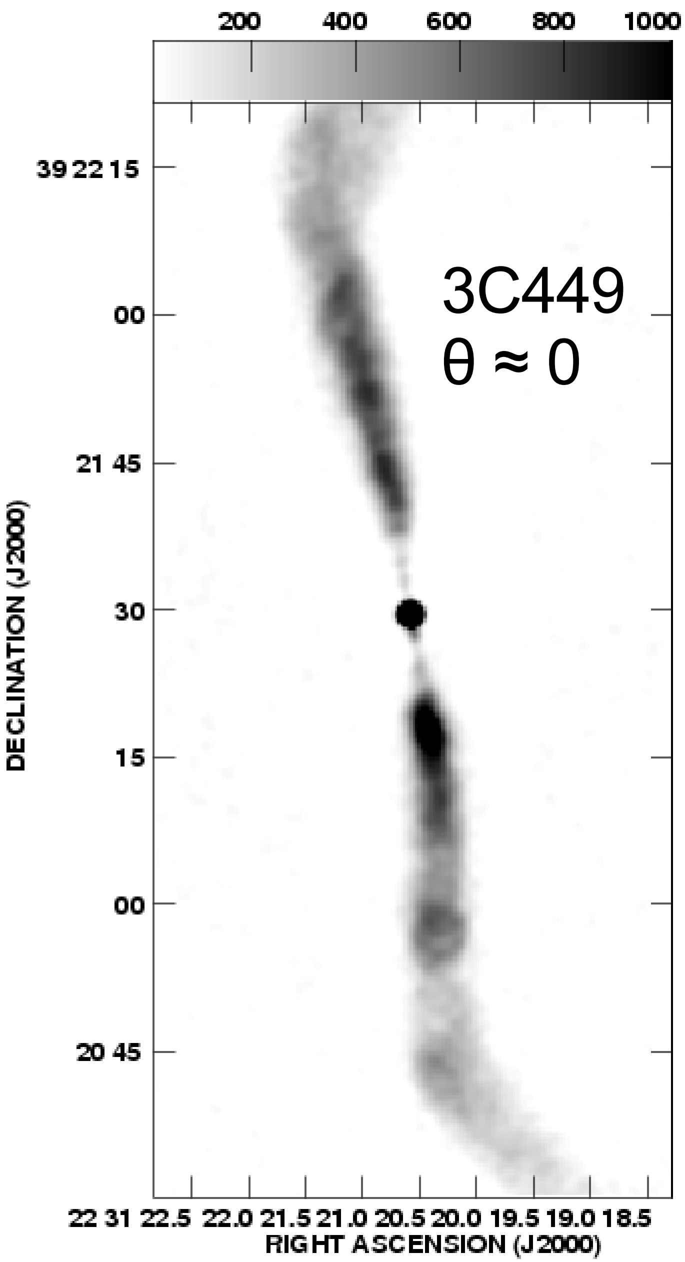
Integrated lobe depolarization

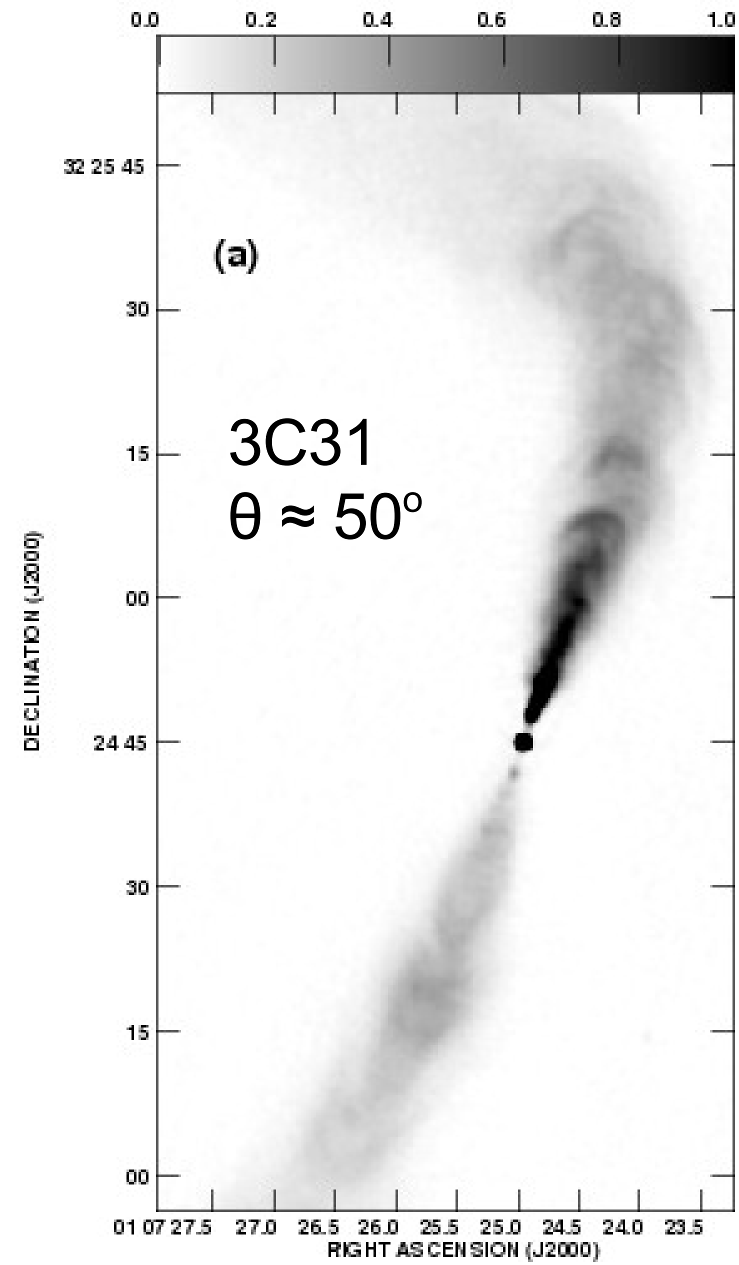
FRI sources with >4:1 ratio jet bases

Morganti et al. (1997)

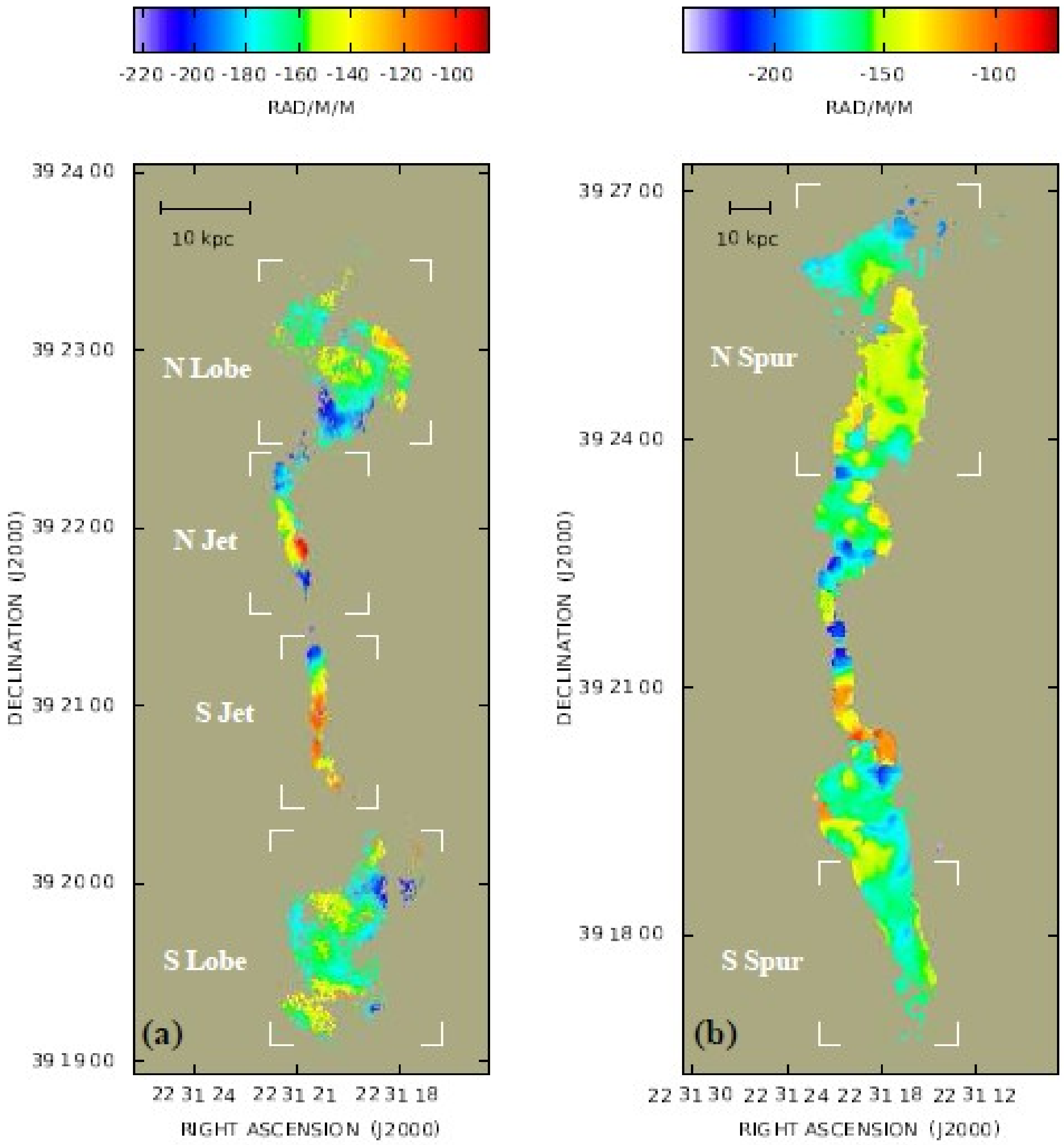
Brighter jet is on near side and has lower path length through Faraday-rotating medium

Two examples





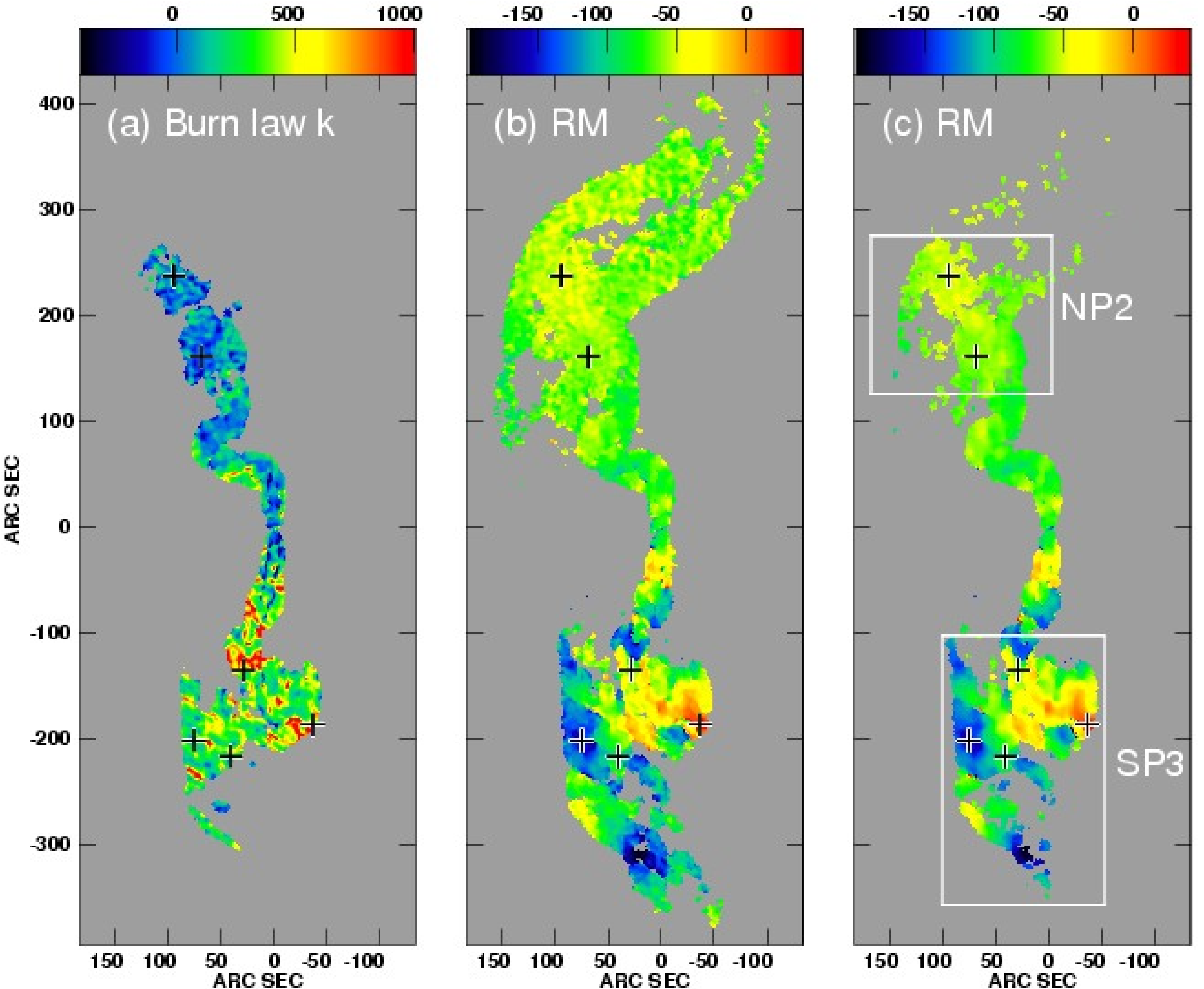
Faraday rotation – 3C449 (side-on)



Guidetti et al. (2010)

Symmetrical distribution of RM fluctuations

Faraday rotation and depolarization - 3C31

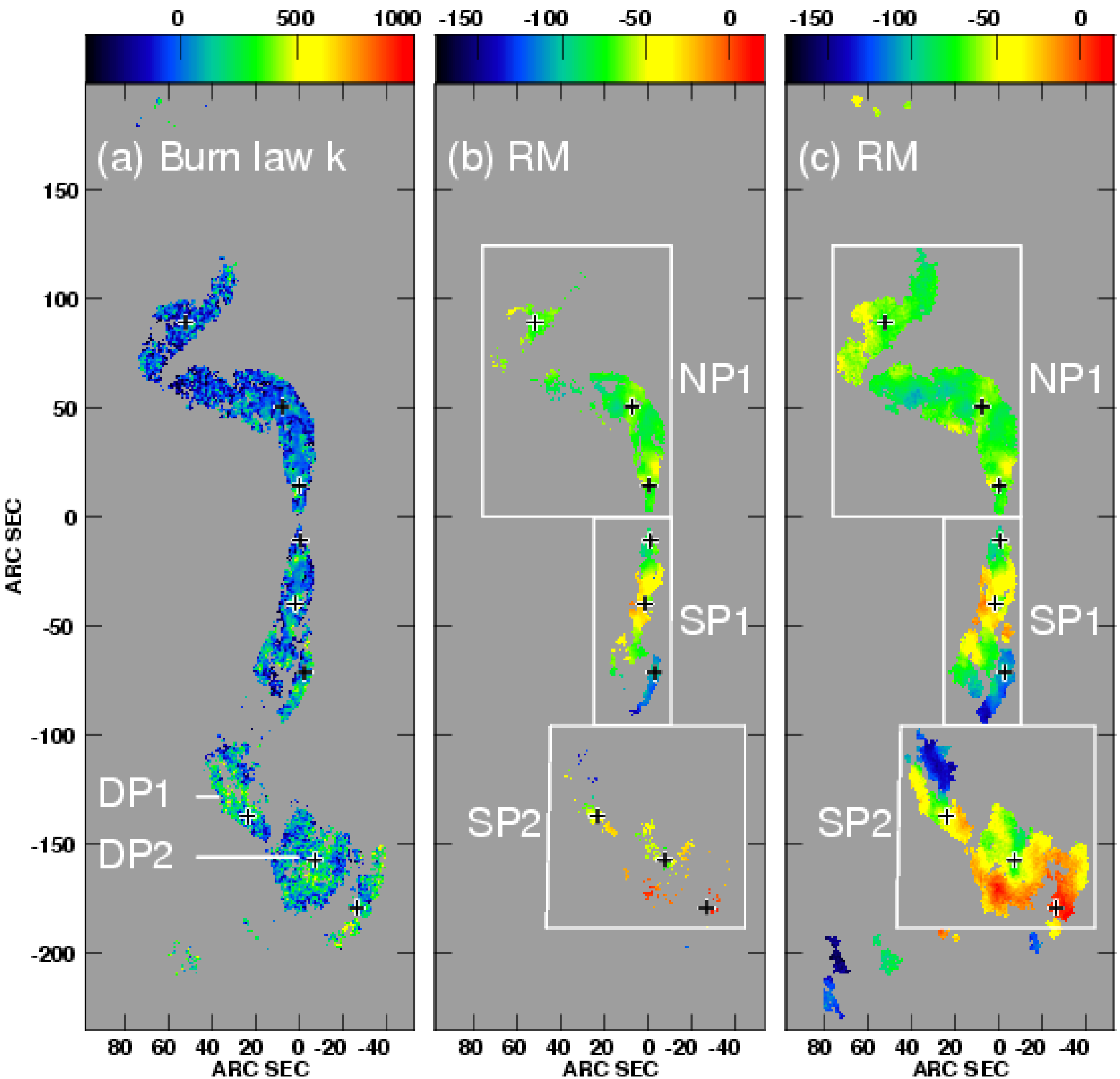


Near side (lower RM)

5.5 arcsec FWHM

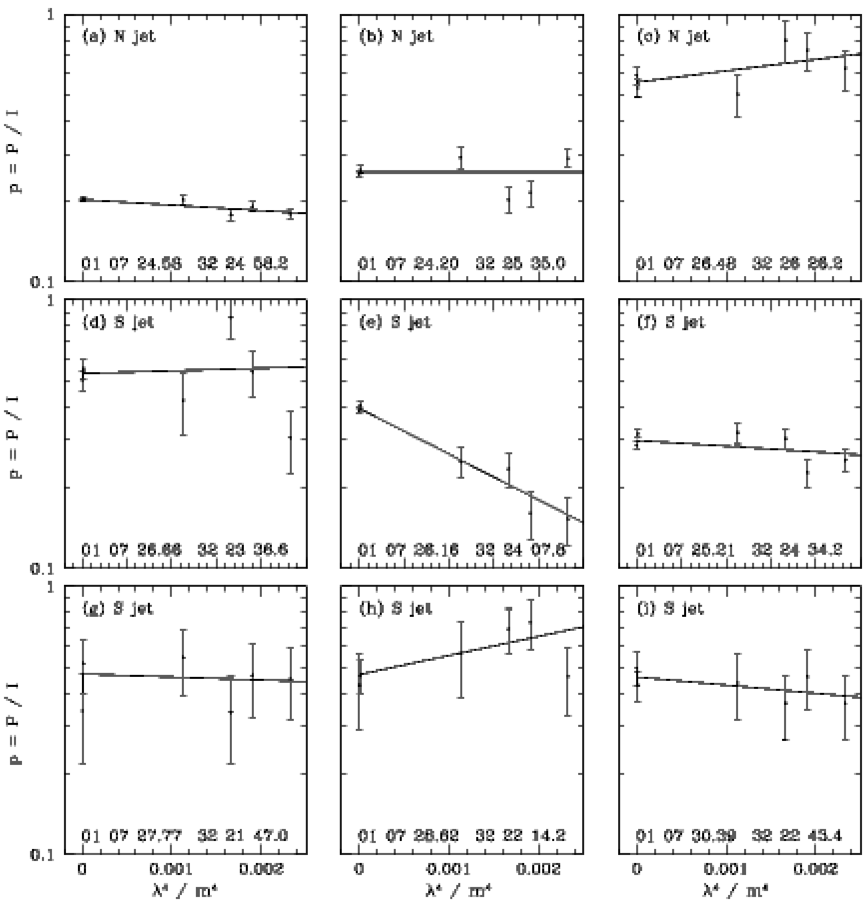
Far side

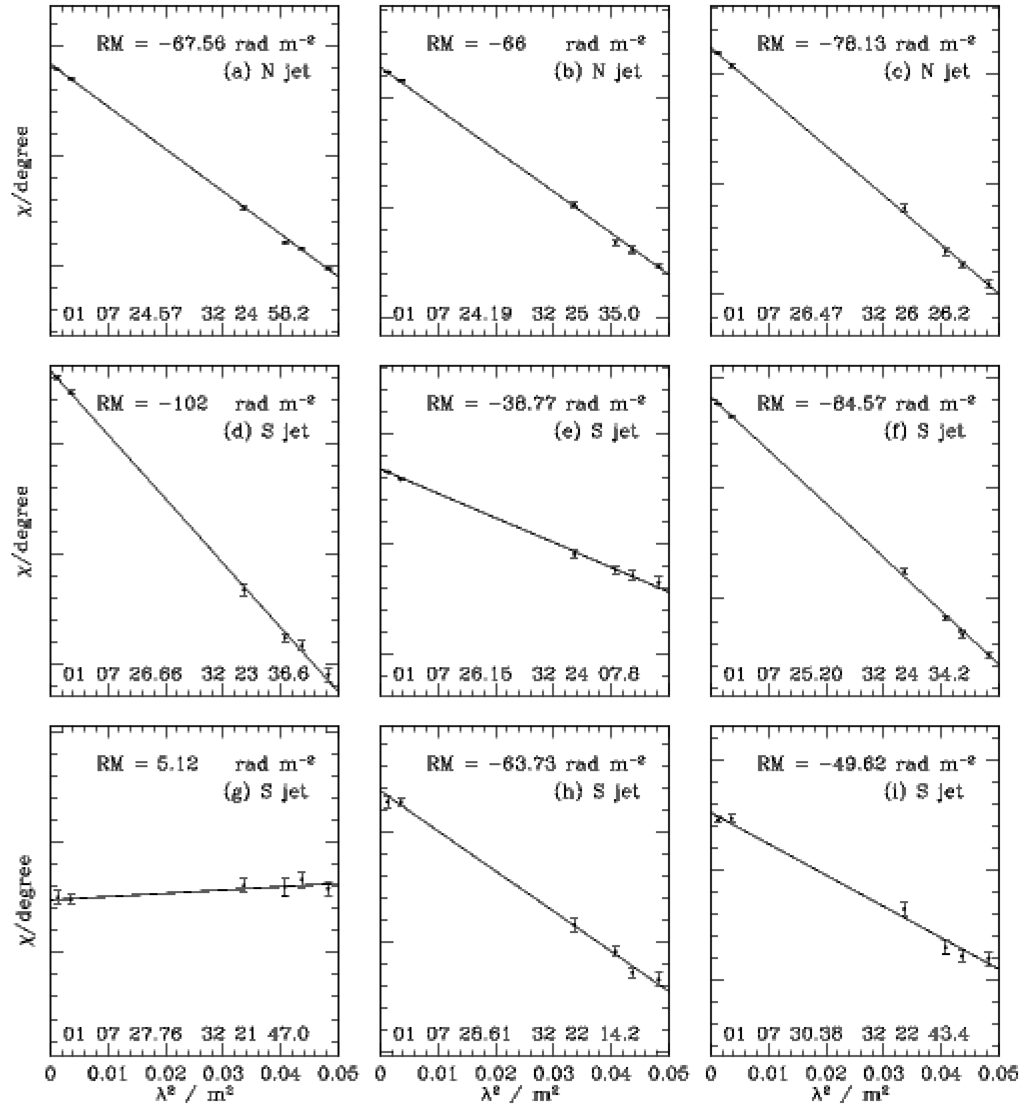
Faraday effects at high resolution



FWHM = 1.5 arcsec
(0.5 kpc)

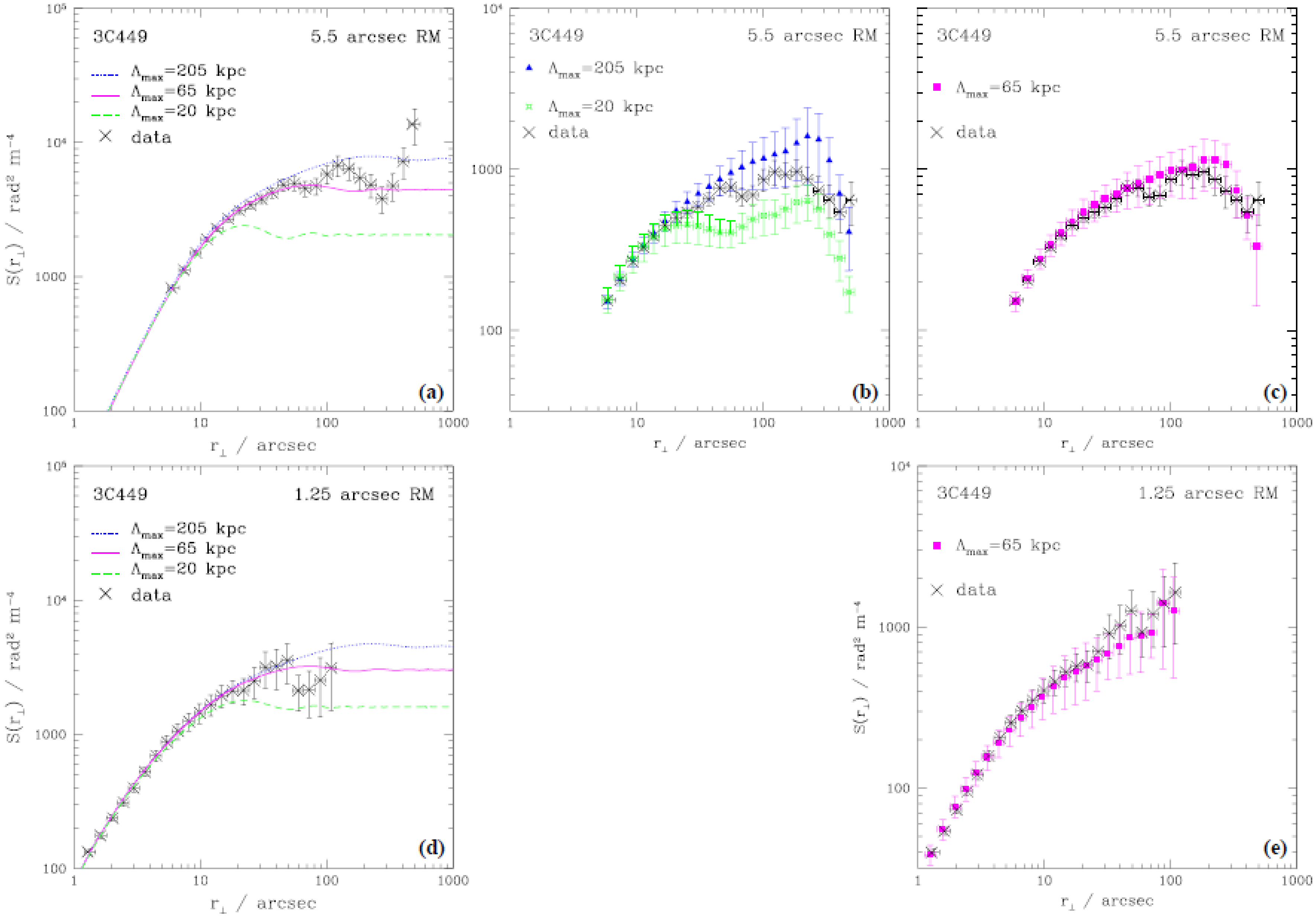
Negligible depolarization and λ^2 rotation





Almost all Faraday effects must be due to foreground material

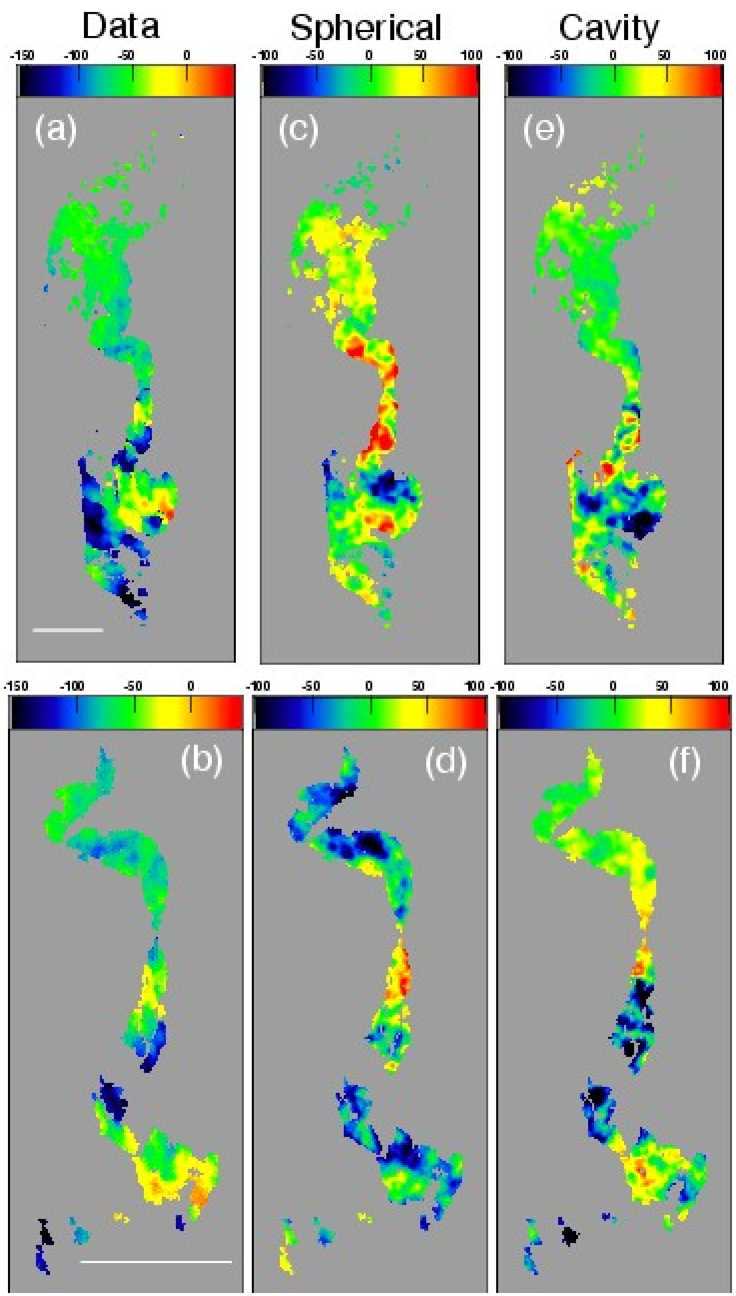
Structure functions

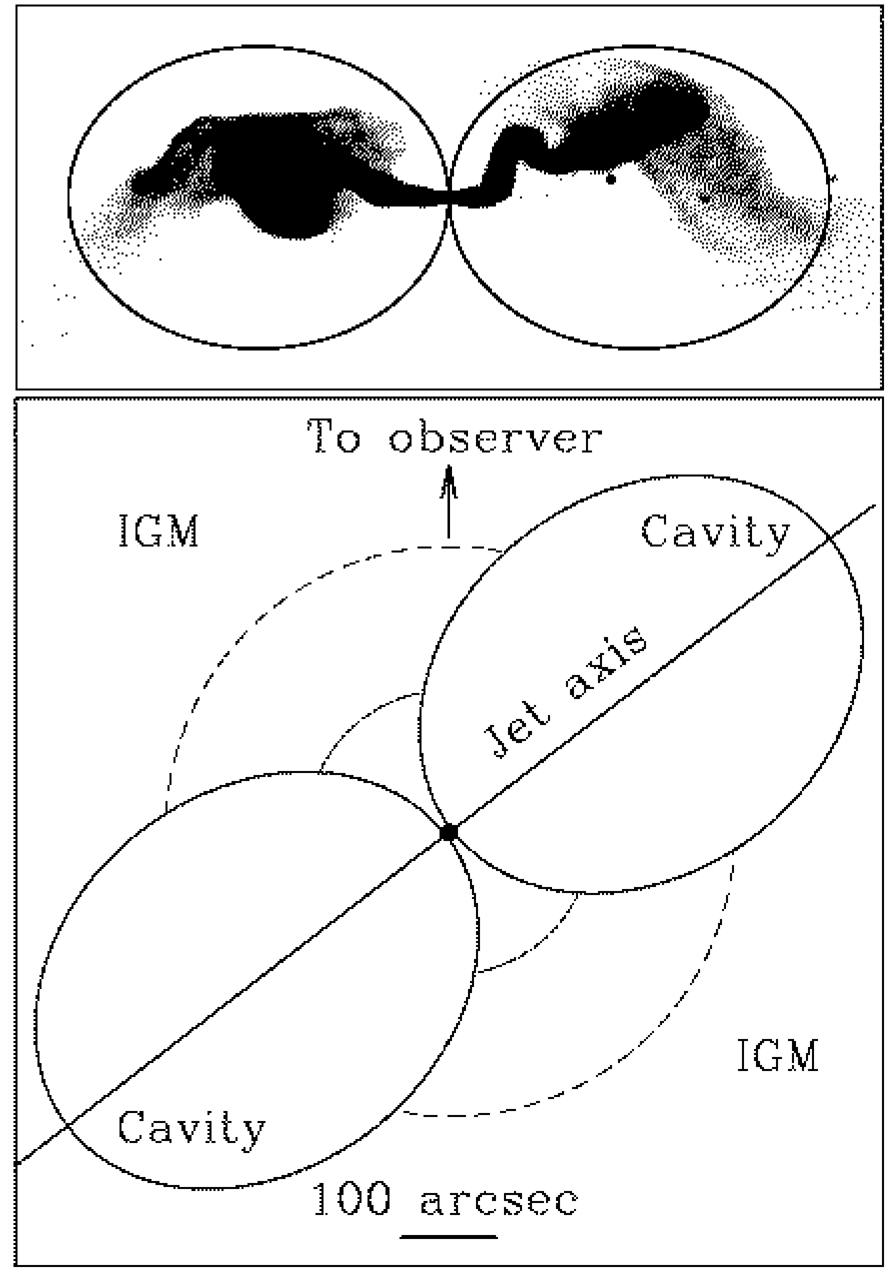


Power spectra and field strengths for 3C31 and 3C449

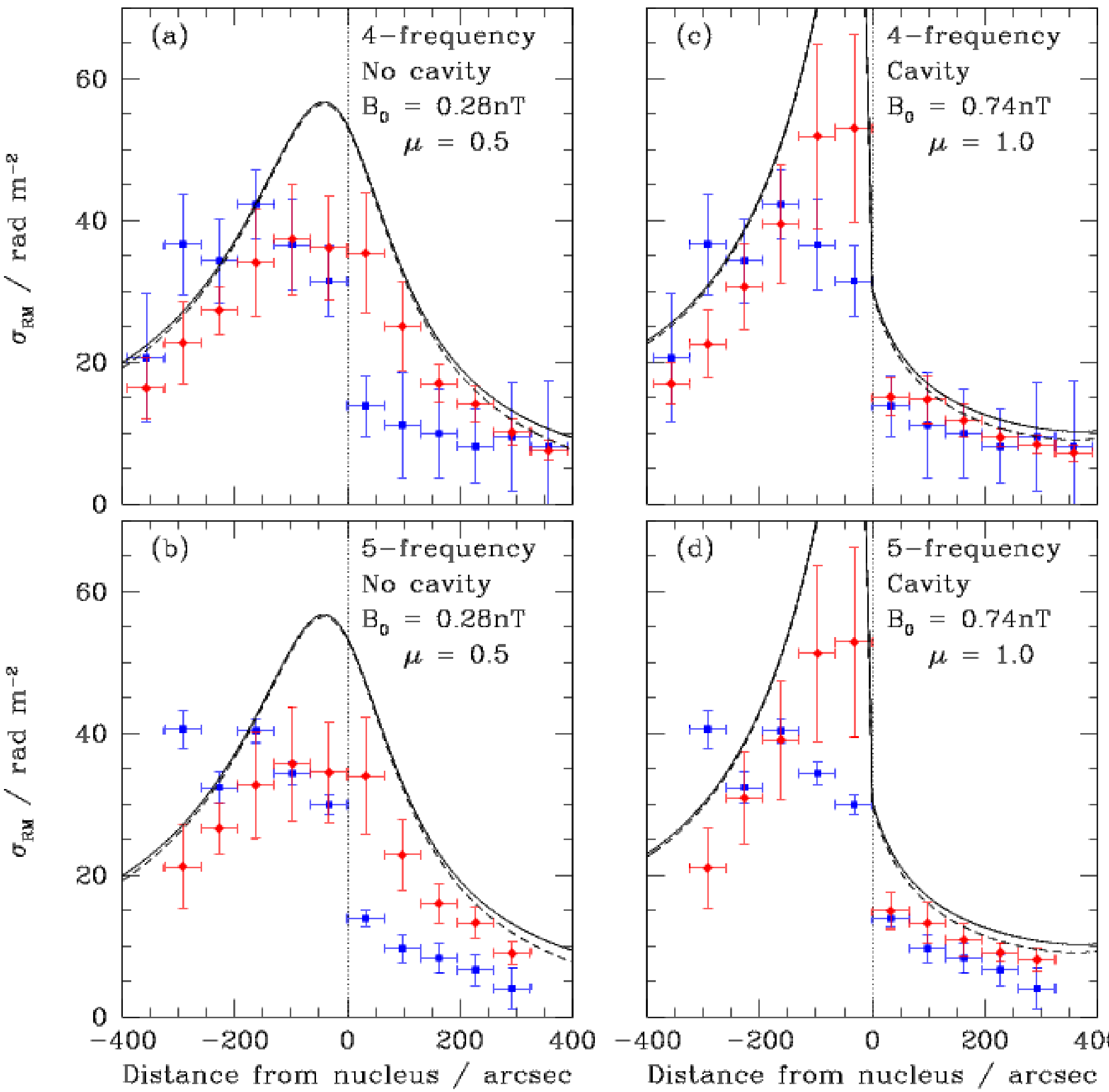
- Central field strengths are similar: 2.8 μG for 3C31 (no cavity) and 3.5 μG for 3C449.
- Broken power law forms for power spectra (not unique!)
- Largest scale ~65 kpc for 3C449; indeterminate for 3C31.
- Power law indices at large spatial scales are 2.3 for 3C31 and 2.1 for 3C449
- Break at 5 kpc (3C31), 11 kpc (3C449)
- Steeper power spectrum on smaller scales: 3.7 (Kolmogorov) for 3C31; 3.0 with a cut-off at 0.2 kpc for 3C449

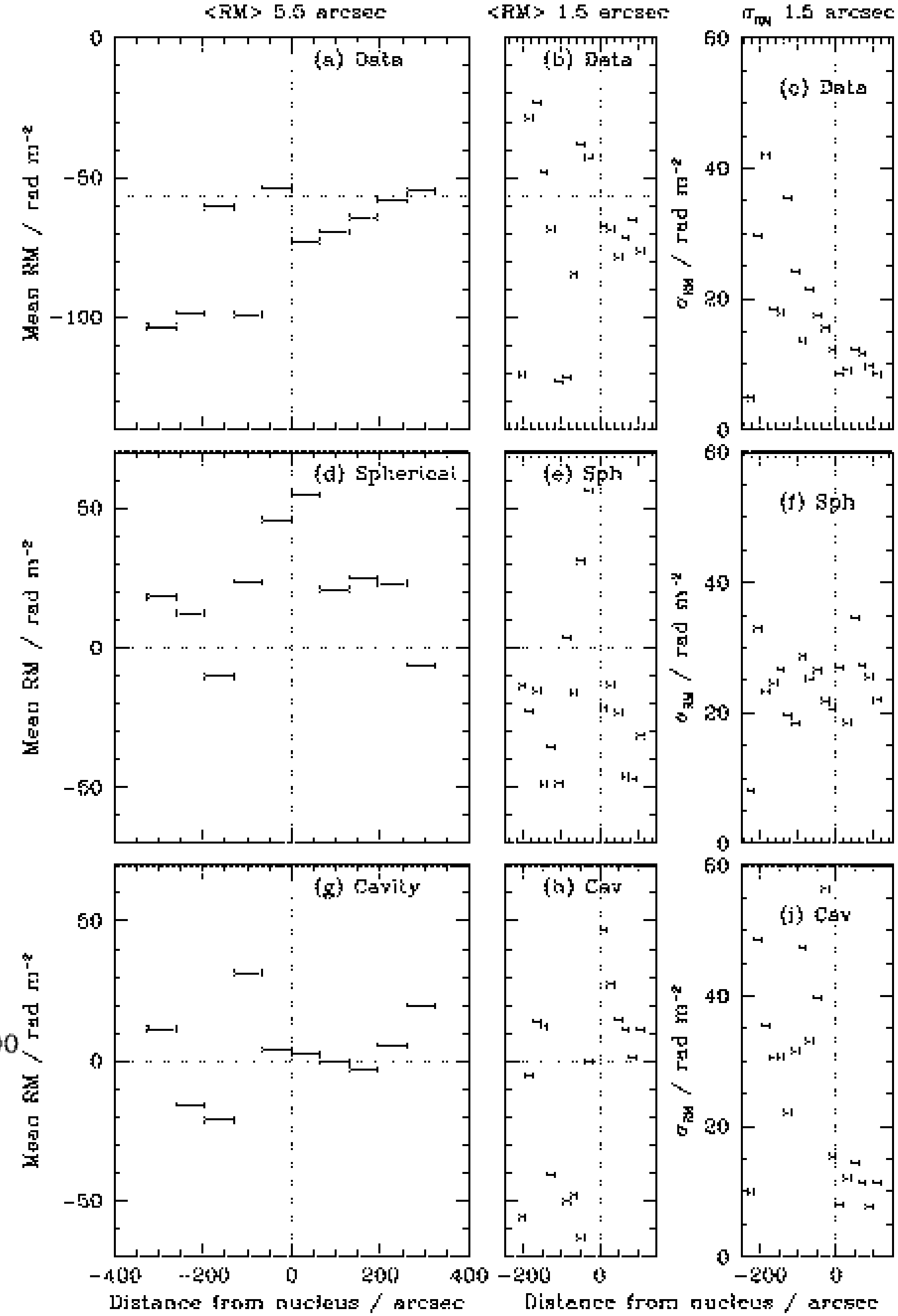
Simulating asymmetry





3D simulations - profiles

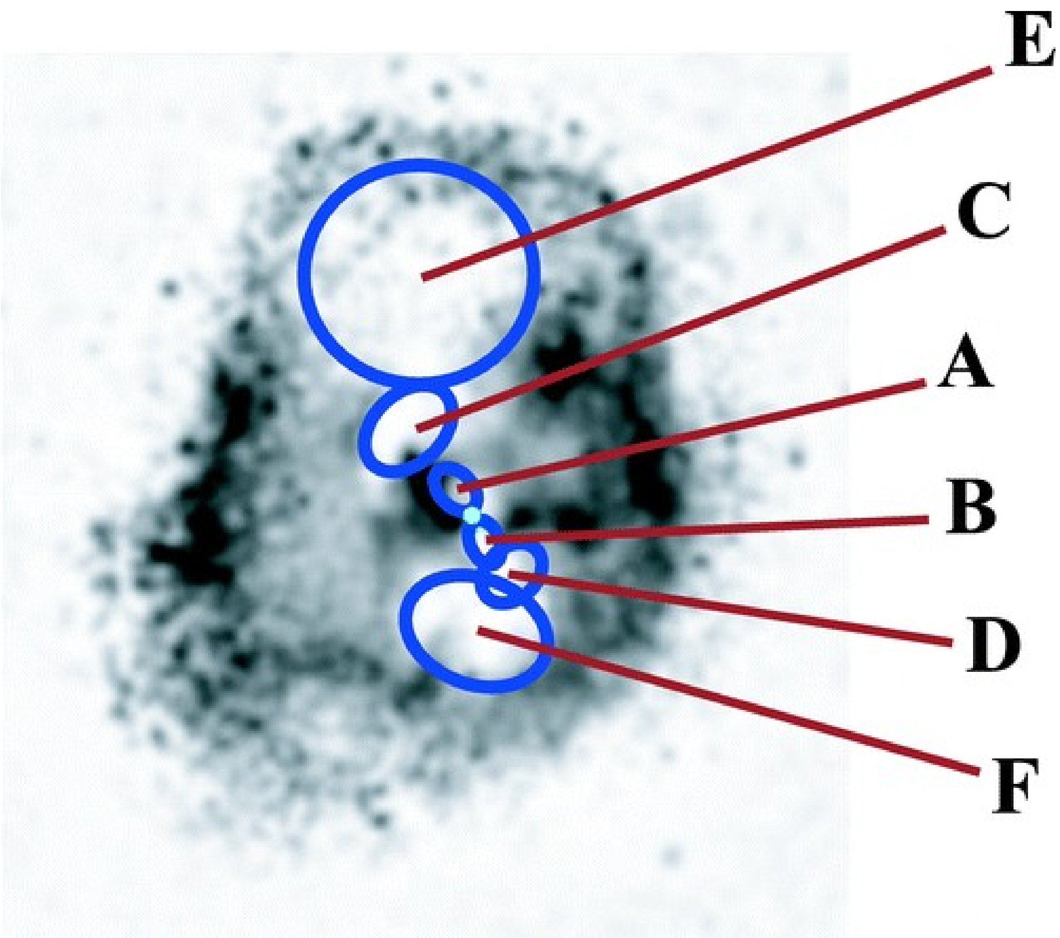


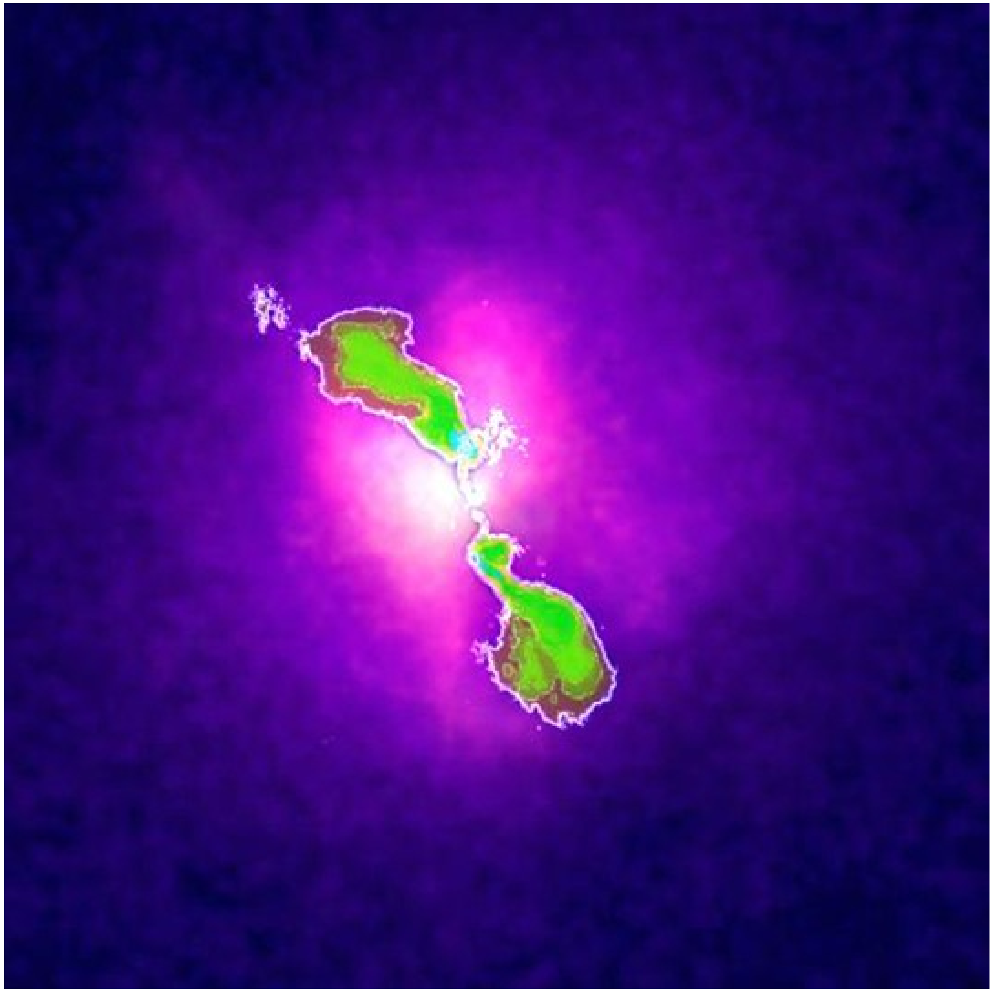


Is this realistic?

- Probably not: latest XMM results are probably inconsistent with very large cavities around the inner jets.
- The problem is modelling the abrupt change in RM fluctuation amplitude across the nucleus.
- We no not yet know whether this is a perversity of 3C31 or more general.
- Geometry and field structure could easily be more complicated than we assume.
- Therefore look at a case where we can see the cavities: Hydra A.

X-ray cavities in Hydra A

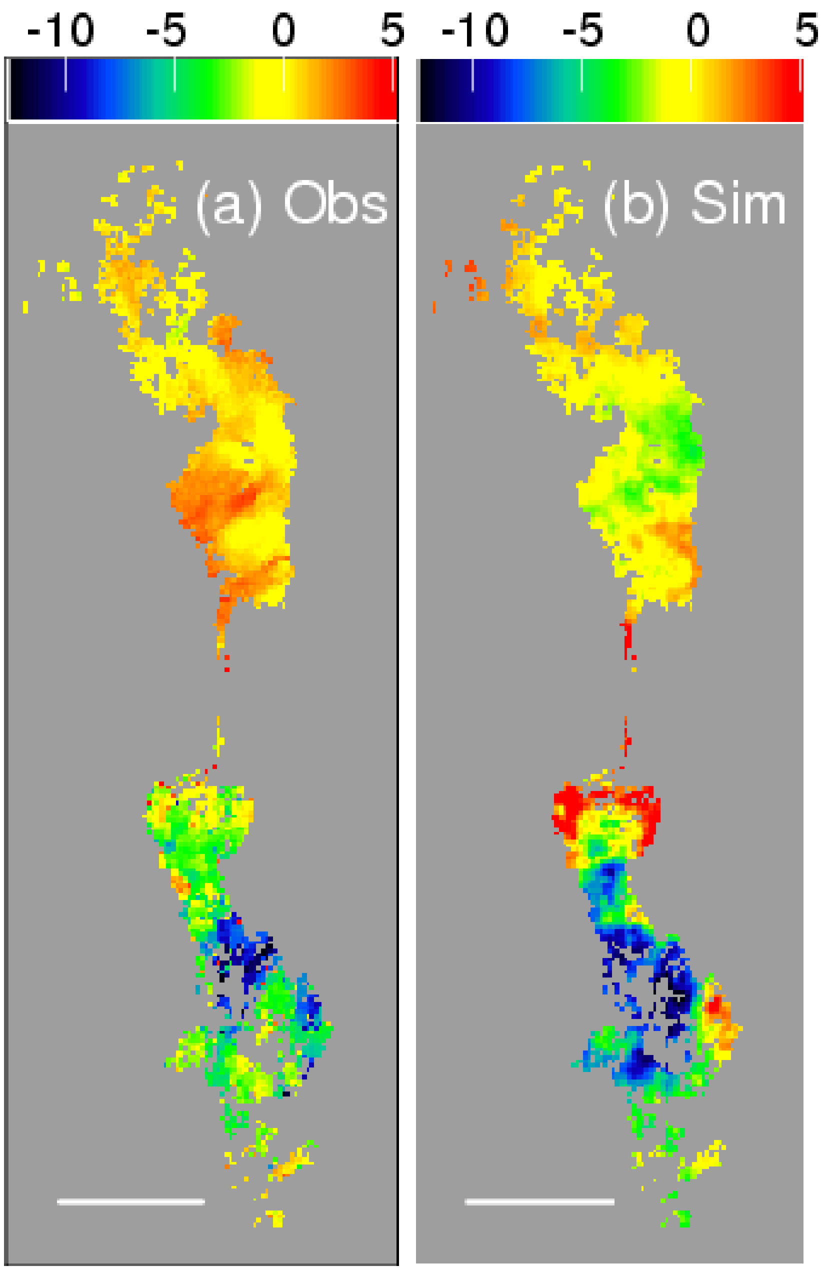




Chandra X-ray (Wise et al. 2007)

Radio/X-ray superposition

3D simulations of Hydra A



Cavity geometry and hot gas parameters from Wise et al. (2007)

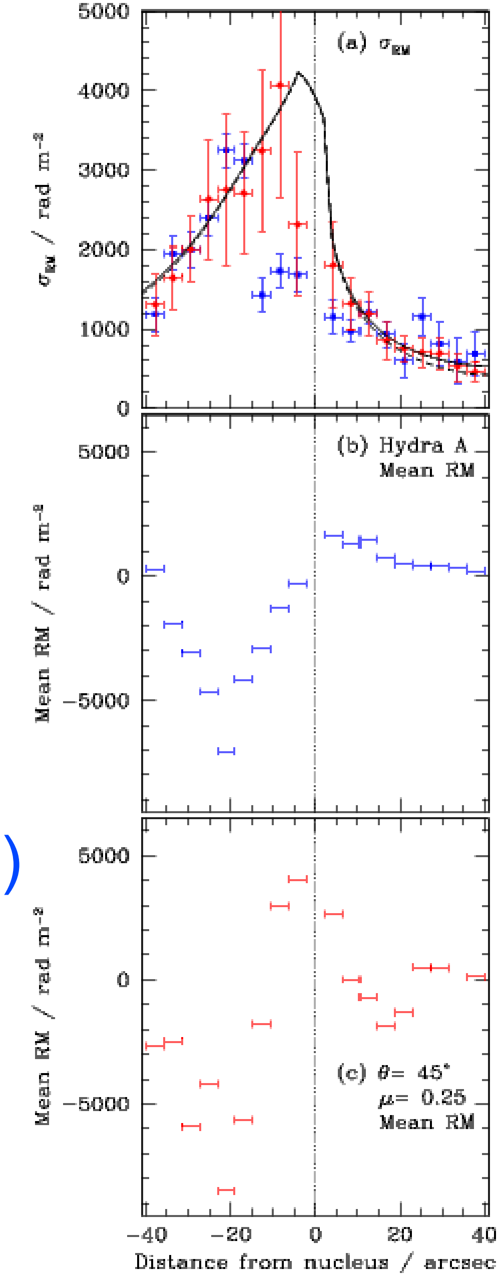
Good fit to σ_{RM} profiles with:

$\theta = 45^{\circ}$

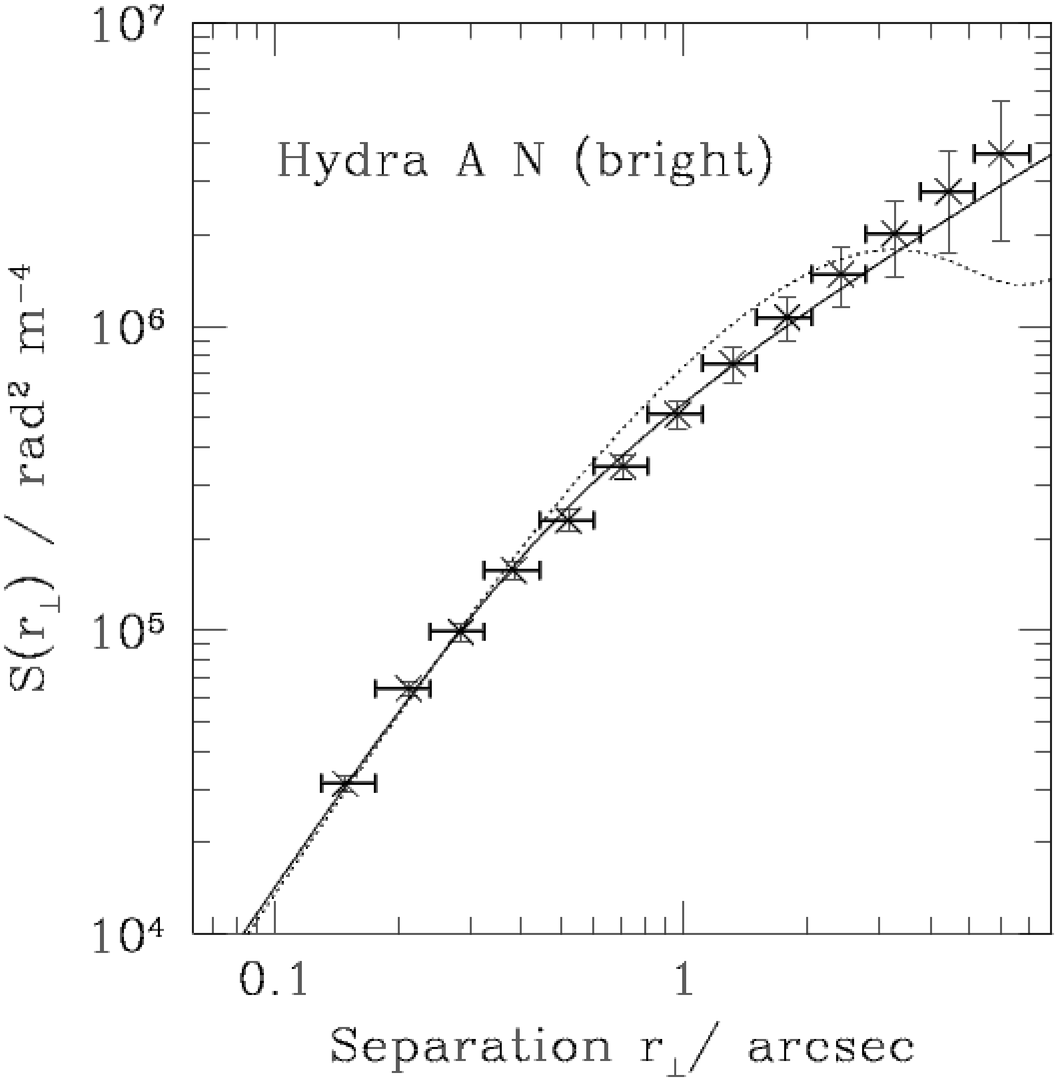
$B_0 = 1.9nT\ (0.19\mu G)$

$B \propto n^{0.25}$

Magnetic power spectrum $\propto f^{-2.77}$



Hydra A – is there a significant disagreement about the power spectrum?

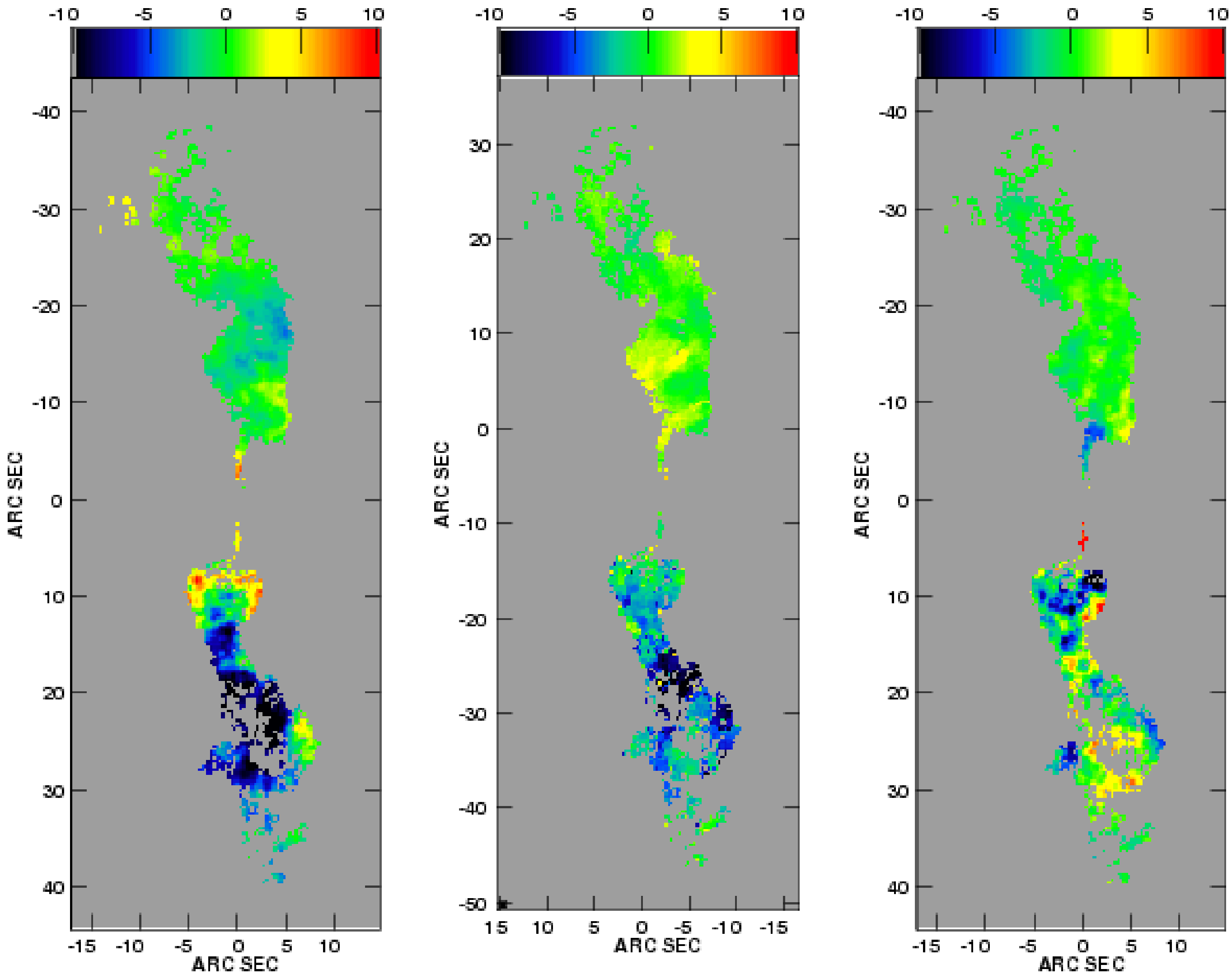


Differences are quite subtle

RL et al. have flatter power spectrum extending to larger scales

Kuchar and Ensslin have steeper PS with cut-off

Simulations of Hydra A with different power spectra



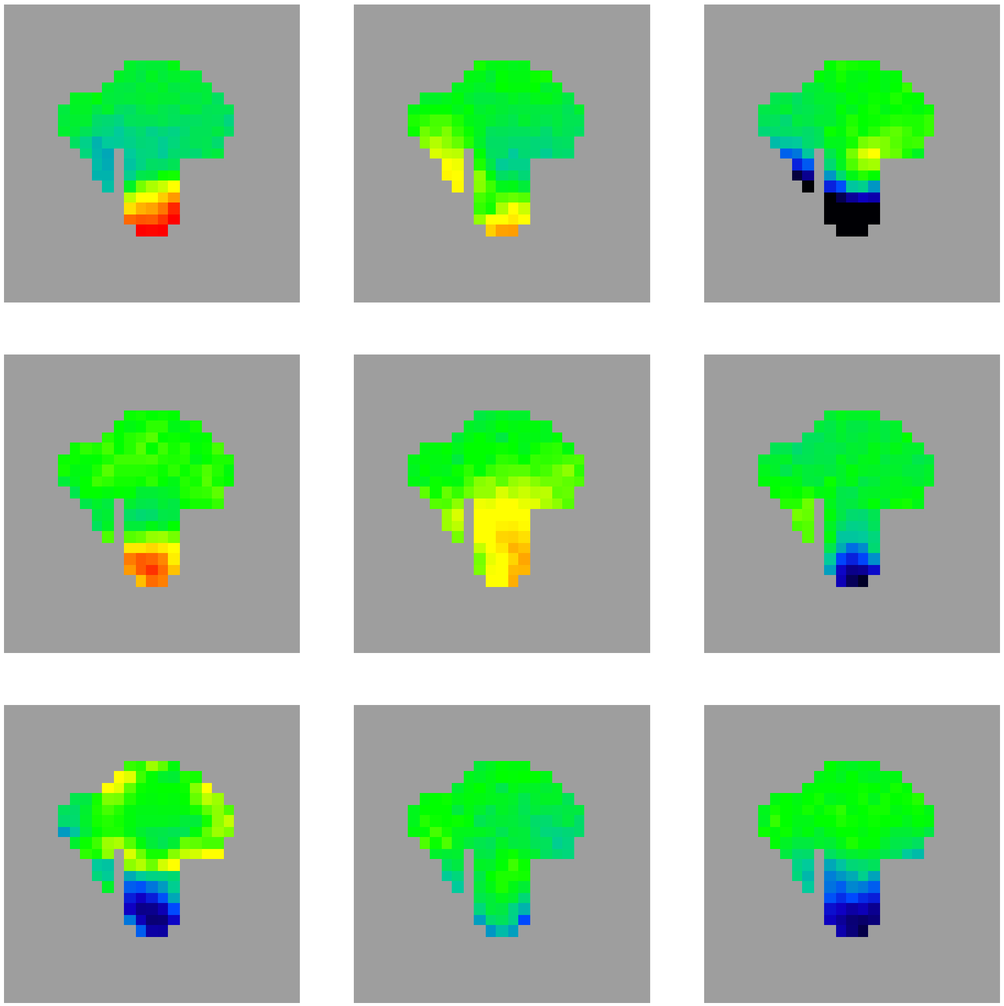
RL et al. Data K&E

Main difference is in mean RM over each lobe

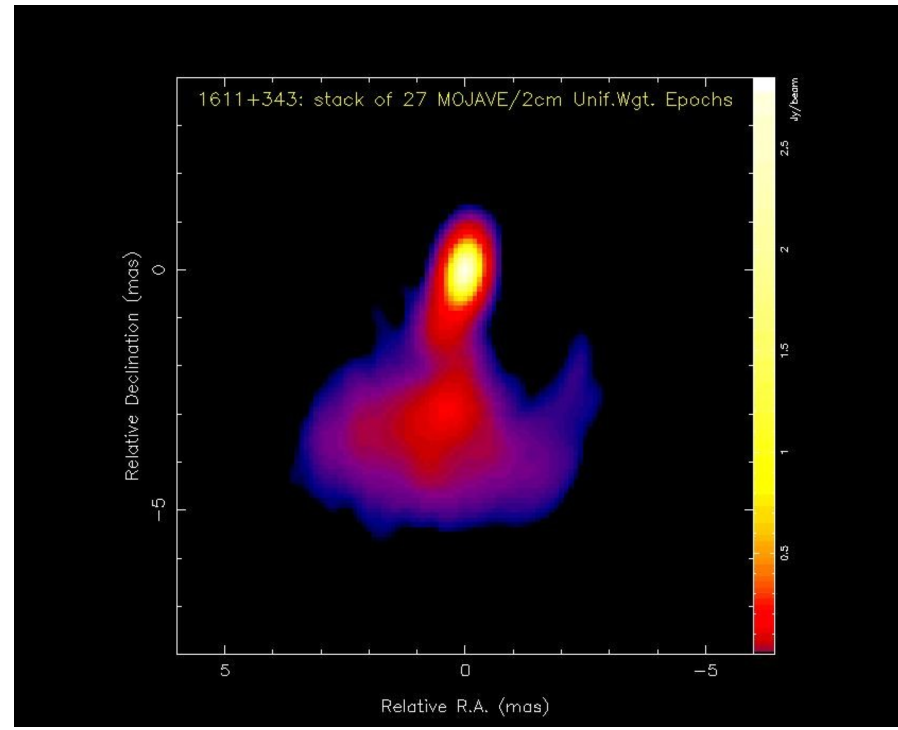
Can random foreground fields produce the RM distributions we see on small scales?

- VLBI RM images kindly provided by Greg Taylor
- Modified versions of 3D simulation code:
  - Density described by double beta model
  - Field is Gaussian random variable with specified power spectrum; scales with density
  - No cavities
  - Small angles to the line of sight (required by VLBI proper motion measurements)
- Gas core radii ~1kpc (dense hot corona in FRI radio galaxies; NLR intracloud gas in quasars) and ~1pc (from free-free absorption mapping of 3C84, Cen A, etc.)
- Simulation blanked as real data + noise

Which is the observation?



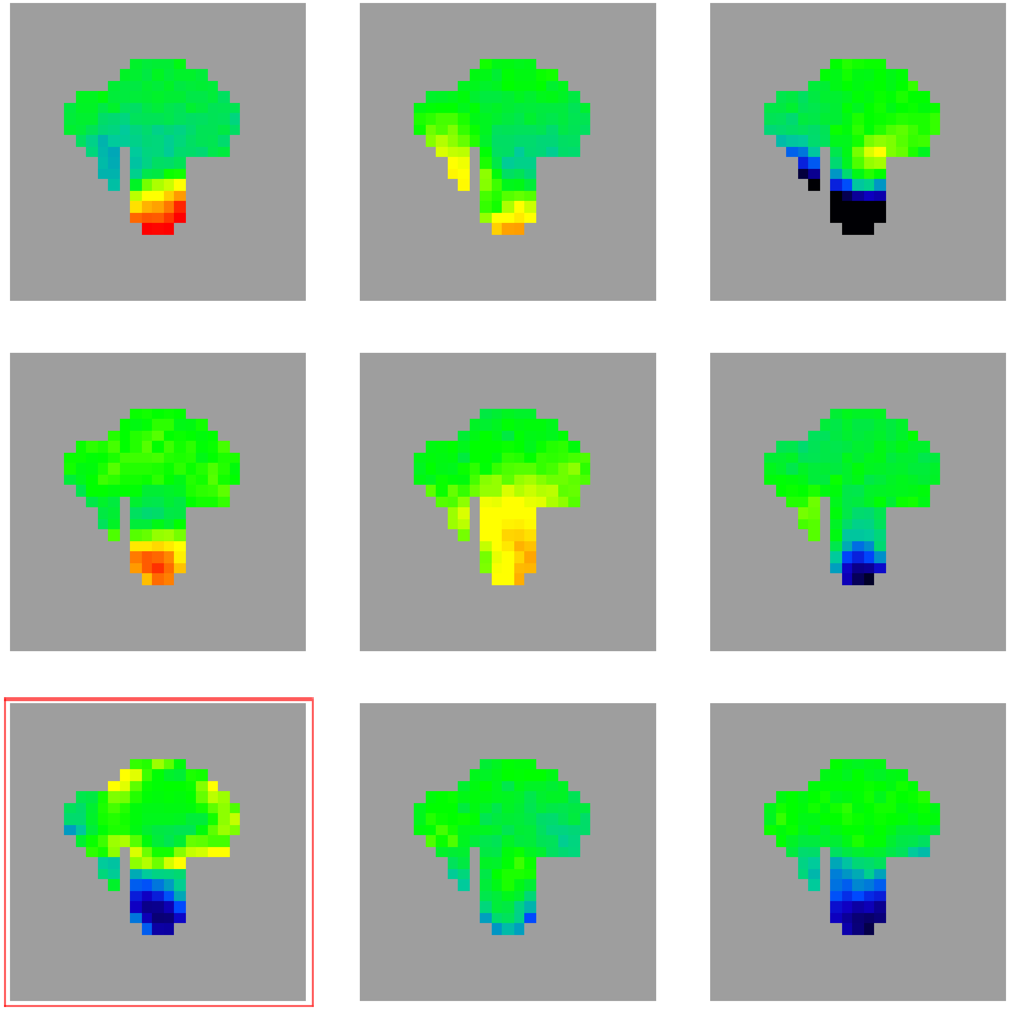
RM image (Greg Taylor) + 8 simulations



MOHAVE image

J1613+342
Quasar z = 1.39

The answer



B randomly distributed in spherical gas cloud with r_c = 1.2 kpc (0.15 arcsec)

θ = 8° (limit from superluminal motion)

Requires $n_0 \sim 2 \times 10^6\ m^{-3}$
$B_0 \sim 2$ nT

$n_0 \sim 2\ cm^{-3}$
$B_0 \sim 20\ \mu G$

or equivalent

Thoughts for the day

- Source geometry is important.
- Qualitatively, RM distributions bethave as we expect for thin sources embedded in spherical gas clouds with distributed fields.
- Slightly more realistic models, including cavities, give better fits to the global variations of RM fluctuation amplitude.
- This cannot be the whole story: radio sources affect the surrounding field (Krause, Guidetti)
- Need Bayesian inference + simulations to develop a robust consensus on RM/field power spectra.
- VLBI RM distributions may not be that different.