Radio Polarimetry

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Introduction

– Polarization state of light tells much about its source and the medium through which it has traveled

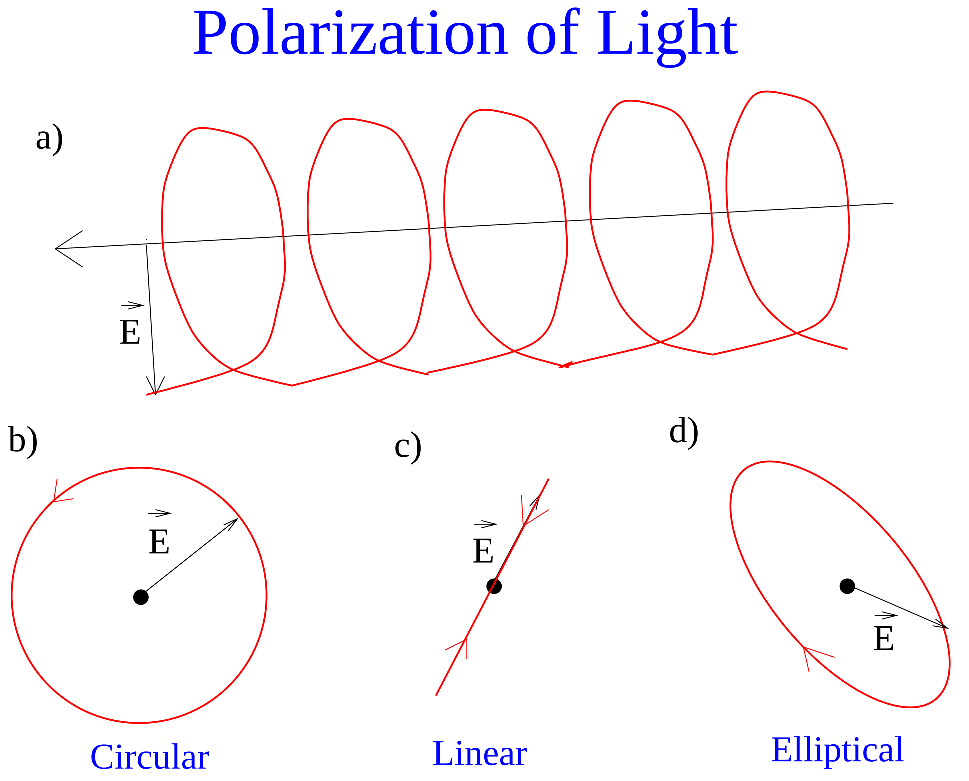
– Polarization readily measured with radio interferometers

– First discuss the physics of polarized light

– Then some astrophysical applications

Physics: What is polarization?

– Light is oscillating E and B fields
– "Polarization" is how the wave oscillates?



Describing Polarization State

- Light from incoherent sources at most partially polarized
- Generally describe partially polarized light by Stokes parameters

  Stokes I = Total intensity of light

  Stokes Q + jU = Linear polarization

  Stokes V = Circular polarization

Relation of Stokes Parameters to Measurable Quantities

Circular feed correlations:

$$v_{rr} = \tfrac{1}{2} g_{ip} g^*_{kp} (I + V),$$
$$v_{rl} = \tfrac{1}{2} g_{ip} g^*_{kq} ((d_{ip} - d^*_{kq}) I + \; e^{-2j\chi}(Q + jU)),$$
$$v_{lr} = \tfrac{1}{2} g_{iq} g^*_{kp} ((d^*_{kp} - d_{iq}) I + \; e^{2j\chi}(Q - jU)),$$
$$v_{ll} = \tfrac{1}{2} g_{iq} g^*_{kq} (I - V).$$

Linear feed correlations:

$$v_{pp} = \tfrac{1}{2} g_{ip} g^*_{kp} (I + Q \ \cos 2\chi + U \ \sin 2\chi),$$
$$v_{pq} = \tfrac{1}{2} g_{ip} g^*_{kq} ((d_{ip} - d^*_{kq}) I - Q \ \sin 2\chi + U \ \cos 2\chi + jV),$$
$$v_{qp} = \tfrac{1}{2} g_{iq} g^*_{kp} ((d^*_{kp} - d_{iq}) I - Q \ \sin 2\chi + U \ \cos 2\chi - jV),$$
$$v_{qq} = \tfrac{1}{2} g_{iq} g^*_{kq} (I - Q \ \cos 2\chi - U \ \sin 2\chi),$$

where χ is paralactic angle, gs are instrumental complex gains and ds are polarization “leakage” terms

Emission Mechanisms

- Thermal emission generally not polarized (except for Zeeman splitting)
- Nonthermal emission is generally polarized
- Synchrotron emission
  - Highly relativistic charged particles in magnetic field
  - Emission intrinsically 60% linearly polarized
  - Polarization angle determined by optical depth and magnetic field
  - Very weak circular polarization
  - Very common in AGN and SNR
- Cyclotron
  - Mildly relativistic charged particles in magnetic field
  - Frequently strong circular polarization
  - Sometimes emitted in solar and stellar flares
- Maser
  - Frequently polarized but poorly understood

Magnetic Fields and Synchrotron Emission

- The more chaotic the field, the less polarized the light
- Orientation of the E–vectors determinied by magnetic field orientation and optical depth
  - Optically thin: E–vector $\perp$ B-field
  - Optically thick: E–vector $||$ B-field
- E–vector may be further rotated by Faraday rotation

Faraday Rotation

- A magnetized plasma is birefringent
- RCP and LCP propagate at different speeds
- This rotates the angle of linear polarization

$$\Delta\Phi = \frac{0.93 \times 10^6 \int N \; H_{\|} \; ds}{(2\pi\nu)^2}$$

where N is the electron density (cm^{-3}),
$H_{\|}$ is the component of magnetic field parallel to the direction of propagation
ν is the radio frequency (Hz) and s is distance along the sight (cm)

- Thus the effect goes as ν^{-2} or λ^2
- Need multiple (optically thin) wavelengths to separate Rotation measure and intrinsic polarization angle
- Faraday rotation measures the product of one component of the magnetic field and the electron density

Zeeman Splitting

- The magnetic field from orbiting electrons in atoms and molecules interact with an external magnetic field
- Slight energy shifts give different emission frequencies in RCP and LCP
- Effect proportional to $B_{\|}$
- Frequency shift depends on species and transition
- Measurement requires narrow line and good sensitivity as shift small

Depolarization

– If a source is polarized at high frequencies and less polarized at low frequencies it is called "depolarized'

– Can be from a number of causes

  ◦ Beam depolarization

    polarization averages across beam smearing it out.

  ◦ Differential Faraday rotation

    either internal to the source

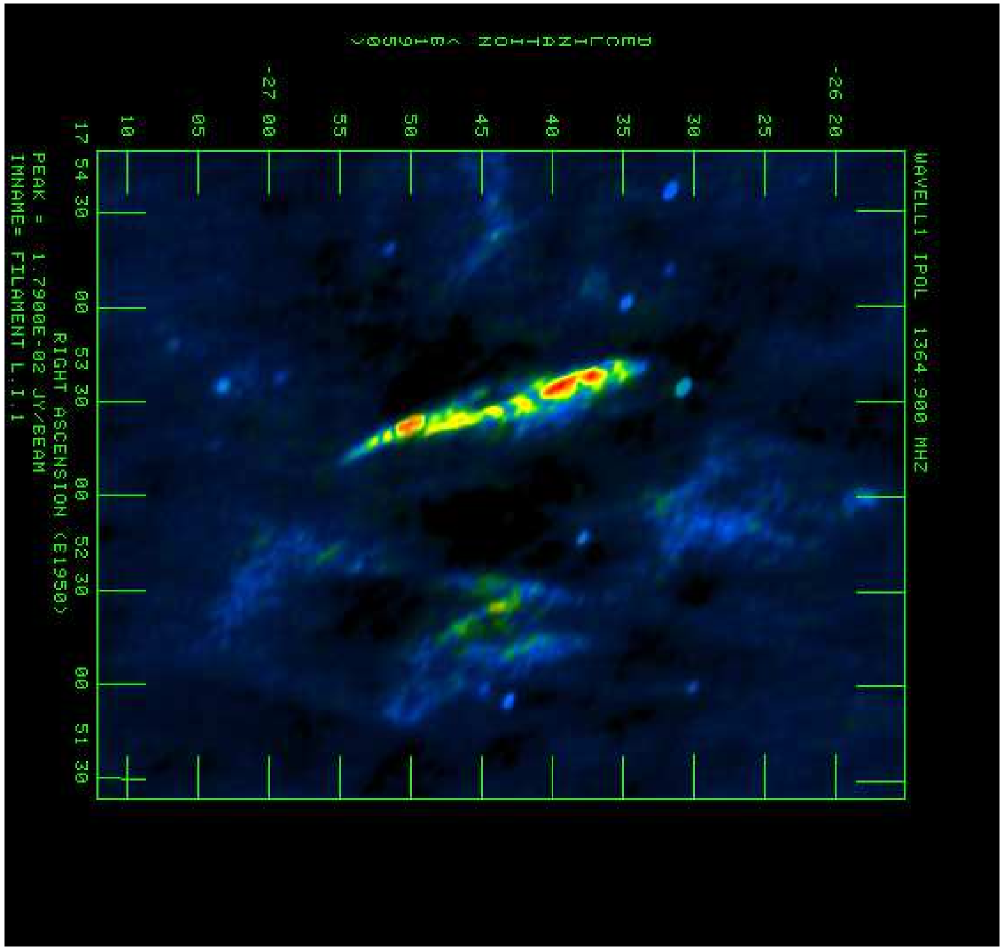
    or in a foreground screen

Astrophysical Applications

Separating thermal and non thermal sources

– Polarized emission usually indicates nonthermal source
– But unpolarized doesn't always mean a thermal source

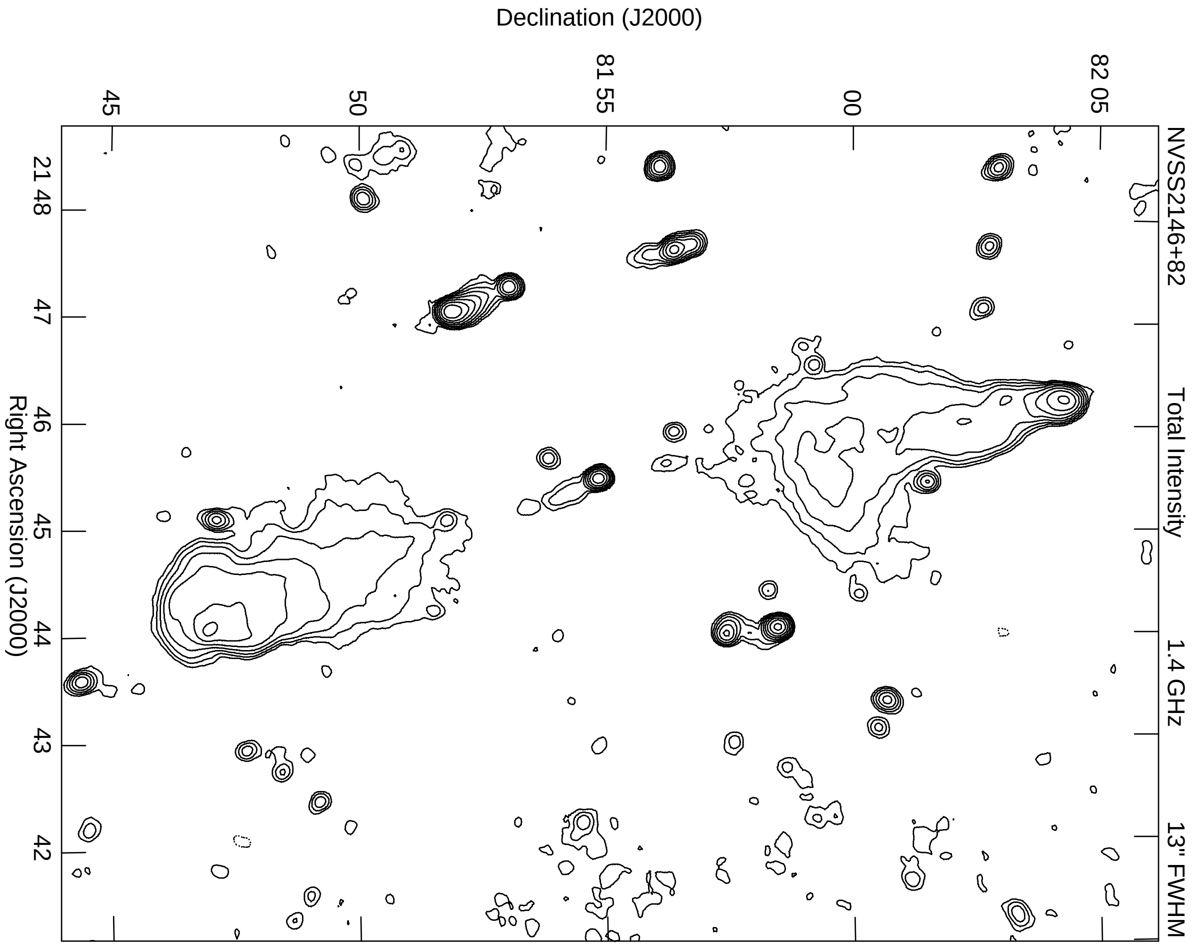
Galactic emission, intensity=intensity, color=polarized



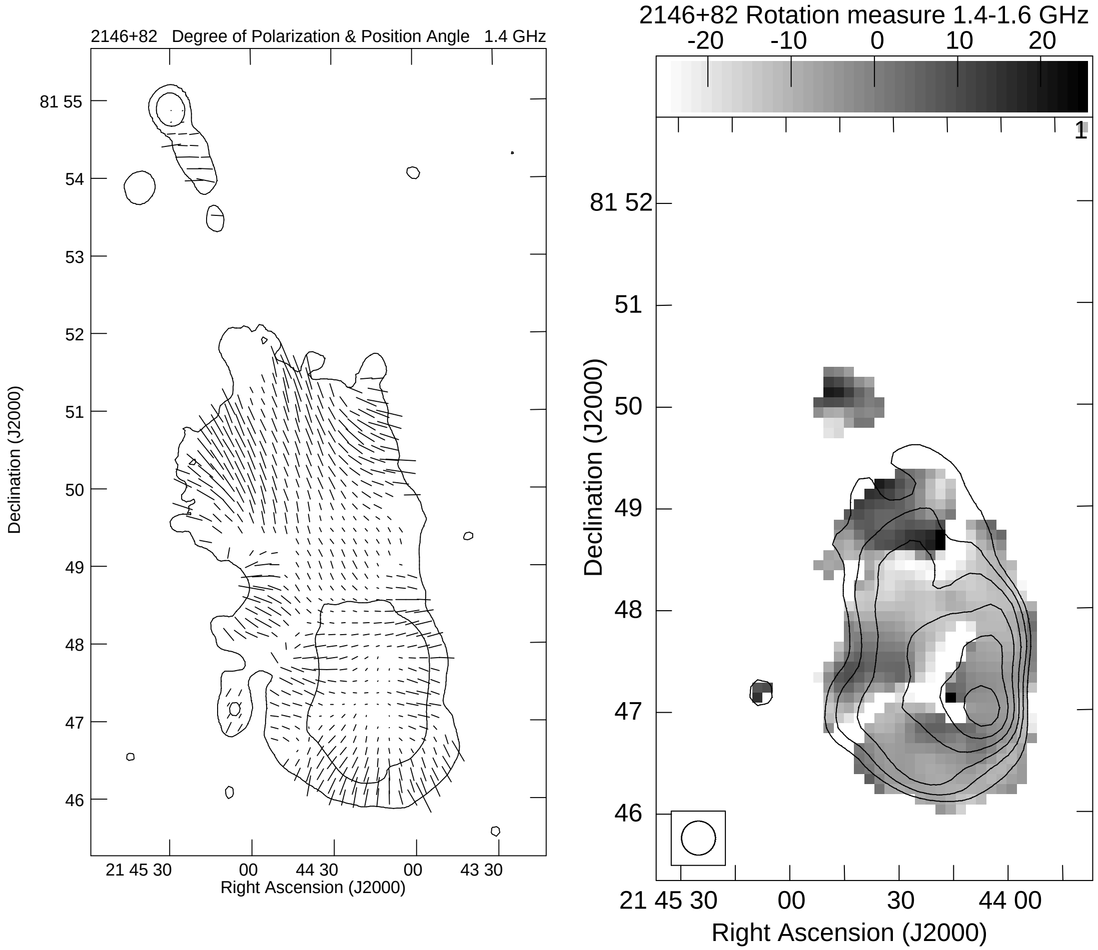
20 cm measurements of a galactic filament (courtesy F. Yusef-Zadeh)

Orientation and Organization of Magnetic Fields

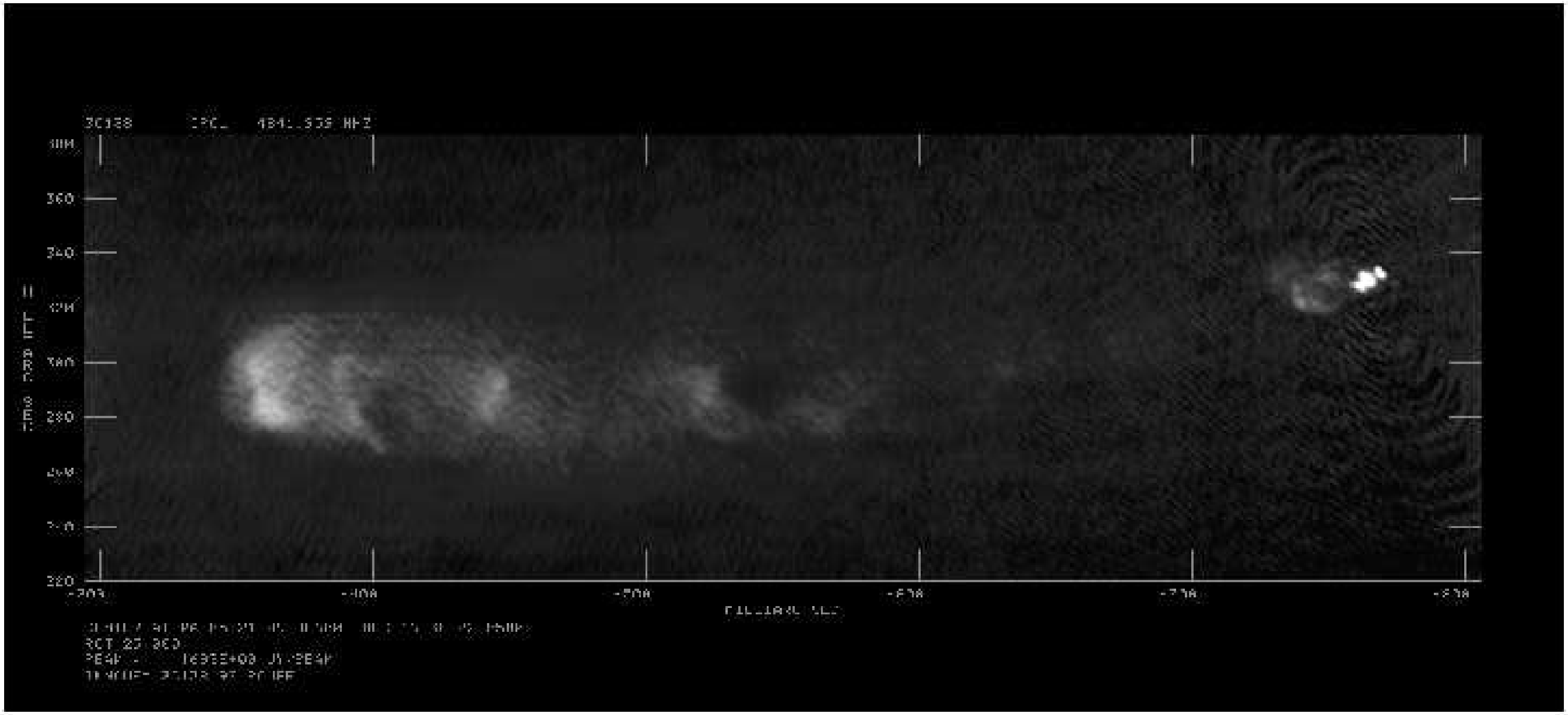
– If source optically thin and no Faraday rotation,
E-vectors are $\perp$ to B field
– High fractional polarization indicates ordered magnetic field



Giant Radio galaxy 2146+82

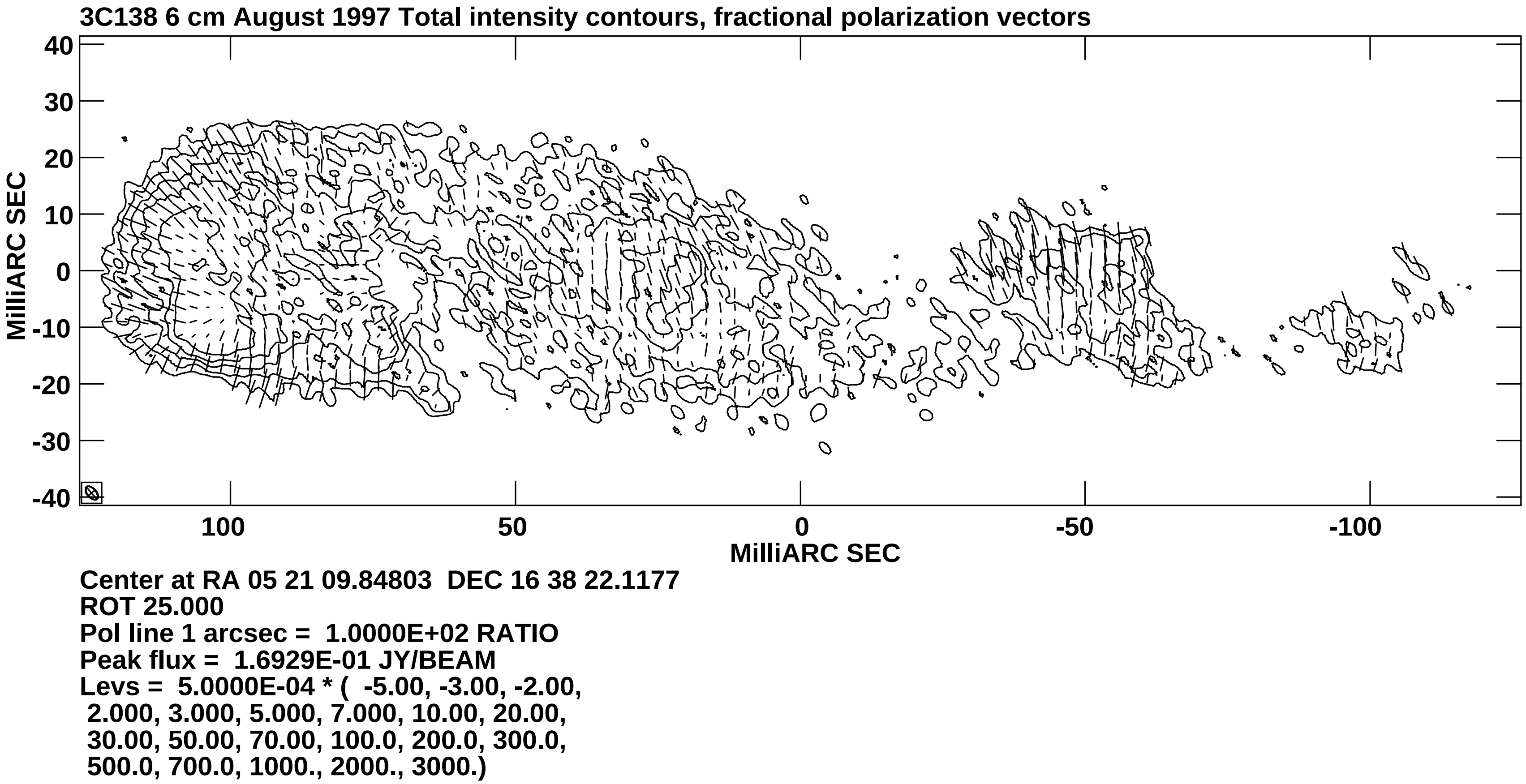


E-vectors and rotation measure of southern lobe of 2146+82



3C138 6 cm August 1997 Ipol

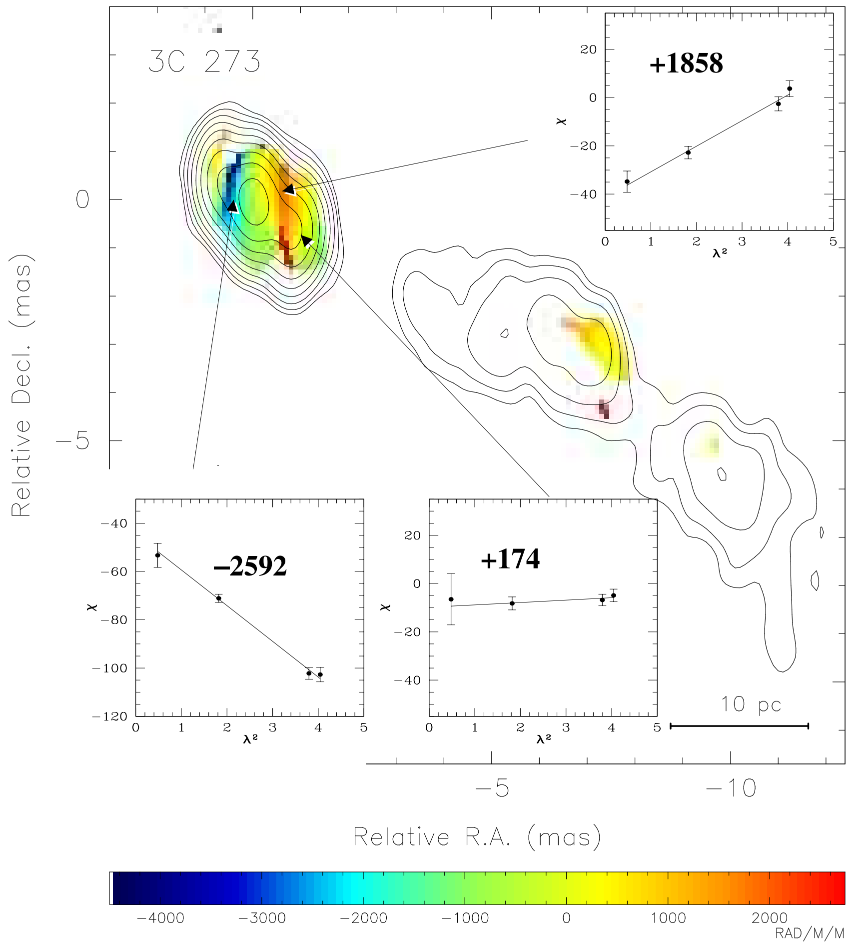
VLBA image of core and jet of the Quasar 3C138



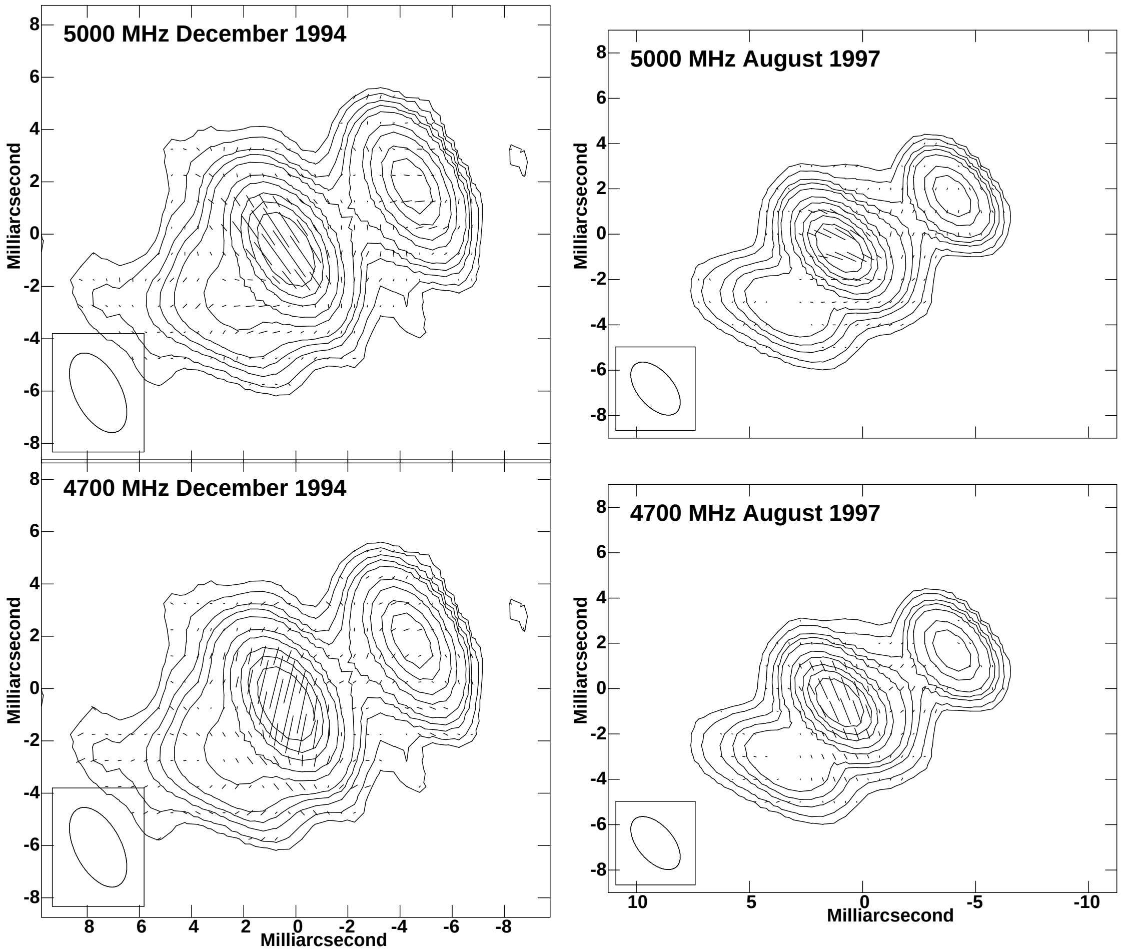
Polarization E-vectors of the jet of 3C138

Mapping Faraday screens in AGN nuclei

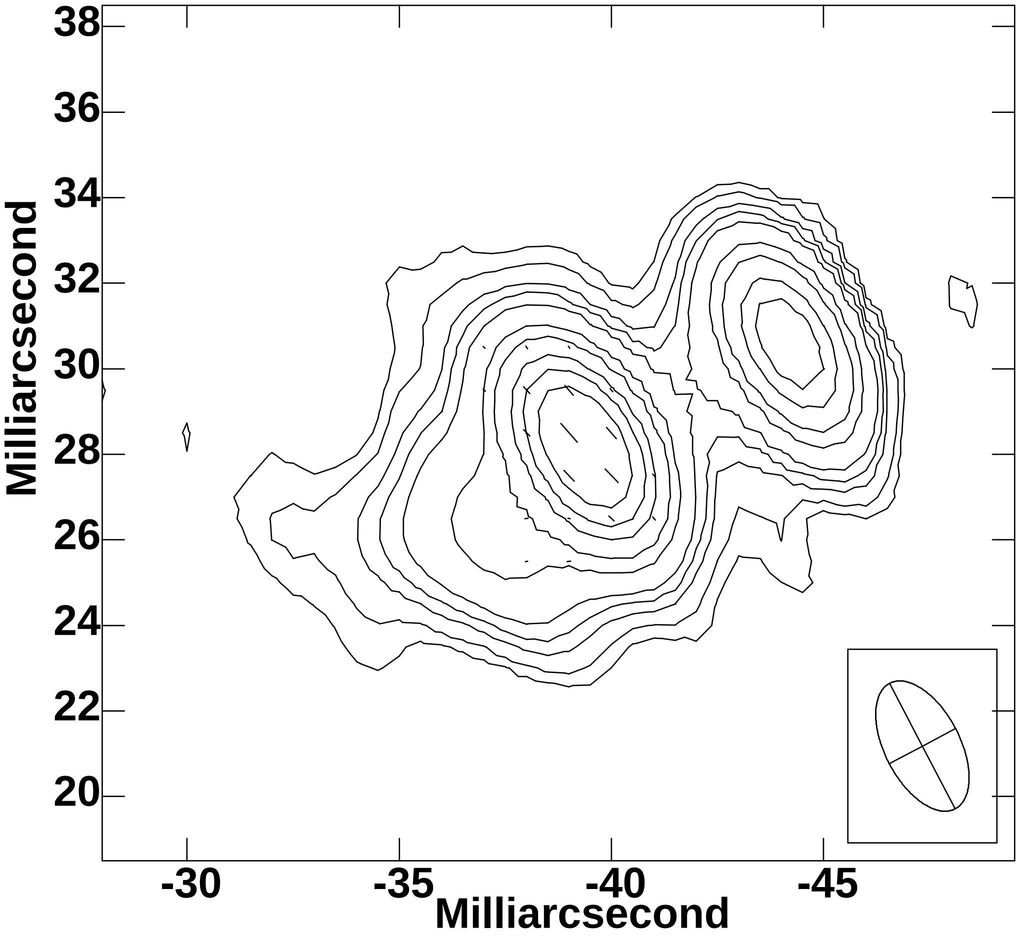
- Narrow line regions in AGN nuclei have dense magnetized plasma
- These can be studied using polarized emission from the radio jets
- Moving components help map Faraday screen



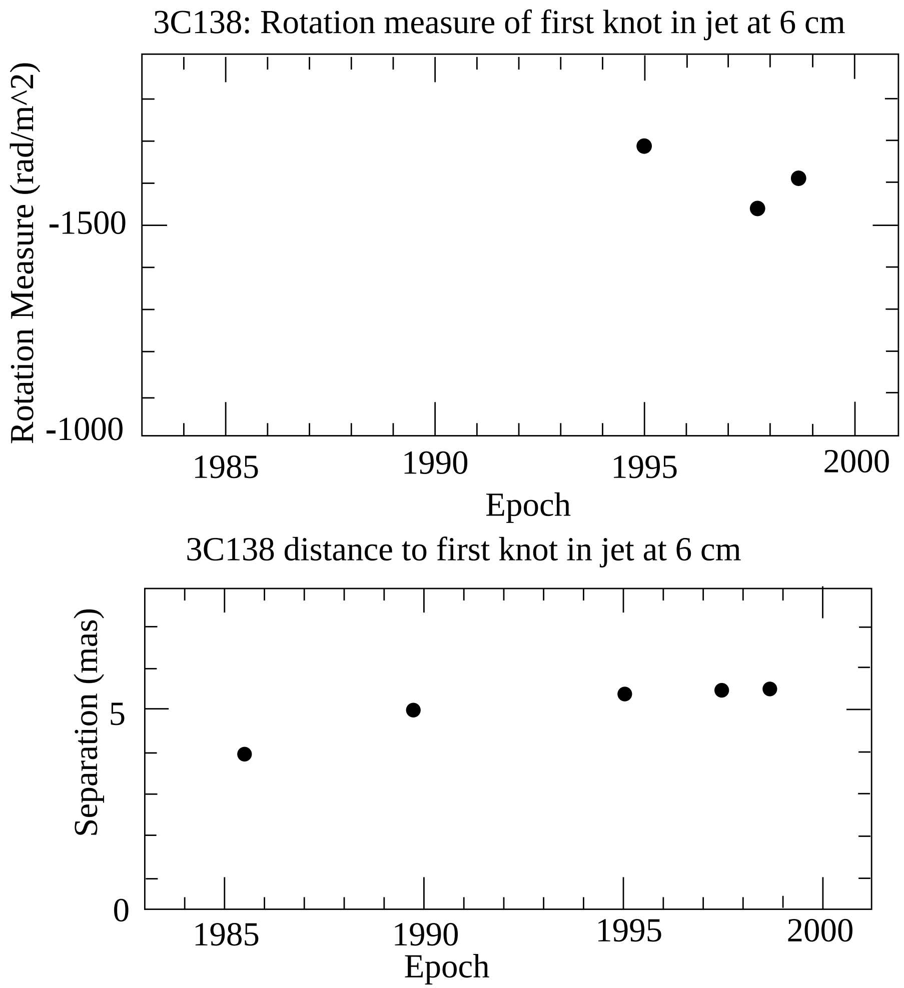
Faraday rotation in the core of 3C273 (Zavala and Taylor, 2001)



Polarization of the core region of 3C138 at two epochs showing variable Faraday rotation



Core of 3C138 showing polarized knot E-vectors corrected for Faraday rotation



Separation from core and Faraday rotation of knot in 3C138 jet.

Modeling velocity field of FRI jet

– FRI (low power) radio galaxies are thought to have jets that are initially relativistic and become subrelativistic

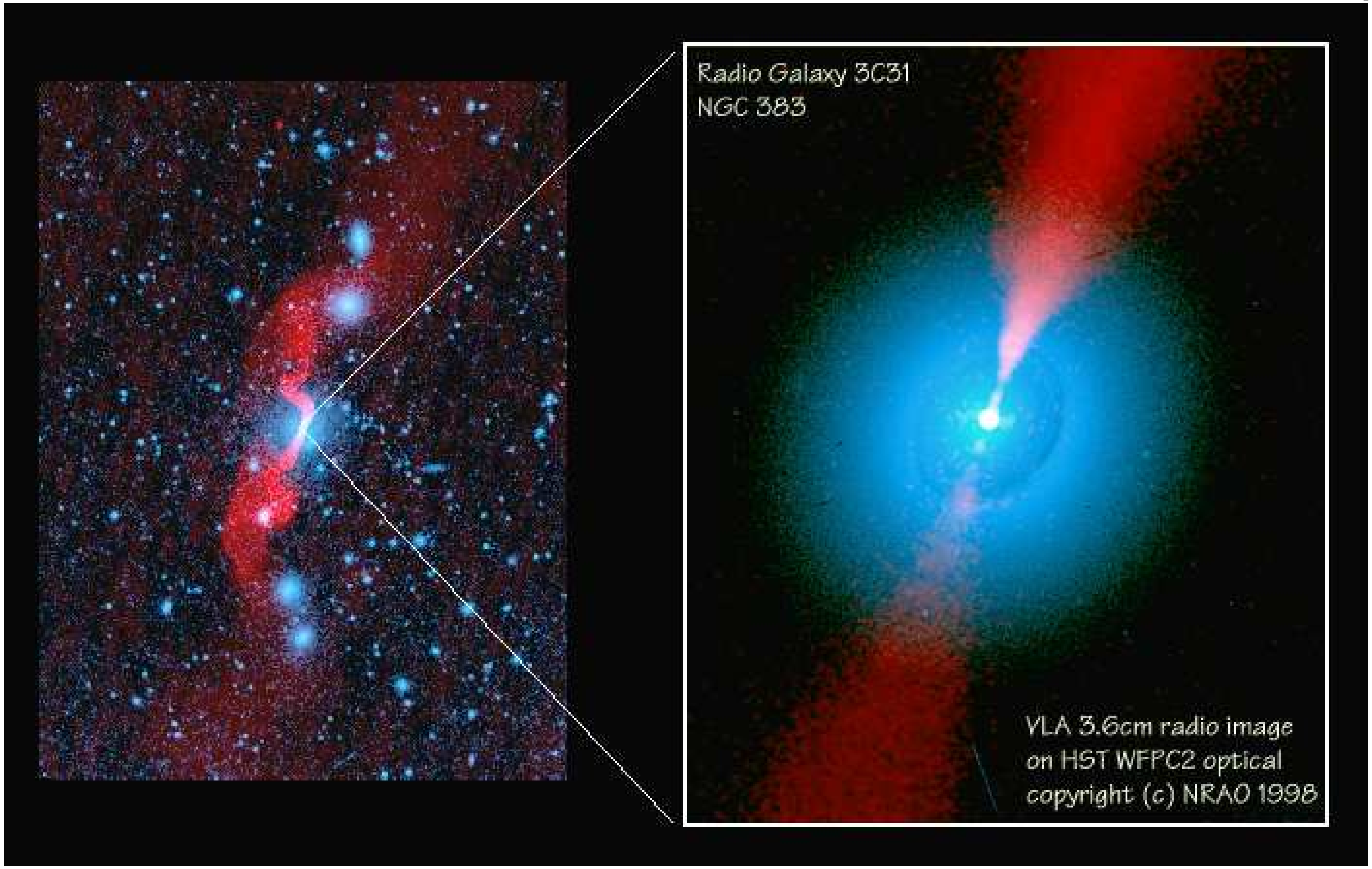
– This is because the jets start very assymetric and become symmetric

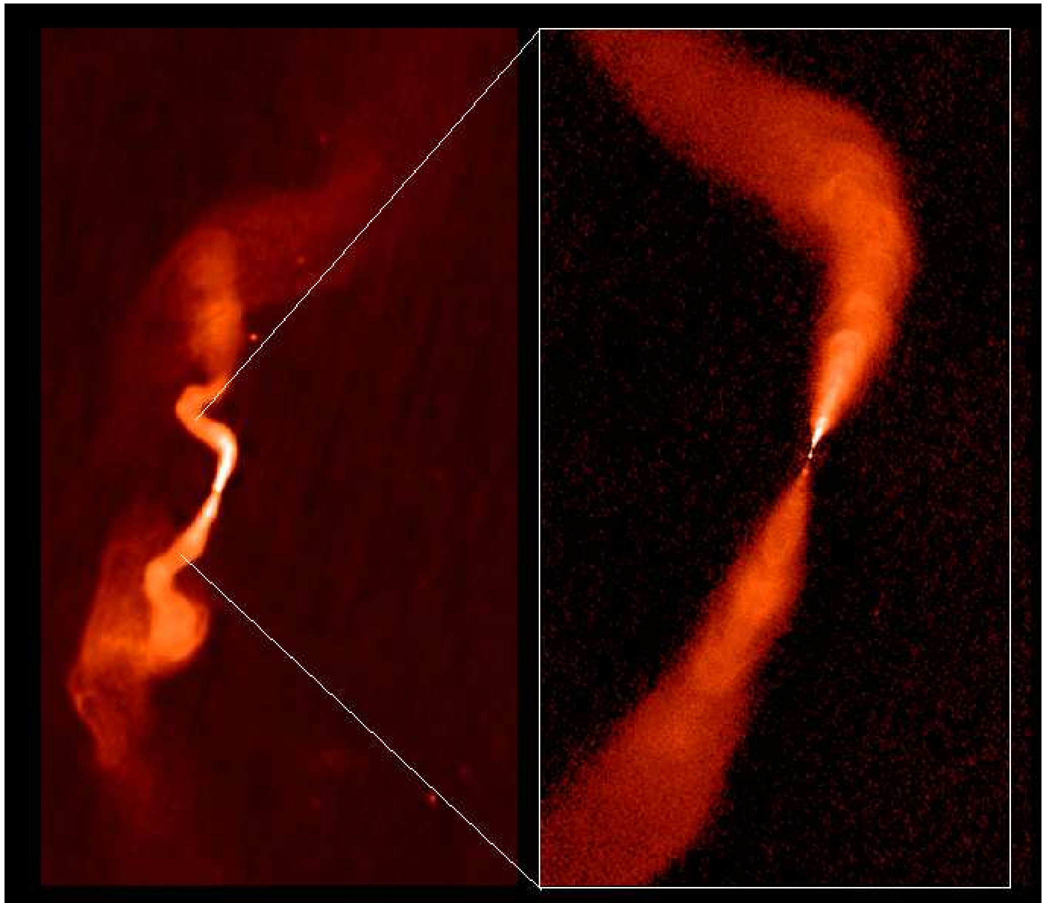
– The assymetry is assumed to be a relativistic abberation

– Laing and Bridle are using brightness assymetries and polarization to model relativistic velocity field

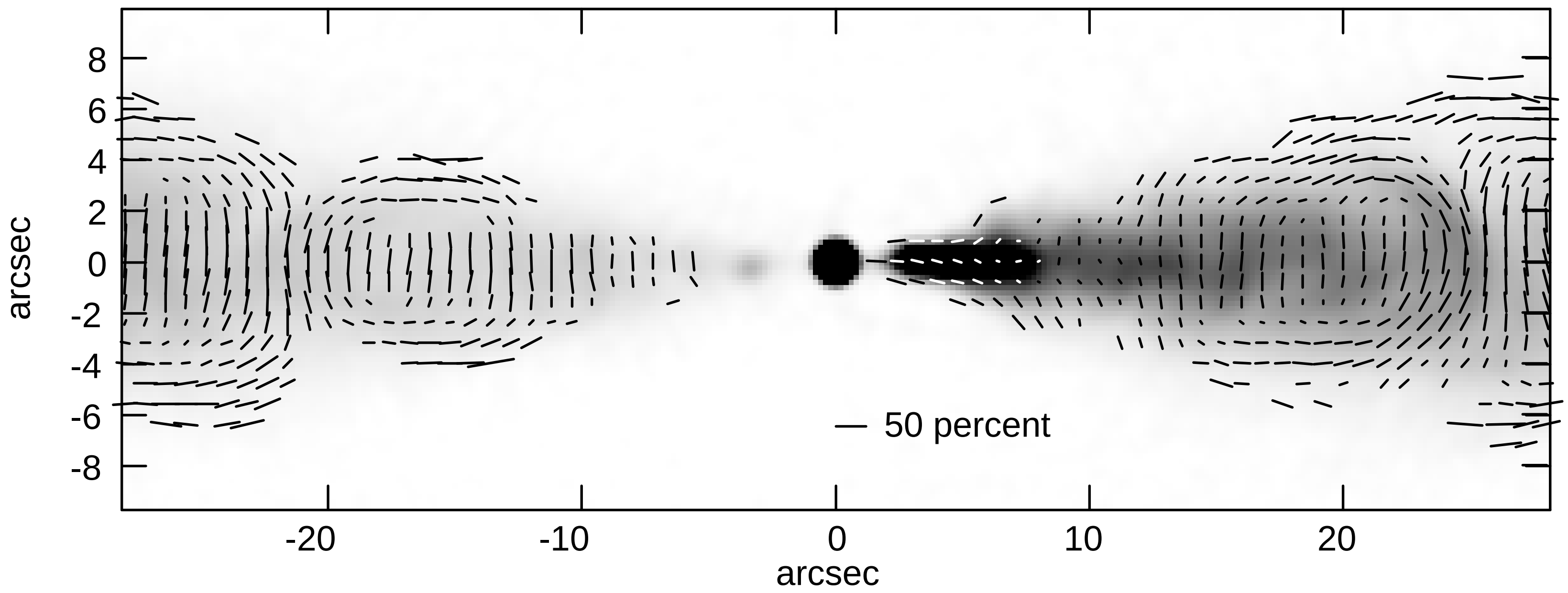
– Relativistic effects abberate both brightness and polarization

– Combined constraints much stronger than just brightness assymetry

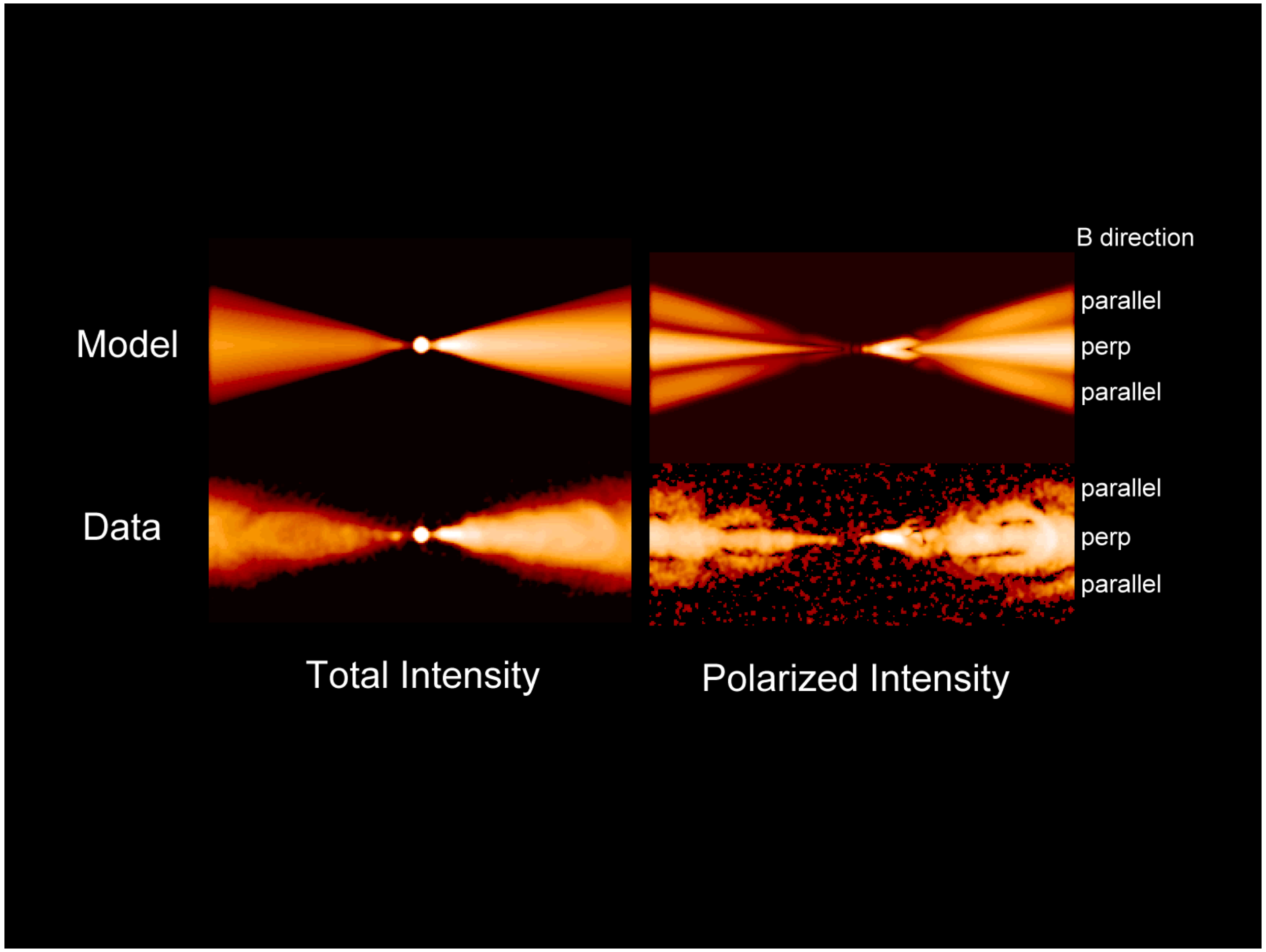

Radio Galaxy 3C31
NGC 383
VLA 3.6cm radio image
on HST WFPC2 optical
copyright (c) NRAO 1998



FR Class I source: radio galaxy 3C31



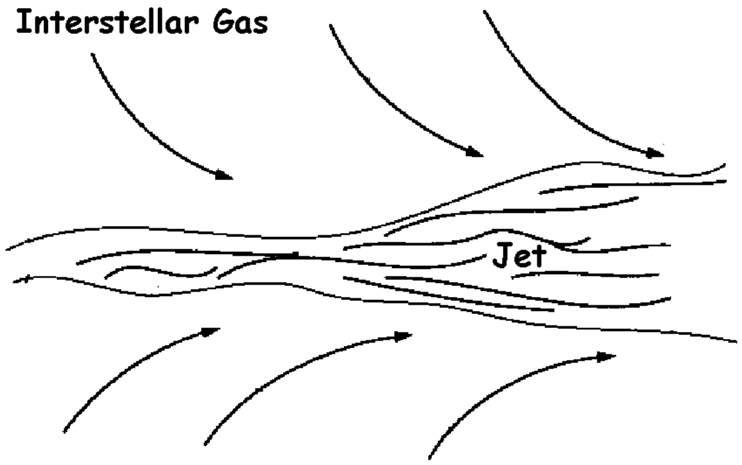
3C31 total intensity in gray, fractional polarization – B field vectors



3C31 inner jet data and model for total and polarized intensity

Velocity field of 3C31

- Multi–velocity structure, fast spine and slower sheath
  Radio Galaxy 3C31 initial test case
- Jet initially slowed by entrainment of mass lost by stars in the jet
- Subsequently entrains mass through boundry of jet



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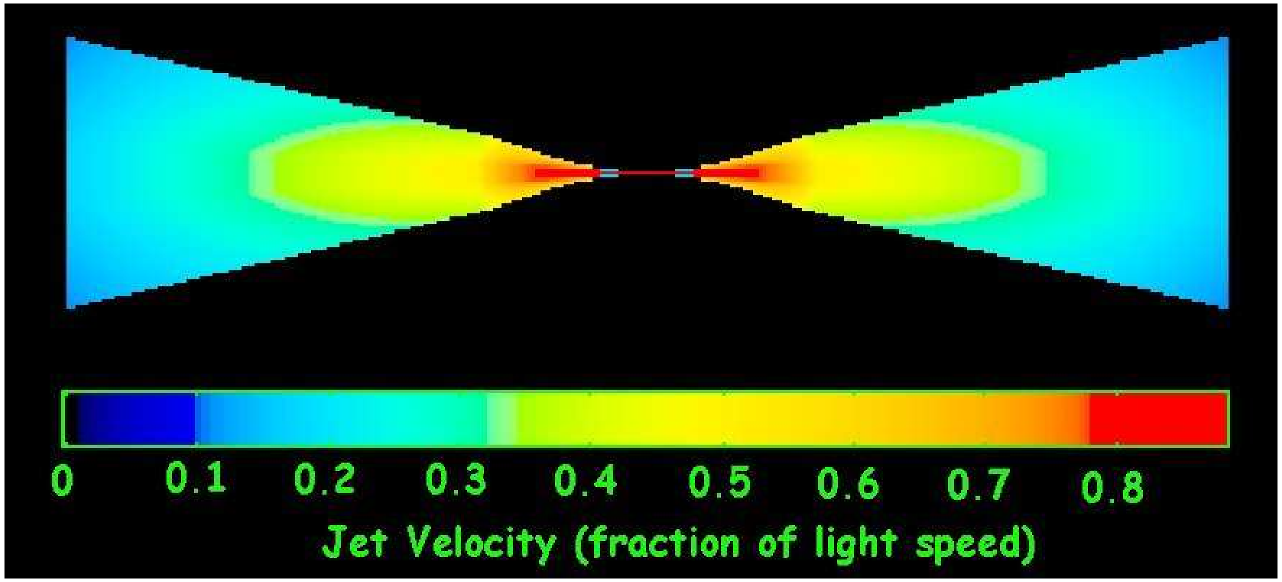
Velocity field of 3C31 continued

– Other constraints:
  - ◦ HST optical imaging for stellar mass profile
  - ◦ Chandra X-ray data for external pressure

– Fitted intrinsic velocity field:



– Jet slows from highly relativistic to subrelativistic on kpc scale