Spectropolarimetric observations of the giant lobes of Centaurus A

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Centaurus A: some numbers

- Distance to host galaxy NGC 5128:
  \[3.84 \pm 0.35 \text{ Mpc} \text{ (Rejkuba, 2004)}\]
- Linear scale: \(1' = 1.1 \text{ kpc}\)
- BH: \(5.5 \times 10^7 \text{ M}_{\text{Solar}}\) (Cappellari et al. 2009)
- Total luminosity: \(\sim 10^{34} \text{ W}\)
- Projected extent: \(6^\circ \times 9^\circ, \sim 500 \text{ kpc}\)
- FR I radio galaxy, \(L_{1.4 \text{ GHz}} \sim 10^{24} \text{ erg/s}\)
- Typical FR I?
  - dust lane, inner lobes over-pressured
- Part of Centaurus group of galaxies
  - \(\sim 50\) members
Impact of radio galaxies

• Why observe radio lobes?
• Important for energy budget of universe \((10^{60} \text{ erg})\)
• Impact on cosmic structure formation
  • (eg. Blundell et al. 2006)
• Total energy output: \(~10^7\) SNe

• Need to know how they are formed & what they are made of & how they transfer energy to IGM
Impact of radio galaxies

- Blow bubbles in surrounding gas, shocks?, impact on star formation: negative or positive?
- Influence galaxy formation, evolution?

- Croston et al. (2011)
- 3C444 Chandra, 6cm VLA
- Perseus cluster
- Fabian et al. (2000)
Impact of radio galaxies

- Study “invisible” objects in front of lobes through depolarization signal

- “Ant”
  
  - Depolarization caused by foreground galaxy

- Fomalont et al. ‘89 (Image by R. Ekers ‘87)
- Image by Uson ‘00
Parkes 210-ft: Polarization

- Bracewell, Cooper & Cousins, Nature, 1962
- 15% at 10 cm

Polarization in the Central Component of Centaurus A

Using the recently completed 210-ft. radio telescope of the Australian National Radio Astronomy Observatory at Parkes, New South Wales, we have detected linear polarization of the radio emission from the central component of Centaurus A. Many maps

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Parkes 210-ft: Faraday Rotation

- Cooper & Price (1962)
- 10 – 30 cm
- Discovery of Faraday rotation of Cen A polarization
- “Majority of the rotation must be occurring in our Galaxy or in outer regions of Cen A”

**RADIOPHYSICS**

Faraday Rotation Effects associated with the Radio Source Centaurus A

Recent observations1-2 with the 210-ft. telescope of the Australian National Radio Astronomy Observatory have revealed the existence of linearly polarized radiation from the source Centaurus A at frequencies of 3.600 MHz and 4.400 MHz.

This communication reports investigation of Faraday rotation effects associated with this radiation. Measurements have been carried out at frequencies ranging from 570 MHz to 1,000 MHz at a number of points in the source. The points, the coordinates of which are given in Table 1, are located in the bright central component and in the northern and southern extensions of the source. The observing methods were essentially those of Gardsch and Whiteoak.

Table 1 lists the observing frequencies and the position angle of the electric vector observed at the various points. The percentage of linear polarization is also given.

In Fig. 1 the position angle of the electric vector is plotted against a frequency variable 10\(\nu_{1000}\)^0 for the three quoted points in the source. It is seen that, within the experimental error, the position angle has a 1/\(\nu_{1000}\) dependence, as expected for the Faraday effect. The agreement being particularly good for the central component. Thus the position angle corresponding to \(\nu_{1000}\) should be the true polarization angle at the source. It is also to be noted that the rotation is in the same sense at all three observed points and the slopes of the three curves do not differ greatly from each other. Curve a exhibits a total rotation from 1,000 MHz to infinite frequency of 206°; curve b, 156°, and curve c, 144°.
Parkes 210-ft: Cen A

- Cooper, Price & Cole (1965)
- Detailed study of emission structure from 6 – 74 cm

A STUDY OF THE DECIMETRIC EMISSION AND POLARIZATION OF CENTAURUS A

By B. F. C. Cooper,* R. M. Price, † and D. J. Cole*

With the greatly improved resolution of the Parkes 210 ft telescope it has proved possible to delineate fine details of the source structure and to reveal the previously unsuspected polarization and Faraday rotation that is associated with the radio emission (Bracewell, Cooper, and Cousins 1962; Cooper and Price 1962). In the

- Degree of polarization as high as 40% in places
- RM values lie between -36 and -84 rad/m²
With the new equipment it has been possible to find unsuspected evidence of emission from several places.

- Degree of polarization as high as 40% in places.
- RM values lie between -36 and -84 rad/m.

Dingle*

With the 6-74 cm radio telescope it has proved possible to reveal the previously unsuspected emission from several places (Dingle 1962). In the future, it may be possible to study the emission from

...
Parkes 210-ft: Depolarization

- Attempt to set upper limit on amount of Faraday rotation occurring within Cen A
- Identify regions of minimal beam effects
- Depth depolarization

Also see Burn (1966)

Curve 5 suggests that the upper limit for the internal rotation measure of the source is about 20 rad/m² and therefore that the net rotation in the source has an upper limit of about 10 rad/m², that is, about one-sixth of the observed rotation.
More recent Parkes observations

- Study by Junkes et al in early to mid 90s
- Strange cutoff behaviour in polarization in SGL at 6 cm
- Not seen at 21 cm; evidence for internal Faraday rotation?

Junkes et al. (1993)
Parkes 64 m: Spectropolarimetry

- 2 - 11 Mar ’09, H-OH receiver
- 1312 – 1480 MHz (wider but cut due to RFI)
- 120 RA scans, 86 DEC scans
- Nyquist sampling (7’)
- 10° x 14° (6° x 9°)
- 0.2 mJy sensitivity
- Zero-spacing for combination with ATCA data
- Cen A giant lobes dominated by large scale diffuse emission
Data Analysis

- Parkespol (https://svn.atnf.csiro.au/trac/parkespol)
- Flux calibration: PKS B1934-638
- Polarization calibration: 3c138, PKS B0043-424

- 168 MHz b/w
- 22x8 MHz channels
- Bandpass 1934
- Copy to pol cal
- Flag pol cal
- Solve for leakages
- Copy to Cen A scans
- Flag Cen A scans
Data Analysis

- Imaging software (E. Carretti)
- 8 MHz maps
- Separate RA and DEC maps (initial baseline removal using edge of image)
- Then combine using the Fourier method outline in Emerson & Graeve (1988)
- I, Q, U, V
Faraday rotation

- Rotation of the plane of polarization as it propagates through a region with free electrons and a magnetic field

\[
\chi_{\text{obs}} = \chi_0 + \frac{e^3 \lambda^2}{8 \pi^2 \varepsilon_0 m^2 c^3} \int n B \cdot dl \equiv \chi_0 + \text{RM} \lambda^2
\]

\[
\text{RM} = 0.81 \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{B}{1 \mu \text{G}} \right) \left( \frac{L}{1 \text{ kpc}} \right) \text{rad m}^{-2}
\]
Data Analysis

- RM synthesis performed at each pixel to extract the peak polarized intensity across the band

\[ P = Q + iU \]

\[ F(\phi) = \frac{1}{N} \sum_{j=1}^{N} P_j e^{-2i\phi(\lambda_j^2 - \lambda_0^2)} \]

- Assume FD for source
- derotate the polarization vector in each individual channel (to a reference wavelength)
- make a polarization map from the average of the derotated channels
- At correct RM, channels add coherently giving sensitivity of the entire bandwidth
Data Analysis

- 21 x 8 MHz Q and U maps => RM synthesis
- RMCLEAN: reconstruction algorithm to account for incomplete wavelength squared coverage
- FWHM of RMSF (ie. RM resolution): 310 rad/m²
Total Intensity structure

- Inner lobes and NML very well studied
- Our focus is on the giant outer lobes

speculated that it was in fact a bridge between our Galaxy and Centaurus A (a suggestion that was not unreasonable at a time when the estimated distance was 700 kpc, but is difficult to accept in view of the present accepted distance of 4 Mpc).
• Diffuse polarized emission from Galaxy as well as polarized emission from Cen A lobes
• Green: RM due to our Galaxy
• Red: excess due to RM associated with Cen A
Due to large angular extent of Cen A on sky => used background sources to investigate the magnetized plasma in the lobes without the complexities added by depth and beam depolarization effects

\[
\langle \text{RM} \rangle_{\text{inside}} = -4.5 \pm 2.8 \text{ rad m}^{-2} \\
\sigma = 30.4 \text{ rad m}^{-2} \\
\langle \text{RM} \rangle_{\text{outside}} = -1.6 \pm 2.1 \text{ rad m}^{-2} \\
\sigma = 26.6 \text{ rad m}^{-2}
\]

3σ upper limit on RM difference ~10 rad/m²

Assuming 1.3 µG equipartition field => volume avg’d $n_e < 5 \times 10^{-5} \text{ cm}^{-3}$
RM structure: Feain et al. (2009)

- Structure function analysis: excess RM component on scales of \(~0.3^\circ (20 \text{ kpc})\)

- Sheath model: 
  \(n_e \sim 10^{-3} \text{ cm}^{-3}\) 
  \(B \sim 0.8 \mu \text{G}\)
RM excess

- Green RM nearby & inside lobes: $\sim -40 \text{ rad/m}^2$
- Red RM associated with Cen A: $\sim -65 \text{ rad/m}^2$
- RM enhancement of $\sim 25 \text{ rad/m}^2$

$$\text{RM} = 0.81 \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{B}{1 \text{ } \mu\text{G}} \right) \left( \frac{L}{1 \text{ kpc}} \right) \text{ rad m}^{-2}$$

- Use equipartition B-field (1.3 $\mu\text{G}$; Hardcastle et al. 2009) & path length through lobes of 200 kpc
- If RM enhancement entirely due to excess thermal electrons $\Rightarrow n_e \sim 10^{-4} \text{ cm}^{-3}$
- Soft X-ray thermal emission $\Rightarrow n_{th} \sim 10^{-4} \text{ cm}^{-3}$
Physical models

- Evacuated cavities (eg. Laing et al. 2008)

- Supported by X-ray obs (eg. Wise et al. 2007)

- Hence, cluster B-field estimates assume no source contribution to RM and use lobe emission from embedded sources (eg. Vogt & Ensslin 2003)

- Objections to this based on possibility of entrainment of ICM/IGM material at edges of lobes (eg. Rudnick & Blundell 2003)
Physical models

- No evidence for RM edge enhancement
- Excess thermal material entrained from host galaxy as the jets decelerate? (eg. Bicknell ‘84, ‘94; Laing & Bridle ‘02)
- Then carried into lobe as buoyant plasma fills the lobes

- Is thermal matter uniformly mixed, clumpy or in layers?
- Require wider frequency coverage (preferably < 1 GHz) to analyse depolarization and conclusively distinguish between various models
Summary

• Parkes @ 50:
  • key component to our understanding of giant lobes of Cen A
  • => understanding physics of radio lobes in general
  • => understanding energy transfer between lobes & IGM
  • => understanding impact on galaxy formation & evolution

• Parkes @ 100:
  • Hope to have answers to all of these questions!
Thank you