Faraday Rotation Measure Synthesis of UGC 10288, NGC 4845, NGC 3044

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CHANG-ES 2016
Overview of RM Synthesis:
- Benefits
- Basic procedure

Individual results:
- UGC 10288 as a Faraday screen (Patrick)
- L+C Combined Analysis of NGC 3044 (Dylan)
- Recovering linear polarization in NGC 4845 (Kendall)
Benefits of Using RM-Synthesis

- More accurate determination of rotation measures (opposed to “classical” linear least-squares fitting)
  - Decomposes resultant rotation into components
- Helps to account for $n\pi$ ambiguities (see e.g. Brentjens & de Bruyn 2005)
- Can observe large rotation measures in more weakly-polarized emission
Preparing Images For Rotation Measure Analysis

• Modified from standard CHANG-ES procedures!
  • robust = 0, no uv-taper nor PB correction
• Requires spectral information
  • Multifrequency synthesis need not apply
• NEW! Generalized Complex CLEAN algorithm (2016)
  • Stokes Q and U
3 limiting parameters: (cf. Brentjens & de Bruyn 2005)

\[ \delta \phi \approx \frac{2 \sqrt{3}}{\Delta \lambda^2} \]

\[ \text{max-scale} \approx \frac{\pi}{\lambda_{\text{min}}^2} \]

\[ \|\phi_{\text{max}}\| \approx \frac{\sqrt{3}}{\delta \lambda^2} \]

Theoretical FWHM in \( \phi \) space

Largest scale one is sensitive to in \( \phi \) space (analogous to largest angular scale)

Max. observable magnitude
• Originally hoped to observe RM of background sources in a combination of D array C band and C array L band
• Expected RMs would be small, which can be a problem when missing S-band
• Since background sources are dim, we cannot use other arrays to identify them—simply not enough flux
While investigating RM grids, explored Blobcat

Package developed to identify ‘blobs’
  • “flood-filled islands of pixels”

Input: Stokes I or linear polarization 2d map

Output: catalogue of sources consistent with some SNR cutoff, and an associated mask file

Another option: SExtractor
  • Creates object catalogue, but no image
THE CASE FOR S-BAND

- Any band / array combination will have a gap for S-band wavelength coverage
- Lack of this data leads to massive residual sidelobes
- Effect is similar to the lack of single-spacing data
- In wavelength-space, this gap is essentially a window function
- In Fourier-transformed / Faraday space, this becomes a convolution with sinc function

\[ rm = 48.86 \pm 3.20, \text{SNR} \sim 4.13 \]
**Generalized Complex CLEAN Algorithm**

- Pratley & Johnston-Hollitt (June 2016)
- Stokes parameters $Q$ and $U$ are traditionally deconvolved independently
  - In reality, $P = Q + iU$ is a complex vector
  - Högbom CLEAN = collection of point sources
  - Complex CLEAN = collection of point sources with *complex amplitude*
- Results are dependent on the axes used during deconvolution

![Clean components – Johnston-Hollitt 2016](image)
**Generalized Complex CLEAN Algorithm**

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**Biased to orientation of axis**

Clean components – Johnston-Hollitt 2016
**Generalized Complex CLEAN Algorithm**

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**Rotationally invariant**

Clean components – Johnston-Hollitt 2016
**GENERALIZED COMPLEX CLEAN ALGORITHM II**

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**Standard Högbom CLEAN**

- Load dirty beam $\Rightarrow B_D$
- Create residual $\Rightarrow R_Q := Q_D$
- Create CLEAN components $\Rightarrow C_Q := 0$

Search for peak in $|R_Q| \rightarrow R_Q(x_m, y_m)$

Test if CLEAN is complete

Subtract point source $\Rightarrow R_Q := R_Q - \gamma R_Q(x_m, y_m)B_D(x - x_m, y - y_m)$

Add to CLEAN components $\Rightarrow C_Q(x_m, y_m) := C_Q(x_m, y_m) + \gamma R_Q(x_m, y_m)$

Restore map $\Rightarrow P_F = Q_F + iU_F$

**Complex Högbom CLEAN**

- Load dirty beam $\Rightarrow B_D$
- Create residual $\Rightarrow R_P := Q_P + iU_P$
- Create CLEAN components $\Rightarrow C_P := 0$

Load dirty beam $\Rightarrow B_D$

Create residual $\Rightarrow R_U := U_P$

Create CLEAN components $\Rightarrow C_U := 0$

Search for peak in $|R_U| \rightarrow R_U(x_m, y_m)$

Test if CLEAN is complete

Subtract point source $\Rightarrow R_P := R_P - \gamma R_P(x_m, y_m)B_D(x - x_m, y - y_m)$

Add to CLEAN components $\Rightarrow C_P(x_m, y_m) := C_P(x_m, y_m) + \gamma R_P(x_m, y_m)$

Search for peak in $|R_P|^2 \rightarrow R_P(x_m, y_m)$

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Pratley & Johnston-Hollitt 2016

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COMPARISON OF RESULTS: STOKES Q IMAGES

SDI (Steer-Dwedney-Ito) CLEAN

Complex SDI CLEAN
UGC 10288
UGC 10288: A Profile

- Inclination ~ 90°
- Radius ~ 11 kpc
- Distance ~ 34 Mpc
- SFR ~ 0.41 M☉/yr
- Morphological type – Sc
A DOUBLE-LOBED BACKGROUND SOURCE APPEARS…

C array / C band
Stokes I
A DOUBLE-LOBED BACKGROUND SOURCE APPEARS...
A Double-Lobed Background Source Appears...

B array / L band
Stokes I

Dec (J2000)

RA (J2000)

CHANG-ES 2016

07/2016
Visible in linear polarization

Stokes I

P (linear pol.)

C array / C band

CHANG-ES 2016

07/2016
Visible In Linear Polarization

Stokes I

B array / L band

CHANG-ES 2016

07/2016
ROTATION MEASURE DISTRIBUTION
Rotation Measure Distribution
EVIDENCE FOR POTENTIAL FIELD REVERSAL... OR MULTIPLE?
EVIDENCE FOR POTENTIAL FIELD REVERSAL... OR MULTIPLE?

CHANG-ES 2016

07/2016
Next Steps For UGC 10288

• Filling in the S-band gap would allow for a much more credible evaluation of the foreground magnetic fields along the LOS
• Zero-spacing GBT data can be used to search for magnetic field structure in the plane of the sky in the foreground halo
• After patching these issues, we can extend the analysis to make use of other CHANG-ES galaxies that have background sources passing through the “Faraday screen”
NGC 3044

- $i = 90$ degrees
- $D = 20$ Mpc
- $R = 9$ kpc
Previous Work

- Magnetic field mapped in CHANG-ES IV using D array C band and D array L band.
- Low resolution of bands prevented detailed analysis of magnetic field
  - Did not utilize RM-Synthesis method
MOTIVATION

• Analyze NGC 3044 magnetic field using advanced method of RM-Synthesis:
  • Single band analysis (C array C band)
  • Combined band analysis (C array C band and B array L band)
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  • Single band analysis (C array C band)
  • Combined band analysis (C array C band and B array L band)

• In order to:
  • Map spatial distribution of the galactic magnetic field using improved band resolution
Magnetic field vectors
C ARRAY C BAND RESULTS

Magnetic field vectors

Distribution of RM values
**Considerations for Single-Band**

- Errors on the order of RMs found, $\sim$200 rad m$^{-2}$

<table>
<thead>
<tr>
<th>RA</th>
<th>DEC</th>
<th>RM</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:53:41</td>
<td>+1:34:54</td>
<td>-95.8</td>
<td>225.3</td>
</tr>
<tr>
<td>9:53:40</td>
<td>+1:34:38</td>
<td>330.3</td>
<td>218.9</td>
</tr>
</tbody>
</table>

- Limited resolution in Faraday space
- Limited polarization within disk
COMBINED BAND RESULTS

Magnetic field vectors

Distribution of RM values
Future Work

• Combined band reveals more polarization within galaxy, but most detections remain outside of disk.
• Galaxy appears to be intrinsically depolarized, preventing any detailed analysis of the magnetic field at these bands.
• Could be better analyzed using a next-gen telescope such as the SKA
NGC 4845

- Inclination ~ 81°
- 17 Mpc away
- 5 kpc in radial direction (2.1 arcmin)
- Known AGN - no obvious effects in radio Stokes I images
• Subject of CHANG-ES V
• Tidal disruption event previously observed in X-ray spectrum (Nikolajuk and Walter, 2013)
  • Also seen in CHANG-ES data
• Polarization data was included in CHANG-ES paper
  • Linear polarization fraction was not found to be >0.5% in L or C band
    • VLA polarization uncertainty is 0.5%, so CHANG-ES V concluded it was likely not significant
    • 2% to 3% circular polarization fraction was observed in L band
      • None found in C band
• Data from all arrays and bands were used in CHANG-ES analysis
Motivation for my work:

• Investigate to see if AGN effects are present in polarization
  • e.g., does the RM correction make a difference in the conclusions we draw about the galaxy?
• What is the structure of the Faraday rotating medium?
• Analyzed B array L band and C array C band
Considerations for single-band data:

• Computer crash! Unable to complete analysis
• Error in finding peak (FWHM / 2*SNR):
  • C / C ~ 300 rad m^{-2}
  • B / L ~ 16 rad m^{-2}
• RM resolution is low due to relatively narrow bandwidths
NGC 4845 (Much-)Improved Procedure

Combined band results:

- Concatenated measurement sets in CASA before imaging
- Errors on the order of $\sim 3$ rad m$^{-2}$
- Used SNR cutoff of 4 to select relevant RMs
- Did not calculate fractional $V$
- Did calculate fractional $P$ to check significance after RM-synthesis
NGC 4845

- Both combined and single-band results
  - But single band results limited because of computer crash
- Circular polarization results match those of CHANG-ES V (~2% polarization), as do uncorrected linear polarization results
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- Corrected linear polarization (post RM-synthesis), has some values > 0.5%
  - But this comes with several caveats:
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Circular polarization results match those of CHANG-ES V (~2% polarization), as do uncorrected linear polarization results
Corrected linear polarization (post RM-synthesis), has some values > 0.5%
  But this comes with several caveats:
    Time variability of source
    No thermal separation correction for I
    But I flux densities will only decrease after the correction, so our polarization fractions serve to constrain lower limits
NGC 4845 Stokes I
RM MAP FOR B / L + C / C
RM MAP FOR B / L + C / C
CORRECTED POLARIZATION VECTORS
PERCENT POLARIZATION INTENSITY
PERCENT POLARIZATION (0.5% CUTOFF)
FURTHER QUESTIONS AND EXPLORATIONS

• Time variation of galaxy
  • Should I be worried about combining separate data sets since N4845’s emission is time-variant?
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- S band data would improve results!
Further Questions and Explorations

- Time variation of galaxy
  - Should I be worried about combining separate data sets since N4845’s emission is time-variant?
- Thermal correction for intensity maps?
- S band data would improve results!

Next steps:
- Combine arrays in same band
- Look into RM gradients spatially (across galaxy) and in different frequencies
- Redo single band calculations
**Final Thoughts**

- RM-synthesis is a very powerful technique for improving polarization studies.
- Background sources (when feasible) can provide an excellent probe of foreground magnetic fields.
- Reasonable to consider making use of the GBT data that we have, and acquiring the S band data that we don’t have.
- Up next: RM-synthesis workshop.