Keeping up with Pictor A

Lexy A. L. Andati[1], Oleg M. Smirnov[1,3]

[1]Centre for Radio Astronomy Techniques and Technologies (RATT),
Rhodes University, South Africa (**andatilexy@gmail.com**).
[3] South African Radio Astronomy Observatory (SARAO), Liesbeek House, Cape Town, South Africa.

Abstract

Pictor A's proximity and brightness make it an ideal source for understanding the evolution of radio galaxies. One way to do so is by probing its magnetic field structure via Faraday rotation effect on its emission. Recently, MeerKAT L-band data was used to perform a new spectropolarimetric study of Pictor A, revealing a wealth of information on its magnetic configuration and showcasing more prominently the its radio jet. With newer MeerKAT UHF and S-band data, we aim to extend that study by performing an in-depth and wideband spectropolarimetric study of Pictor A, while using the data as a testbed to develop new spectropolarimetric data processing tools.

1 Introduction

Radio galaxies are some of the most powerful astrophysical sources in the universe. Typically, they are believed to consist of a central supermassive blackhole (SMBH) that accretes matter onto it, leading to an energetic release of energy through collimated outflows known as radio jets. Sometimes, these jets terminate suddenly, forming what are known as hotspots, while some of the material inflates the jets' surroundings forming radio lobes. Emissions from radio galaxies in radio frequencies are believed to be of synchrotron origin. Thus, because synchrotron emission occurs due to the acceleration of electrons in a magnetic field, it can be used to probe magnetic field structures within radio galaxies and around their environments. We use radio telescopes, such as the MeerKAT telescope in South Africa, to observe radio galaxies such as Pictor A. Additionally, MeerKAT's wideband capabilities enable spectropolarimetric studies. We show an image of Pictor A from our data in Fig. 1, where we have labelled the key components of a radio galaxy. An important feature of this new image is the clarity of the radio jet which was not very clearly visible in older radio observations of this source (obtained using the VLA telescope in 1997), which underscores the power of this instrument.

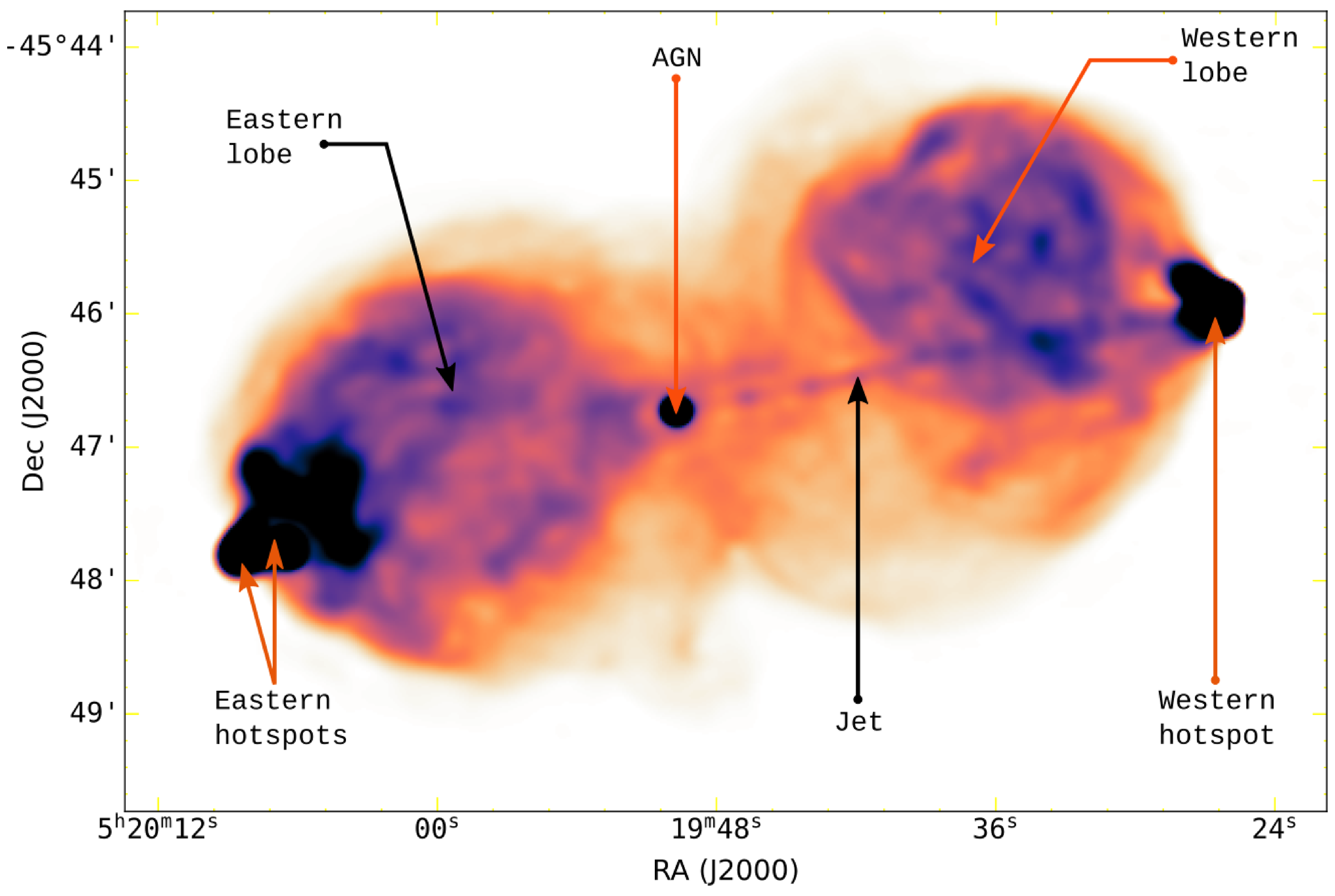

Figure 1: A radio image of Pictor A at 7.5″ from MeerKAT L-band data (Andati, Baidoo, *et al.*, 2024).

2 Objectives

- A wideband spectropolarimetric study of Pictor A with UHF, L and S-band data
- Spectral index studies of the source
- Fast and efficient radio spectropolarimetric processing software for RM-synthesis and other enhanced data products (EDPs)

3 Methods and Tools

3.1 RM-Synthesis

Since magnetic fields are not directly observable, we probe magnetic fields by examining their effects on observable quantities. One such diagnostic is the Faraday rotation effect, where the polarization angle of polarized emission, $\psi = 1/2\arctan(U/Q)$, is rotated due to its interaction with magneto-ionic media along an arbitrary line-of-sight to an observer. Because synchrotron emission is mostly linearly polarized, the observed polarization angles are rotated by a rotation measure, RM, such that $\psi_{\rm obs} = \psi + RM(\lambda^2)$. This can tell us a story about the effects the emission has encountered before being received by the observing instruments. We describe emission using Stokes parameters I, Q, U and V – where I represents the total intensity, Q and U denote the linear polarization, and V represents circular polarization – to reconstruct the picture. Therefore, the complex linear polarization is given as:

$$P(\lambda) = Q + iU \tag{1}$$

Astronomers commonly use the RM-Synthesis technique (Brentjens *et al.*, 2005) to reconstruct the Faraday rotation contributions along a line-of-sight. This takes advantage of the Fourier relationship of the observed quantities in λ^2-space and ϕ-space given as:

$$P(\lambda^2) = \int_{-\infty}^{\infty} F(\phi)e^{2i\phi\lambda^2}d\phi \tag{2}$$

$$F(\phi) = \int_{-\infty}^{\infty} P(\lambda^2)e^{-2i\phi\lambda^2}d\lambda^2, \tag{3}$$

where, ϕ is the Faraday depth described by:

$$\phi = 0.81\int_L^{\rm observer} n_e\mathbf{B}_{||}\cdot dr, \tag{4}$$

and $\mathbf{B}_{||}$ is the magnetic field parallel to the line-of-sight, n_e is the electron density, and r is the path length along a line-of-sight.

3.2 `Dask` + `FITS`

Figure 2: Technologies we aim to use.

We are processing newly observed raw UHF and S-band data from MeerKAT using the `CARACal` pipeline (Józsa *et al.*, 2020) to obtain our full-Stokes (Stokes I, Q, U and V) multiple sub-band radio images. We will then apply the RM-synthesis – a technique for the analysis of Faraday rotation effect on polarized radio emission – on the resulting images to perform a wideband spectropolarimetric study of Pictor A, extending our current L-band based work (Andati, Baidoo, *et al.*, 2024).

Application of RM-synthesis to wideband data requires processing of large full-Stokes data cubes (one direct cause of this is the increased frequency samples). Fast and efficient software is required to do this. We aim to develop `Dask`-backed (Rocklin, 2015) astronomical image processing tools to achieve this task.

[1]`https://mulan-94.github.io/scrappy/`

4 Preliminary Outcomes

4.1 `Scrappy` and `Polarvis`

For our previous data (Andati, Baidoo, *et al.*, 2024), we had 2389 individual lines of sight across this source. While it is useful to examine spectra associated with each line-of-sight, this task could quickly prove drudging and repetitive. Furthermore, determining the location of these lines of sight on the source would require manually taking note of its pixel numbers on an astronomical image and associating them with a region on the source. Therefore, a quick alternative for identifying these trends associated with specific components is useful.

To this end, we developed the Polarimetric Visualizer (**`PolarVis`**, Andati, Smirnov, *et al.* 2023), which is a web-based tool capable of displaying interactive plots associated with various selected lines of sight with a click of a button. For Pictor A, the lines of sight are available at:
`https://pica.ratt.center`
and a widescreen computer monitor ((e.g. a monitor or laptop)) is highly recommended for the best viewing experience. Scan the QR-code to the right to interact with **`PolarVis`**.

Additionally, we developed a suite of Python scripts for the automated pre-generation of the line-of-sight data used and displayed in **`PolarVis`**. These scripts were bundled into a single package, **`Scrappy`**, which is installable via pip, the Python package installer.[1] **`Scrappy`** is currently under development and undergoing refactoring to improve efficiency and robustness. However, the current scripts perform the following major tasks:

1. Generate valid and independent regions (lines-of-sight) across Pictor A.
2. For each region, the associated I, Q, and U data were recorded.
3. For each valid region, perform the RM-synthesis and linear fitting of $\psi(\lambda^2)$ and generate the data.
4. Use the data generated by Steps 2 and 3 to create interactive plots.

4.2 Stimela Based Pipelines

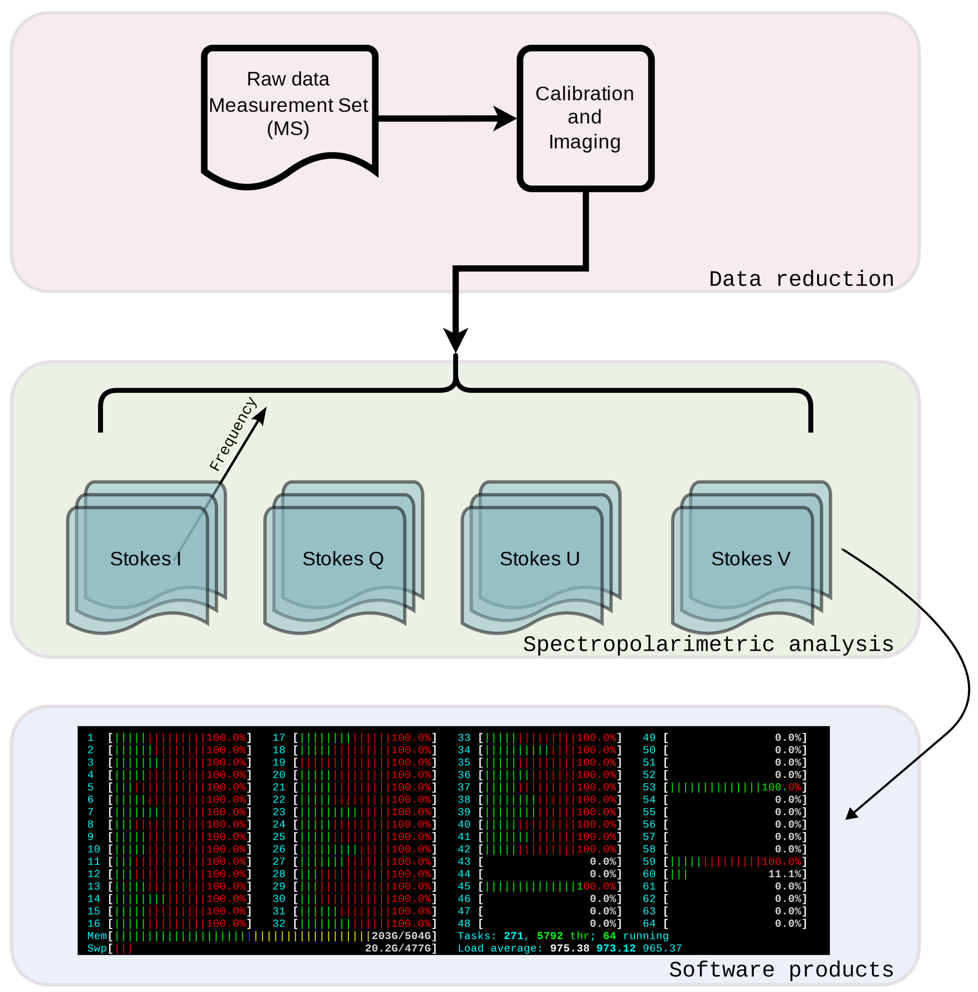

Figure 3: A simple workflow for spectropolarimetric diagnostics.

We are working towards producing full-polarization self-calibration pipelines for MeerKAT that will be readily available as reference recipes to end-users of the MeerKAT telescope. Moreover, the resulting data products will also be available mainly for the benefit of the larger astronomical community.

We are also working to produce efficient software tools to process large data cubes with limited hardware, with functionalities that permit scaling to many CPUs where possible. This tool will substantially impact the data analysis capabilities of the science end-users, not only of MeerKAT but also of other telescopes.

5 Summary

Studies of radio galaxies such as Pictor A advance and enhance our understanding of the astrophysical causes of the structures we observe. Furthermore, since MeerKAT is a precursor telescope to the forthcoming and much larger radio observatory, the Square Kilometer Array (SKA), its data provide a testing ground for big-data algorithms and software in preparation of its arrival.

Acknowledgements

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