



UHF OBSERVATIONS OF THE TAIL-LIKE REGION OF THE HYDRA A RADIO GALAXY

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RADIO GALAXIES

Class of Active Galactic Nuclei (AGN) with high intensity radio emission in regions outside their visible extent.

Display a 'core-jet-lobe' morphology.

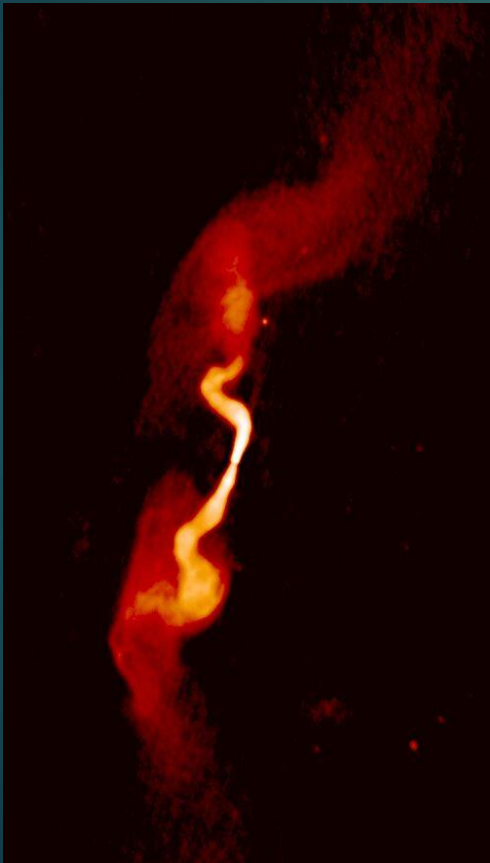
Categorized into FR-I and FR-II groups based on their large scale extended structures.

FR-I radio galaxies typically inhabit clusters and have their surface brightness dominated by the core region.

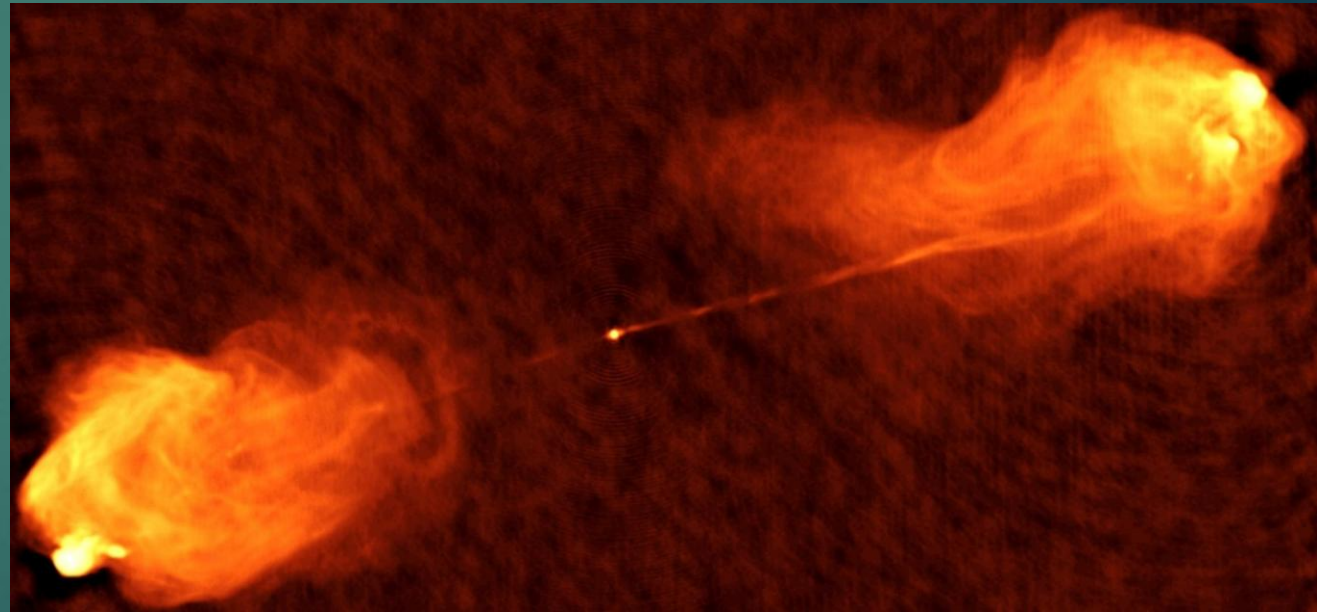
FR-II radio galaxies are found in isolated environments with their edges displaying hotspots of radio emission.

RADIO GALAXIES

FR-I RADIO GALAXY (3C31)



FR-II RADIO GALAXY
(CYGNUS A)



CYGNUS A: Carilli et al (1996), A&AR
3C31: Padovani (2016), A&AR

HYDRA A RADIO GALAXY

- ▶ FR-I type radio galaxy found at the centre of the Abell 780 cluster at a redshift of $z=0.054$.
- ▶ Previous low radio frequency and X-ray observations have revealed the galaxy to be comprised of:
 - ▶ (a) Bright central core.
 - ▶ (b) Pair of relativistic jets.
 - ▶ (c) Pair of inner radio lobes.
 - ▶ (d) Pair of outer radio lobes with the southern lobe having a tail-like extension.
 - ▶ (e) Three pairs of X-ray cavities surrounding the lobes

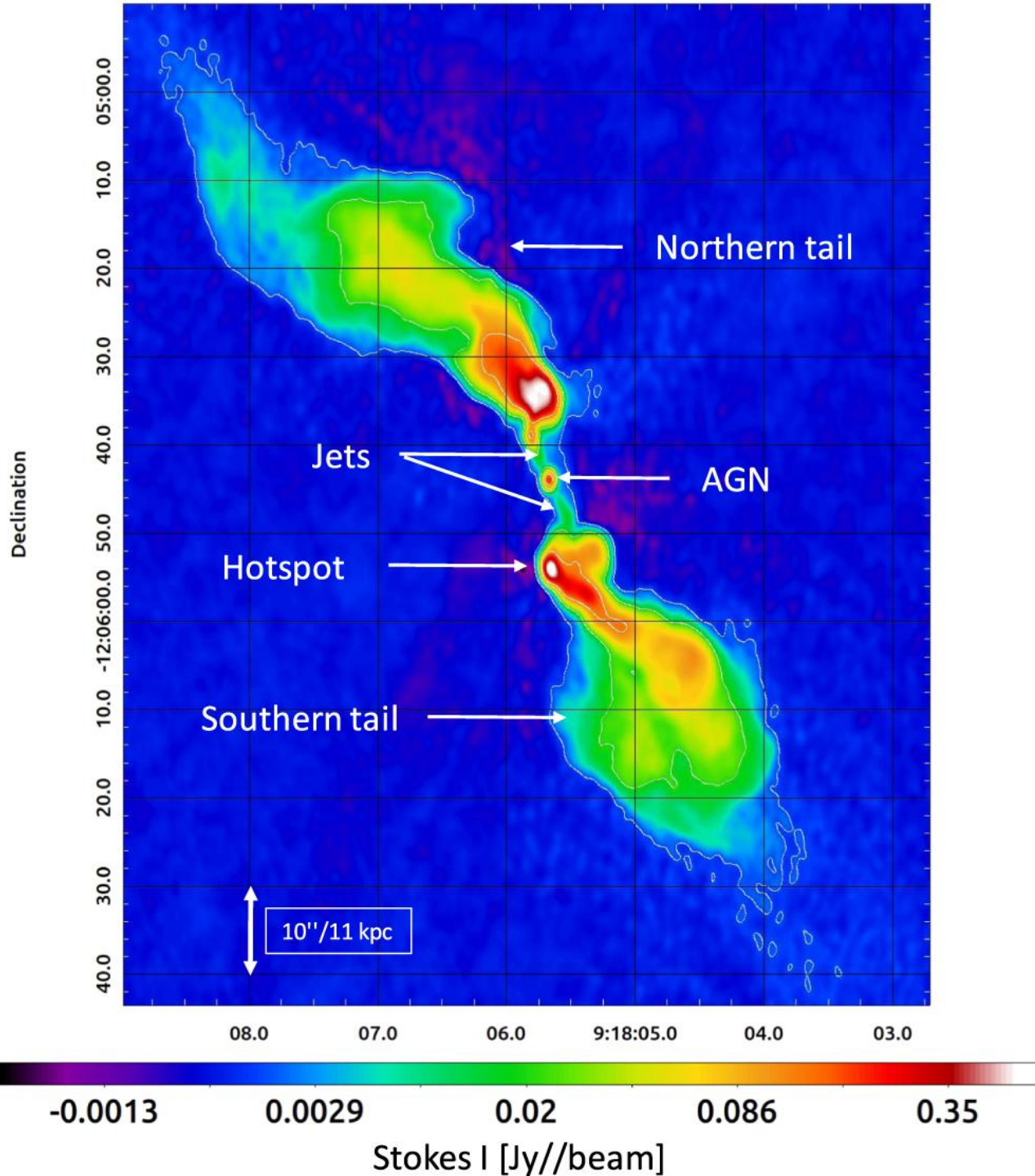


Image credit: Baidoo et al (2023), ApJ

VLA AND MeerKAT L-BAND OBSERVATIONS

- ▶ VLA and MeerKAT L-band (865-1711 MHz) observations were conducted by Lane (2004) and Naidoo (2023) respectively.
- ▶ Naidoo (2023) used the VLA observations from Lane (2004) ,at 74 MHz and 330 MHz, alongside the L-band observations, at 1000, 1100, 1330 and 1485 MHz, to determine the spectral age of three regions of Hydra A.
- ▶ The three regions of Hydra A were: (a) Northern Lobe, (b) Southern Lobe and (c) Tail region.

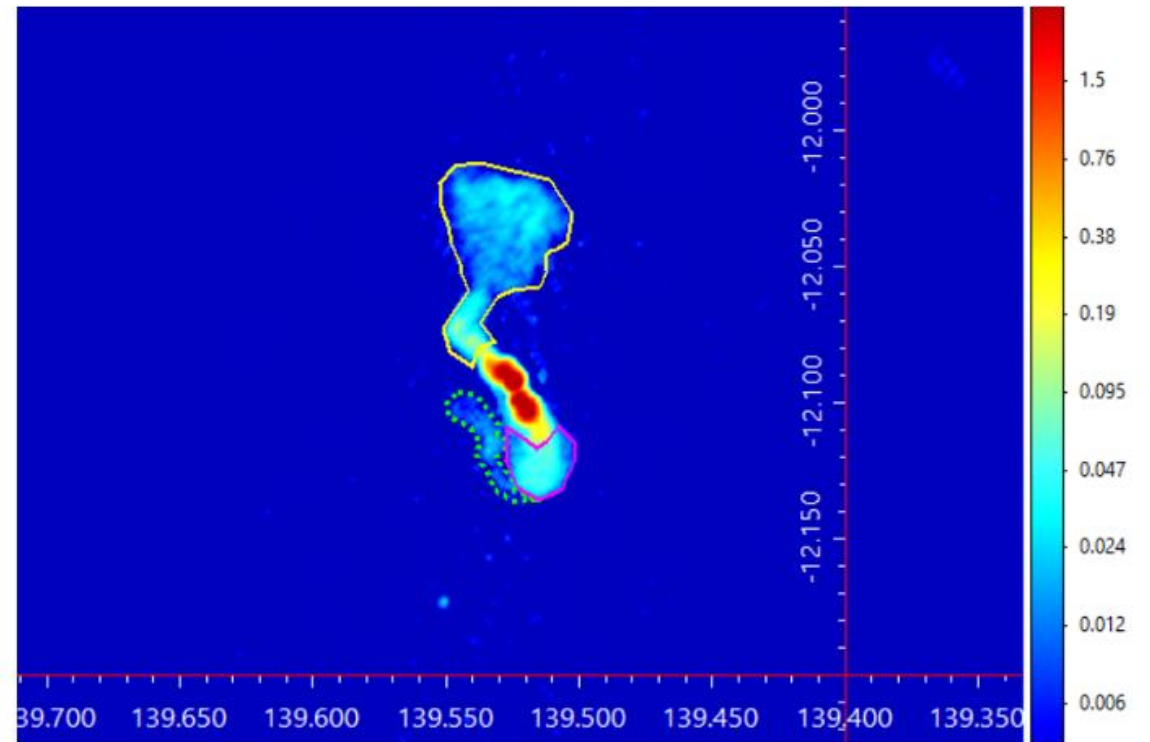


Image credit: Naidoo (2023), Masters Thesis

Lane study: Lane et al (2004), AJ

VLA AND MeerKAT L-BAND OBSERVATIONS

- ▶ Spectral age is a measure of the timescale at which electrons in the lobe region dissipate their energy via synchrotron emission.
- ▶ Determined using Kardashev-Pacholczyk (KP) model due to presence of spectral break in the radio spectrum.
- ▶ Assumptions of model are:
 - (a) Single injection event of power law distributed electrons into emission region.
 - (b) Electron interaction with magnetic field causes energy loss via synchrotron emission.
 - (c) Electron pitch angle with respect to the magnetic field is uniform during their entire radiative lifespan.

KP model: Kardashev (1962), Soviet Astronomy & Pacholczyk (1970), W.H. Freeman and Co. (San Francisco)

AIMS OF THE STUDY

- ▶ Our research aims to build off the Naidoo (2023) study and directly measure the spectral break frequency in the radio spectrum of the tail-like region of Hydra A using MeerKAT's UHF band (544-087 MHz) observations.
- ▶ By directly determining the spectral age of the tail-like region and we hope to investigate the possible emission mechanisms and history of electron injection in the region.

Image credit: <https://www.sarao.ac.za/science/meerkat/about-meerkat/>



DATA ANALYSIS: DATA COLLECTION

Three scans of Hydra A took place on the 13th and 16th of February 2024 with each scan lasting 30 minutes.

The field J0408-6545 | 0408-658 was used as a bandpass calibrator with two 5-minute scans of it conducted.

The J1008+070 field was the complex gain calibrator with three 150-second scans conducted.

DATA ANALYSIS: DATA REDUCTION

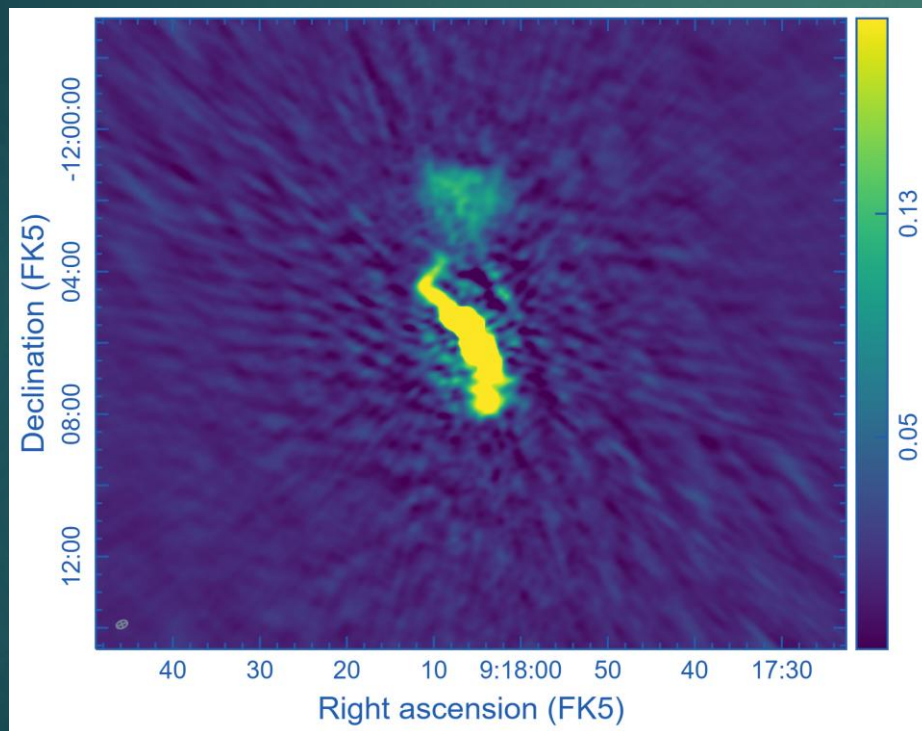
- ▶ Observational data was stored into three measurement set files corresponding to the different observation epochs.
- ▶ Data reduction tasks were handled by the Containerised Automated Radio Astronomy Calibration (CARACal) pipeline.
- ▶ CARACal contains a collection of Python scripts known as 'workers' which correspond to a different data reduction process.
- ▶ The main tasks were flagging, cross-calibration and self-calibration.
- ▶ The *selfcal* worker was also responsible for the imaging of the data.
- ▶ It split the data into four frequency sub-bands with central frequencies of 612, 748, 884 and 1020 MHz.
- ▶ It also utilized the WSClean tool produce final images, in Flexible Image Transport System (FITS) format, that were 5000 × 5000 pixels in size with each pixel being 1.7 × 1.7 arcsec.

CARACAL: Makhathini et al (2022), Astronomical Data Analysis Software and Systems XXX

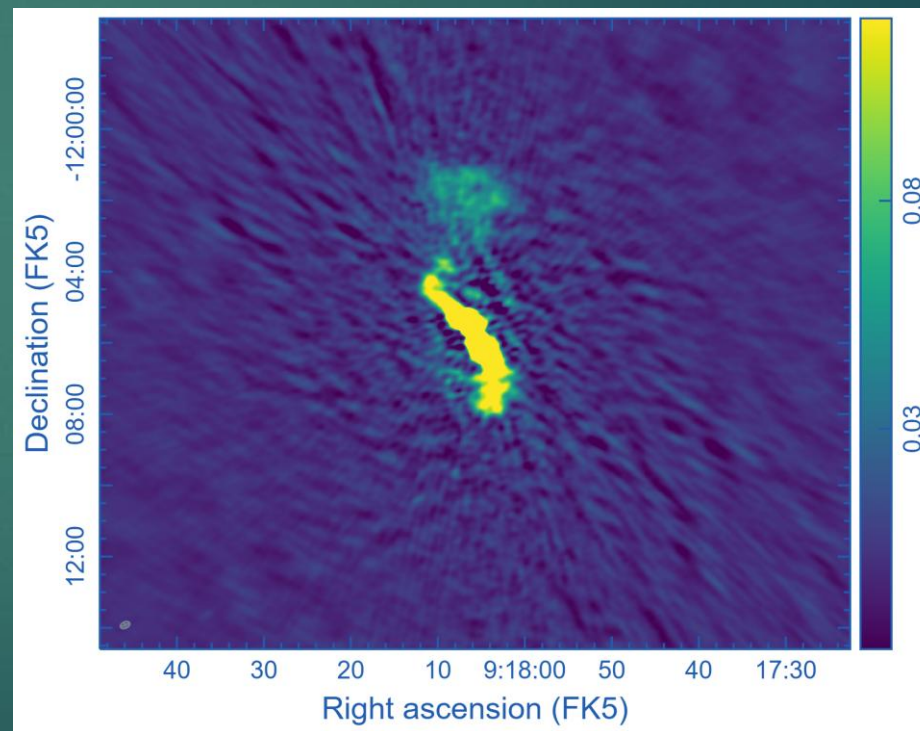
WSCLEAN: Offringa et al (2014), MNRAS

DATA ANALYSIS: FINAL IMAGES FOR MS1

612 MHz IMAGE

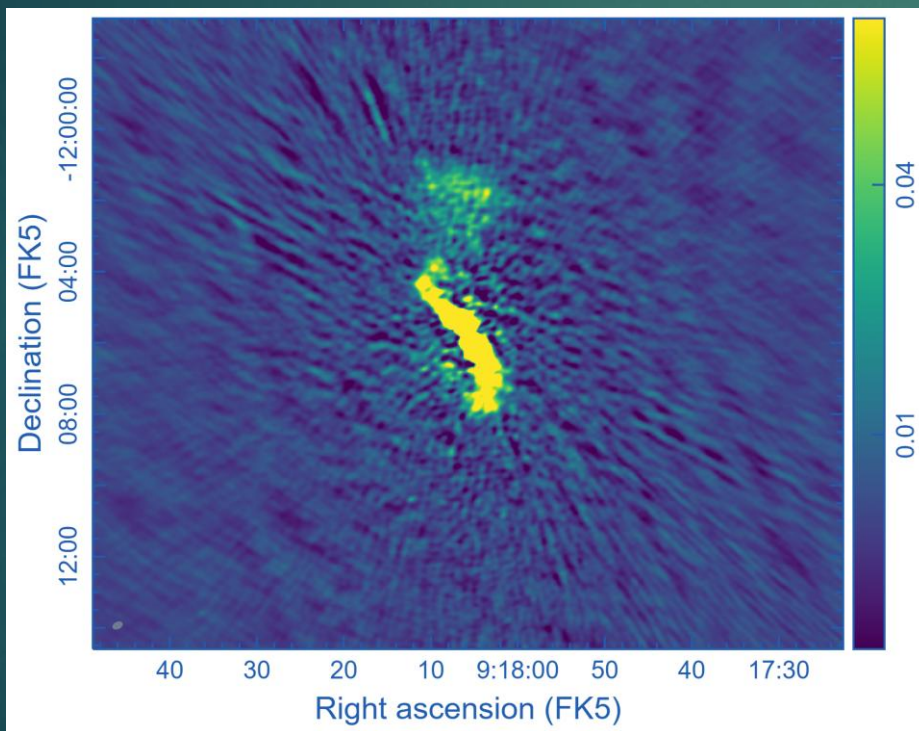


748 MHz IMAGE

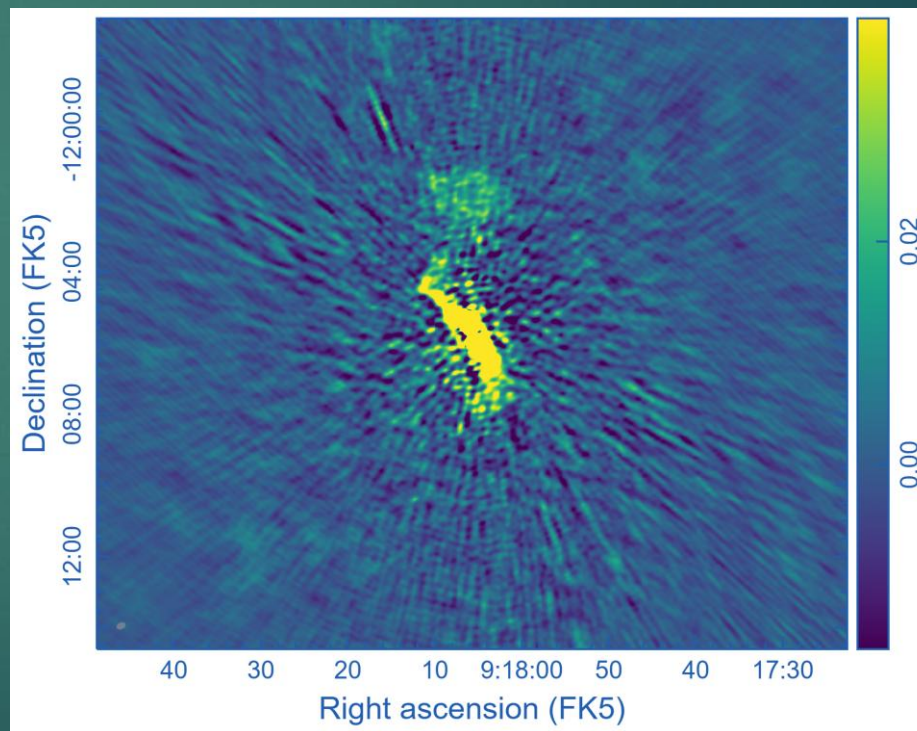


DATA ANALYSIS: FINAL IMAGES FOR MS1

884 MHz IMAGE

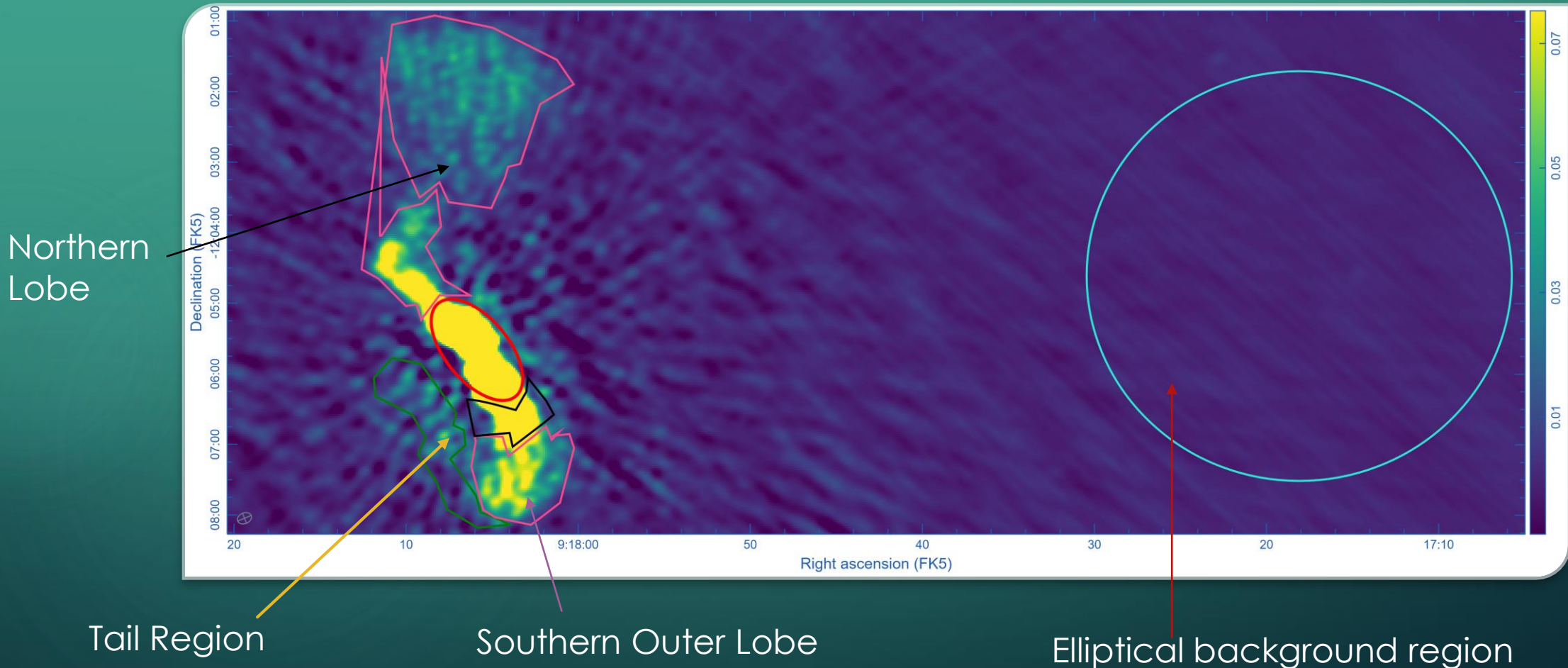


1020 MHz IMAGE



DATA ANALYSIS:FINAL IMAGES

- Cube Analysis and Rendering Tool for Astronomy (CARTA) was used to view the images.



CARTA: Comrie et al (2021), Astrophysics Source Code Library, record ascl: 2103.031

DATA ANALYSIS: FLUX DENSITY AND UNCERTAINTY MEASUREMENTS

- ▶ CARTA was used to measure the flux densities for the three regions of interest. Their corresponding uncertainties were calculated via the formula

$$\Delta S_\nu = \sqrt{(\sigma_{\text{amp}} S_\nu)^2 + (\sigma_{\text{rms}} \sqrt{N_{\text{beam,reg}}})^2}$$

- ▶ The equation is a quadrature summation of errors from uncertainty in the flux measurements of the unresolved sources used in the calibration process and uncertainty from the extended nature of the diffuse radio emission.
- ▶ The flux densities and their corresponding errors were obtained for all the three different measurement sets.
- ▶ We decided to combine the results from each measurement for each region using the weighted average technique. The 1020 MHz flux was discarded for the tail region due to the third measurement set producing a negative flux.

Formula credit: Parekh et al (2020), MNRAS

DATA ANALYSIS: FLUX DENSITY AND UNCERTAINTY MEASUREMENTS

Frequency (MHz)	Weighted flux density (Jy)	Weighted flux density error (Jy)
74	21.981	2.2
330	2.394	0.24
612	1.01	0.18
748	0.66	0.16
884	0.43	0.14
1000	0.275	0.005
1100	0.218	0.004
1330	0.114	0.002
1485	0.093	0.003

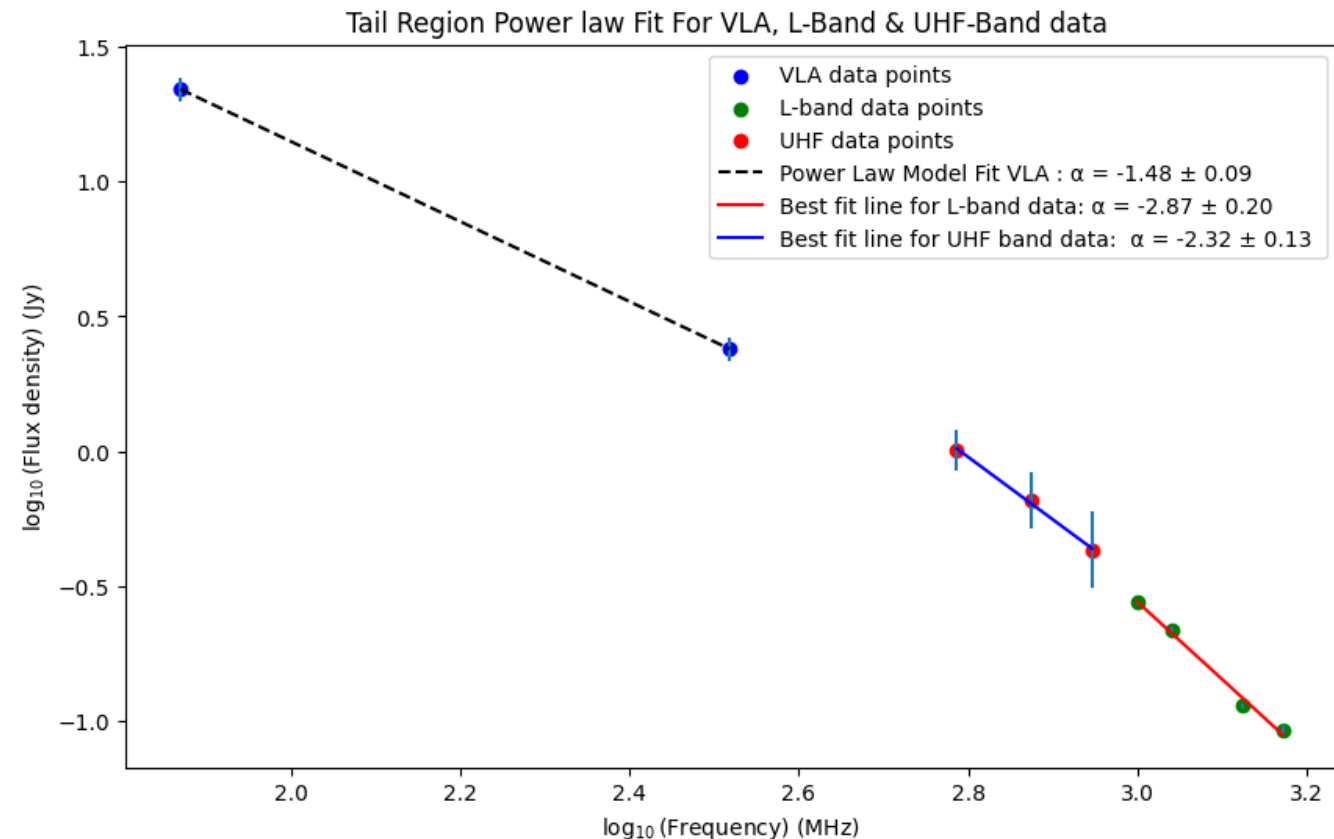
Table 1: Flux density measurements and their corresponding errors for the tail-like region of Hydra A ordered as VLA, UHF-band and L-band subsets respectively.

SPECTRAL ANALYSIS: RADIO SPECTRUM PLOTS

- ▶ To obtain the spectrum of each region, we fitted MeerKAT's UHF and L-band flux densities to a power law while the two VLA data points were fitted using the formulae shown.
- ▶ An older electron population is associated with advanced spectral steepening; therefore, it is expected that the tail region will be the oldest of the three regions.
- ▶ We can infer that there is a spectral break between the VLA and UHF data subset whereby the radio spectrum assumes a broken power law shape hence we can fit the data using the Karadashev-Pacholczyk (KP) spectral age model.

$$\alpha = \frac{\log\left(\frac{S_{\nu_1}}{S_{\nu_2}}\right)}{\log\left(\frac{\nu_1}{\nu_2}\right)}$$

$$\Delta\alpha = \frac{\sqrt{\left(\frac{\Delta S_{\nu_1}}{S_{\nu_1}}\right)^2 + \left(\frac{\Delta S_{\nu_2}}{S_{\nu_2}}\right)^2}}{|\log\left(\frac{\nu_1}{\nu_2}\right) \ln 10|}$$



SPECTRAL ANALYSIS: KP SPECTRAL AGE MODEL

The radio spectra for the three regions of interest of Hydra A were fitted to the KP model in order to determine their spectral ages.

The model was implemented via a Python code which performs a grid search to find the magnetic field and spectral age pair that produces the minimum chi-square value.

SPECTRAL ANALYSIS: OPTIMIZATION OF BEST FIT B AND T VALUES.

- ▶ We had two datasets, one which excluded UHF observations (UHF exclusive) and one which included them (UHF inclusive).
- ▶ The spectral age and magnetic field values reported by Naidoo were optimized using the LMFIT software package for both datasets.
- ▶ The optimization parameters were the magnetic field (bmu), initial normalization factor (k0) and the spectral age (t).
- ▶ The results from the UHF inclusive dataset are consistent with those from Naidoo (2023) for all the three regions.

LMFIT: <https://lmfit.github.io/lmfit-py/>

Tail Region Optimal Parameters	VLA + L-band data	UHF exclusive data	UHF inclusive data
Log-scale normalization factor (k_0)	10	9.83 ± 0.68	12.13 ± 0.66
Magnetic field (μG)	1.99 ± 0.49	1.97 ± 0.20	1.93 ± 0.13
Spectral age ($Myrs$)	138.75 ± 2.5	136.81 ± 5.73	138.45 ± 4.34

Table 2: A comparison between the optimal magnetic field, spectral age and initial normalization factor for the Tail region of Hydra A from Naideo (2023) and those obtained in the present work from optimizing both the UHF exclusive and inclusive datasets.

SPECTRAL ANALYSIS: OPTIMIZATION OF BEST FIT B AND T VALUES

SPECTRAL ANALYSIS: CONTOUR PLOTS AND MODEL FITTING



The penultimate step of the radio spectrum modelling process was to determine and plot the contours associated with the different confidence levels.

The main objective was to visualize the (T-B) parameter space and see whether the inclusion of UHF data constrains it further.

The boundaries of the grid search were expanded until they fully encompassed the 99% contour for each region to ensure a full view of the contour lines.

There were three degrees of freedom, corresponding to the number of optimized parameters, and confidence levels of 68% and 99%. This resulted in chi-square statistic values of 3.51 and 11.34 respectively.

SPECTRAL ANALYSIS: CONTOUR PLOTS AND MODEL FITTING

- ▶ The optimal spectral age and magnetic field combinations were the same for both the UHF exclusive and inclusive datasets.

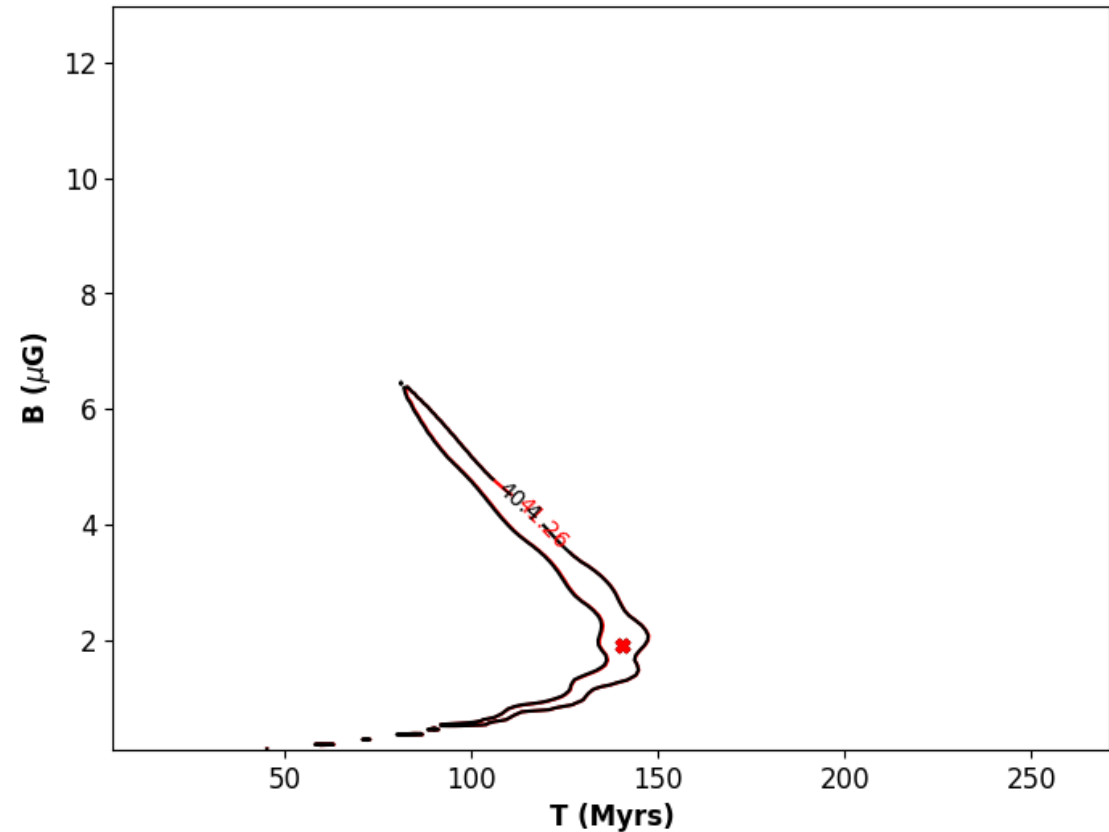
Parameters	Northern Lobe	Southern Outer Lobe	Tail Region
Spectral age (Myrs)	$9.14^{+0.33}_{-0.33}$	$49.68^{+1.01}_{-1.26}$	$140.24^{+1.79}_{-3.59}$
Magnetic field (μG)	$35.70^{+1.61}_{-1.61}$	$11.08^{+0.06}_{-0.18}$	$1.91^{+0.51}_{-0.51}$

Table 3: The spectral age and magnetic field results for the three regions of Hydra A after the addition of MeerKAT's UHF band data.

SPECTRAL ANALYSIS: CONTOUR PLOTS AND MODEL FITTING

- ▶ A comparison between the UHF exclusive and inclusive 3σ contours was conducted to see whether the addition of the UHF dataset further constrains the range of possible best fit values for the spectral age and magnetic field.
- ▶ The three regions showed minimal constraint on the range of spectral age and magnetic field combinations.

UHF EXCLUSIVE (BLACK) & UHF INCLUSIVE (RED) 3σ CONTOUR PLOT COMPARISON



SPECTRAL ANALYSIS: CONTOUR PLOTS AND MODEL FITTING

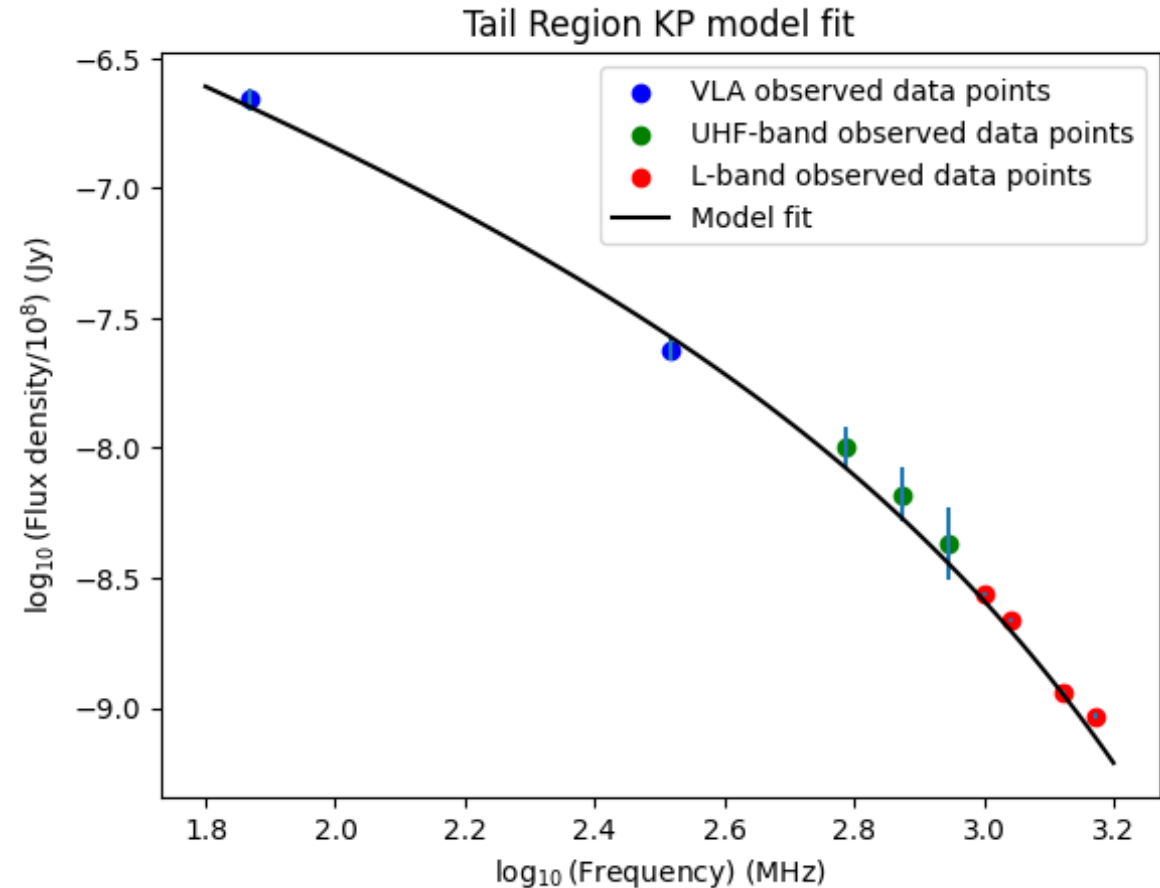
- ▶ The projections of the 3σ contour onto the magnetic field gives a more accurate representation of the possible values for the spectral age as it pertains to each region. The largest and smallest spectral age value the model can attain for the three regions is shown by the table.

Region	Minimum possible spectral age (Myrs)	Maximum possible spectral age (Myrs)
Northern Lobe	~3	~32
Southern Outer Lobe	~38	~63
Tail	~40	~145

Table 4: The minimum and maximum possible spectral age values based on the outlines of the plotted 3σ contour.

SPECTRAL ANALYSIS: CONTOUR PLOTS AND MODEL FITTING

- ▶ The KP model with the best fit UHF inclusive spectral age and magnetic field was fitted onto the original dataset.
- ▶ A notable drawback with the KP model is the neglect of inverse-Compton emission effects which become important for low values of the magnetic field.
- ▶ At magnetic fields below $4\text{ }\mu\text{G}$, synchrotron emission become less important than inverse-Compton scattering as the main emission mechanism.



CONCLUSIONS

- ▶ One of the objectives of our research was to gain a better understanding of the inner workings of the regions associated with Hydra A especially when it comes to the injection history of electrons in a particular region.
- ▶ As previously stated, the tail region is expected to be the oldest in the radio galaxy due to its advanced spectral steepening and the results for the spectral age reinforce this statement.
- ▶ This large spectral age can be ascribed to the minimal contact between the tail-like region and the relativistic jets which results in sluggish injection rates as compared to the other regions such as the northern lobe.

FUTURE WORK

Employing

Employing the use of the Markov Chain Monte Carlo (MCMC) for model fitting and error estimation.

Breaking

Breaking degeneracy by conducting independent magnetic field observations through polarization measurements.

Determining

Determining the spectral age through the Tribble model.
