

A Study of the Lobes of the Radio Galaxy Hydra A using MeerKAT Observations

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Declaration

I, Mika Naidoo, declare that this proposal is my own, unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted for any degree or examination at any other university.

A handwritten signature in black ink, appearing to read 'Maidoo', written over a horizontal line.

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17 March 2023

Abstract

Hydra A is a powerful radio galaxy located at the center of the galaxy cluster Abell 780. It hosts a pair of hundred-kiloparsec scale radio lobes that are being powered by the closest of the three most powerful cluster-scale AGN outbursts known to date. In this study we use observations of Hydra A carried out using the MeerKAT radio telescope in the L-band. We reduced the data using the CARACal pipeline and present four radio maps at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz. We find the radio morphology of Hydra A can be described by a core region, a pair of bright inner lobes, a pair of large diffuse outer lobes- one in the northern direction and one in the southern direction- and an interesting tail-like region that extends out from the southern outer lobe. In this study, we analyse the northern outer lobe, southern outer lobe and tail-like region in detail. This includes computing the radiative flux densities of each region and performing a spectral analysis of each region. We find that the population of synchrotron-emitting electrons in the tail-like region has undergone significant spectral aging and is most likely the oldest region in the Hydra A system. We model the spectrum of Hydra A and find the Kardashev-Pacholczyk model for spectral aging satisfactorily represents the spectrum. We set constraints on the age and magnetic field values for all three regions. It is most likely the case that the northern and southern lobes are still connected to the jets and are being injected with young electrons, whereas, the tail-like region is completely disconnected from the jets and is a remnant of an older generation of AGN activity. We estimate the age of the Hydra A system to be ~ 140 Myrs, which is consistent with previous age estimates.

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List of Abbreviations

AGN	A ctive G alactic N uclei
BL Lac	BL Lac ertae
CARACal	C ontainerised A utomated R adio A stronomy C alibration
CASA	C ommon A stronomy S oftware A pplications
CI	C ontinuous I njection
CMB	C osmic M icrowave B ackground
FRI	F anaroff- R iley type one
FST	F leurs S ynthesis T elescope
FWHM	F ull W idth H alf M aximum
IC	I nverse C ompton
ICM	I ntracluster M edium
JP	J affe- P erola
KP	K ardashev- P acholczyk
PSF	P oint S pread F unction
Quasar	Q uasi S tellar R adio source
RIME	R adio I nterferometry M easurement E quation
SMBH	S uper M assive B lack H ole
SPW	S pectral W indow
VLA	V ery L arge A rray telescope
WAT	W ide A ngle T ailed

Chapter 1

Introduction

1.1 AGN and Radio Galaxies

In this thesis, we present a study of the radio galaxy Hydra A. In this chapter we present a brief introduction to AGN and radio galaxies. For an extended discussion on the topics presented here, refer to Chapter 16 of [1] and Chapter 28 of [2].

1.1.1 AGN

It is now well accepted that a supermassive black hole (SMBH) lies at the center of nearly all galaxies- some of which are actively feeding off of the surrounding gas and dust in their immediate environment. Supermassive black holes that are powered by the accretion and infall of matter are known as active galactic nuclei (AGN). About 90% of AGN do not exhibit strong radio emission and are classified as radio-quiet AGN. The second most common type of AGN are radio galaxies (see Section 1.1.2). Radio galaxies are characterised by strong radio emission. Surrounding material falls in toward the central SMBH and matter is ejected outwards in the form of highly collimated jets containing ionised particles travelling at relativistic speeds. These jets come in pairs that are channeled by twisted magnetic fields that direct their motion outward. The relativistic electrons from these jets interact with these magnetic fields and emit non-thermal radiation in the form of radio waves, for this reason; radio galaxies are classified as radio-loud AGN. Other kinds of radio-loud AGN include Quasi-Stellar

radio sources (Quasars) [3], which are the most luminous type and BL Lacertae (BL Lac) objects, which are characterised by their rapid variability. Both radio-loud and radio-quiet AGN emit over a broad range of the electromagnetic spectrum; notably in optical and X-ray [4].

1.1.2 Radio Galaxies

When the relativistic jets encounter the intracluster medium (ICM), their energy is dissipated in the form of giant lobes of radio-emitting plasma. These lobes generally have substantial projection sizes, with the largest known structure made by a single galaxy to date being around ~ 5 Mpc (outside the galaxy cluster) [5]. Within galaxy clusters, surface brightness depressions called X-ray cavities have been found in the X-ray emitting gas in the vicinity of radio galaxies [6]. The cavities are seen to closely surround the radio-emitting plasma providing strong evidence that the expansion of the radio lobes is the mechanism that is displacing the X-ray-emitting gas (see Figure 1.13). The energy content of the radio lobes can be estimated using pressure arguments since the inward pressure of the thermal ICM should be balanced by the outward pressure of material within the cavities. The mechanical energy required to expand cavities with volume, V into the ICM with pressure, p ranges between $2pV$ and $4pV$ [7], for radio galaxies as powerful as Hydra A, this translates to a mechanical energy of 10^{61} ergs. However, it is important to note that the principal mechanism responsible for the pressure support in the bubbles is not known with certainty; other mechanisms that could be responsible include cosmic-ray hadrons[8,9], hot plasmas[10], or magnetic fields[11].

AGN and radio galaxies play a crucial role in regulating the formation and growth of galaxies as well as the structure and evolution of galaxy clusters. AGN form an integral part in regulating mechanical feedback processes such as star formation. AGN can provide positive feedback for star formation by compressing the hot gas in the ICM and triggering star formation. It has been found that AGN driven gas outflows can enhance star formation in certain galaxies [12]. AGN can also provide negative mechanical feedback by heating up the ICM and in some cases blowing it away thus preventing star formation from occurring. AGN and radio galaxies also play an important part in radiative feedback processes such as cooling of the cores of clusters. If the temperature of the gas in a galaxy is sufficiently high, the gas may cool through radiative losses in a process known as thermal bremsstrahlung. Thermal

bremsstrahlung occurs in an ionized gas when free electrons in thermal equilibrium interact with ions resulting in the emission of high energy photons- usually X-rays and gamma rays. The emission of radiation causes the temperature of the gas to decrease. The characteristic of cooling time of the gas is given by

$$t_{cool} = \frac{3NkT}{dE/dt} = 10^{10} \frac{T^{1/2}}{N} \text{years}, \quad (1.1)$$

where N is the number density of ions, T is the temperature in Kelvins, k is Boltzmann's constant and $\frac{dE}{dt}$ is the total energy loss rate. At the center of galaxy clusters, this characteristic cooling results in the central gas being cooler than the external hot gas. At constant pressure, the gas density increases resulting in a slow subsonic flow called the cooling flow [13]. However, X-ray observations of clusters containing a cooling flow, such as Hydra A [14], reveal the absence of this expected cool gas at the center of these clusters. This has led researchers to believe that there must be some mechanism responsible for reheating the gas at the center of these galaxies. The cavities identified in the X-ray emitting gas surrounding radio galaxies have shown that the plasma in the radio lobes is responsible for displacing the X-ray emitting gas. The energy input required from the AGN in these galaxies has been shown to be sufficient to balance the cooling flows [15]. This feedback mechanism between the AGN and the surrounding galaxy has become the leading explanation for explaining the cooling flow problem. AGN and radio galaxies are thus important objects to study in the context of galaxy evolution and the role they play in clusters of galaxies. The mechanical and radiative feedback processes from AGN can regulate both star formation in galaxies and the cooling of the cores of clusters, providing a crucial understanding of the relationship between AGN and their host galaxies.

1.2 Radiative Processes

A detailed description of the physical radiative processes summarised below can be found in Chapters 5 and 6 of [16]. The radio spectrum of a source can be determined by investigating the relationship between the flux density of the source- S_ν and the frequency- ν in the form

$$S_\nu \propto \nu^{-\alpha}, \quad (1.2)$$

where α is the spectral index. Electrons are initially injected into the lobes and evolve thereafter according to the kinetic energy equation

$$\frac{\partial N(E)}{\partial t} = \frac{\partial}{\partial E}[b(E)N(E)] + Q(E), \quad (1.3)$$

where $b(E)$ is the energy losses ($\frac{dE}{dt}$), $N(E)$ is the electron spectrum and $Q(E)$ is the source term. If we assume that the electrons are injected at an initial time with no subsequent injections, $Q(E)=0$. At the point of acceleration, the electron population initially takes the form

$$N(E) = N_0 E^{-\gamma}, \quad (1.4)$$

where N_0 is a normalisation factor and γ is the power law index of the initially injected electron energy distribution. The electrons experience energy losses due to synchrotron radiation and Inverse Compton (IC) scattering with cosmic microwave background (CMB) photons. Synchrotron radiation is produced when highly relativistic electrons interact with a magnetic field. In the presence of a magnetic field, a force perpendicular to the magnetic field (the Lorentz force) is exerted on the electrons causing them to accelerate perpendicular to the magnetic field direction resulting in a helical trajectory; this acceleration results in the radiation of photons (see Figure 1.1). IC scattering results from a low-energy photon colliding with a relativistic electron, resulting in an electron with a lower energy and a photon with an increased energy. The universe is filled with an abundance of low energy photons; CMB photons that are the tell-tale signature of the Big Bang. The electrons in radio galaxies lose their energy through IC scattering with these CMB photons. IC losses become dominant when the CMB energy density given by

$$\begin{aligned} U_{CMB} &= aT_{CMB} \\ &= 4.2 \times 10^{-13} \frac{\text{erg}}{\text{cm}^3} (1+z)^4, \end{aligned} \quad (1.5)$$

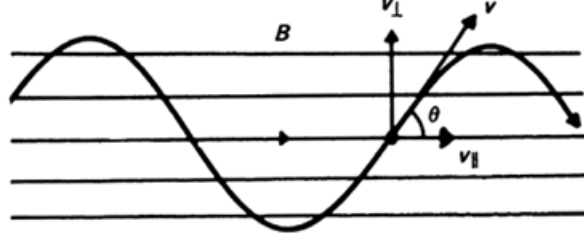


FIGURE 1.1: A Schematic diagram showing the synchrotron radiation mechanism [13]

is greater than the energy density of the magnetic field within the interacting region U_B ; that is, $U_{CMB} > U_B$ or

$$B < \sqrt{8\pi a} T_{CMB} \\ \approx 3.2 \times 10^{-6} G (1+z)^2.$$

In general, for magnetic fields $< 4\mu G$, IC losses become more dominant. In Equation 1.3.

The losses due to synchrotron radiation go as $\tau \sim \frac{1}{E}$ - this means that electrons with a higher energy radiate their energy on a shorter time scale. This process, known as spectral aging, results in the steepening that is seen in the characteristic power-law radio spectrum (see Figure 1.2). By studying the radio spectrum of a source, the spectral age can be computed as,

$$t_{spec} = 50.3 \frac{B^{1/2}}{B^2 + B_{CMB}^2} ((1+z)\nu_b)^{-1/2} Myrs, \quad (1.6)$$

where B is the magnetic field strength, B_{CMB} is the magnetic field strength of the CMB, z is the redshift of the source and ν_b is the break frequency. The break frequency is the frequency at which radiative losses begin to play a significant role on the shape of the spectrum. In the case where the magnetic field strength is not known, models describing the spectrum can be used to estimate the magnetic field strength and age of the source.

The two most common physical models used are the Kardashev-Pacholczyk (KP) model(1970)[17, 18] and the Jaffe-Perola (JP) model(1973)[19]. The KP model assumes that the electrons keep the same pitch angle (the angle between an electron velocity vector and the magnetic field) during their lifetime. The energy loss term depends on the model used to describe the radio

spectrum. For the KP model the energy loss term is given by

$$b = c_2 B^2 \left[\sin^2 \theta + \left(\frac{B_{IC}}{B} \right) \right], \quad (1.7)$$

where B is the magnetic field strength within the region of the radiating electrons, θ is the pitch angle, $B_{IC} = \sqrt{\frac{2}{3}} B_{CMB}$ and $B_{CMB} = 3.25 (1+z)^2$. The constant c_2 is a constant defined by Pacholczyk (1972); $c_2 = 2.37 \times 10^{-3}$ (CGS units). The spectrum in the KP model exhibits a spectral break at some frequency, which means after a certain energy, the spectrum continues as a power law but with a different spectral index. The JP model assumes that the electrons change their pitch angle on shorter time scales compared to their lifetimes such that the expression for the energy loss term is given by

$$\begin{aligned} b &= c_2 B^2 \left[\langle \sin^2 \theta \rangle + \left(\frac{B_{IC}}{B} \right) \right] \\ &= c_2 B^2 \left[\frac{2}{3} + \left(\frac{B_{IC}}{B} \right) \right], \end{aligned} \quad (1.8)$$

where $\langle \sin^2 \theta \rangle$ represents the time-averaged pitch angle. The spectrum for the JP model produces an exponential cut-off that moves at lower energies when time increases.

The solution to Equation 1.3 is given by

$$N(E, \theta, t) = \begin{cases} E^{-\gamma} (1 - bEt)^{\gamma-2} & \text{if } E < \frac{1}{bt} \\ 0 & \text{if } E > \frac{1}{bt}. \end{cases} \quad (1.9)$$

This expression is computed for the different models based on the treatment of b . The energy E is the energy per particle and is given by $E = c_1 \sqrt{\frac{\nu}{x}}$ with $c_1 = \frac{4 \times 10^{-10}}{\sqrt{B}}$ (CGS units), ν is the frequency at which the emission is observed and $x = \frac{\nu}{\nu_b}$, where ν_b is the frequency at which the radiative losses begin to play a significant role on the observed spectrum called the break frequency. For the KP model, the flux density is computed as

$$S(\nu)_{KP} = S_0 \sqrt{\nu} \int_0^\pi \sin^2 \theta \int F(x) x^{-1.5} N(x, \theta) d\theta dx, \quad (1.10)$$

and the flux for the JP model can be computed as

$$S(\nu)_{JP} = S_0 \sqrt{\nu} \int F(x) x^{-1.5} N(x) dx, \quad (1.11)$$

where S_0 is a flux density scaling factor and $F(x) = x \int_x^\infty K_{5/3}(z) dz$ with $K_{5/3}$ being the modified Bessel function. The KP and JP models are the simplest and most frequently used models.

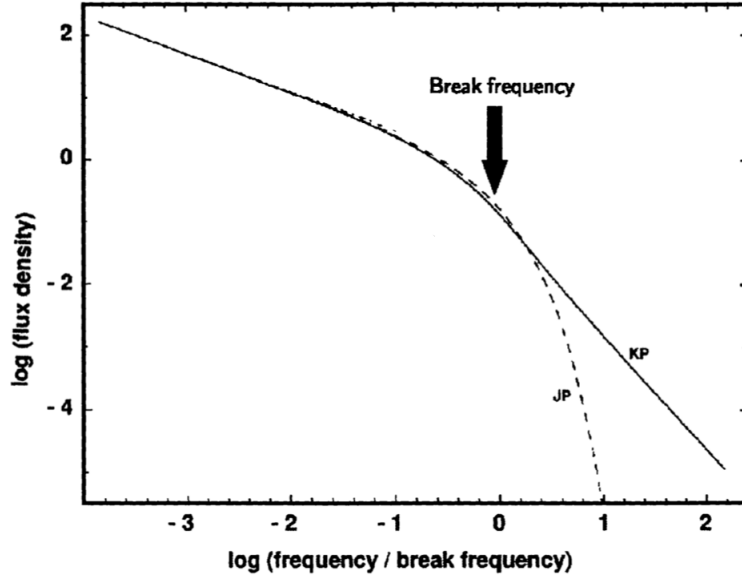


FIGURE 1.2: The predicted radio spectral shapes due to synchrotron radiation. The solid line represents the spectral shape in the case of the KP model and the dashed line represents the spectral shape in the case of the JP model. The position of the break frequency is also shown on the plot [20].

In both cases, the model assumes a constant magnetic field distribution and a single constant injection of relativistic electrons at some initial time with no subsequent injections.

In addition to the KP and JP models, there are more complex models. The Tribble model (1993) [21] describes a scenario in which the magnetic field fluctuates, not only in direction but also in intensity; this makes it physically more realistic given the turbulent environment. In the case of the Tribble method, the final spectrum is a broken power law with a high-frequency cut-off. The continuous injection (CI) model (1994) [22] no longer applies the assumption that there is only one initial injection of electrons. In this model, the $Q(E)$ term in Equation 1.3 does not equal zero. In the CI model, there is a spectral break in the radio spectrum, with the break frequency moving towards lower frequencies as time progresses. The flickering model (2020) [23] explores the possibility of a continuous injection phase which is later terminated,

i.e., a combination of the CI model and the JP model, with the CI model taking place first. Given the two phases, the spectral shape seen is a broken power law with an exponential decrease at high frequencies.

1.3 Hydra A and Its environment

This section serves as a literature review in which we will discuss the structure of Hydra A with a focus on radio observations of Hydra A, followed by a discussion of the immediate surrounding environment of Hydra A which will be focused on the X-ray observations.

1.3.1 Radio Observations

The structure of Hydra A has been studied both at low frequencies (<2 GHz) and high frequencies (up to 90 GHz). Low-frequency observations enable the study of large-scale, diffuse radio structures.

Large scale radio structure (low-frequency observations)

In 1983 [24], Hydra A was observed with the Fleurs Synthesis Telescope (FST) at 1415 MHz. These results- shown in Figure 1.3- reveal the large-scale structure of Hydra A. The authors find that Hydra A has a lobe structure consisting of two lobes, with the southern lobe being at least twice as bright as the northern lobe. The authors describe the northern lobe as the head and the southern lobe as the tail and classify the galaxy as a head-tail galaxy. The paper finds that Hydra A is situated at a redshift $z=0.053$ and consists of a double optical nucleus suggesting that a merger event could have occurred at some point in the past.

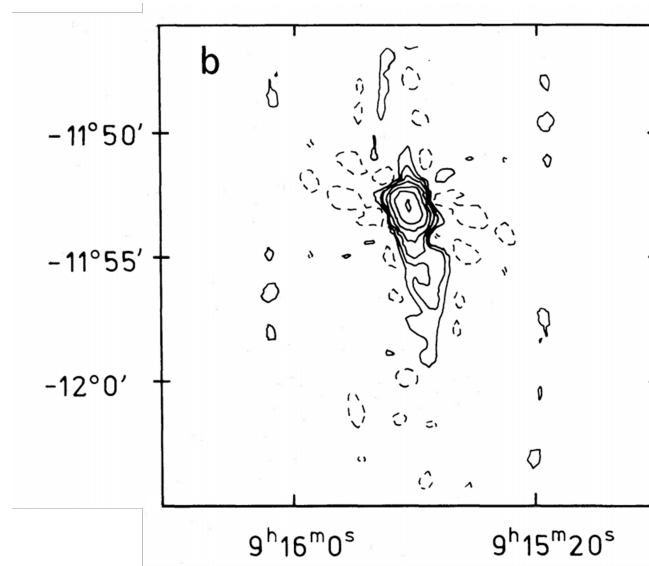


FIGURE 1.3: Map of Hydra A at 1415 MHz using the Fleurs Synthesis Telescope[24].

In 1995 [26], observations were made with the Very Large Array (VLA) telescope at 1465 MHz; these results are shown in Figure 1.4. The authors find that there is indeed emission in both the northern and southern directions, and the emission is quite extended. The authors find that the entire structure extends $\sim$ eight arcmins in the northern and southern directions. However, the angular resolution of the image is low (~ 50 arcsecs), so the finer details are obscured and the structure is not well resolved.

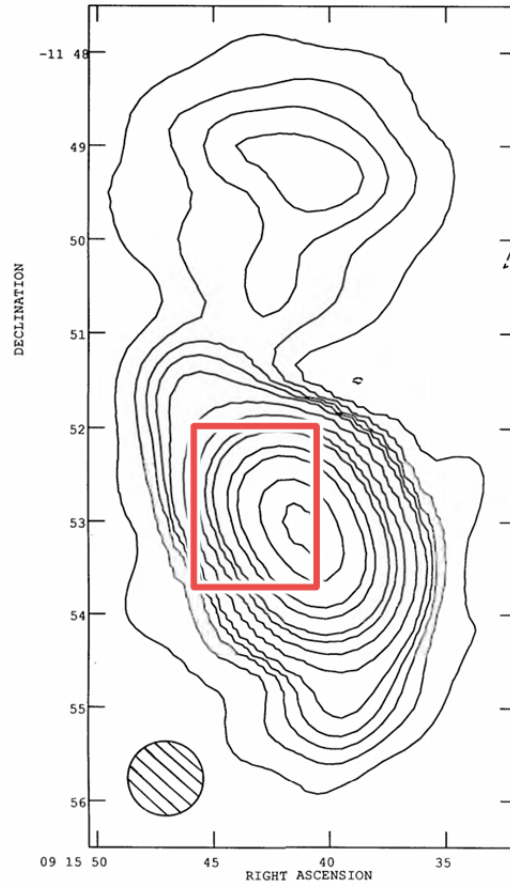


FIGURE 1.4: Map of Hydra A at 1465 MHz using VLA with a resolution of $50''$. The contours are at —0.0085 (dashed), 0.0085, 0.025, 0.042, 0.060, 0.085, 0.17, 0.34, 0.60, 0.85, 1.7, 2.5, 4.9, and 7.8 mJy/arcsec^2 [26]. The red box indicates the position of the 1374 MHz emission presented in [25] in Figure 1.5.

In 1994 observations were carried out at similar frequencies using VLA [25]. The continuum image of Hydra A at 1347 MHz is shown in Figure 1.5. From this image, one can much better see the bilobal structure alluded to in [24] and [26]. The increased resolution of the image is due to the use of the VLA instrument in a different configuration.

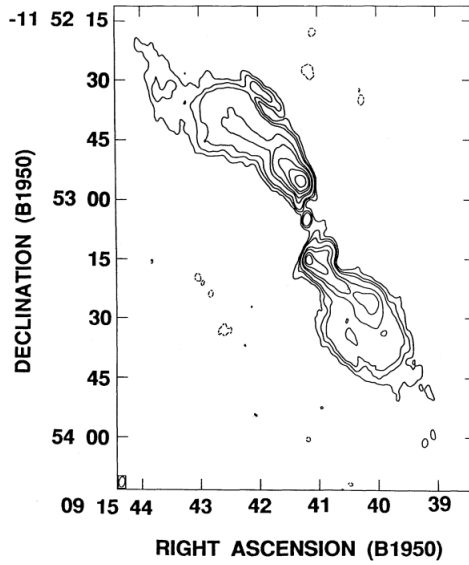
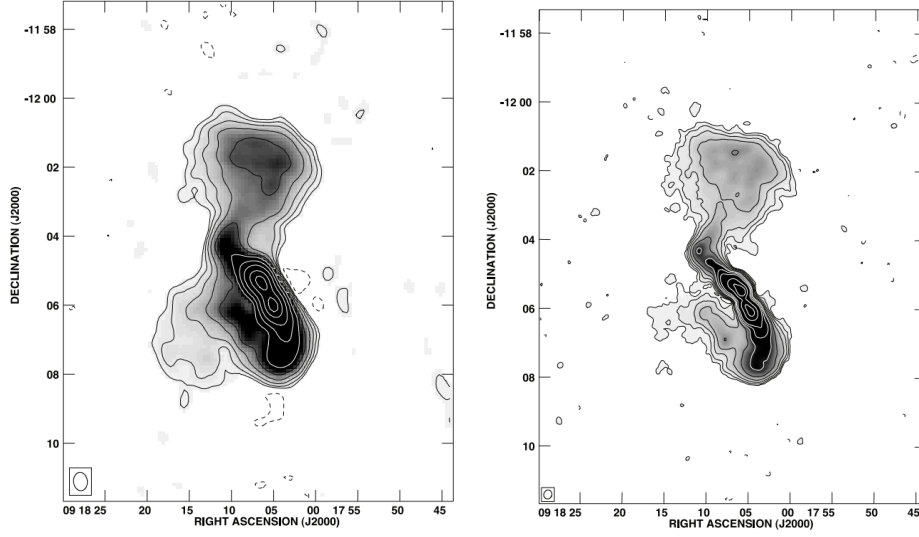


FIGURE 1.5: Map of Hydra A at 1347 MHz using VLA. The synthesised beam is 2.7×1.5 arcsec² at a position of -9.19° . The contours are at -15, 15, 33, 60, 18, 300, 600, 900 and 1500 mJy/beam [25].

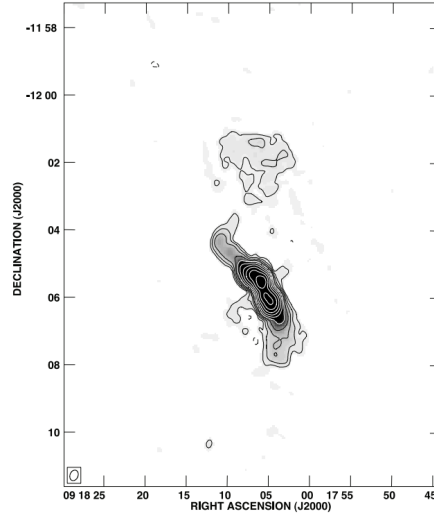
The most detailed study of the extended lobe structure of Hydra A, to date, was carried out in 2004 [27]. Observations were made using the VLA telescope at 74 MHz, 330 MHz and 1415 MHz and their results are presented in Figure 1.6. These maps have an increased angular resolution (~ 20 arcsecs) from the maps produced in [26]. The observations do not resolve the core region. The authors find a pair of northern and southern inner jets that extend out into a pair of inner radio lobes. The inner lobes are then seen to bend and expand into a pair of diffuse outer lobes. However, at 1415 MHz, the bridge of emission connecting to the northern outer lobe is not seen as well as emission in the southern lobe. The authors find that the structure extends to approximately 8 arcmin, equivalent to a projected distance of 530 kpc. The study identifies a steepening of the spectral index with distance from the core in both the northern and southern lobes. The comparison of the spectral index between 74 MHz and 330 MHz and the spectral index between 330 MHz and 1415 MHz is shown in Figure 1.7. The steeper spectral indices between 330 MHz and 1415 MHz are attributed to the spectral aging of high-energy electrons. The authors find that the southern lobe has a steeper spectral slope and that given the radio structure and spectral analysis, it is likely that the northern lobe is bending toward the observer- with the jet exhibiting a 90° bend before expanding into the lobe- and the southern lobe is bending away from the observer- with the jet bending nearly

180° as it expands into the lobe. The steeper spectral slope in the southern lobe is attributed to an overlapping of the jet and lobe along the line of sight.



(A) Contour map of Hydra A at 74 MHz made using VLA. The size of the clean beam at 6.4° is $31.9 \times 23.7 \text{ arcsec}^2$. The contours are at multiples of the 3σ noise level, $0.1993 \times (-1, 1, 2, 4, 8, 16, \dots)$ Jy/beam.

(B) Contour map of Hydra A at 330 MHz made using VLA. The size of the clean beam at -21.5° is $15.7 \times 13.9 \text{ arcsec}^2$. The contours are at multiples of the 3σ noise level, $0.01605 \times (-1, 1, 2, 4, 8, 16, \dots)$ Jy/beam.



(C) Contour map of Hydra A at 1415 MHz made using VLA. The size of the clean beam at -21.4° is $19.3 \times 14.3 \text{ arcsec}^2$. The contours are at multiples of the 5σ noise level, $0.0126 \times (-1, 1, 2, 4, 8, 16, \dots)$ Jy/beam.

FIGURE 1.6: Radio maps of Hydra A between 74 MHz and 1415 MHz produced using VLA [27].

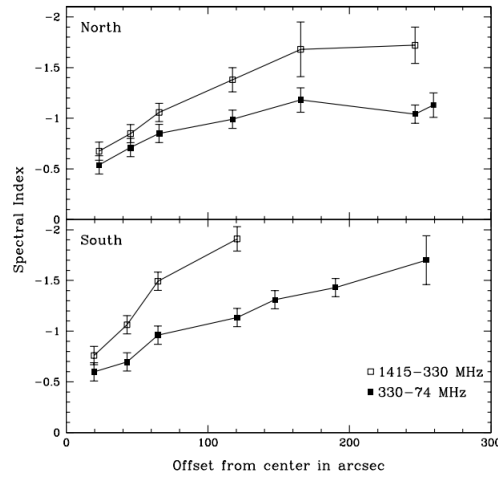


FIGURE 1.7: Comparison of the spectral index between 74 MHz and 330 MHz and the spectral index between 330 MHz and 1415 MHz with distance from the core [27]. The figure shows the spectral steepening attributed to spectral aging.

Inner radio structure of Hydra A (High-frequency radio observations)

At high frequencies, the extended radio structures are no longer visible due to an increase in resolution. These frequencies enable the study of finer details and the inner structure of radio galaxies.

Between 1987 and 1990, Hydra A was observed with the VLA telescope [26] at frequencies ranging between 4 GHz and 15 GHz. The intensity map at 4635 MHz is presented in Figure 1.8 and has an angular resolution of 0.6 arcsecs. In both cases, the authors identify a bright central region that extends out symmetrically in the northeast and southwest directions for about 69 kpc. The jets expand into a pair of extended lobes, referred to as the inner lobes. Due to edge darkening, the authors classify Hydra A as a type I Fanaroff-Riley (FRI) [28] radio galaxy. FRI-type galaxies are characterised by a bright center with the brightness decreasing as you extend further out. The authors produce a spectral index map of the inner region and find a steepening of the spectral index, reaching indices of ~ 2 at the furthest parts of the inner lobes. The spectral luminosity is estimated to be $P_{178} = 3 \times 10^{26}$ W, where P_{178} refers to the power at 178 MHz as computed by Fanaroff and Riley [28]. This over-luminosity is unusual for FRI-type galaxies. The authors find the minimum energy magnetic field (estimated by minimising the total energy content) for the northern region to be $\sim 6.5 \mu\text{G}$ and an age estimate

to be ~ 47 Myrs. The authors find a clear "wobble" of the jets and attribute this precession of the jets to two black holes orbiting one another- they estimate this precession period to be $\sim 3 \times 10^5$ Myrs and believe this precession to be responsible for the symmetry of the galaxy.

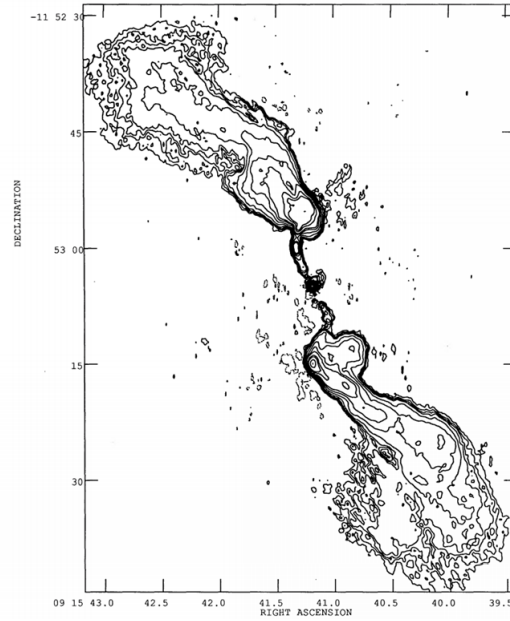
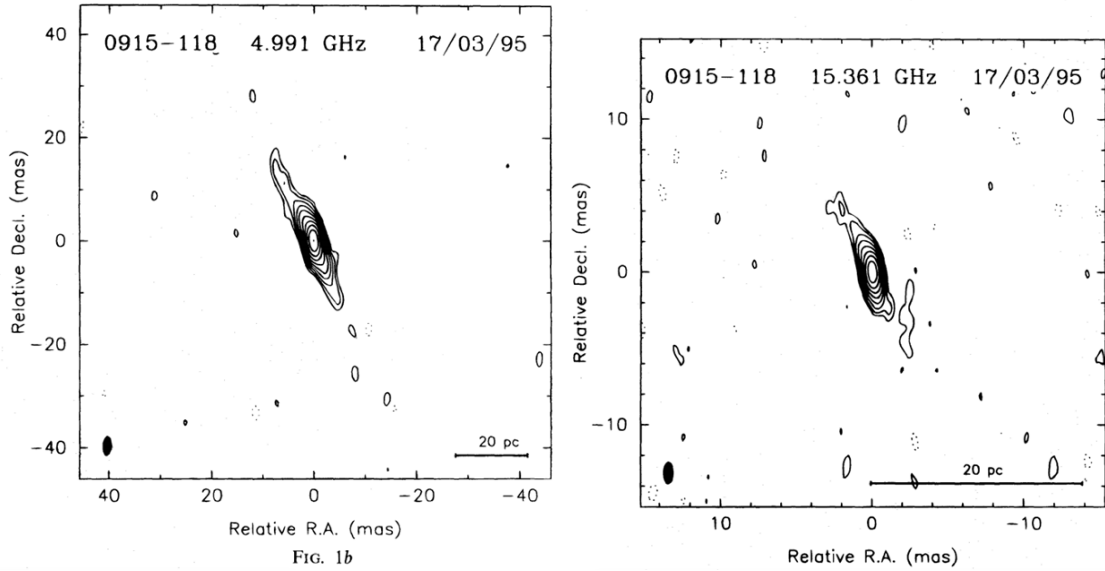


FIGURE 1.8: VLA intensity map of Hydra A at 4635 MHz at a 0.6 arcsecond resolution. The contour levels are at -3.7, -0.5, 2.7, 3.7, 5.1, 10, 21, 37, 51, 103, 154, 311 and 466 mJy/arcsec² [26].

Using the same observations published in [26], the authors, in a later paper [29], derive a model to describe the high rotation measure values seen in Hydra A. The rotation measure is the measure of the amount of rotation of the polarisation of the radio waves as they travel through an intervening magnetic field. The rotation measure is useful in understanding the manner in which the magnetic field is ordered. For Hydra A the authors find that the model consists of a large-scale, disc-shaped, ordered magnetic field. Using their best fit model parameters, the authors estimate a uniform magnetic field strength of $5.7\mu\text{G}$, a random magnetic field component of $30\mu\text{G}$ and the inclination of the source to be 48° . This model was successful in describing the rotation measure distribution, but this disc-like structure of the magnetic field is not seen in any other observations.

A study of the nuclear region of Hydra A using VLA observations at 5 GHz and 15 GHz [30] reveals a symmetric inner jet structure. These results are shown in Figure 1.9. The symmetric

structure of the jets, along with the inverted steep spectrum of the emission in the core, indicates a dependency of the jets on their immediate surrounding environment and the presence of a dense core.



(A) VLA Contour map of Hydra A at 5 GHz. Contours are drawn at -0.3, 0.3, 0.6, 1.2, 2.4, 4.8, 9.6, 19.2, 38, 77 and 154 mJy/beam. (B) VLA Contour map of Hydra A at 15 GHz. Contours are drawn at -0.6, 0.6, 1.2, 2.4, 4.8, 9.6, 19.2, 38 and 77 mJy/beam.

FIGURE 1.9: Radio maps of the nuclear region of Hydra A at 5 GHz and 15 GHz [30].

The results of the above study are corroborated by a later study of the core region [31] in which the authors use observations of Hydra A made at 90 GHz using the MUSTANG 3 mm bolometer camera. The authors find the spectral index along the jets to steepen significantly, suggesting that the particle acceleration either halts or slows down dramatically not far out in the jet.

Summary of the radio observations

The radio observations at high frequencies reveal the presence of a bright central core, two jets and two inner radio lobes that are connected to the jets. Observations at lower frequencies reveal an extended diffuse structure comprising of two kpc scale lobes, one that extends in the northern direction and the other extending in the southern direction.

1.3.2 X-ray Observations

Probing the X-ray emission in the vicinity of radio galaxies can aid in understanding various properties of the ICM such as its temperature and density. These measurements can explain processes including heating and cooling mechanisms, gas outflows and feedback mechanisms between galaxies and black holes (see Chapter 1.1). X-ray observations of the gas surrounding radio galaxies enable the study of large scale structures such as shock fronts and cavities that are often around radio galaxies. Given that this thesis is a radio study, this section will briefly overview X-ray observations relevant to this study.

The observations presented in this section were all accumulated using the Chandra X-ray Observatory or obtained from the Chandra archive.

Observations of the central region of Hydra A were carried out in 1999 [32] for a total integration time of 40 ks. The observations reveal two surface brightness depressions in the X-ray emitting gas approximately 25-35 kpc in diameter seen ~ 25 kpc to the north and south of the cluster center. These cavities appear to surround the inner radio lobes (lobes seen at 6 cm from [26]) of Hydra A and exhibit a remarkably similar shape, as seen in Figure 1.10. Because there is no evidence suggesting that the gas in which the radio source is embedded is hotter than the surrounding gas of the cluster, the authors suggest that the best explanation for their observations is the surrounding gas being displaced by the radio lobes. The authors find the minimum mechanical power required for the southern jet to maintain the cavity is $\sim 6 \times 10^{43}$ erg·s⁻¹.

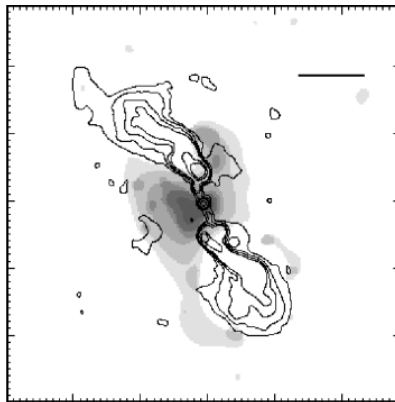
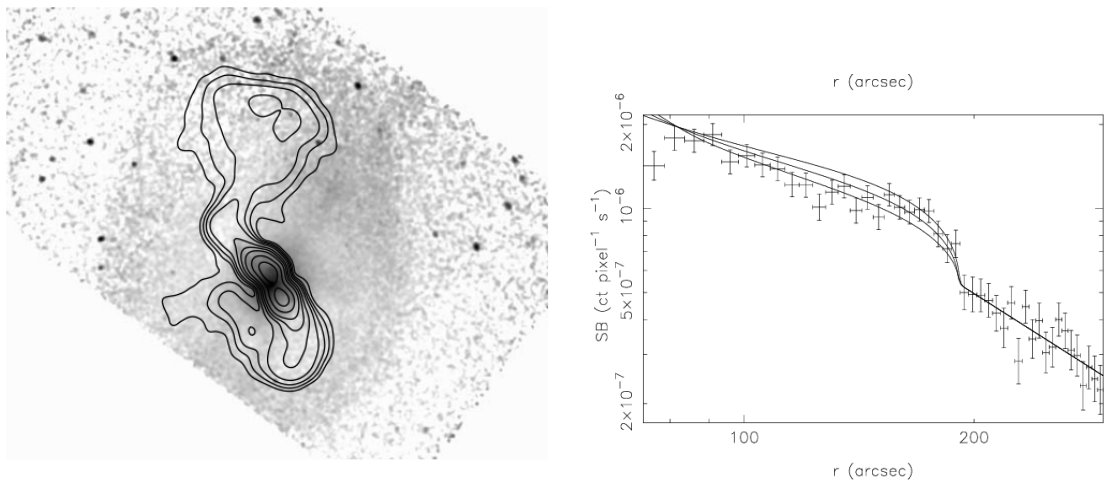


FIGURE 1.10: X-ray image of the central region of Hydra A centered on the nuclear X-ray point source (shown inset), with the 6cm radio contours overlaid [32].

An X-ray study of a broader area of Hydra A was conducted in 2004 [33]- this observation had a total integration time of 98.2 ks- more than two times that of the study conducted in 1999. The authors identify the inner cavities seen in [32] as well as an additional two outer cavities- one in the north-eastern direction with a radius of 40 kpc and one in the south-western direction associated with the 330 MHz south-western radio lobe. Figure 1.11 shows the 330 MHz radio contours overlaid on the X-ray image. An edge in the X-ray surface brightness is seen around the AGN (see Figure 1.11b) and it is interpreted as a shock front. The abrupt change in the slope of the surface brightness profile indicates a sudden decrease in the gas density at around 211 kpc from the cluster center. This is interpreted as a shock front since a shock front causes gas to suddenly compress and heat producing an abrupt increase in X-ray emitting gas just behind the shock and a decrease in X-ray emission just ahead of the shock front. The northern radio lobe is seen to lie close inside the northern region of the shock front and exhibits a similar shape; the authors suggest that this behavior implies that the cavities are shock fronts that are driven by the original outburst that resulted in the formation of the radio lobes. The authors use a spherically symmetric hydrodynamic model of a point source outburst responsible for driving the shock front to determine the age of the system. The authors find that although some assumptions do not hold for their model, the surface brightness profile is well reproduced by their model and estimate the age of the outburst to be around 140 Myrs.



(A) 330 MHz radio contours overlaid on the X-ray observation. The contours located at the center indicate the position of the inner cavities.

(B) 0.6– 7.5 keV surface brightness profile of the shock front in the northeast, centered at 2.9 arcmin north of the AGN

FIGURE 1.11: Figure showing (A) 330 MHz radio contours overlaid on the X-ray observation. The contours located at the center indicate the position of the inner cavities and (B) 0.6– 7.5 keV surface brightness profile of the shock front in the northeast, centered at 2.9 arcmin north of the AGN [32].

Using the Chandra X-ray observatory archive, the authors of [15] compute the age of the Hydra A system based on three age estimates for one the cavities. The projected distance from the cavity center to the radio core is 28.5 kpc. The first method assumes that the cavity expands at the speed of sound in the cluster. The time then required to reach the projected distance from the core is given by $t_{cs} = 30$ Myrs. The second estimate is given by the time it would take for the cavity to rise buoyantly into the cluster atmosphere travelling at the local free-fall velocity $t_{buoy} = 51$ Myrs. The final method computes the age based on the time required to refill the volume displaced by the cavity as it expands $t_r = 87$ Myrs.

In 2007, observations of the hot plasma in the Hydra A cluster were carried out four times for a total exposure time of 240 ks [7]. The authors identify at least three pairs of X-ray cavities that exhibit a "Swiss-cheese"-like morphology. The inner pair of cavities have diameters of 40-50 kpc, while the second set of cavities is an asymmetrical pair with diameters of 50 kpc and 80 kpc projected 100 kpc and 60 kpc from the inner pair. The final pair is a set of large cavities that are seen to extend 225 kpc to the north and 100 kpc to the south and have diameters of between 100 kpc and 200 kpc. Figure 1.12 shows the position of all three sets of cavities. The identification of three pairs of cavities (an increase from previous observations) is due to the increased integration time of the observation providing deeper data. The presence of three sets of cavities indicates that the central AGN has experienced three outbursts at consecutive ages. The following age estimates are the buoyancy age estimates for the different cavities. The age of the inner cavities is found to be ~ 50 Myr (consistent with the results produced in [15]) and the age of the second pair is found to be between 100 and 200 Myr. The outer cavities are thought to be associated with an earlier, more energetic stage of activity, with an age of ~ 200 -500 Myr and an estimated AGN power output of $6 - 7 \times 10^{44}$ ergs $\cdot$ s $^{-1}$.

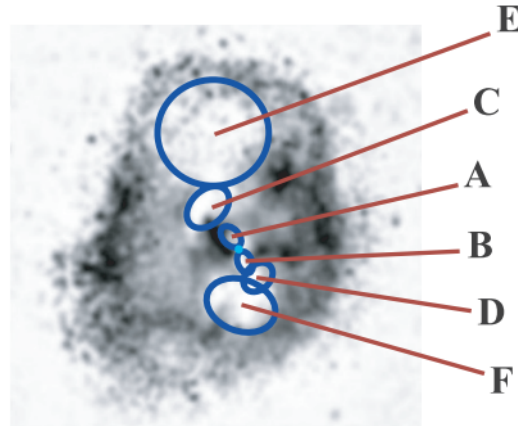


FIGURE 1.12: X-ray surface brightness profile of Hydra A indicating the three pairs of cavities. The blue dot at the center shows the position of the central source [7].

Summary of X-ray observations

The X-ray observations reveal the presence of surface brightness depressions within the X-ray emitting gas surrounding the Hydra A cluster. In total, three pairs of cavities are identified. The X-ray observations also reveal the presence of a shock front near the location of the northern lobe. The age estimate of the system based on modeling of the shock front found at around 200 kpc from the cluster center is given by ~ 140 Myr, whereas the buoyancy age estimate for the outer most cavity extending around 225 kpc to the north is given by ~ 500 Myr. The discrepancy between these age estimates is not discussed in the literature.

1.3.3 Summary of the structure of Hydra A

Hydra A is a type I Fanaroff-Riley galaxy located at $z=0.05$. It consists of a double optical nucleus and a dense core. The radio structure includes a bright central region, a pair of inner jets, a pair of bright inner lobes and a pair of hundred kpc scale diffuse outer lobes. X-ray cavities have been identified in the X-ray emitting gas in which Hydra A is embedded. The cavities appear to surround the inner and outer lobes, suggesting that the radio-emitting plasma inside the lobes is responsible for pushing the gas outwards. Three pairs of these cavities have been identified, providing evidence for three generations of outbursts. Figure 1.13 shows a summary of the radio and X-ray structure of Hydra A [7].

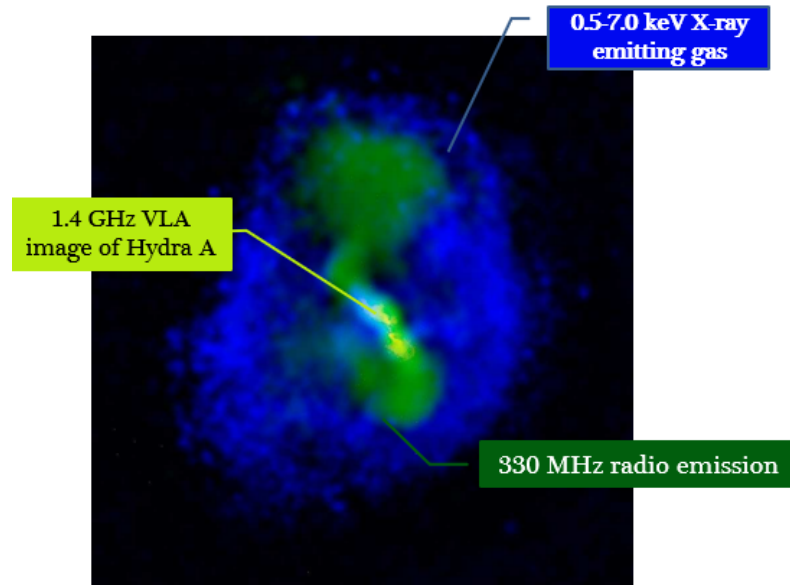


FIGURE 1.13: Summary of the radio and X-ray emission of Hydra A [7]. The dark green emission indicates the low frequency radio emission presented in [27].

1.4 Radio Interferometry

Radio interferometry studies sources at radio frequencies using multiple radio dishes synthesised as one large telescope. This section will serve as a brief overview of the important concepts in radio interferometry; however, the topic is well covered in literature- some notable textbooks include [34] and [1]. Radio interferometry is often seen as the “hunt” for angular resolution. The angular resolution of an instrument is its ability to resolve individual sources and is given by

$$\Delta\theta = 1.22 \times \frac{\lambda}{D} \quad (1.12)$$

where λ is the wavelength of the observed radiation and D is the diameter of the dish. It is clear from this equation that the larger the aperture (dish), the tighter the angular resolution. One way to improve the angular resolution would be to build a bigger telescope (increase the diameter); however, there are physical limitations on the size of a single dish. Radio astronomers use interferometry to synthesise one large aperture to overcome these limitations, thus improving the angular resolution. Interferometry works using the simple concept of interference. A schematic diagram of a simple two-element interferometer is shown in Figure 1.14.

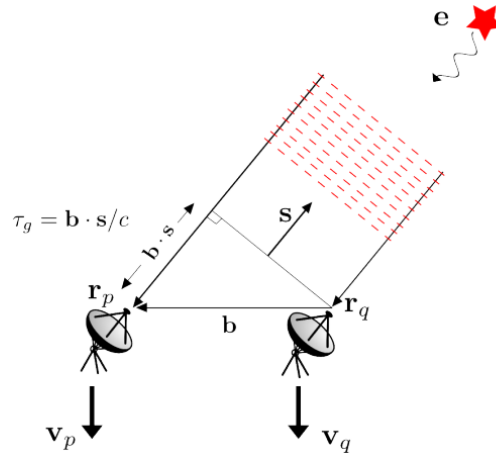


FIGURE 1.14: Schematic of a simple two-element interferometer.

When a plane wave travels from a far enough source, different waves travel along different path lengths, resulting in geometric delays (τ_g) and creating an interference pattern. Radio interferometers directly measure this interference pattern. Figure 1.15 shows the angular

pattern of a typical primary beam. The maximum sensitivity of the antenna is located at the peak of the main lobe- points that are not located on this peak will have a flux attenuated by the beam pattern. The angular resolution of a single dish is a measure of the size of the main lobe in the beam pattern. To correct the effects of the primary beam, the beam pattern for the telescope must be divided out from the final image. The details of this process are discussed in Section 2.2.

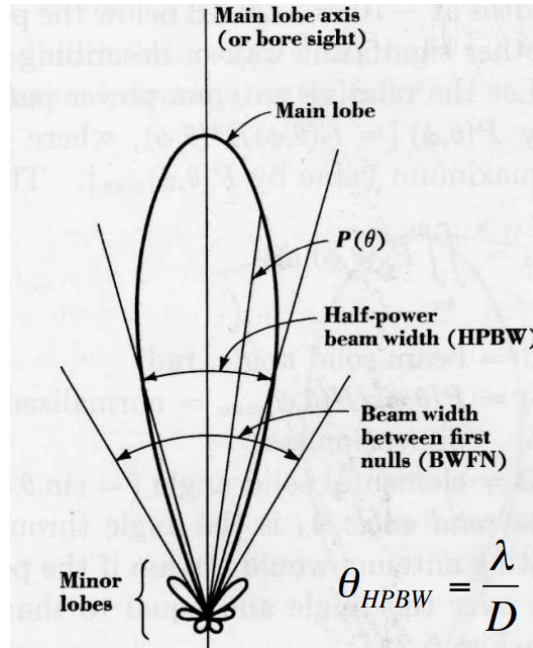


FIGURE 1.15: Angular pattern of a typical primary beam [35].

As mentioned above, the interferometer does not measure the intensity distribution of the sky; instead, it measures coherence from the sky in the visibility space. The visibility space is the 2D inverse Fourier transform of the emission of the sky plane. Figure 1.16 shows the geometric relation between the sky plane and the visibility space. In the sky plane, the intensity distribution is labelled $I(l, m)$, where l and m are the east-west and north-south angles in the sky measured in radians. The two-element interferometer is located on the ground and described by the (u, v, w) coordinate plane; u and v are the east-west and north-south spatial frequencies measured in radians and w is the delay distance in wavelengths between the two antennas. Mathematically, the 3D visibility is given by

$$V(u, v, w) = \iint I(l, m) e^{-2i\pi(ul+vm+w\sqrt{1-l^2-m^2}-1)} \frac{du dv dw}{\sqrt{1-l^2-m^2}}. \quad (1.13)$$

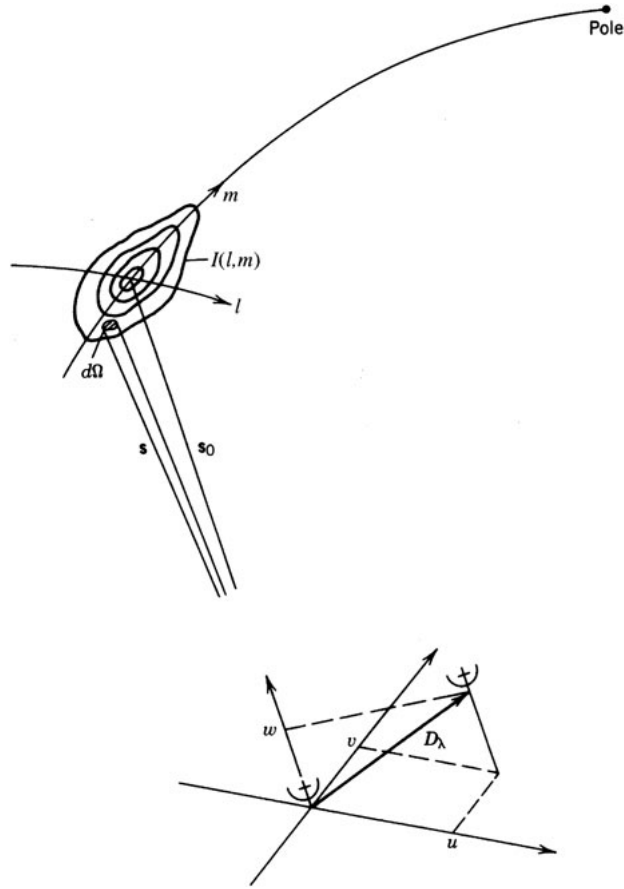


FIGURE 1.16: Geometric relation between the sky plane and the visibility space [34].

This can be reduced to its 2D form if the phase factor is small enough, that is,

$$w\sqrt{1-l^2-m^2} \ll 1.$$

This is possible in the case of narrow field imaging where $|l|$ and $|m|$ are sufficiently small, such that

$$w\sqrt{1-l^2-m^2} \approx 0,$$

or if all baselines lie in a common plane, i.e., $w=0$. In wide field instruments, imaging algorithms such as w-projection and w-stacking [36] can be used to correct for the w component of the baseline. Once this is accounted for the 2D visibility can be written as

$$V(u, v, w) = \iint I(l, m) e^{-2i\pi(ul+vm)} dl dm. \quad (1.14)$$

The 2D visibility is the 2D Fourier transform of the Sky brightness distribution and vice versa. i.e.,

$$V(u, v) \Longleftrightarrow I(l, m)$$

For an in-depth discussion of the mathematics of the Fourier transforms used in radio astronomy, refer to Appendix A2 in [34]. Each visibility $V(u, v)$ is a complex quantity that can be represented as (real, imaginary) or (amplitude, phase). The amplitude expresses the amount of a certain spatial frequency and the phase expresses the position of the spatial frequency. Each baseline, i.e., two-element antenna pair, gives one visibility measurement per correlator integration time, per channel and per correlation product. It is important to sample enough visibilities from as many baselines as possible to synthesise one large aperture. The MeerKAT radio telescope is an interferometer made up of 64 antennas; Figure 1.17 shows the antenna configuration of MeerKAT.

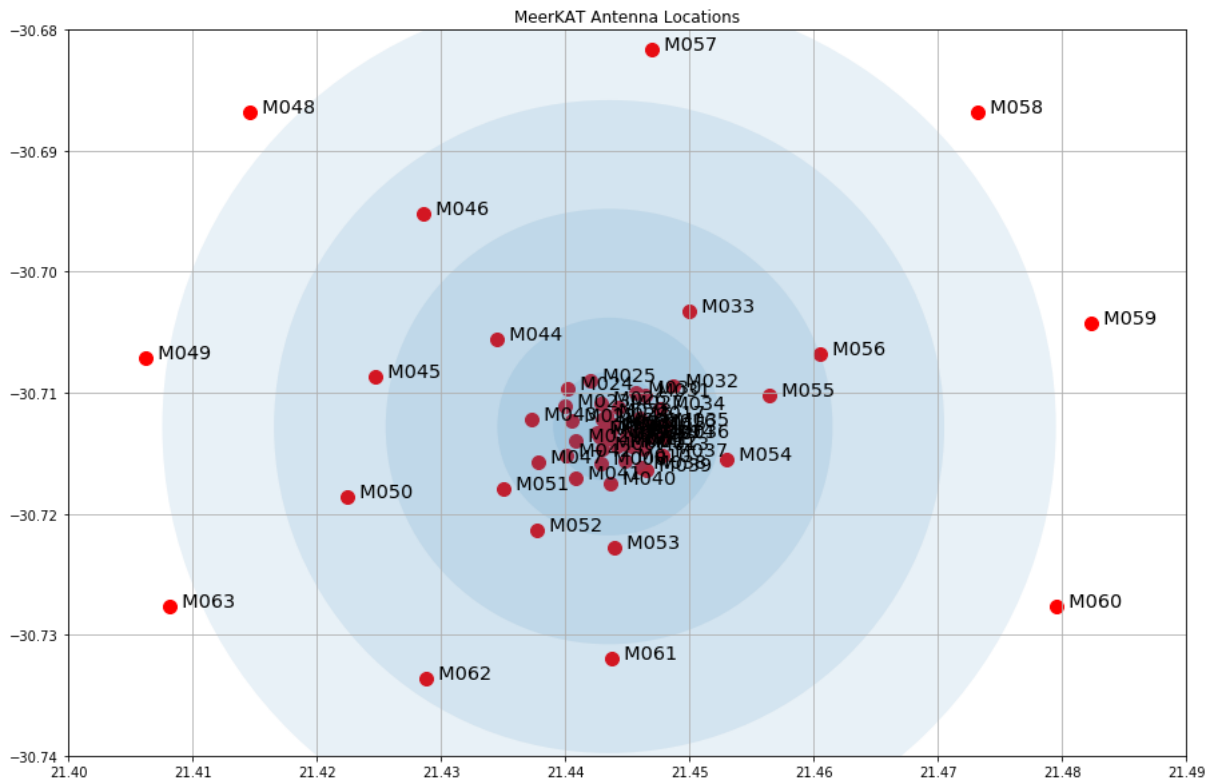


FIGURE 1.17: MeerKAT antenna configuration obtained from the [MeerKAT specifications](#) web page.

70% of the antennas are based in the center with a maximum baseline of one km, and the remaining 30% are placed further out with a maximum baseline of 8 km. The outer boundary

telescopes, i.e., the longer baselines, are responsible for observing small scale structures and finer details, whereas the internal antennas aid in observing diffuse emission. The antennas between these boundaries try to compensate for information lost due to insufficient coverage. Theoretically, with a filled-up aperture plane, the u-v sampling could be 100% precise, and the exact sky brightness distribution could be reconstructed; however, there will always be missing space in the u-v coverage. This unsampled space gives a response pattern with side lobes. This is the interferometer's response to a point-like source, known as the point spread function (PSF) and often referred to as the “dirty beam”. The PSF is convolved with the sky brightness distribution creating the “dirty image”. The PSF must be deconvolved from the dirty image in a process known as deconvolution. The most widely used algorithm for deconvolution is the “CLEAN” algorithm by Hogbom [37]. A detailed outline of the deconvolution process can be found in Section 2.2.

There can be distortions through the interstellar medium, the atmosphere, and through instrumental effects that can corrupt the signal, resulting in a difference between the measured and actual visibilities. The difference is described in the following linear equation for a two-element interferometer with antennas p and q:

$$V_{pq} = J_{pq}(t)X_{pq}(t) + \epsilon_n \quad (1.15)$$

where V_{pq} are the measured visibilities, J_{pq} is a Jones matrix, $X_{pq}(t)$ are the true visibilities and ϵ_n is an additive noise factor. The Jones matrix summarises all the signal propagation effects. The full radio interferometry measurement equation (RIME) is given by

$$V_{pq} = M_{pq}K_{pq}B_{pq}G_{pq}E_{pq}P_{pq}F_{pq} \times X_{pq} \quad (1.16)$$

In practice, only three fundamental matrices are generally applied to correct the visibilities. K_{pq} the delay calibration, corrects for geometric and fractional delay errors, the bandpass response B_{pq} , describes frequency-dependent electronic gains that must be corrected for and the complex gain correction G_{pq} , corrects for amplitude and phase effects introduced by antenna electronics or the atmosphere.

To correct for all these effects, cross-calibration is implemented. Cross-calibration is done by

inferring the gain terms of a known field and applying them to the science source. Generally, all suitable calibrators are point-like sources or sources with well-known models. The first step of cross-calibration is delay and bandpass calibration. Slow-varying calibrators are used for delay and bandpass calibration since they are frequency-dependent. After delay and bandpass calibration, all remaining distortions will be antenna-based and often time-dependent. Antenna gain calibration tracks variable properties caused by varying conditions in the atmosphere and instrument. Gain calibrators are chosen near the target to better represent the atmosphere toward the target. Because gain calibration is time-dependent, it is carried out frequently. Finally, the flux density values must be corrected after calibrating for both frequency distortions and time variations. For flux calibration, the calibrator must have a known flux density. The visibilities of the target can then be re-scaled since the flux for the calibrator is proportional to the source flux density. Once calibration is completed, the solutions are applied to the calibrators to see how well calibration was carried out.

Before calibration is carried out, flagging is performed to identify bad data; these sources of interference are usually very bright compared to astronomical sources of interest and their removal is essential. Flagging is an important step carried out before and after cross-calibration. Cross-calibration has advantages, but residual amplitude and phase errors can still be present because the calibrators are observed at different times and located at different positions. To correct for any residual errors, the calibration solutions are derived from and applied to the target, a process called self-calibration. The solutions from the self-calibration are then applied iteratively to the image until there are no significant improvements in image quality.

1.5 Overview

In this study, we reduce observations of Hydra A obtained using the MeerKAT radio telescope in the L-band configuration. Using these observations between 1000 MHz and 1485 MHz, we describe the radio morphology of Hydra A. We conduct an in-depth spectral analysis of the outer lobes. Studying the spectral aging of the electron population, we set constraints on values for the magnetic field and age of the system and compare these estimates with previous work from the literature.

Chapter 2

Methodology

In this section, we present the details of the MeerKAT data reduction process, the method we followed in computing the flux densities, how we performed our spectral analysis and the process of modelling the spectrum of Hydra A. The data reduction process can often be lengthy and requires the diagnosis of errors along the way. In the data reduction section, we share images we arrived at before we got to the final image. It is important to note that these preliminary images are not unusual and essential in the reduction process.

2.1 Radio Data

2.1.1 MeerKAT Data

For this study, Hydra A was observed using the MeerKAT radio telescope. The MeerKAT radio telescope is an array of 64 offset Gregorian antennas. Each dish is 13.5 m in diameter, and the longest baseline is 8 km. The telescope has three operational frequency bands; the L-band, which covers a frequency range of 900 MHz to 1670 MHz, the UHF band, which has a frequency range between 580 MHz and 1015 MHz and the S-band which spans a frequency range of 1.75 GHz to 3.5 GHz. There are three channelisation modes; wide band coarse (4K), wide-band fine (32K), and narrow-band extended (32K). MeerKAT has been optimised for sensitive high-fidelity imaging of faint extended radio emission. MeerKAT is well suited for studying diffuse radio structures such as the faint emission from early AGN activity.

For this study, observations were made over a five hour period that was equally split in four

epochs. Each epoch observed the target for 30 minutes. We spread the observation out this way to maximise coverage in the u-v plane for optimised imaging. The observations were made on 31 May 2019. The observations were done in the L-band with a 4096 (4K) channelisation of 209 kHz per channel. Hydra A is centered at a right ascension (RA) of 139.52 degrees (deg) and a declination (Dec) of -12.10 deg. The field J1008+0740 (RA=152 deg, Dec=-12.10 deg) was used as the phase calibrator for the observation. A scan of J1008+0740 was performed every 15 minutes, and each scan was 80 seconds long. For the standard flux and bandpass calibrator, the field J1331+3030, also known as 3C 286, was used. The flux and bandpass calibrator was scanned for 10 minutes in total. These observations are based on a proposal from the first open call for MeerKAT proposals (Proposal ID: SCI-20190418-PA-01; PI: Prokhorov) for the University of the Witwatersrand.

2.1.2 VLA Data

The Very Large Array (VLA) radio telescope, located in New Mexico, is an array made up of 27 active antennas that are each 25 m in diameter. The array has four main configurations with maximum baselines ranging between 1 km and 36 km. We used the VLA radio maps published in [27] to complement our study, serving as "low-frequency" observations of the lobes of Hydra A. A detailed description of the VLA radio data can be found in Chapter 2 of [27]. The authors of [27] provided us with the images at 74 MHz and 330 MHz, allowing us to conduct an independent scientific analysis of their observations, and to perform a joint study of Hydra A emission by combining our results from MeerKAT observations and their results from VLA observations. Originally the primary beam for the image at 74 MHz was poorly modelled; however, the image was corrected by an improved more accurate primary beam shape that was modelled and derived from the VLSSr survey [39]. Therefore, the 74 MHz image used in this study differs slightly from the previously published map. The size of the beam in the form *major axis* $\times$ *minor axis* is given by $31.90 \times 23.00 \text{ arcsec}^2$ at 74 MHz and $15.74 \times 13.94 \text{ arcsec}^2$ at 330 MHz.

2.2 MeerKAT Data Reduction

Measurement Set (MS) files for the four observation epochs were stored on the Wits Center for Astrophysics (CfA) computer cluster. The Wits CfA computer cluster contains four nodes, each consisting of 24 cores with 192 GB of RAM and 100 TB of disk storage. We divided our data into sub-bands using the Common Astronomy Software Applications (CASA) [38] package. CASA is a data processing software that integrates Python interfaces to carry out various radio reduction tasks. These tasks include but are not limited to visualisation, simulation, imaging, analysis, calibration, and flagging of the data set. Because the entire data set is large, we performed the initial reduction on only the fourth epoch to find the optimal reduction parameters more efficiently. We used the `mstransform` task to select the spectral windows (spw) 980 MHz to 990 MHz. The `mstransform` package takes an input MS file and outputs a new MS file after performing the reduction specified by the user. CASA's tasks have multiple parameters that can be adjusted for specific functionality. In this case, the input MS file was the fourth epoch over the entire frequency band (900 MHz-1670 MHz), and the output Measurement Set was the data within a frequency range of 980 MHz to 990 MHz. .

Once we produced the MS file at a central frequency of 985 MHz, we performed further radio reduction using the Containerised Automated Radio Astronomy Calibration (CARACal)[40] pipeline. CARACal is an open-source radio reduction pipeline that operates using a number of Python/ Stimela scripts. Stimela is a radio interferometry scripting framework that allows the execution of multiple different data reduction packages in a Python environment. For example, CASA can be run directly using Stimela scripts within the framework of a data reduction pipeline. CARACal groups many Stimela scripts (called workers) and runs them sequentially to reduce radio data.

To run the CARACal pipeline, the user must present a configuration file that follows the YAML syntax rules. The configuration file contains all the workers (and their parameters) that the user wishes to run on the Measurement Set file. A list of all the CARACal workers and a brief description of their functionality can be found in [the CARACal documentation](https://caracal.readthedocs.io/).¹

For the first configuration file for the 985 MHz MS file, we implemented the following workers: the compulsory workers; general, getdata and obsconf, and the optional workers;

¹<https://caracal.readthedocs.io/>

transform, prep, flag, crosscal, inspect, mask, selfcal, ddcal and line. The workers that played the most important role in the data reduction were the flag, crosscal and selfcal workers.

Flagging

The flagging process works in three steps. The first step is to flag known interference using a flagging mask implemented by the telescope. The second step is to manually flag bad data by inspection. The final step is employing the flag worker which uses automatic flagging which implements flagging strategies such as aoflagger² [41] and tricolour³.

Cross-calibration

We implemented the crosscal worker that performs cross-calibration of the data set. The first step is to calibrate the primary calibrator. The order in which calibration was applied to the primary calibrator was KGBAKGB. This means that delays were first solved, then gains, then bandpass. Automatic flagging was then performed and the process was repeated. The delays were solved for amplitude only, while the gains and bandpass were solved for amplitude and phase. The next step is to perform calibration of the secondary calibrator. It is important to try select a field that is nearby the source as the secondary calibrator. Calibration of the secondary calibrator uses the gains solved when performing calibration of the primary calibrator. The order of calibration was KGAKF. First the delays were solved for, then the gains (based on the primary calibrator gains), followed by automatic flagging. Thereafter the delays are solved for and finally the gains (note that the F stands for gains that have a corrected flux scale).

Self-calibration and imaging

We used the selfcal worker to perform self-calibration. Self-calibration is the process whereby the source is calibrated using a model of the source itself. Standard calibration is applied to make an image of the target; this image is then used to calibrate the data and the solutions from this calibration are applied to the data to create a better model. Self-calibration is an

²<https://gitlab.com/aroffringa/aoflagger>

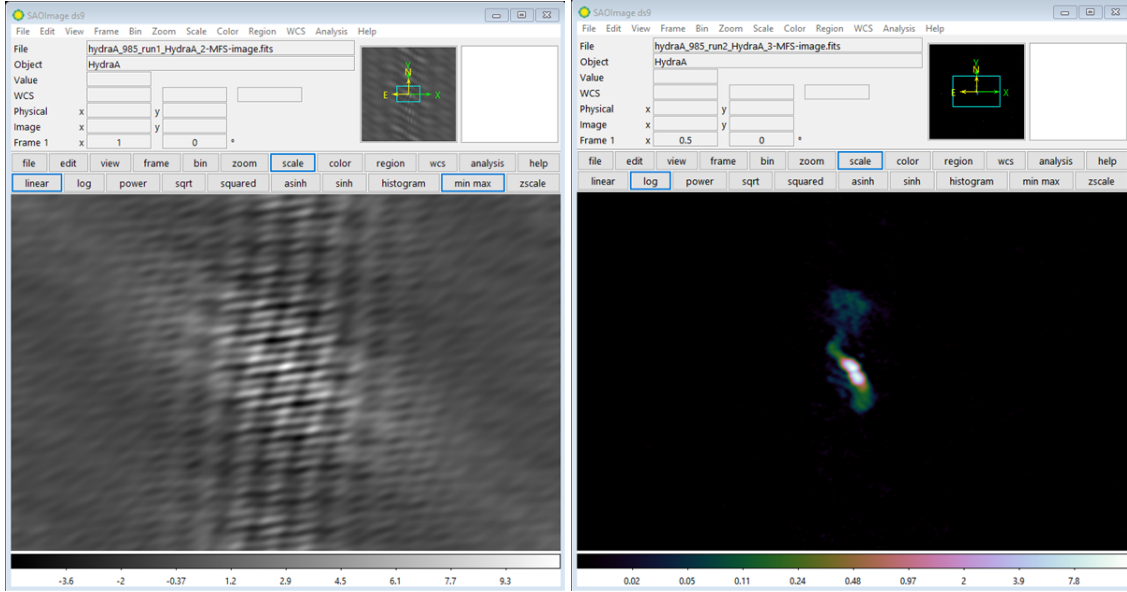
³<https://github.com/ratt-ru/tricolour>

iterative process repeated multiple times until there is no significant improvement between iterations. The `selfcal` worker creates the final restored image by using `WSClean`⁴ [36] to implement the “CLEAN” [37] algorithm. The algorithm works by iteratively finding the greatest absolute intensity in the “dirty” image, multiplying a fraction of this peak by the PSF, and storing the peak in a list. The fractional peak is then subtracted from the dirty image. The process is repeated, gradually subtracting the PSF response until the peak value is less than some user-defined/default threshold. The list of peak values is used to create the model. The model is convolved with the restoring beam, an elliptical Gaussian fit to the PSF, resulting in the restored image. The residual image/noise (what is left of the dirty image after subtracting the model) is added to the restored image giving the final brightness distribution of the observation in units of Jy/beam. To diagnose the success of the self-calibration in our analysis, we studied the model images as well as the residual images. The `selfcal` worker is also used to define the weighting scheme used, the size of the final image (in pixels) and the size of each pixel (in arcsecs). For our final images we used a Briggs robust value of 0 for our weighting scheme, the size of our image was 3000 by 3000 pixels and the size of each pixel was 1.3 arcsecs. The first round of self-calibration is phase only and the second is phase and amplitude.

Preliminary Images

A run of the CARACal pipeline produces several products, the most important being the image of the object. This image is the restored image in units of Janskys per beam (Jy/beam). We use the image to complete the scientific analysis once satisfied with the reduction. The first run of the pipeline rarely produces the perfect image; therefore, it is vital to diagnose problems that occurred during the reduction process. The most important steps to check are calibration and flagging. The results of the first run are presented in Figure 2.1a, which shows that the image we first produced was corrupted. To diagnose the problem, we analysed the gains from the cross-calibration. A “good” data set has gains with amplitudes close to unity, phases close to 0, and delays on the order of a few nanoseconds. The gains plots indicated that the data set was acceptable, and the cross-calibration went fine. The next step was to check how much of the data was flagged. Upon inspection, we found that 96% of the data was flagged; for this reason,

⁴https://wscclean.readthedocs.io/en/latest/further_information.html



(A) The radio intensity map produced after the first run of the pipeline. (B) The radio intensity map produced after implementing the tricolour flagging strategy.

FIGURE 2.1: Comparison between the image after the first run of the pipeline with the image after we changed the flagging strategy. The colour bar represents the radio intensity in units of Jy/beam.

we implemented the tricolour flagger with a less harsh flagging strategy than the aoflagger flagging strategy we initially used. The results of this run are shown in Figure 2.1b.

Using this improved version of the configuration file, we split the fourth epoch of the data into four frequency bands, each with a bandwidth of 80 MHz. The radio maps are centered on 1000 MHz, 1100 MHz, 1330 MHz, and 1485 MHz. These preliminary maps are presented in Figure 2.2.

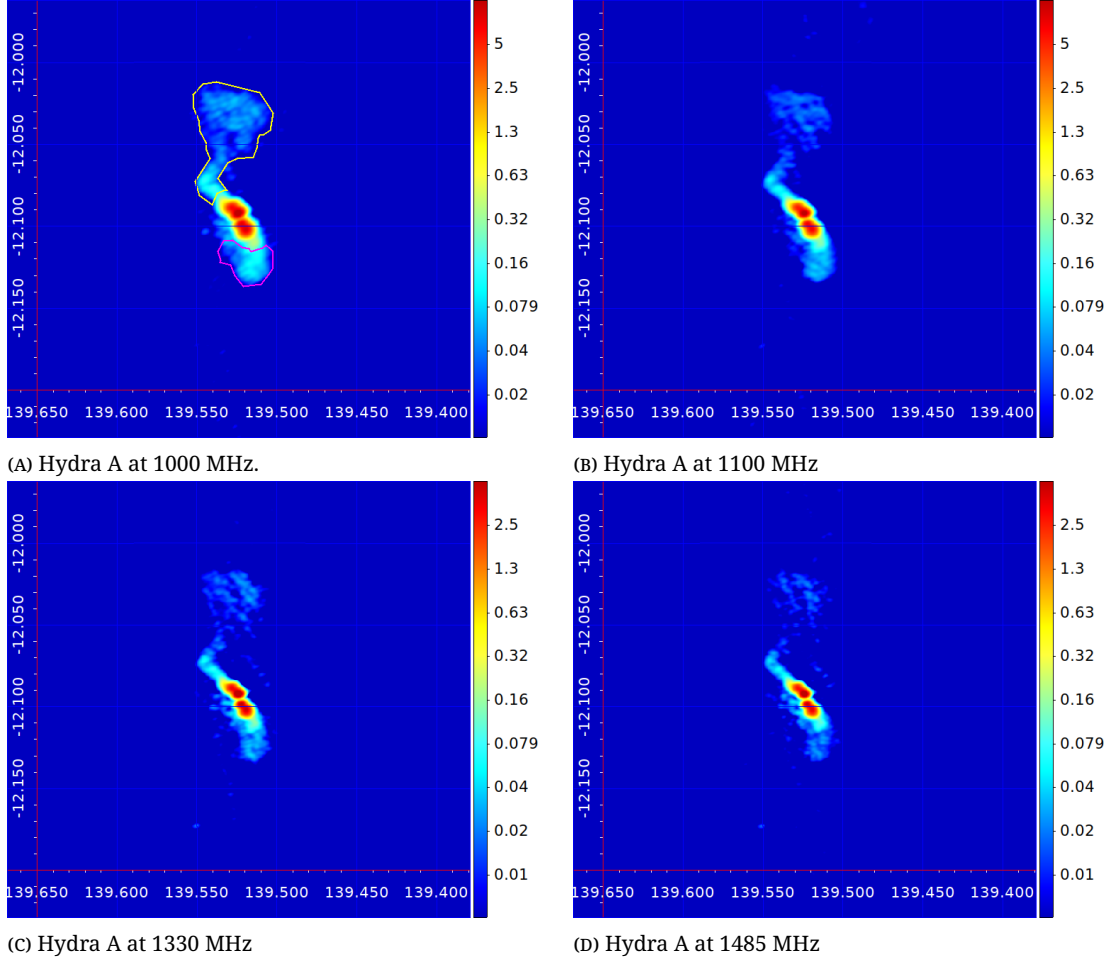


FIGURE 2.2: Radio maps of Hydra A between 1000 MHz and 1485 MHz produced from the data set corresponding to the fourth epoch. The magenta and yellow polygons outline the regions defined as the southern and northern lobes, respectively. The maps are in equatorial coordinates of right ascension (deg.) and declination (deg.). The colour bar represents the radio intensity in units of Jy/beam.

We ran the version of the configuration file with the improved flagging strategy on the first epoch to perform a cross-check with the fourth epoch before implementing it on the combined four epochs. We ran the configuration file on the first epoch for a 20 MHz band centered at 985 MHz. We analysed the models created for the first and fourth epochs during self-calibration and found that the model produced for the fourth epoch included the inner and outer regions while the model produced for the first epoch had only a counterpart for the inner region. The comparison between the first and fourth epoch models is presented in Figure 2.3. We improved the model by increasing the number of self-calibration iterations from the default of 3 to 6. We found the image produced from this reduction to be consistent with the image

produced from the fourth epoch. We implemented the configuration file used in this run (see [A.1](#)) for all subsequent pipeline runs. The radio map of Hydra A at 985 MHz produce from the first epoch of data is present in Figure 2.4

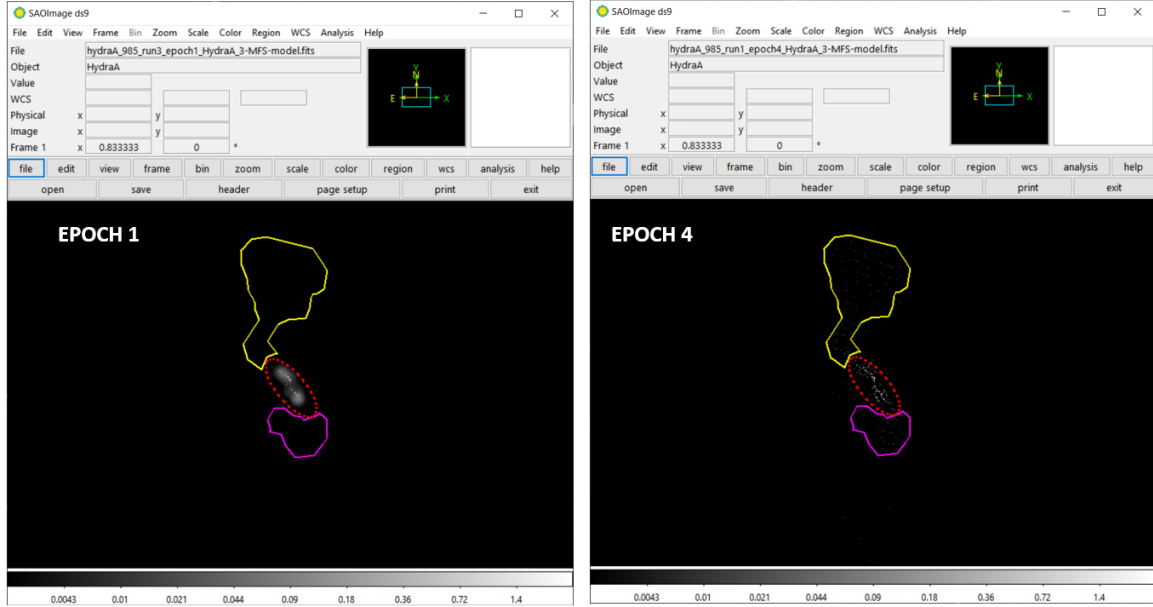


FIGURE 2.3: A comparison between the models produced from the first epoch (left) and the fourth epoch (right) of the data set. The model of the first epoch has only a counterpart for the inner region, whereas the model for the fourth epoch includes a counterpart for both the inner and outer regions.

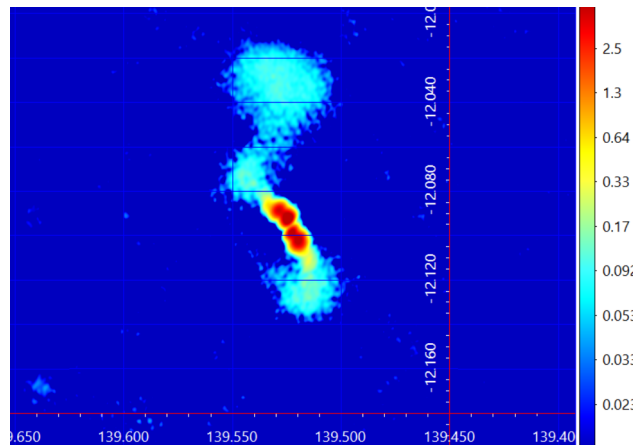


FIGURE 2.4: Radio map of Hydra A at 985 MHz produced from the data set corresponding to the first epoch. The map is in equatorial coordinates of right ascension (deg.) and declination (deg.). The colour bar represents the radio intensity in units of Jy/beam.

Final Images

Once the pipeline produced compatible results from the first and fourth epochs, we combined all the epochs into one Measurement Set. We did this by implementing the `concat` task in CASA, which concatenates multiple visibility files into a single visibility file. We ran the configuration file on the full data set, selecting four different spectral windows, each with a bandwidth of 80 MHz. The central frequencies for the final four images are 1000 MHz, 1100 MHz, 1330 MHz, and 1485 MHz. The produced radio maps are the image of the sky multiplied by the primary beam/ attenuated power pattern associated with each telescope within the array. To correct for the effects of the primary beam, we divided the final image from the pipeline by the MeerKAT attenuation pattern [42] given by

$$a_b \left(\frac{\rho}{\theta_b} \right) = \left[\frac{\cos(1.89\pi\rho/\theta_b)}{1 - 4(1.89\rho/\theta_b)} \right]^2, \quad (2.1)$$

ρ is the angular offset in the image with respect to the pointing centre given by

$$\rho = \theta \left(\sqrt{x^2 + y^2} \right), \quad (2.2)$$

where θ is the size of 1 pixel in the image in arcminutes and x and y are the i th and j th pixels in the $i \times j$ image. θ_b is the FWHM of the primary power pattern given by

$$\theta_b = 57.5' \left(\frac{\nu}{1.5\text{GHz}} \right)^{-1}, \quad (2.3)$$

where ν is the central frequency of the image given in GHz. We refer to the images produced from the reduction of all four epochs combined as the final radio images and present them in Section 3. In the final radio images, the size of the restoring beam in the form *major axis* $\times$ *minor axis* is $13.54 \times 9.59 \text{ arcsec}^2$ at 1000 MHz, $10.77 \times 8.86 \text{ arcsec}^2$ at 1100 MHz, $9.078 \times 7.40 \text{ arcsec}^2$ at 1330 MHz, and $8.00 \times 6.74 \text{ arcsec}^2$ at 1485 MHz. We used these radio maps for the data analysis presented in Section 2.3.

2.3 Data Analysis

2.3.1 Flux Calculations

We used the final images to compute the radio fluxes of the outer lobes. The outer lobe structure consists of three regions; the northern lobe, the southern lobe and the tail-like region that extends from the southern lobe. We selected these regions by constructing a polygon that encloses the emission of the region. The regions are overlaid on the image at 1000 MHz in Figure 3.1a. The magenta and yellow polygons outline the regions defined as the southern and northern lobes, respectively, and the green dashed polygon encloses the tail-like region. We computed the flux densities for each region at 74 MHz and 333 MHz (VLA frequencies) and at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz (MeerKAT frequencies).

Computing the flux

As a result of the “CLEAN” ing process, the final images are convolved with the restoring beam. The brightness I_ν is, therefore, in units of Jy/beam. To get the total flux density F_ν from the images in units of Jy, the brightness per pixel needs to be summed over the defined region and then divided by the number of pixels in the restoring beam. The number of pixels in the restoring beam is given by Equation 2.4.

$$\text{No. of pixels in the restoring beam} = \frac{Area_{beam}}{Area_{pixel}} \quad (2.4)$$

The beam is an elliptical Gaussian beam with an area

$$Area_{beam} = 2\pi\sigma_{maj}\sigma_{min}, \quad (2.5)$$

where $\sigma = \frac{FWHM}{2\sqrt{2\ln 2}}$, and FWHM corresponds to the full-width half maximum of the semi-major and semi-minor axes of the beam in arcseconds. The FWHM values are found in the header of the FITS file under BMAJ and BMIN. We computed the flux density over a specified region using

$$F = \frac{\sum_{n=0}^{no.of\ pixels} I_n}{Area_{beam} / Area_{pixel}}. \quad (2.6)$$

We computed the sum of the brightness $\sum_{n=0}^{no.of\ pixels} I_n$ for each region with the astronomical imaging software SAOImageDS9 [43]. We used this procedure to compute the fluxes for the three regions separately for the MeerKAT and VLA radio maps.

To compute the flux density for a combination of all three regions, we summed the flux densities of the individual regions.

Flux Errors

We computed the errors on the fluxes of the MeerKAT images by implementing the radio flux routine by M. J Hardcastle⁵. The module takes a FITS file, a foreground region- one of the three defined regions, and a background region. We defined the background as a region fairly local to the source but ensured that no emission from the source is included in the region. The module uses this background region to estimate the RMS noise of the image and returns an error associated with the flux for the given region. We selected a background region with high noise levels due to residual artefacts to ensure conservative error measurements.

To account for the lower resolution of the 74 MHz and 330 MHz VLA images, we applied an error of 10% on the flux values for those data points - this is best our best estimate of the true systematic error, relative to the MeerKAT data. The following factors contribute to the uncertainty:

- Map errors
- Calibration reliability
- Primary beam response
- leakage between regions

We used Equation 2.7 to compute the error on the flux density for a combination of all three regions

$$\text{Error on sum of flux densities} = \sqrt{Error_{Northern-Lobe}^2 + Error_{Southern-Lobe}^2 + Error_{tail}^2}. \quad (2.7)$$

The flux densities and their associated errors are presented in Section 3.2.

⁵<https://github.com/mhardcastle/radioflux>

2.4 5σ Noise Level Computation

We computed the 5σ noise level for each of the four radio maps. The 1σ noise level is given by

$$1\sigma_{noise} = \frac{1\sigma \text{ error on flux of the background region}}{\sqrt{\text{no. of beams in the background region area}}}.$$

The 1σ error on flux of the background region is obtained by running the `radioflux` routine on the background region. The number of beams in the background region is given by

$$\text{no. of beams in background region} = \frac{\text{area of the background region}}{\text{area of the beam}}.$$

The area of the background region is a circle with a radius of 107.37 arcsec^2 , hence,

$$\begin{aligned} \text{Area of the background region} &= \pi \times r^2 \\ &= \pi \times (107.37)^2 \\ &= 36215.93 \text{ arcsec}^2. \end{aligned} \tag{2.8}$$

The computation of the area of the beam is given by Equation 2.5.

2.5 Spectral Analysis

2.5.1 Radio Spectrum

We used the flux densities and their corresponding uncertainties derived from the four sub-band MeerKAT observations and the two low-frequency VLA observations to determine the spectrum for the three regions of Hydra A. Given that the relationship between the flux density and frequency is described by;

$$F_\nu \propto \nu^\alpha \tag{2.9}$$

We fitted the four flux densities within the MeerKAT frequency range to a power law in the form

$$y = P_0 x^{P_1}$$

by implementing the method of least squares. We used the python function `scipy.optimize.leastsq`, which returns the parameters P_0 and P_1 and their associated errors, where P_0 is a fitting constant and P_1 is the spectral index. We used this method to obtain values for the spectral index, α , and its associated error, $\Delta\alpha$, for the three regions in the MeerKAT frequency range.

Using the two flux density values within the VLA frequency range, we computed the spectral index using the following equation which follows from Equation 2.9,

$$\alpha = \frac{\log\left(\frac{F_{\nu_1}}{F_{\nu_2}}\right)}{\log\left(\frac{\nu_1}{\nu_2}\right)} \quad (2.10)$$

with an associated error

$$\Delta\alpha = \frac{\sqrt{\left(\frac{\Delta F_{\nu_1}}{F_{\nu_1}}\right)^2 + \left(\frac{\Delta F_{\nu_2}}{F_{\nu_2}}\right)^2}}{\log\left(\frac{\nu_1}{\nu_2}\right) \ln(10)} \quad (2.11)$$

We used Equation 2.11 to compute the associated error of our VLA flux densities.

2.5.2 Spectral index maps

For our study, we constructed two spectral index maps of Hydra A, the first being within the VLA frequency range, between 74 MHz and 330 MHz, and the second a spectral map over the MeerKAT frequency range of 1000 MHz - 1485 MHz. Because the angular resolution tightens with the frequency, we convolved the maps at higher frequencies with a 2D elliptical Gaussian beam to smooth them to the angular resolution of the map at the lowest frequency. This way, all the maps will have the same angular resolution, and we can make a meaningful analysis.

VLA Spectral Index Map

We created the VLA spectral index map using the two VLA sub-band images at 74 MHz and 330 MHz. The map at 330 MHz had to be rebinned and smoothed to match the size and angular resolution of the map at 74 MHz. To smooth the map, we used a 2D elliptical gaussian beam model with a major axis FWHM defined by

$$FWHM_{maj} = \sqrt{FWHM_{maj-74MHz}^2 - FWHM_{maj-330MHz}^2} \quad (2.12)$$

and a minor axis FWHM defined by

$$FWHM_{min} = \sqrt{FWHM_{min-74MHz}^2 - FWHM_{min-330MHz}^2} \quad (2.13)$$

We converted the 74 MHz and 330 MHz maps from units of Jy/beam to units of Jy/pixel by dividing them by the beam area defined in Equation 2.5 and smoothed the 330 MHz map to the resolution of the 74 MHz map. Using the maps in units of Jy/pixel, we computed the spectral index per pixel using Equation 2.10 for the flux density values for each pixel at 74 MHz and 330 MHz producing the VLA spectral index map.

MeerKAT Spectral Index Map

We smoothed the maps at 1100 MHz, 1330 MHz and 1485 MHz to the resolution of the map at 1000 MHz using a 2D gaussian beam with FWHM values given by

$$FWHM_{maj} = \sqrt{FWHM_{maj-1000MHz}^2 - FWHM_{maj-high-frequency}^2} \quad (2.14)$$

and a minor axis FWHM defined by

$$FWHM_{min} = \sqrt{FWHM_{min-1000MHz}^2 - FWHM_{min-high-frequency}^2} \quad (2.15)$$

where *high-frequency* is 1100 MHz, 1330 MHz and 1485 MHz. We converted the maps from Jy/beam to Jy/pixel. To compute the spectral index per pixel for the four frequencies, we fitted the flux density values at each frequency to a power law using the method of least squares as detailed in Section 2.5.1. The generated VLA and MeerKAT spectral index maps are shown in Figure 3.5.

2.6 Modelling the Radio Spectrum of Hydra A

Because the radio spectrum of Hydra A is characterised by a spectral break, i.e. there is roughly a broken power-law shape, we used the Kardashev Pacholzyk (KP) model (see Section 1.2) to fit the radio spectrum. We used the following assumptions for the model:

- Electrons have an injection spectrum in the form of a power law

$$N(E) = k_0 E^{-\delta}$$

where E is the energy, k_0 is a normalisation factor and δ is the injection index.

- Electrons are interacting with a magnetic field, $\mathbf{B}$
- Electrons evolve for a time, t , which we define as the age of the system
- Electrons experience Energy losses due to:
 1. Synchrotron radiation (interaction with the magnetic field)
 2. Inverse Compton scattering with Cosmic Microwave Background (CMB) photons
- Each electron keeps a constant pitch angle with the magnetic field direction during its lifetime (KP model)

The main fitting procedure of our model computes a value for the flux density as shown in Equation 1.10 by integrating over θ (the pitch angle). The fitting procedure is detailed below:

1. Give the model different values for the injection index. For the northern lobe, we sampled 13 evenly spaced values for the spectral index between 1.8 and 3.0, and for the southern lobe and tail region, we took 11 evenly spaced values between 2.0 and 3.0. The fitting procedure computes the model flux values for each injection index for a range of B - t combinations. For the magnetic field strength and age, we took:
 - 100 evenly distributed values for the magnetic field strength with a minimum value of $1 \mu\text{G}$ and a maximum value of $50 \mu\text{G}$.
 - 140 evenly distributed values for the age with a minimum value of 5 Myrs and a maximum value of 180 Myrs.

These input parameter values and ranges were motivated by the general trends for B , δ and t seen for radio galaxies similar to Hydra A

2. Search for the best normalisation factor (k_0).
3. Compare the calculated set of values at each frequency with the observed data. This is done by computing the χ^2 values for each B , t combination. The χ^2 statistic is calculated

using

$$\chi^2 = \sum \left(\frac{y_i - f(x_i)}{\sigma_i} \right)^2 \quad (2.16)$$

where the index i runs over the number of data points, y_i represents the observed flux values, $f(x_i)$ is the model flux values and σ_i represents the error on the observed fluxes.

4. Find the best fitting values for the age and magnetic field by identifying the set corresponding to the lowest χ^2 value (the minimum χ^2).

The complete code for this procedure applied to the northern lobe with an injection index of 2.00 is presented in A.2. The `xdata`, `ydata` and `yerr` values change in accordance to region, and for each region the `superfit` routine takes a different value for the initial spectral index.

The fitting procedure produces a χ^2 grid of the B-t parameter space for each input injection index, i.e., 13 χ^2 grids for the northern lobe and 11 χ^2 grids for the southern lobe and tail region. We then confirmed the best-fit parameters by creating a "global minimum χ^2 " grid from all χ^2 grids for each region. To create this "global minimum χ^2 " grid, we compared each χ^2 grid for each region and kept only the minimum χ^2 value. This process resulted in the creation of a single map with all the minimum χ^2 values, which we then searched for the global minimum χ^2 . The values for the injection index, age and magnetic field corresponding to this global minimum χ^2 value are taken as the best fit model parameters. We overlaid 1σ and 3σ contours on the global χ^2 grid which enabled us to study the allowed B-t combinations for the age and magnetic field to a 3σ confidence interval. The grids showing the χ^2 values for the B-t parameter space for all three regions is presented in Figure 3.6.

We compared the best-fit model to the data by plotting the best-fit model with the observed data and by creating a residual plot. We computed the residual for each point using

$$\text{Residual} = \frac{y_{\text{model}} - y_{\text{data}}}{y_{\text{error}}} \quad (2.17)$$

where y_{model} is the model flux, y_{data} is the observed flux and y_{error} is the error on the observed flux. The best model fits and residuals for the northern lobe, southern lobe and tail-like region are presented in Figure 3.7, Figure 3.8 and Figure 3.9, respectively.

Chapter 3

Results and Discussion

3.1 Spatial Morphology

3.1.1 Final Images

The images we produced from the final reduction of the combined observation are shown in Figure 3.1. We have presented radio maps at 1000 MHz, 1100 MHz, 1330 MHz, and 1485 MHz, and the $5\text{-}\sigma$ noise levels are given by 6.51 mJy/beam, 6.18 mJy/beam, 2.74 mJy/beam and 2.81 mJy/beam respectively. The noise values of our images are significantly higher than the theoretical noise estimates calculated using [the SARA sensitivity calculator](https://skaafrika.atlassian.net/wiki/spaces/ESDKB/pages/1486750321/Sensitivity+calculators)¹ (around 10s of μJy); however, it is not always useful to compare the actual noise values with theoretical noise since theoretical noise estimates do not account for flagging. It is worth noting that based on our analysis of the residual images, our final images seem to be limited by deconvolution artefacts and this could be contributing to this significant difference between the theoretical noise estimate and our actual noise values. The pronounced difference in the noise levels between the two lower sub-bands and the two higher sub-bands is also worth noting, however, this difference is not entirely unexpected given that it is more challenging to model the source flux at lower frequencies given the lower resolution. The flagging for different frequency bands could also be contributing to this difference in noise levels and is worth investigating.

¹<https://skaafrika.atlassian.net/wiki/spaces/ESDKB/pages/1486750321/Sensitivity+calculators>

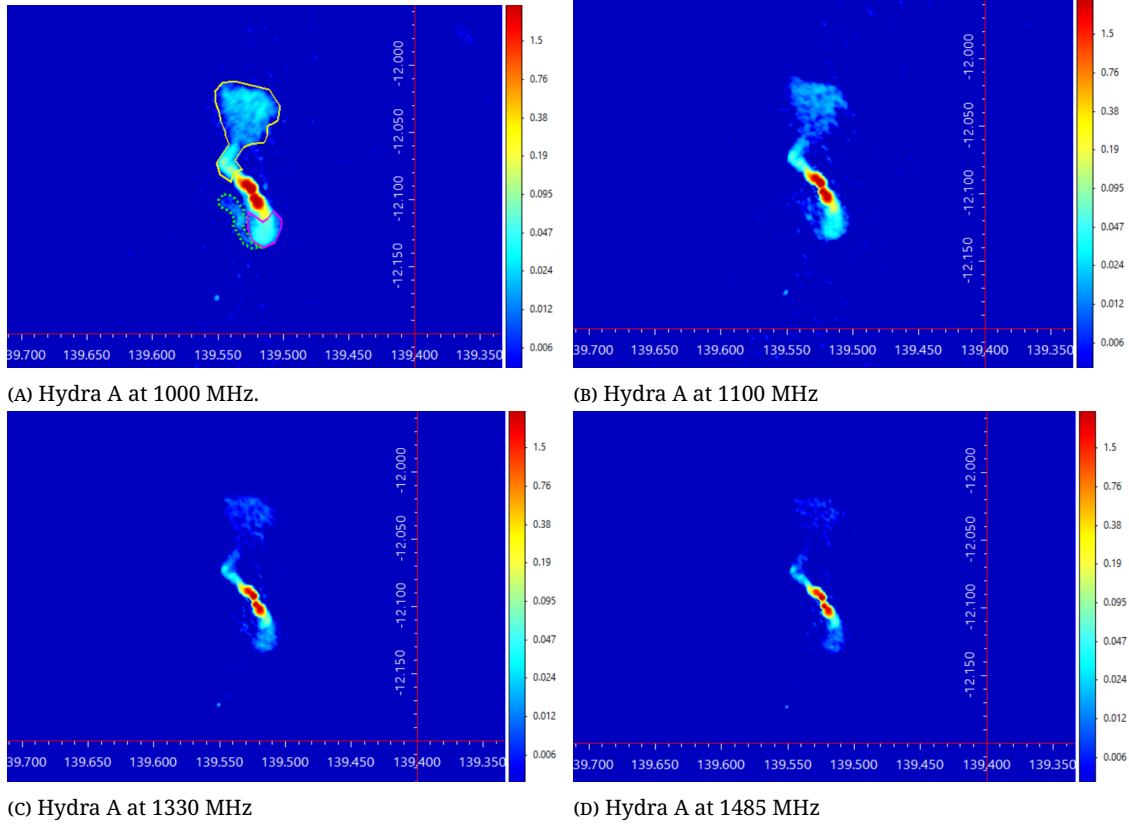


FIGURE 3.1: Radio maps of Hydra A between 1000 MHz and 1485 MHz produced from the combination of all four epochs. The magenta and yellow polygons outline the regions defined as the southern and northern lobes, respectively. The green dashed polygon encloses the tail-like region that cannot be seen in the preliminary images. The maps are in equatorial coordinates of right ascension (deg.) and declination (deg.). The colour bar represents the radio intensity in units of Jy/beam. The 5σ noise levels of the maps at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz are given by 6.51 mJy/beam, 6.18 mJy/beam, 2.74 mJy/beam and 2.81 mJy/beam respectively.

The radio maps produced using MeerKAT are in good agreement with the morphology of Hydra A seen in Figure 1 of [27]. The MeerKAT images reveal two bright inner lobes extending in the northern and southern directions and two diffuse extended outer lobes. Our MeerKAT observations resolve finer details than the maps at 1415 MHz presented in [27], for example, the bridge connecting the bright inner lobe and outer lobe in the northern region, located at (RA=139.53 deg, Dec=-12.06). The VLA map at 1415 MHz presented in [27] has a 5σ noise level at 12 mJy/beam, while our map based on MeerKAT observations at 1.33 GHz has a 5σ noise level at 2.74 mJy/beam. The lower noise level of the MeerKAT images is a crucial factor in revealing the bridge between the northern inner and outer lobes. The radio maps also reveal a tail-like structure extending from the southern outer lobe. This tail-like structure can be

seen in the 74 MHz and 330 MHz VLA image [27]; however, it cannot be seen in the 1415 MHz VLA image. This demonstrates the increased sensitivity achievable with the MeerKAT radio telescope compared with other interferometers. The morphology of the tail-like region follows an unexpected trajectory. The emission in this region appears to extend out of the southern lobe as if some mechanism has caused it to undergo an unusual bend. Although this could be the case, it is not likely since a similar structure is not seen in the northern lobe. More often than not, wide-angle-tailed (WAT) radio sources tend to display bent tail-like features in both jets[44]. Because Hydra A has experienced three generations of outbursts, it seems most likely that this faint emission is a remnant of an earlier generation of AGN activity.

3.2 Flux Results

In this section, we present the flux densities we computed from the MeerKAT maps at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz, and the VLA maps at 74 MHz and 333 MHz. We computed the results using the procedure outlined in Section 2.3.1. Tables 3.1, 3.2 and 3.3 summarise the flux densities and their associated errors for the northern, southern and tail-like regions, respectively.

Frequencies (MHz)	Flux (Jy)	Error on flux (Jy)
74	91.44	9.14
330	16.80	1.68
1000	3.18	0.02
1100	2.68	0.02
1330	1.82	0.01
1485	1.49	0.01

TABLE 3.1: Flux measurements for the northern outer lobe of Hydra A from the VLA radio maps at 74 MHz and 333 MHz, and the MeerKAT images at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz.

Frequencies (MHz)	Flux (Jy)	Error on flux (Jy)
74	43.58	4.36
330	7.81	0.78
1000	1.26	0.01
1100	1.01	0.01
1330	0.65	0.00
1485	0.52	0.01

TABLE 3.2: Flux measurements for the southern outer lobe of Hydra A from the VLA radio maps at 74 MHz and 333 MHz, and the MeerKAT images at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz.

Frequencies (MHz)	Flux (Jy)	Error on flux (Jy)
74	21.98	2.2
330	2.39	0.24
1000	0.27	0.01
1100	0.22	0.00
1330	0.11	0.00
1485	0.09	0.00

TABLE 3.3: Flux measurements for the tail-like region of Hydra A from the VLA radio maps at 74 MHz and 333 MHz, and the MeerKAT images at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz.

We see that the flux densities decrease as the frequency increases. This steep decline in the flux seen at higher frequencies is expected since electrons at higher energies radiate their energy more efficiently. It is not unusual that the errors for the northern lobe are greater than those for the southern lobe and tail-like region. The noise is proportional to the number of beams in the selected region; therefore, the larger the region, the greater the absolute error in the measurement.

Previously computed values for the flux densities of the outer lobes of Hydra A are presented in [6]. The information about the template selection is not provided in their paper; however, we assume that the region defined as the outer lobes would include the regions we define as the northern outer lobe, southern outer lobe, and tail-like regions combined. The flux densities and corresponding errors of the sum of all three regions are presented in Table 3.4.

Frequencies (MHz)	Flux (Jy)	Error on flux (Jy)
74	157.00	10.37
330	27.00	1.87
1000	4.71	0.02
1100	3.91	0.02
1330	2.58	0.01
1485	2.10	0.01

TABLE 3.4: Flux measurements for the sum of the northern outer lobe, southern outer lobe and tail-like region of Hydra A. The flux densities were computed from the VLA radio maps at 74 MHz and 330 MHz, and the MeerKAT images at 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz.

The radio flux of the outer lobes computed in [6] at 74 MHz and 330 MHz are given by 221 ± 30 Jy and 36 ± 10 Jy, respectively. These radio flux densities are higher than the flux densities we computed for the outer lobes (the sum of the three regions). This difference is expected given that the VLA radio maps used in our computation were corrected by a more accurate beam shape.

3.3 Spectral Analysis

Using the flux density values presented in Tables 3.1, 3.2 and 3.3, we determined the spectrum for the three regions of Hydra A in the VLA and MeerKAT frequency ranges. The spectrum for the northern lobe, southern lobe and tail-like regions are presented below in Figure 3.2, Figure 3.3 and Figure 3.4, respectively. We computed the spectral index for each region within the MeerKAT and VLA frequency ranges. The values for the spectral index, α and associated error, $\Delta\alpha$ for each region are presented in Table 3.5. The spectrum in all three regions shows a steepening within the MeerKAT frequency range. The change in the spectral index between the VLA frequency range and the MeerKAT frequency range is established in all three regions. This change in the spectral index provides evidence that the spectrum exhibits a spectral break- that is, after a certain energy, the spectrum continues as a power-law but with a different spectral index (broken power-law).

	Northern Lobe		Southern Lobe		Tail	
	α	$\Delta\alpha$	α	$\Delta\alpha$	α	$\Delta\alpha$
VLA frequency range	-1.14	0.07	-1.16	0.07	-1.49	0.07
MeerKAT frequency range	-1.93	0.04	-2.27	0.03	-2.88	0.19

TABLE 3.5: Summary of the values for the spectral index and its associated errors for the three different regions of Hydra A

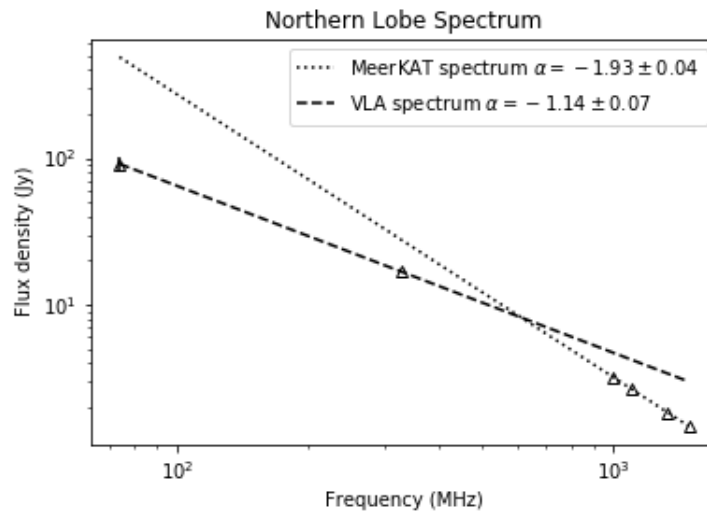


FIGURE 3.2: Northern lobe spectrum in the VLA and MeerKAT frequency ranges.

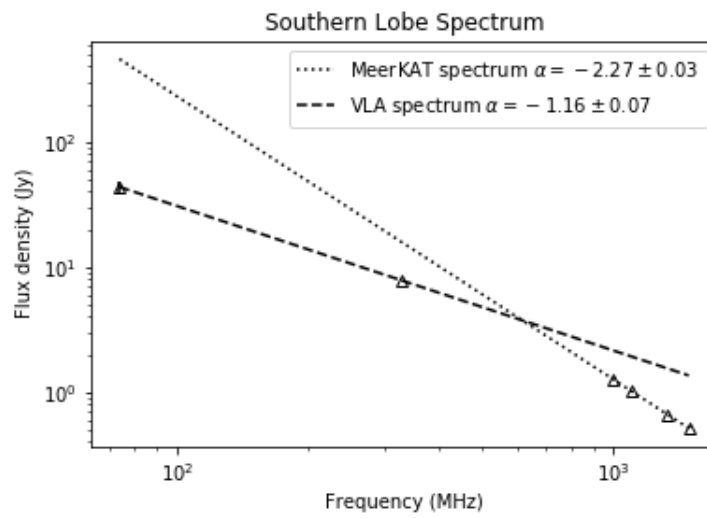


FIGURE 3.3: Southern lobe spectrum in the VLA and MeerKAT frequency ranges.

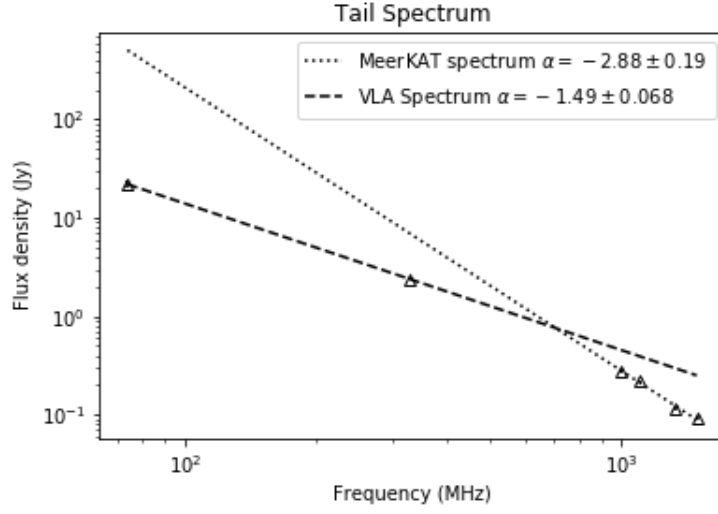


FIGURE 3.4: Spectrum for the tail-like region in the VLA and MeerKAT frequency ranges.

To create the MeerKAT and VLA spectral index maps, we smoothed each map to the resolution of the lowest resolution map using a 2-D Gaussian elliptical beam. Within the VLA frequency range, we smoothed the map at 330 MHz to the resolution of the map at 74 MHz using a beam with a size defined in Equation 2.13 given by $27.75 \times 18.29 \text{ arcsec}^2$. For the MeerKAT spectral index map, we smoothed the maps at 1100 MHz, 1330 MHz and 1485 MHz to the resolution of the map at 1000 MHz using beams as defined in Equation 2.14, given by $8.21 \times 3.67 \text{ arcsec}^2$, $10.05 \times 6.10 \text{ arcsec}^2$ and $10.92 \times 6.82 \text{ arcsec}^2$, respectively. The VLA spectral index map between 74 MHz and 330 MHz is shown in Figure 3.5a, and the MeerKAT spectral index map between 1000 MHz and 1485 MHz is shown in Figure 3.5b.

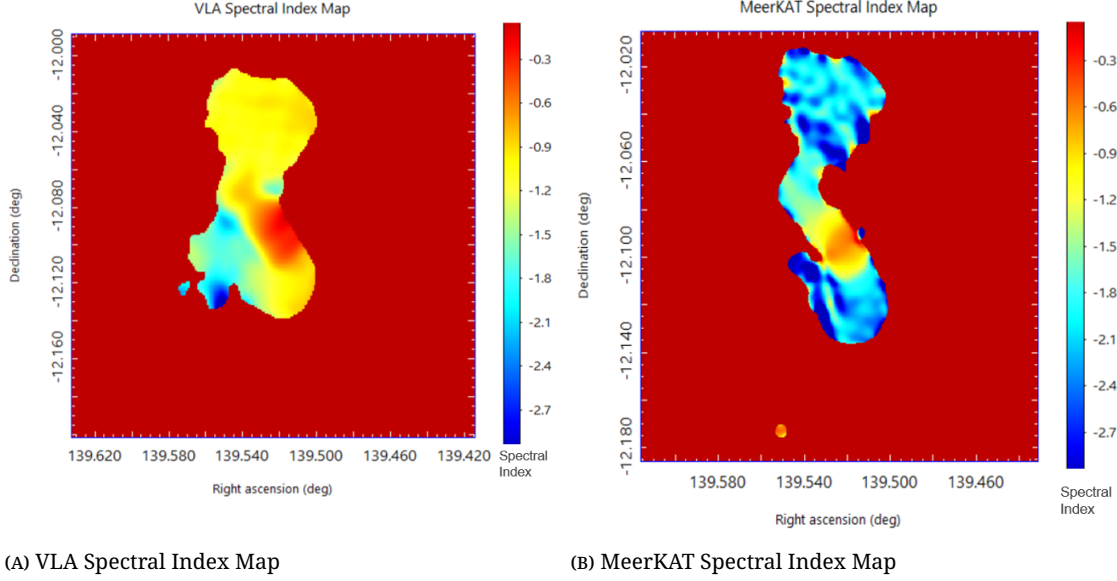


FIGURE 3.5: Spectral index map in the (A) VLA frequency range and (B) MeerKAT frequency range.

In both spectral index maps, we see a steepening with distance from the core. We refer to the MeerKAT spectral index map for the following analysis, although a similar trend is seen for both maps. In the MeerKAT spectral index map, the core and inner lobes appear to have a relatively flat spectrum with spectral indices ranging between -0.3 and -0.9 , the spectral index then steepens to values of ~ -2.7 in the northern and southern lobes. The tail-like region exhibits the steepest spectral index, reaching values of ~ -3 in some areas. The tail-like region showing the steepest spectrum indicates that it has undergone significant spectral aging, suggesting that the emission in the tail-like region was produced during a different generation of activity than in the northern and southern lobes. Another possibility is that the northern and southern lobes exhibit a flatter spectral index due to the mixing of electron populations- if the northern and southern lobes are not completely disconnected from the jets, it is plausible that they are being injected with younger electrons that are mixing with the older population of electrons.

3.4 Modelling the radio spectrum in Hydra A

In this section, we present the results for the modelling of the spectrum in Hydra A. We tested the KP model for several fixed injection indices for each region and accepted the best fit model

as the model that produced the lowest χ^2 value.

The global χ^2 grids for the B-t parameter space for the northern lobe, southern lobe and tail-like region are presented in Figures 3.6a, 3.6b and 3.6c, respectively.

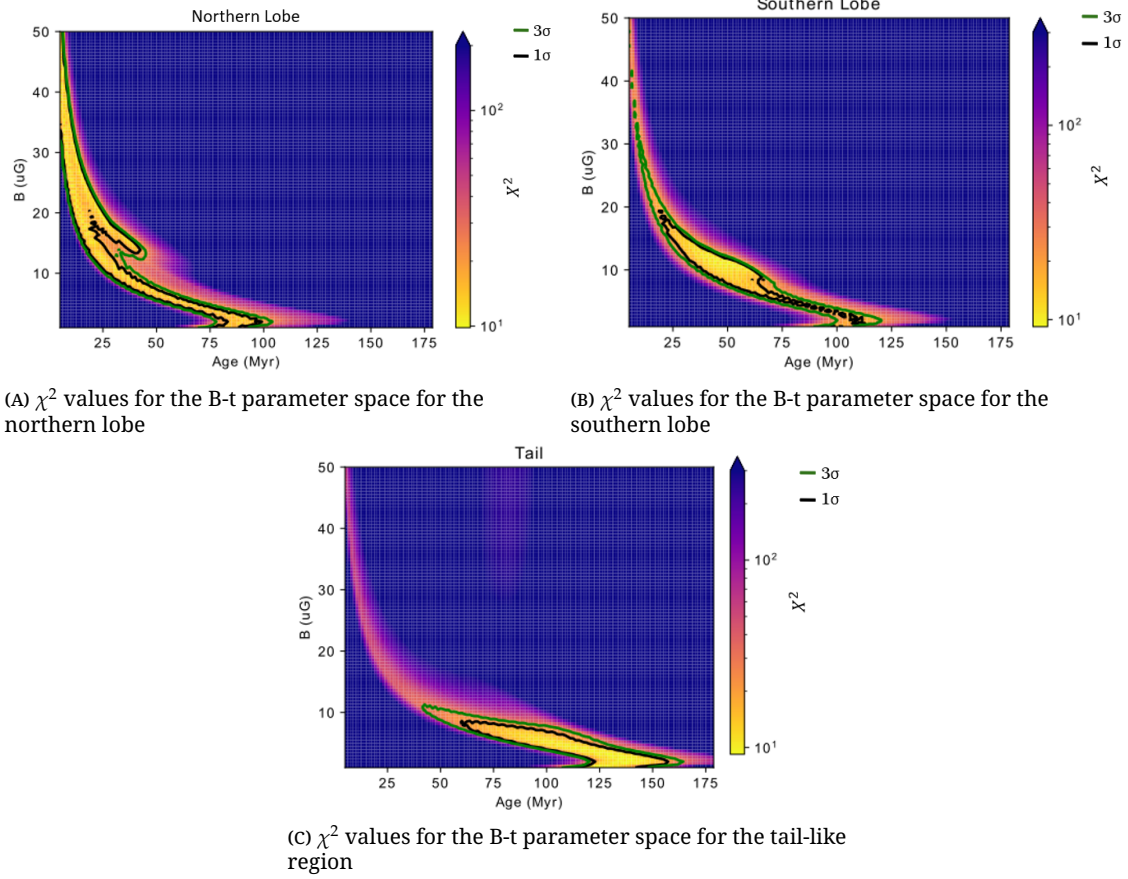


FIGURE 3.6: Grid showing χ^2 values for the B-t parameter space for the (A) northern lobe, (B) southern lobe and (C) tail-like region. The 1σ and 3σ contours are overlaid in black and green, respectively.

For the northern lobe, the model with an injection index of 2.00, a magnetic field strength of $37.13 \pm 0.99 \mu\text{G}$ and an age of 8.75 ± 1.25 Myrs produced the minimum χ^2 value of 9.83. It is important to note that every B-t combination that falls within the 3σ confidence interval contours is a plausible B-t combination; hence, it is possible to have ages up to ~ 100 Myrs for the northern lobe if the magnetic field strength is low. A cut-off in the B-t χ^2 grid is seen for a magnetic field of $\sim 3\mu\text{G}$. As detailed in Section 1.2, this cut-off is expected because radiative losses due to Inverse Compton scattering with CMB photons become the dominant energy

loss mechanism for low magnetic field values. Beyond this cut-off, the model no longer accurately represents the data; however, because the best fit case in all three regions does not fall anywhere near this cut-off, the model is sufficient in predicting the age of the system. Although more complex models could be employed in future work, the KP model satisfactorily describes the overall spectrum. For the southern lobe, we find the best-fit model with a minimum χ^2 value of 9.20 to have an injection index of 2.10, a magnetic field strength of $10.90 \pm 0.49 \mu\text{G}$ and an age of 50 ± 1.25 Myrs, and for the tail-like region, we find the best-fit case with a minimum χ^2 of 13.05 to have an injection index of 2.80, a magnetic field strength of $1.99 \pm 0.49 \mu\text{G}$ and an age of 138.75 ± 2.5 Myrs. We fit the best model to the MeerKAT and VLA data and present the best fits and their residuals (as defined in Equation 2.17) for the northern lobe, southern lobe and tail-like regions in Figures 3.7, 3.8 and 3.9, respectively.

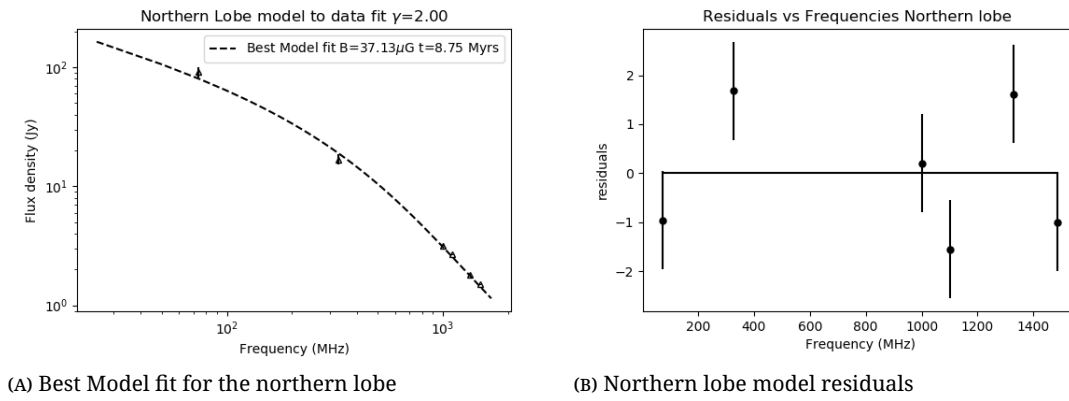


FIGURE 3.7: Northern Lobe (A) best-fit model and (B) associated residuals.

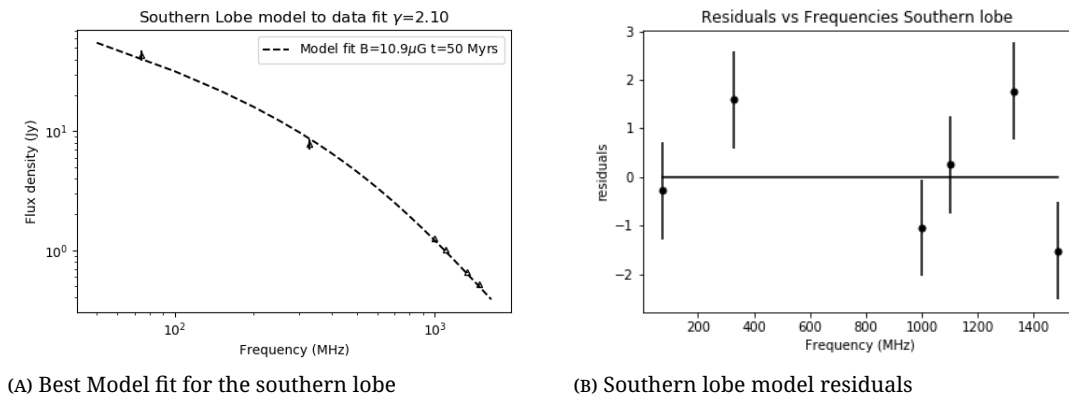


FIGURE 3.8: Southern Lobe (A) best-fit model and (B) associated residuals.

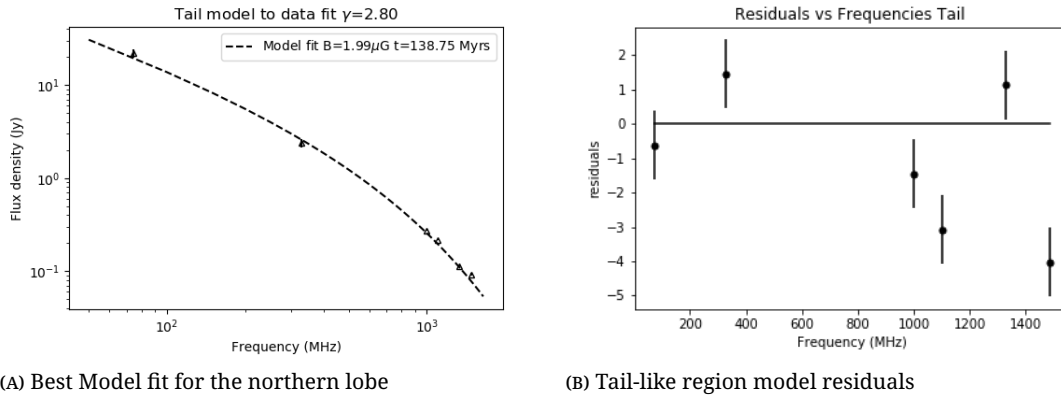


FIGURE 3.9: Tail-like region (A) best-fit model and (B) associated residuals.

The tail-like region appears to be the oldest region of the galaxy, supporting the scenario in which the tail is disconnected from the jets and is a remnant of an older generation of AGN activity. A study of the nuclear region of Hydra A shows that it has a precession period of $\sim 3 \times 10^5$ yr [26]; hence, it is possible that the outburst responsible for the emission in the tail-like region was emitted in a different direction than the current direction of the jets. The northern and southern lobes are most likely still connected to the jets and being injected with young electrons. We estimate the age of the system to be ~ 140 Myrs based on the best-fit parameters for the tail-like region (given that it is the oldest region of the galaxy). This estimate is consistent with previous age estimates of Hydra A based on hydrodynamic models of the shock front produced by the outburst [33] and dynamical age estimates [7]. Our estimates of the magnetic field values in all three regions are on the same order of magnitude of previous estimates for the magnetic field values in the Hydra A cluster [29].

3.5 Comparison Between Hydra A and other radio galaxies

The Fornax A [23] (Figure 3.10) and Circinus [45] (Figure 3.11) radio galaxies were both observed using the MeerKAT radio telescope and analysed using the CARACal pipeline- as in this study. Both these galaxies exhibit similar features to Hydra A; all three galaxies are active galactic nuclei with large diffuse radio lobes. However, Hydra A differs substantially from both these galaxies. The lobes of the Circinus radio galaxy display edge brightening, consist

of plume-like structures and have hot spots. We do not see these features in the lobes of Hydra A. The structure of Circinus appears to be symmetric, strongly resembling Fermi bubbles [46], whereas we find the radio structure of Hydra A to be more asymmetrical.

Although Hydra A and Fornax A share similar structural features, their spectral properties differ significantly. The lobes in Fornax A have a flat spectral index and a high break frequency, indicating that there is no current nuclear activity. In the case of Hydra A, the core has a flat spectral index suggesting that the AGN is likely experiencing an active phase. The spectral index in the lobes of Hydra A exhibit a steepening with distance from the core, indicating that there have been multiple episodes of activity. The difference between Fornax A and Hydra A is that the period between nuclear activity and inactivity is on very short time scales in Fornax A. Hydra A appears to be in an active phase where the jets are still injecting relativistic electrons into the northern and southern lobes with only the tail-like region no longer being injected with electrons. The difference in the break frequencies of the outer lobes, i.e., the high break frequency for the lobes of Fornax A and the low break frequency for the lobes of Hydra A explains why gamma rays have been found in the outer lobes of Fornax A but not detected in the outer lobes of Hydra A[47].

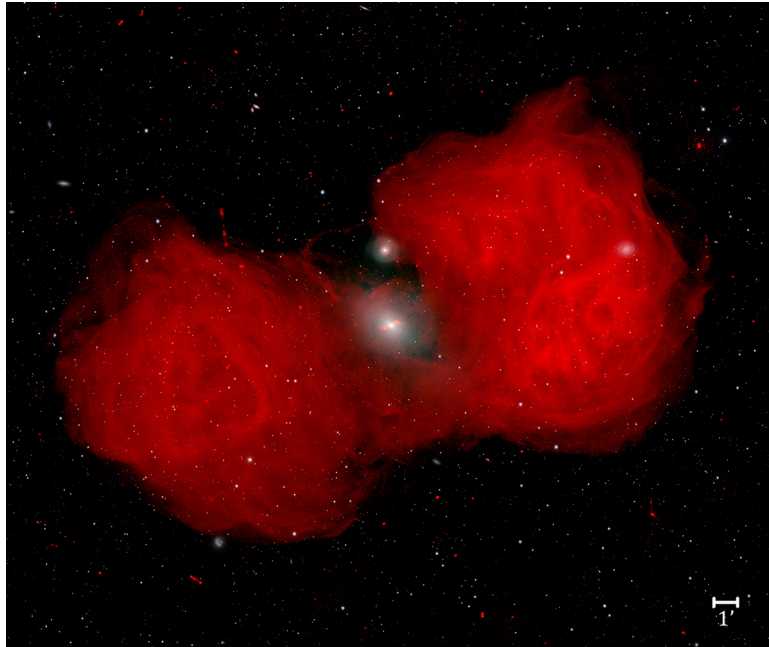


FIGURE 3.10: MeerKAT radio image of Fornax A at 1.44 GHz [23].

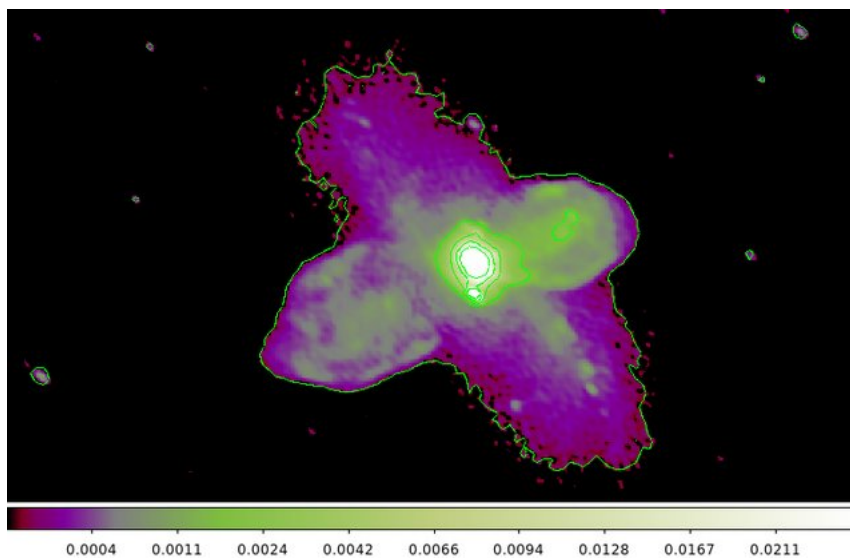


FIGURE 3.11: MeerKAT radio image of Circinus at 1.38 GHz [45].

Chapter 4

Conclusion

4.1 Summary of results

Hydra A was observed using the MeerKAT radio telescope; using these observations, we produced the most sensitive images of Hydra A in the frequency range between 1000 MHz and 1485 MHz to date. From our analysis of the morphology of Hydra A, we find that Hydra A is made up of a central core region, two inner lobes, and two outer radio lobes, one extending in the northern direction and one in the southern direction. We find an interesting tail-like structure extending out from the southern lobe, exhibiting an almost unusual bend. From our spectral analysis, we find that the spectrum of Hydra A is characterised by a spectral break and not a single power law. We find that the tail-like region shows the steepest spectral index, while the northern lobe exhibits the flattest spectral index. Finally, our modelling of the spectrum in Hydra A reveals that the Kardashev Pacholczyk (KP) model for spectral ageing satisfactorily describes the overall spectrum. We find that the tail-like region is the oldest region of the galaxy, and we set an age estimate for the system to be ~ 140 Myrs.

4.1.1 Summary of possible scenarios

There are two possible scenarios that could explain the results of the morphological analysis, spectral analysis and modelling of the spectrum:

- i. The bend that is seen in the southern lobe leading into the tail-like region is the result of some asymmetries in the ICM, i.e., a change in the density of the ICM in this region may

be responsible for the change in direction of the emission - this can be checked with X-ray observations, if the observations are deep enough.

- ii. The northern and southern lobes are still connected to the jets and are being injected with younger electrons. The tail-like region is a remnant of an older generation of AGN activity and is completely disconnected from the jets. The precession of the nuclear region suggests that an earlier outburst could have been emitted in a different direction than the outburst responsible for the northern and southern lobes, resulting in the unusual tail-like region of emission.

In summary, radio observations of Hydra A made using the MeerKAT radio telescope were carried out successfully. We reduced the data and created four radio maps between 1000 MHz and 1485 MHz. We classified the radio morphology of Hydra A and performed a spectral analysis. We modelled the radio spectrum in Hydra A and set constraints on the magnetic field strength and age of the three regions of interest. We found that the magnetic field ranges between $2\mu G$ and $37\mu G$ for different regions of the galaxy and estimate the age of the system to be around 140 Myrs based on the oldest region of the galaxy.

4.2 Future Work

We are currently preparing a proposal for the MeerKAT 2023 open call. We propose to obtain observations of Hydra A to explore the intersection point between the spectra fitted to the VLA observations and those fitted to our MeerKAT observations. This would fall in the intermediate frequency range (between 330 MHz and 1000 MHz) located within the MeerKAT UHF band. The UHF band is well suited for the study of faint emission (such as that of the tail-like region) due to its high sensitivity at low frequencies. These observations will allow us to conduct a deep study of the tail-like structure extending from the southern lobe and investigate the observed spectral break in the power-law spectrum.

Appendix A

Appendix

A.1 Data Reduction

```

1 schema_version: 1.1.0
2 general:
3   prefix: Lband_1485MHz
4   rawdatadir: /mnt/storage1/MeerKAT/hydra/scratch/kat #<-----
5   msdir: /mnt/storage1/users/MikaNaidoo/msdir
6   output: L-band1485MHz
7   getdata:
8     dataid:
9     - '*'
10    extension: ms
11  obsconf:
12    refant: auto
13  transform:
14    enable: true
15    field: calibrators
16    label_out: cal
17    split_field:
18    enable: true
19    spw: "*" :1445~1525MHz" # discard bandpass rolloff when splitting
20  <-----
21    col: data
22  prep:
23    enable: true
24    label_in: cal

```

```
25 field: calibrators
26 specweights:
27 enable: true
28 mode: uniform
29 flag:
30 enable: true
31 field: calibrators
32 label_in: cal
33 flag_autocorr:
34 enable: true
35 flag_spw:
36 enable: true
37 chans: '*:856~880MHz , *:1658~1800MHz, *:1419.8~1421.3MHz'
38 ensure_valid: true
39 flag_antennas:
40 enable: false
41 antennas: m021,m038
42 flag_scan:
43 enable: false
44 scans: '4'
45 flag_mask:
46 enable: true
47 mask: meerkat.rfimask.npy
48 uvrange: '0~500'
49 flag_rfi:
50 enable: true
51 flagger: tricolour
52 tricolour:
53 strategy: gorbachev.yaml # make sure the file is in the input folder
54 crossscal:
55 enable: true
56 uvrange: '>150'
57 label_in: cal
58
59 set_model:
60 enable: true
61 meerkat_skymodel: true
62 primary:
63 reuse_existing_gains: true
```

```
64 order: KGBAKGB
65 combine: ["", "", "", null, "", "", scan]
66 solint: [inf, inf, inf, null, 60s, 60s, inf]
67 calmode: [a, ap, ap, null, a, ap, ap]
68 b_fillgaps: 70
69 plotgains: true
70 secondary:
71 reuse_existing_gains: true
72 order: KGAKF
73 apply: B
74 combine: ["", "", null, "", ""]
75 solint: [inf, inf, null, inf, inf]
76 calmode: [a, ap, null, a, ap]
77 plotgains: true
78 apply_cal:
79 applyto:
80 - gcal
81 - bpcal
82 inspect:
83 enable: true
84 label_in: 'cal'
85 label_plot: 'lgc'
86 field: 'calibrators'
87 dirname: crosscal
88 real_imag:
89 enable: false
90 avgtime: '60'
91 amp_phase:
92 enable: false
93 avgtime: '60'
94 amp_uvwave:
95 enable: false
96 avgtime: '60'
97 amp_ant:
98 enable: false
99 avgtime: '60'
100 phase_uvwave:
101 enable: false
102 avgtime: '60'
```

```

103 amp_scan:
104 enable: false
105 avgtime: '60'
106 shadems:
107 enable: true
108 default_column: CORRECTED_DATA
109 plots_by_field:
110 - "-x BASELINE_M -y FREQ -c amp"
111 - "-x real -y imag -c SCAN_NUMBER --cnum 100"
112 - "-x real -y imag -c ANTENNA1 --cnum 100"
113 - "-x ANTENNA1 -y ANTENNA2 -c SCAN_NUMBER --cnum 100 --aaxis phase --ared
114 std"
115 - "-x ANTENNA1 -y ANTENNA2 -c SCAN_NUMBER --cnum 100 --aaxis amp --ared
116 mean"
117 - "-x UV -y amp -c SCAN_NUMBER --cnum 100"
118 - "-x UV -y amp -c ANTENNA1 --cnum 64"
119 - "-x UV -y phase -c ANTENNA1 --cnum 64"
120 - "-x FREQ -y amp -c SCAN_NUMBER --cnum 100"
121 - "-x FREQ -y amp -c ANTENNA1 --cnum 64"
122
123 - "-x U -y V -c amp"
124 - "-x U -y V -c phase --cmin -5 --cmax 5"
125 plots:
126 - "-x real -y imag -c SCAN_NUMBER --cnum 100 --col
127 CORRECTED_DATA/MODEL_DATA --iter-field"
128 - "-x real -y imag -c ANTENNA1 --cnum 100 --col
129 CORRECTED_DATA/MODEL_DATA --iter-field"
130 # - '-x FREQ -y phase --ymin -40 --ymax 40 -c SCAN_NUMBER --cnum 100
131 --field {bpcal} --dir {msbase}-bpcal-byant --iter-ant'
132 # - '-x FREQ -y phase --ymin -40 --ymax 40 -c SCAN_NUMBER --cnum 100
133 --field {gcal} --dir {msbase}-gcal-byant --iter-ant'
134 # - '-x FREQ -y phase --ymin -40 --ymax 40 -c ANTENNA1 --cnum 100 --field
135 {all_fields} --dir {msbase}-byscan --iter-scan'
136 - '-x FREQ -y amp:I -c SCAN_NUMBER --cnum 100 --cmin 0 --cmax 30 --field
137 {bpcal} --dir {msbase}-bpcal-iamp-byant --iter-ant'
138 # - '-x FREQ -y amp:I -c SCAN_NUMBER --cnum 100 --cmin 0 --cmax 8 --field
139 {gcal} --dir {msbase}-gcal-iamp-byant --iter-ant'
140 # - '-x FREQ -y amp:I -c ANTENNA1 --cnum 100 --cmin 0 --cmax 30 --field
141 {all_fields} --dir {msbase}-iamp-byscan --iter-scan'

```

```

142 # - '-x FREQ -y amp:Q -c SCAN_NUMBER --cnum 100 --cmin 0 --cmax 5 --field
143 {bpcal} --dir {msbase}-bpcal-qamp-byant --iter-ant'
144 # - '-x FREQ -y amp:Q -c SCAN_NUMBER --cnum 100 --cmin 0 --cmax 5 --field
145 {gcal} --dir {msbase}-gcal-qamp-byant --iter-ant'
146 # - '-x FREQ -y amp:Q -c ANTENNA1 --cnum 100 --cmin 0 --cmax 5 --field
147 {all_fields} --dir {msbase}-qamp-byscan --iter-scan'
148 - '-x ANTENNA1 -y ANTENNA2 -a CORRECTED_DATA:amp --ared std --cmap pride
149 --dir {msbase}-stdamp-byscan --iter-scan'
150 - '-x ANTENNA1 -y ANTENNA2 -a CORRECTED_DATA:phase --ared std --cmap pride
151 --dir {msbase}-stdphase-byscan --iter-scan'
152 - '-x FREQ -y SCAN_NUMBER -a CORRECTED_DATA:amp --ared std --cmap pride
153 --dir {msbase}-stdamp-byant --iter-ant'
154 - '-x FREQ -y SCAN_NUMBER -a CORRECTED_DATA:phase --ared std --cmap pride
155 --dir {msbase}-stdphase-byant --iter-ant'
156 - '-x BASELINE_M -y FREQ --iter-scan -a CORRECTED_DATA:imag --ared std
157 --amin 0 --amax 2 --cmap pride --dir {msbase}-stdimag-byscan'
158 ignore_errors: true
159 transform__2:
160   enable: true
161   split_field:
162     enable: true
163   spw: "*:1445~1525MHz"
164   otfcsl:
165     enable: true
166   label_cal: '1gc1'
167 prep__2:
168   enable: true
169   label_in: corr
170   field: target
171   specweights:
172     enable: true
173   mode: uniform
174 flag__2:
175   enable: true
176   field: target
177   label_in: corr
178   flag_rfi:
179     enable: true
180   col: DATA

```

```

181 flagger: tricolour
182 tricolour:
183 strategy: gorbachev.yaml # make sure the file is in the input folder
184
185 selfcal:
186 enable: true
187 img_npix: 3000
188 img_cell: 1.3
189 cal_timeslots_chunk: 15
190 cal_niter: 6
191 image:
192 enable: true
193 calibrate:
194 enable: true
195 gsols_timeslots: [15,]
196 transfer_model:
197 enable: false

```

A.2 Modelling the radio spectrum of Hydra A

```

1  #!/usr/bin/env python
2  # coding: utf-8
3
4  # In[ ]:
5
6
7  import numpy as np
8  import math as m
9  from matplotlib import pyplot as plt
10
11 def F(t):
12     res=1.78*(t**0.3)*m.exp(-t)
13     return res
14
15 def integral(x, y):
16     n=x.size
17     res=0.0
18     for i in range(0, n-1):

```

```

19     a=(x[i+1]-x[i])
20     b=(y[i]+y[i+1])/2.
21     res=res+a*b
22     return res
23
24
25 def pachol_radio_data(k0, s, t, bmu, xdata):
26
27 #pro pachol_radio_data,k0,s,t,bmu,xdata,emiss
28 #;k0: intial normalisation
29 #;s: initial spectral index  $E^{-s}$ 
30 #;t: final age in Myr
31 #;bmu: magnetic field value in microG
32 #;xdata: all the frequencies in MHz
33     tfin=t*1e6*3.156e7 #; in seconds
34     gelm=1000
35     assegl=np.zeros(gelm+1)
36     for i in range(0, gelm):
37         assegl[i]=10**(1.0+5.0*i/gelm)
38     ngel0=np.zeros(gelm+1)
39     for i in range(0, gelm):
40         ngel0[i]=(assegl[i])**(-s)
41
42     ngel=np.zeros(gelm+1)
43     thm=1000
44
45     assest=np.zeros(thm+1)
46
47     for j in range(0, thm+1):
48         #assest[j]=m.pi/18.0+(m.pi/2.0-m.pi/18.0)*j/thm
49         assest[j]=0.+(m.pi/2.)*j/thm
50
51     z=0.055 #redshift
52     intth=np.zeros(thm+1)
53
54     assenu=xdata
55     num=assenu.size
56
57

```

```

58  neterm=1e-6# ;cm^-3
59  r0=2.82e-13# ;cm
60  me=0.511e-3# ;GeV
61  c=3.0e10# ;cm/s
62  nu0=2.8*bmu*1e-6# ;MHz
63  nup=8980.*neterm**0.5*1e-6# ;MHz
64  a=2.0*m.pi*m.sqrt(3.)*r0*me/c*1e6*nu0
65  integel=np.zeros(gelm+1)
66  emiss=np.zeros(num)
67
68  for k in range(0, num):
69      nu=assenu[k]
70      for i in range(0, gelm):
71          gel=assegel[i]
72          x=2.*(nu/(3.*nu0*gel**2.))#*(1.+(gel*nup/nu)**2.)*(3./2.)
73          for j in range(0, thm):
74              theta=asseth[j]
75              if (theta==0):
76                  intth1=0.0
77              else:
78                  intth1=m.sin(theta)*F(x/m.sin(theta))*m.sin(theta)*0.5
79                  bic=(1.37e-20)*(1.0+z)**4 # (1.0e-6) to delete
80                  bsyn=(1.94e-21)*(bmu*m.sin(theta))**2
81                  btot=bsyn+bic
82                  gelmax=1./(btot*tfin)
83                  if (gel<gelmax):
84                      intth2=k0*(gel**(-s))*(1.0-btot*tfin*gel)**(s-2.0)
85                  else:
86                      intth2=0.
87                  intth[j]=intth1*intth2
88                  integel[i]=a*integral(asseth,intth)
89      emiss[k]=integral(assegel,integel)
90  return emiss
91
92
93 def fit_norm(xdata,ydata,yerr,frad, val):
94     nm=xdata.size
95     fitfrad=np.zeros(nm)
96     tempchi=np.zeros(nm)

```

```

97     im=1000
98     assenorm=np.zeros(im+1)
99     for i in range(0, im+1):
100         assenorm[i]=0.98+0.04*i/im
101     chiq=np.zeros(im+1)
102     for i in range(0, im+1):
103         norm=assenorm[i]
104         for n in range(0, nm):
105             fitfrad[n]=norm*frad[n]
106             tempchi[n]=((ydata[n]-fitfrad[n])**2)/(yerr[n])**2
107         chiq[i]=np.sum(tempchi)
108     chimin=np.min(chiq)
109     normchimin=assenorm[np.argmin(chiq)]
110     return chimin if val>0.0 else normchimin
111
112
113 def superfit_hydra(s, xdata, ydata, yerr):
114     jm=100#100
115     bmin=1#
116     bmax=50#90
117     asseb=np.zeros(jm)
118     for j in range(0, jm):
119         asseb[j]=bmin+(bmax-bmin)*j/(jm-1)
120     km=140#35
121     tmin=5#25
122     tmax=180#100
123     asset=np.zeros(km)
124     for k in range(0, km):
125         asset[k]=tmin+(tmax-tmin)*k/km
126     chi=np.zeros((jm, km))
127
128     for j in range(0, jm):
129         b=asseb[j]
130         for k in range(0, km):
131             t=asset[k]
132             emiss=pachol_radio_data(1., s, t, b, xdata)
133             chi[j,k]=fit_norm(xdata, ydata, yerr, emiss*1.821/emiss[4], 1.0)
134             #print(100.0*j+k)
135     chimin=np.min(chi)

```

```

136
137     for j in range(0, jm):
138         b=aseb[j]
139         for k in range(0, km):
140             t=asset[k]
141             if (chi[j,k] == chimin):
142                 jbar=j
143                 kbar=k
144                 bbest=b
145                 tbest=t
146                 emiss=pachol_radio_data(1., s, tbest, bbest, xdata) # DP
147                 #print(emiss)
148                 norm2=fit_norm(xdata, ydata, yerr, emiss*1.821/emiss[4], -1.0) # DP
149                 print(np.multiply(emiss, norm2*1.821/emiss[4])) # DP
150     print(bbest,tbest,chimin)
151
152     blow=0.
153     bup=0.
154     tlow=0.
155     tup=0.
156
157     if (jm >= 3):
158         for j in range(0, jm-1):
159             if ((chi[j,kbar] >= chimin+1) and (chi[j+1,kbar]<=chimin+1)):
160                 blow=abs(aseb[j]-bbest)
161                 print(j, blow, asseb[j])
162             if ((chi[j,kbar] <= chimin+1) and (chi[j+1,kbar]>=chimin+1)):
163                 bup=abs(aseb[j+1]-bbest)
164                 print(j+1, bup, asseb[j+1])
165         #print(blow,bup)
166
167     if (km >= 3):
168         for k in range(0, km-1):
169             if ((chi[jbar,k] >= chimin+1) and (chi[jbar,k+1]<=chimin+1)):
170                 tlow=abs(asset[k]-tbest)
171                 print(k, tlow, asset[k])
172             if ((chi[jbar,k] <= chimin+1) and (chi[jbar,k+1]>=chimin+1)):
173                 tup=abs(asset[k+1]-tbest)
174                 print(k+1, tup, asset[k+1])

```

```
175     #print(tlow,tup)
176
177     np.savetxt('/home/MikaNaidoo/finalmastersplots/test_wiC_2p00_min10v2NEWFINAL.out', chi)
178     import astropy.io.fits as pyfits
179     hdu = pyfits.PrimaryHDU(chi)
180     hdu.writeto('/home/MikaNaidoo/finalmastersplots/test_wiC_2p00_min10v2NEWFINAL.fits')
181
182
183 xdata=np.array([74.0, 327.0, 1000, 1100, 1330, 1485])
184 ydata=[91.444, 16.802, 3.181, 2.682, 1.821, 1.494]
185 # for the confused background region:
186 yerr=[9.1444, 0.093, 0.018672, 0.018989, 0.009504, 0.010558]
187
188
189
190 superfit_hydra(2.00, xdata, ydata, yerr)
```

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