A study of the lobes of the radio galaxy Hydra A using MeerKAT observations

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Abstract. The radio galaxy Hydra A hosts a pair of hundred-kiloparsec diameter radio lobes that are being powered by one of the most powerful AGN outbursts known to date. Observations in the radio band provide us with an excellent probe for studying a high-energy electron population residing in the lobes. Using the MeerKAT observations of Hydra A, we computed the flux densities of these giant lobes at several frequencies and combined them with previous results from VLA observations at lower frequencies. We found that the spectrum in the MeerKAT frequency range is well described by a power law, while the overall spectrum indicates a steepening with frequency. We set constraints on the magnetic field strength and the age of the giant lobes through modelling of the temporal evolution of electron spectra under the influence of synchrotron losses.

1. Introduction

The powerful radio galaxy Hydra A lies at the center of the galaxy cluster Abell 780, which is located at a redshift of $z = 0.054$. Hydra A is classified as a type I Fanaroff-Riley (FRI)[1] radio galaxy, which is characterised by a high surface brightness near the center and a lower surface brightness further out. When matter accretes onto a central supermassive black hole (SMBH), a large amount of energy is expelled into the ambient medium in the form of highly collimated, highly relativistic jets. When these jets encounter the intracluster medium (ICM), they inflate giant radio lobes. This expulsion of energy can occur more than once during the lifetime of the radio galaxy resulting in multiple generations of outbursts. Depressions in the X-ray emission surrounding Hydra A have been discovered [2,3] and are coincident with the radio lobes. This suggests that the inflation of radio lobes is the driving mechanism responsible for the displacement of the X-ray emitting gas in the ICM. Hydra A has experienced three

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generations of outbursts, indicated by the three pairs of X-ray cavities [3] and radio bubbles of different ages and energetics[4].

The energetics involved in an AGN outburst can be huge, even exceeding 10^{61} erg, which corresponds to the amount of energy released in tens of billions of supernovae explosions [5]. The most powerful AGN outbursts are found in MS 0735+7421, Hercules A, and Hydra A[5]. The bubbles in these systems have ages of about 100 million years. Their energy content is determined using arguments of pressure balance between the thermal ICM and the relativistic plasma within the bubbles. The energy required to expand bubbles with volume V into a surrounding ICM with pressure p ranges from $2pV$ to $4pV$ [3]. However, the nature of the principal component responsible for the pressure support and which fills the bubbles in the ICM is not known to date. Among the possibilities for the pressure support in the bubbles are cosmic-ray hadrons or electrons, hot plasmas, or magnetic fields. While gamma-ray observations allow us to test a hadronic model [6,7] and measurements of the Sunyaev-Zel'dovich effect are a tool to test hot plasmas [8] and non-thermal electrons [9] inside the bubbles, observations in the radio band provide us with a probe of magnetic fields.

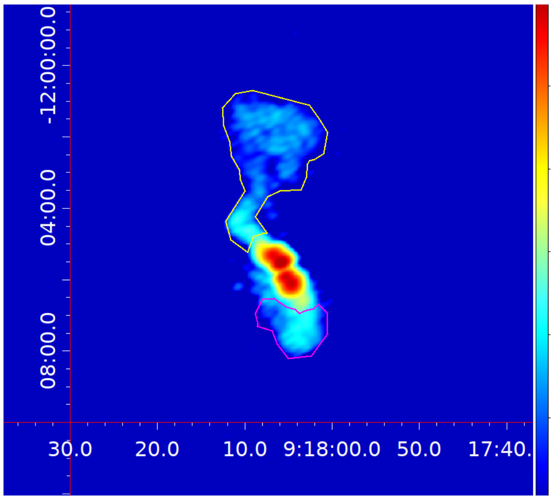
Synchrotron radiation and inverse Compton scattering cause energy losses of high-energy electrons. The former is dominant if the magnetic field strength is above several μG. The radiative cooling of electrons results in time evolution of an electron spectrum. As electrons lose energy, the radio spectrum steepens, a phenomenon known as spectral aging [10, 11, 12]. A theory of synchrotron aging has been applied to the lobes of FRI radio galaxies (e.g., Fornax A [13]) and FRII radio galaxies (e.g., Cygnus A [14]).The previous detection of the giant Hydra A lobes at 74 MHz, 327 MHz, and 1415 MHz [4] suggested that the spectrum steepens in this frequency range. In these proceedings, we report the preliminary results obtained from our spectral analysis of MeerKAT observations of Hydra A between 960 MHz and 1525 MHz.

2. Observations and analysis

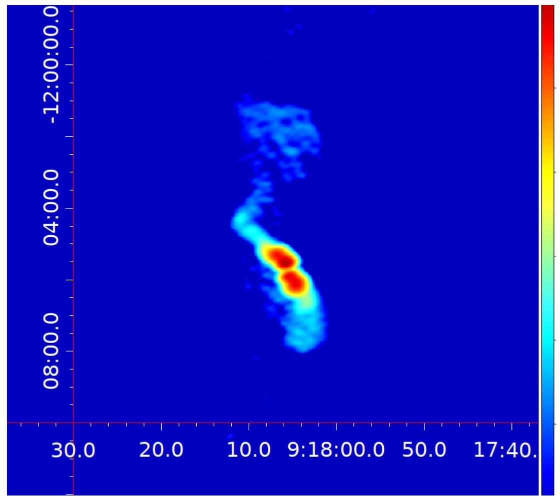
Hydra A was observed with the MeerKAT radio telescope on 30 May 2019 (Proposal ID: SCI-20190418-PA-01; PI: Prokhorov). The observations were made using the entire array which is made up of 64 antennas, each 13.5 m in diameter. MeerKAT is equipped with L-band receivers and a correlator with 4096 channels. For this study, we used 30 minutes of these observations accumulated over a frequency range of 856 MHz - 1712 MHz. We reduced the data using the Containerised Automated Radio Astronomy Calibration (CARACal) pipeline [15]. To derive the flux densities from the radio maps obtained with CARACal, we used the radioflux routine by M J Hardcastle (https://www.extragalactic.info/ mjh/radio-flux.html).

3. Results

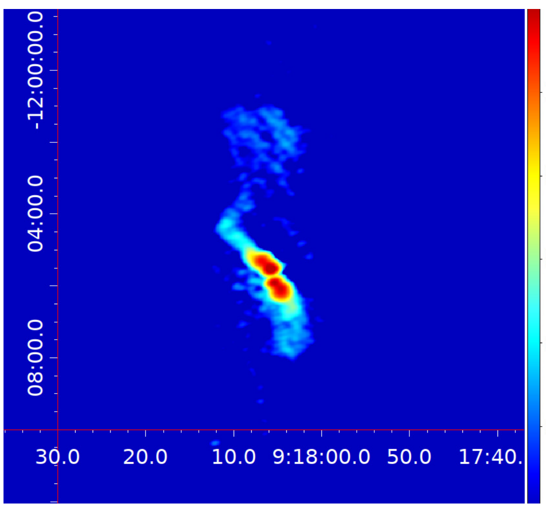
We produced four radio maps of Hydra A at four frequencies, 1000 MHz, 1100 MHz, 1330 MHz and 1485 MHz with a bandwidth of 80 MHz and in units of Jy/beam. These maps shown in Figure 1 reveal two bright inner lobes extending in the northern and southern directions and two larger outer lobes. The morphology of these spatial structures is in good agreement with that obtained from the observations of the Very Large Array (VLA) telescope (Figure 1 in [4]) at 1415 MHz. The MeerKAT and VLA radio maps display similar spatial structures. However, the MeerKAT observations for the first time reveal finer details such as the bridge at (RA, Dec)=(9h18m8s, -12d03m28s) between the bright central source and the northern outer lobe.



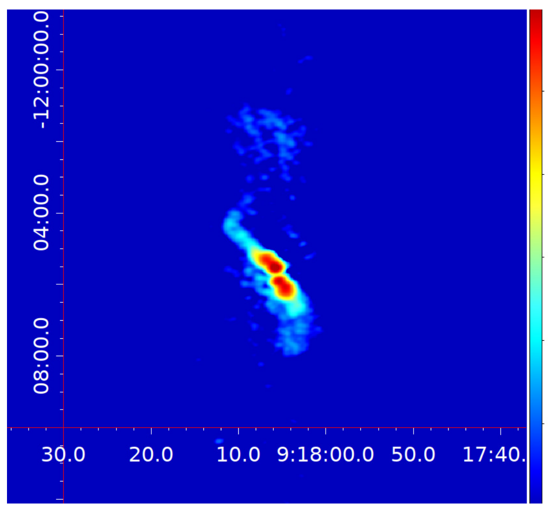
(a) Hydra A at 1000 MHz.



(b) Hydra A at 1100 MHz.



(c) Hydra A at 1330 MHz.



(d) Hydra A at 1485 MHz.

Figure 1: Radio maps of Hydra A between 1000 MHz and 1485 MHz shown in equatorial coordinates of right ascension (hours) and declination (deg.). The colour bar represents the radio intensity in units of Jy/beam. The size of the beam is 20×12 arcsec^2 at 1000 MHz, 18×11 arcsec^2 at 1100 MHz, 15×9 arcsecs^2 at 1330 MHz, and 13×8 arcsec^2 at 1485 MHz.

To study the spectral behaviour between 960 MHz and 1525 MHz, we computed the flux densities and corresponding uncertainties for the outer lobes using the MeerKAT observations. The regions that we have defined as the outer lobes are indicated in Figure 1a. The fluxes are computed from the regions which significantly exceed in size the synthesized beams at the four frequencies.

We combined our data points with the two low-frequency data points at 74 MHz and 327 MHz adopted from [3, 15] to produce the multi-frequency radio spectrum of Hydra A shown in Figure 2. We checked and found that the fluxes obtained from the VLA maps do not depend strongly on the template selection, this will be addressed in a future journal paper. The spectrum in the

MeerKAT frequency range is well described by a steep power law with a spectral index of 2.05 with a statistical error of 0.04. Extrapolating the derived power law to the 74 MHz frequency, assuming a best fit spectral index of 2.05 gives a flux density of $\sim$ 500 Jy which is significantly higher than the measured flux density given by 221 $\pm$ 30 Jy. This suggests that a spectral break is present in the overall spectrum. The most likely mechanism to produce this break is spectral aging.

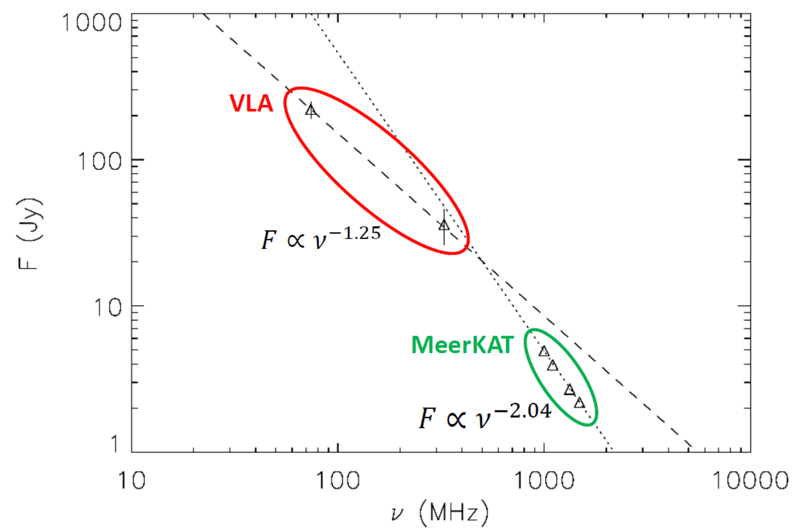


Figure 2: The radio spectrum of Hydra A using our four MeerKAT data points combined with the two low-frequency data points at 327 MHz and 74 MHz.

We find that the Kardashev-Pacholczyk model [9,10] for spectral aging satisfactorily describes the overall spectrum. To model the spectral steepening (see Figure 3), we assumed values for the age and magnetic field strength of 35 million years and 18 μG, respectively. The best-fit values are found using automated χ^2 minimization.

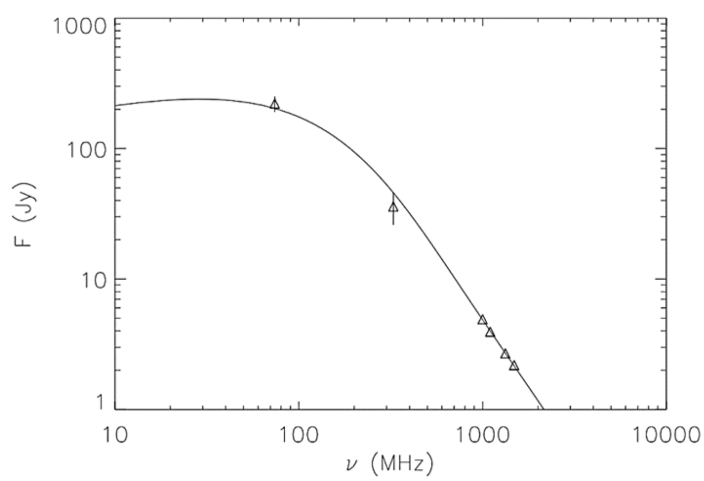


Figure 3: An illustrative model for the overall radio spectrum of the outer lobes of Hydra A. The values of the magnetic field strength and age of the outer lobes are derived from the modelling.

4. Conclusion

We present four MeerKAT radio maps of Hydra A at 1000, 1100, 1330 and 1485 MHz. These radio maps reveal an extended radio structure that consists of two bright inner radio lobes and two giant outer radio lobes. The entire spatial structure is consistent with previous observations. We computed the flux densities and combined them with those from the previous low-frequency VLA observations. We found that the spectrum for the giant lobes in the MeerKAT frequency range is well described by a steep power law with a spectral index $\alpha = 2.05 \pm 0.04$. The MeerKAT data, in conjunction with the low frequency VLA observations, reveal the presence of a spectral break. To explain this spectral break, we used the Kardashev-Pacholczyk model for spectral aging due to synchrotron losses of high-energy electrons.

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References

[1] Fanaroff B L and Riley J M 1974 The morphology of extragalactic radio Sources of high and low Luminosity *MNRAS* **167** 31P-36P
[2] Nulsen P E J, McNamara B R, Wise M W and David L P 2005 The cluster-scale AGN outburst in Hydra A *ApJ* **628** 629-36
[3] Wise M W, McNamara B R, Nulsen P E J, Houck J C and David L P 2007 X-Ray supercavities in the Hydra A cluster and the outburst history of the central galaxy's active nucleus *ApJ* **659** 1153-58
[4] Lane W M, Clarke T E, Taylor G B, Perley R A and Kassim N E 2004 Hydra A at low radio frequencies *AJ* **127** 48-52
[5] McNamara B R and Nulsen P E J 2007 Heating hot atmospheres with active galactic nuclei *ARA&A* **45** 117-75
[6] H.E.S.S. collaboration et al. 2012 Constraints on the gamma-ray emission from the cluster-scale AGN outburst in the Hydra A galaxy cluster *A&A* **545** id.A103
[7] Prokhorov D A and Churazov E M 2017 Confinement and diffusion time-scales of CR hadrons in AGN-inflated bubbles *MNRAS* **470** 3388-94
[8] Prokhorov D A, Moraghan A, Antonuccio-Delogu V and Silk J 2012 Simulating Sunyaev-Zel'dovich intensity maps of giant active galactic nucleus cocoons *MNRAS* **425** 1753-62
[9] Colafrancesco S 2005 The SZ effect from cluster cavities *A&A* **435** L9-L12
[10] Kardashev N S 1962 Nonstationarity of spectra of young sources of nonthermal radio emission *SvA* **6** 317
[11] Pacholczyk A G 1970 *Radio Astrophysics: Nonthermal Processes in Galactic and Extragalactic Sources* vol XXI+269 (San Francisco: Freeman)
[12] Jaffe W and Perola G 1973 Dynamical models of tailed radio sources in clusters of galaxies *A&A* **26** 423-35
[13] Maccagni F M, Murgia M, Serra P, Govoni F, Morokuma-Matsui K, Kleiner D, Buchner S, Józsa G I G, Kamphuis P, Makhathini S et al. 2020 The flickering nuclear activity of Fornax A *A&A* **634** A9
[14] Carilli C L, Perley R A, Dreher J W and Leahy J P 1991 Multifrequency radio observations of Cygnus A: spectral aging in powerful radio galaxies *ApJ* **383** 554-73
[15] Józsa G I G, White S V, Thorat K, Smirnov O M, Serra P, Ramatsoku M, Ramaila A J T, Perkins S J, Molnár D C, Makhathini S et al. 2020 *ASPC* **527** 635
[16] Bîrzan L, McNamara B R, Nulsen P E J, Carilli C L, and Wise M W. 2008 Radiative efficiency and content of extragalactic radio sources: toward a universal scaling relation between jet power and radio power *ApJ* **686** 859-80