J1615+5452: a remnant radio galaxy in the ELAIS-N1 field

Z. Randriamanakoto,1 C. H. Ishwara-Chandra2,3 and A. R. Taylor3,4,5

1South African Astronomical Observatory, PO Box 9, Observatory 7935, South Africa
2National Centre for Radio Astrophysics, TIFR, Post Bag No. 3, Ganeshkhind Post, 411007 Pune, India
3Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
4Department of Physics and Astronomy, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa
5Inter-University Institute for Data Intensive Astronomy, Private Bag X3, Rondebosch 7701, South Africa

ABSTRACT

We report the discovery of a remnant radio active galactic nucleus (AGN) J1615+5452 in the field of ELAIS-N1. GMRT continuum observations at 150, 325, and 610 MHz combined with archival data from the 1.4 GHz NVSS survey were used to derive the radio spectrum of the source. At a redshift $z \sim 0.33$, J1615+5452 has a linear size of $\sim 100$ kpc and spectral indices ranging between $\alpha_{1400}^{150} \sim -1.5$ and $\alpha_{150}^{325} \approx -0.61 \pm 0.12$. While the source has a diffuse radio emission at low frequencies, we do not find evidence of core, jets, or hotspots in the 1.4 GHz VLA data of $\sim 5$ arcsec angular resolution. Such morphological properties coupled with a curved radio spectrum suggest that the AGN fueling mechanisms undergo a shortage of energy supply which is typical of a dying radio AGN. This is consistent with the observed steep curvature in the spectrum $\Delta \alpha \approx -1$, the estimated synchrotron age of $t_s = 76.0^{+7.4}_{-8.7} \text{Myr}$ and a $t_{off}/t_s$ ratio of $\sim 0.3$.

Key words: galaxies: active – galaxies: individual: J1615+5452 – radio continuum: galaxies.

1 INTRODUCTION

In the active stage that usually lasts $\sim 10$–100 Myr (Cordey 1986), the classical morphology of a radio galaxy is characterized by the presence of a core, a pair of lobes and including jets, and/or hotspots. Such features indicate the continuous injection (CI) of relativistic electrons that fuel the active galactic nuclei (AGNs). Following the active phase of the radio AGNs, the source enters the so-called remnant or dying phase, as the nuclear engine switches off and the active phase of the radio AGNs, the source enters the so-called

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In the typical case of a remnant AGN, its low-frequency spectral indices, i.e. \(\Delta \alpha = \alpha_{\text{high}} - \alpha_{\text{low}}\), and its value correlates with the different evolutionary stages of the radio galaxy. In the typical case of a remnant AGN, \(\Delta \alpha \ll -0.5\) (Murgia et al. 2011).

Since remnant AGNs represent the final stage in the evolution of a radio galaxy, they are important objects for understanding of the radio galaxy life cycle, i.e. from the triggering of relativistic jets to the nuclear engine switch off, possibly followed by a restarting radio galaxy life cycle, i.e. from the triggering of relativistic jets and radiative losses are expected to regulate the evolution of the remnant radio plasma once the radio jets switch off. thorough investigations of the AGN duty cycle and its dynamics are thus crucial to put constraints on the radio galaxy evolution models (e.g. Brienza et al. 2017; Mahatma et al. 2018; Shabala et al. 2020). An extensive analysis of these sources will also help to address one of the key questions in the field of galaxy evolution: the co-evolution process between the supermassive black hole (SMBH) and its host galaxy (e.g. Silk & Rees 1998; Kormendy & Ho 2013; Sijacki et al. 2015). Although the tight correlation between the SMBH growth and the galaxy build-up has already been widely acknowledged, the impacts of the AGN physical properties and AGN feedback on the cosmic evolution of the host galaxy and its environment are still under debate (Jahnke & Macciò 2011; Fabian 2012 and references therein).

Because of the rapid time-scale of particle energy decay, and the paucity of high-sensitivity data at multiple wavelengths, only a handful of steep spectrum dying radio sources have been observed, especially in the cm wavelength regime. However, in addition to their spectral signature, fossil AGNs may be recognizable in deep low-frequency images as relatively bright and diffuse emission devoid of a core and/or hotspots and with resolutions of a few arcseconds. Such emission arises from low-energy particles that are relatively unaffected by the fast spectral evolution (Parma et al. 2007; Murgia et al. 2011; Brienza et al. 2017; Morganti 2017).

In this work, we report the discovery of a new remnant radio galaxy, J1615+5452, in the field of the European Large-Area *ISO* Survey-North 1 (ELAIS-N1 or EN1; Oliver et al. 2000) from the GMRT 610 MHz observations. We use the archival low-frequency GMRT observations at 150 MHz and 325 MHz and 1400 MHz data from the Karl G. Jansky Very Large Array (VLA) to obtain the source radio spectrum and to reconstruct its history of AGN activity.

The paper is structured as follows. We describe the observations and data processing in Section 2. Radio morphology and integrated spectra of the source are reported in Sections 3 and 4. This section investigates the nature of the remnant AGN. We discuss the results in Section 5 and provide a summary of the work in Section 6. We adopt the following cosmological parameters throughout the paper: \(H_0 = 67.8\, \text{km}\, \text{s}^{-1}\, \text{Mpc}^{-1}\), \(\Omega_m = 0.308\), and \(\Omega_{\Lambda} = 1 - \Omega_m\) (Planck Collaboration XIII 2016).

### 2 OBSERVATIONS AND DATA PROCESSING

**Table 1.** Log of the GMRT observations of the ELAIS-N1 field.

| Band (MHz) | Central Fqcy (MHz) | BW (MHz) | Project Code and PI | Obs. date | On-source time (h) | Resolution (arcsec) | \(\sigma_{\text{rms}}\) (\(\mu\text{Jy beam}^{-1}\)) |
|-----------|-------------------|---------|---------------------|----------|-------------------|---------------------|---------------------|
| 150       | 153               | 6       | 12MDBG01, Dennefeld  | May 2007 | 17 x 0.5          | 38 x 21             | 3500                |
| 325       | 323               | 32      | 24_026, Wadadekar    | May 2013 | 2 x 8.5           | 9                   | 70                  |
| 610       | 610               | 32      | 19_064, 20_020, 21_086, 22_057, Taylor | 2011−2017 | 3 x 1            | 6                   | 40                  |

**Notes:** Columns 1 and 2: nominal and precise central frequencies; Column 3: bandwidth used for mapping the field; Column 4: GMRT project code and name of the principal investigator; Column 5: date of the observations; Column 6: on-source integration time; Columns 7 and 8: angular resolution and rms noise of the radio image.
an ~5 min secondary calibrator observation to track the ionospheric conditions, the RFI contamination, and any variations in the receiver system throughout the entire observing run. We have processed this archival data through the same CASA-based pipeline used to analyse the wide-area 610 MHz data. 3C 286 and 3C 48 were used for flux calibration and 1459+716 for phase calibration. Each day’s data were calibrated separately and the split files of target field were combined before imaging with CASA tclean using the default robust weighting of 0. We performed four rounds of phase-only self-calibration followed by five rounds of amplitude and self-calibration, which included residual-based flagging in between each round. The final image reached a sensitivity down to $\sigma \approx 70 \, \mu$Jy beam$^{-1}$ without applying direction-dependent calibration. Primary beam correction was done following standard procedures. Primary calibration was performed for flux calibration and 1459+716 for secondary calibration. J1615+5452 is clearly detected in this image and the source is much smaller than the largest angular size that can be imaged using the GMRT at 325 MHz (~30 arcmin).

We searched for J1615+5452 in the 150 MHz TIFR GMRT Sky Survey (TGSS; Intema et al. 2017) and the source was not clearly detected. The nearest survey pointing centre is 1.6 deg away which is close to the half-power beamwidth at 150 MHz. There is a faint source at the expected location with a peak flux density of about 20 mJy and a total flux density of 95 ± 21 mJy. Since the peak flux is less than 5 times the local rms, it did not get listed in the TGSS catalogue. We searched for other 150 MHz archival data with the GMRT and found long observations with ~5 h on-source time, taken in 2007 May (PI: Demnfeld). The signal bandwidth was 6 MHz with a correlator bandwidth of 8 MHz split into 128 channels to minimize the effects of bandwidth smearing. 3C 147 and 3C 48 were observed for primary calibration and 1459+716 for secondary calibration. The data were analysed using the SPAM pipeline (Intema et al. 2009) following standard procedure which included direction dependent calibration for total intensity continuum imaging (robust = 0). The rms noise of the image is ~3.5 mJy beam$^{-1}$ with a resolution of 37.7 × 20.9 arcsec at the position angle of 52 deg. The source is clearly detected in this image which is the one we use for the flux density estimate at 150 MHz (Table 2).

### 2.2 VLA observations at 1.4 GHz

A snapshot image of J1615+5452 is retrieved from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). At a resolution of ~45 arcsec coupled with a sensitivity of ~2.5 mJy beam$^{-1}$ above 5$\sigma$, the 1.4 GHz survey records a flux density of 5.6 mJy for this given source. We also retrieved the radio image from the Faint Images of the Radio Sky at Twenty-Centimeters survey (FIRST; Becker, White & Helfand 1995), but the NVSS point-like source is only detected in FIRST below 4$\sigma$ with a very weak intensity <0.4 mJy. We did not find radio counterparts as well in the 10 sq. degrees 1.4 GHz VLA image of the EN1 field published by Banfield et al. (2011). The local rms noise is ~90 $\mu$Jy beam$^{-1}$. Unlike NVSS, these two VLA observations are at a higher angular resolution of ~5 arcsec. No compact feature at high resolution suggests the absence of core emission.

### 3 PROPERTIES OF J1615+5452

#### 3.1 Host galaxy

Fig. 1 shows the 610 MHz radio continuum contours of J1615+5452 overlaid on a $i$-band image from the Sloan Digital Sky Survey Data Release 12 (SDSS-DR12; Alam et al. 2015). A red spheroidal galaxy is located coincident with the peak of the radio emission and slightly ~1.9 arcsec East of the centroid of the radio source. Based on spectroscopic observations from the SDSS-DR14 (Abolfathi et al. 2018), this galaxy has a redshift of $z = 0.32936 \pm 0.00005$ at which 1 arcsec corresponds to 4.89 kpc. With no obvious nebular emission lines from young blue stars, its integrated spectrum retrieved from the SDSS Catalogue Archive Server is rather characterized by a prominent break around 4000 Å and the presence of Ca H and K lines along with other strong absorption lines like Mg I and Na D. Such features are typical of an early-type elliptical galaxy (Kennicutt 1992).

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**Table 2. Properties of the peculiar radio source.**

| Source name | J1615+5452 |
|-------------|------------|
| RA (J2000)  | 16h15m31.1s |
| DEC (J2000) | +54°52′28″ |
| $z$         | 0.32936    |
| $S_{150}$   | 81.1 ± 6.3 mJy |
| $S_{250}$   | 50.5 ± 2.5 mJy |
| $S_{500}$   | 24.8 ± 1.2 mJy |
| $S_{1500}$  | 6.7 ± 0.8 mJy |
| $\alpha_{1400}$ | -1.12 ± 0.06 |
| $\alpha_{1400}$ | -1.58 ± 0.15 |
| $\alpha_{1400}$ | -1.21 ± 0.15 |
| $\alpha_{1500}$ | -0.61 ± 0.12 |
| $\Delta \alpha$ | -0.97 ± 0.19 |

$L_{1.4 \text{GHz}}$ = $2.64 \times 10^{24}\,\text{WHz}^{-1}$

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**Figure 1.** The 610 MHz radio continuum contours (levels ~2, 2.5, 3, 5, 10, 30, 40, 45, 50, 50 × $\sigma$ (40 $\mu$Jy beam$^{-1}$)) overlaid on the SDSS-DR12 $i$-band image. The cross is the centroid of the radio emission. The filled ellipse in the lower left represents the FWHM contour of the synthesized beam at 610 MHz.
Figure 2. Radio maps of the source J1615+5452 with the synthesized beam shown in the bottom left corner. Overlaid are the total intensity contours: (top left) GMRT 150 MHz map, levels $-2, 2, 3, 5, 7, 10 \times \sigma (3.1 \, \text{mJy beam}^{-1})$; (top right) GMRT 325 MHz map, levels $-3, 3, 5, 10, 30, 100 \times \sigma (70 \, \mu\text{Jy beam}^{-1})$; (bottom left) GMRT 610 MHz map, levels $-3, 3, 5, 10, 30, 50 \times \sigma (40 \, \mu\text{Jy beam}^{-1})$; (bottom right) NVSS 1400 MHz map, levels $-2, 2, 3, 5, 7 \times \sigma (0.34 \, \text{mJy beam}^{-1})$.

The newly detected remnant radio emission is likely associated with the SDSS galaxy. In fact, the slight misalignment between the position of the optical galaxy and the peak of the radio emission is consistent with a host galaxy that is moving away from the relic radio plasma after its AGN activity ceases (e.g. Duchesne & Johnston-Hollitt 2019). Such an offset has also been reported by Gentile et al. (2007) when studying 3C 338, a restarted radio galaxy where the remnant plasma of the source is clearly disconnected from the host galaxy.

The potential host galaxy does not belong to any cluster of galaxies detected in EN1 field (V. Parekh, private communication). However, there are three SDSS galaxies with $g < 22$ mag within its 0.5 arcmin radius. Such a proximity to other galaxies suggests that the host galaxy could reside in a loose group environment. It is worth investigating the nature of the galaxy environment since Murgia et al. (2011) reported that fossil lobes of cluster-based remnant radio galaxies tend to be more confined than the ones associated with a dying radio source found in the field. Unfortunately, no X-ray observations covered this area of the sky to help investigate the effects of the surrounding intercluster medium on the radio source.

3.2 Morphology and flux densities

Fig. 2 shows the radio images at all four frequencies. As noted in Table 1, the GMRT angular resolution ranges from 6 arcsec at 610 MHz to 20 arcsec at 150 MHz. We used PyBDSF (Mohan & Rafferty 2015) to measure the flux density of the source from all the available images. The derived values are presented in Table 2 with the associated errors $\sigma_1$ computed following the expression...
outlined by Hopkins et al. (2003) but with a slight modification to account for our instrumental and pointing errors:

\[
\sigma_{1} = I \sqrt{\frac{2.5 \sigma^2}{T}} + 0.05^2, \tag{1}
\]

where \( I \) is the integrated flux density and \( \sigma \) the local rms noise.

We first noticed the peculiarity of J1615+5452 by cross-matching the GMRT 610 MHz radio image of EN1 with the high resolution 1.4 GHz VLA data. While the source is easily detectable at 610 MHz with a projected linear size of \( \sim 92 \text{kpc} (0.31 \text{arcmin}) \) at \( z \sim 0.33 \) and a flux density of \( S_{610} = 24.8 \pm 1.2 \text{mJy} \), no 1.4 GHz contours however, have been recovered. The VLA high resolution images did not reveal any compact core, jets, or hotspots. Such a non-standard morphological structure is worth an investigation as it was also observed by e.g. Brienza et al. (2016) when studying a remnant radio galaxy in a particularly low-density environment.

The radio emission is also featured at 150 MHz with a flux density of \( S_{150} = 81.1 \pm 6.3 \text{mJy} \). In the 325 MHz image, the source has extended diffuse emission with \( S_{235} = 50.5 \pm 2.5 \text{mJy} \) and a projected size of 100 kpc (0.34 arcmin). The source extraction with PyBDSF in the low resolution NVSS data resulted in a flux density of \( S_{1400} = 6.7 \pm 0.8 \text{mJy} \) which translates to a radio luminosity of \( L_{1.4 \text{GHz}} = 2.64 \times 10^{24} \text{W Hz}^{-1} \).

We also estimated an upper limit of the radio core prominence (CP) which is a parameter used by e.g. Giovannini et al. (1988), Hardcastle et al. (2016), Brienza et al. (2016), Brienza et al. (2017), and Mahatma et al. (2018) in their search for candidate remnant AGNs. This was done by taking the ratio between the 3\( \sigma \) local rms noise in the high resolution VLA image from Banfield et al. (2011) and the total flux density at 150 MHz. We derived a value of \( \text{CP} \lesssim 3.3 \times 10^{-3} \). However, given that this value changes depending on the observing frequencies and that a low CP is expected for a flat-spectrum core component combined with a steep-spectrum of the total radio emission (Hardcastle & Looney 2008), we also considered an alternative method to investigate the AGN activity in the core. By taking the value of \( L_{1.4 \text{GHz}} \), we used the following empirical relation established by de Ruiter et al. (1990)

\[
\log \text{CP} = -0.55 \log L_{1.4 \text{GHz}} + 11.76 \tag{2}
\]

to predict a much higher value of CP \( \sim 0.02 \). The de Ruiter et al. (1990) relation states that the CP is inversely proportional to the radio power, i.e. low-luminosity radio sources (with radio powers smaller than \( 10^{26} \text{W Hz}^{-1} \)) are expected to have a relatively higher CP compared to the high-luminosity ones.

The values of the CP and the absence of the compact radio structure suggest that J1615+5452 could be a dying AGN (see Section 5). The analysis of the source radio spectrum in Section 3.3 will help determine whether the AGN activity has indeed switched off.

### 3.3 Radio spectrum

In the active stage, a broken power-law fit also known as the CI model (Kardashev 1962; Jaffe & Perola 1973) best describes the radio source spectrum with a spectral index \( \alpha \sim \alpha_{\text{inj}} \) below the break frequency and \( \alpha \sim \alpha_{\text{inj}} - 0.5 \) above \( \nu_{b} \). If the source is young enough and the observing frequency range is limited to \( \sim \text{GHz} \) frequencies, then a simple power law with \( \alpha \sim \alpha_{\text{inj}} \) produces a reasonable fit to its radio spectrum still unaffected by the radiative losses.

For J1615+5452, the best-fitting model\(^2\) of the integrated spectrum (see Fig. 3) is a broken power-law fit combined with an exponential break frequency \( \nu_{b, \text{exp}} \). At low frequencies, the spectral shape is typical of active radio galaxies with an index of \( \alpha_{\text{150 GHz}}^{150 \text{GHz}} \sim -0.61 \pm 0.12 \). Steep spectra with \( \alpha_{\text{150 GHz}}^{1400 \text{GHz}} = -1.12 \pm 0.11 \) and \( \alpha_{\text{610 GHz}}^{610 \text{GHz}} = -1.58 \pm 0.15 \) are, however, recorded above a certain spectral break likely occurring between 325 and 610 MHz. The values of such a parameter and the resulting synchrotron age are derived in Section 4.2.

In the frequency range 150–1400 MHz, \( \alpha_{\text{150 GHz}}^{1400 \text{GHz}} = -1.12 \pm 0.06 \), and the SCP \( \Delta \alpha = \alpha_{\text{150 GHz}}^{150 \text{GHz}} - \alpha_{\text{150 GHz}}^{610 \text{GHz}} \) is equal to \( -0.97 \pm 0.19 \). The measured values of the SCP and the spectral indices are reported in Table 2.

The spectral break at low frequencies, the steep high-frequency spectra as well as a SCP \( \lesssim -0.5 \) imply the predominance of non-thermal synchrotron emission and the central engine switch off. Such characteristic features of the spectra classify once again J1615+5452 as a dying radio AGN (e.g. Parma et al. 2007; Murgia et al. 2011; Brienza et al. 2016).

### 4 INVESTIGATING THE DYING RADIO AGN

#### 4.1 Source energetics

A first-order approximation of the synchrotron age requires an estimate of the magnetic field strength. We assume minimum energy conditions between particles and magnetic field to derive the equipartition magnetic field \( B_{\text{eq}} \) which is given by

\[
B_{\text{eq}}[G] = \left( \frac{24\pi}{7} \frac{\nu_{\text{min}}}{\nu_{b}} \right)^{1/2}. \tag{3}
\]

Assuming an uniform magnetic field and an isotropic particle distribution, we computed the minimum energy density \( \nu_{\text{min}} \) following

\[2\text{The best-fitting } \text{Cl}_{\text{eff}} \text{ model by Komissarov & Gubanov (1994) is briefly described in Section 4.2.}\]
the Govoni & Feretti (2004) formula

\[
u_{\text{min}} \left[ \frac{\text{erg}}{\text{cm}^3} \right] = \xi(\alpha, v_1, v_2)(1 + k)^{1/7}(v_0 [\text{MHz}] - 4e^{-7/7}) \\
\times (1 + z)^{12 - 4\alpha/7}(I_0 \left[ \frac{\text{mJy}}{\text{arcsec}^2} \right])^{4/7} \left( d [\text{kpc}] \right)^{-4/7},
\]

(4)

where the parameter \( \xi \) is dependent on frequencies \((v_1 = 10 \text{ MHz} \) and \( v_2 = 100 \text{ GHz} \)) and the synchrotron spectral index \( \alpha < 0 \) presumed for the observed spectrum; \( k \) is the relativistic proton-to-electron energy density ratio. \( I_0 \) is the source surface brightness measured at the frequency \( v_0 \) and \( d \) is the source depth.

At \( \alpha = -0.61 \) with \( v_0 = 325 \text{ MHz} \), we find \( \nu_{\text{min}} = 1.54 \times 10^{-12} \text{ erg cm}^{-3} \) and \( B_{\text{eq}} \sim 4.1 \mu \text{G} \). The other parameters in equation (4) are as follows: \( k = 1, I_0 = 0.43 \text{ mJy arcsec}^{-2} \), and \( d \sim 100 \text{ kpc} \) (the average of the angular extents of the source). Note that the value of \( \alpha \) is consistent with the observed injection index \( \alpha_{\text{inj}} \) measured at \( v_0 \) where the steepening is still not affecting the shape of the radio spectrum. Regarding the frequency interval, the choice of a relatively low value of \( v_1 = 10 \text{ MHz} \) is motivated by the importance of the energy density of relativistic electrons radiating their energy at lower frequencies (e.g. Pacholczyk 1970; Beck & Krause 2005). The value of \( v_2 \) is however less critical for the minimum energy estimates. In fact, if \( v_2 = 10 \text{ GHz} \) for \( \alpha = -0.61 \), \( \nu_{\text{min}} \) only decreases by 9 percent from its current value.

Previous works have reported that the classical formula used to calculate \( B_{\text{eq}} \) may underestimate the magnetic field strength because of inadequate assumptions of the frequency integration limits (e.g. Brunetti, Setti & Comastri 1997; Beck & Krause 2005). A revised estimate is

\[
B_{\text{eq}} [\mu \text{G}] \sim 1.1\nu_{\text{min}} \left( \frac{\nu_b}{\nu_{\text{min}}} \right)^{-7/10} B_{\text{eq}}^{1/10} (\text{MHz}) (\text{MHz}) (\text{Myr})
\]

(5)

where \( B_{\text{eq}} \) is a modified equipartition magnetic field based on a limit of the Lorentz factors \( \gamma \) assuming \( \nu_{\text{min}} \gg \nu_{\text{max}} \). For \( \nu_{\text{min}} = 100 \) and \( \nu_{\text{max}} = 10^6 \), we find \( B_{\text{eq}} \sim 4.9 \mu \text{G} \) using the 325 MHz radio emission. Because of the flat radio spectrum at low frequencies, we only expect \( \sim 20-30 \) percent deviation of the revised value from the classical \( B_{\text{eq}} \) (Beck & Krause 2005). In this work, such a variation is only around 16 percent. We thus adopt the magnetic field strength \( B_{\text{eq}} \sim 4.1 \mu \text{G} \) in the remainder of this work.

### 4.2 Synchrotron age

With estimates of the magnetic field strength \( B_{\text{eq}} \) and the break frequency \( \nu_b \), one can calculate to first order the spectral age \( t_\nu \) using the following expression (Murgia et al. 2011):

\[
t_\nu [\text{Myr}] = 1590 \left( \frac{(B_{\text{eq}} [\mu \text{G}])^{1/2}}{(B_{\text{eq}}^2 + (B_{\text{IC}} [\mu \text{G}])^2)^{1/2}(1 + z)^{1/2}(\nu_b [\text{GHz}])^{1/2}} \right)^{1/2}.
\]

(6)

where \( B_{\text{IC}} = 3.25 (1 + z)^{2} \) is the Inverse Compton equivalent magnetic field. By setting a lower limit to the break frequency such that \( \nu_b = 610 \text{ MHz} \), an upper limit to the source age is of the order of 120 Myr.

We also run BRATS\(^3\) (Harwood et al. 2013; Harwood, Hardcastle & Croston 2015) to fit the radio spectrum and to ultimately get a more robust estimate of the synchrotron age. Given the remnant

\(^3\)The Broadband Radio Astronomy ToolS is a software package that uses spectral ageing models to derive the properties and morphology of a radio source. For more details, visit http://www.askanastronomer.co.uk/brats.

### Table 3. Fitting results from BRATS CL\(_{\text{eff}}\) model.

| \( \alpha_{\text{eq}} \) | \( B_{\text{eq}} \) | \( \nu_b \) | \( \nu_{\text{exp}} \) | \( t_\nu \) | \( t_{\text{off}}/t_{\nu} \) | \( \chi^2_{\text{red}} \) |
|---|---|---|---|---|---|---|
| 0.40 | 12.5 | 347 | 1024 | 35.9 | 0.6 | 1.42 |
| 0.61 | 4.1 | 384 | 5029 | 76.0 | 0.3 | 8.86 |

Notes. Columns 1 and 2: the injection index and the magnetic field as input parameters; Column 3: the break frequency; Column 4: the off-component break frequency; Columns 5 and 6: the computed synchrotron age of the source and the ratio between the quiescent and the active time-scales; Column 7: the reduced chi-square of the fit.

Of the source, we fit the KGIP model to the data. This remnant radio emission model developed by Komissarov & Gubanov (1994) is also known as the CL\(_{\text{eff}}\) model and it is a modification of the standard continuous injection model (Kardashev 1962; Jaffe & Perola 1973) to account for the AGN switch off.

By considering an injection index \( \alpha_{\text{eq}} = -0.61 \) (the spectral index at low frequencies), a minimum and maximum Lorentz factor of \( \gamma_{\text{min}} = 100 \) and \( \gamma_{\text{max}} = 10^6 \), a magnetic field strength \( B_{\text{eq}} = 4.1 \mu \text{G} \), with the other input parameters set to their default values, BRATS returns a fitted age of \( t_{\text{eq}} = 76.0 \pm 8.8 \text{ Myr} \), a break frequency \( \nu_b = 384 \text{ MHz} \) and an off component break \( \nu_{\text{off}} = 5029 \text{ MHz} \). The time-scales during active (\( t_{\text{on}} = 54.9 \pm 8.7 \text{ Myr} \)) and quiescent (\( t_{\text{off}} = 21.0 \pm 6.4 \text{ Myr} \)) phases were also computed. With \( t_{\text{on}} = t_{\text{off}} + t_{\text{off}}/t_{\text{off}} \), we get a \( t_{\text{off}}/t_{\text{off}} \) ratio of \( \sim 0.3 \). The off component break frequency, \( \nu_{\text{of}} = \nu_{\text{off}} (t_{\text{off}}/t_{\text{off}})^2 \), does not lie within the available frequency coverage because the source is observed soon after the radio core switch off according to the fitting model, i.e. the timescale of the quiescence phase is significantly shorter than that of the active phase (Parma et al. 2007). In that case, \( \Delta t \sim 1 \) (derived in Section 3.3) can only be considered as an upper limit of the SCP.

The source age of 76 Myr is in agreement with the source morphology and the steep spectral properties reported in Section 3. Note, however, that the computed value is dependent on some critical parameters such as \( \alpha_{\text{eq}} \). For instance, the derived age falls between 37 and 106 Myr while varying the injection index \( \alpha_{\text{eq}} \) between 0.5 and 0.8. Such a range is consistent with the upper limit to the source age as well as the typical ages (a few tens of Myr) for dying radio galaxies (e.g. Blandford & Ostriker 1978; Murgia et al. 2011; Brienza et al. 2016).

Although we can achieve the best-fitting model with \( \alpha_{\text{eq}} = 0.40 \) and \( B_{\text{eq}} = 12.5 \mu \text{G} \) as free parameters (\( \chi^2_{\text{red}} = 1.42 \), dashed line in Fig. 3), we decided to consider BRATS outputs associated with fixed values of \( \alpha_{\text{eq}} = 0.61 \) and \( B_{\text{eq}} = 4.1 \mu \text{G} \). The latter parameters are consistent with the radio properties of the source (e.g. the spectral index at lower frequencies) and the resulting model still gives a reasonable fit to the radio spectrum (\( \chi^2_{\text{red}} = 8.86 \), solid line in Fig. 3). Table 3 summarizes BRATS fitting results in both cases.

### 5 DISCUSSION

A low CP may result from the very weak or no core emission, a potential evidence of the central AGN switch off. In the case of J1615 + 5452, the observed CP of \( \lesssim 3.3 \times 10^{-3} \) falls within the range of CP \( <10^{-3} \) that are associated with the remnant radio sources from the literature (e.g. Giovannini et al. 1988; Hardcastle et al. 2016; Brienza et al. 2017; Mahatma et al. 2018). Such a low value is well below CP \( \sim 0.02 \) (the CP value expected for a source of the same radio power assuming the empirical correlation...
found by de Ruiter et al. 1990) and it is in agreement with a quiescent nuclear engine or an active one but at a very weak level than what is observed in typical radio sources. Furthermore, the value of CP ∼ 0.02 also falls within the interval of 0.1–0.001, which is a CP range reported by de Ruiter et al. (1990) for B2 sources with radio powers between 10^{24}–10^{26} W Hz^{-1} including a very small fraction of remnant radio AGNs. Nevertheless, classifying a radio source as a remnant based only on its core activity is deemed unreliable, especially for lower resolution and sensitivity observations where a faint core may be missed (e.g. Mahatma et al. 2018). It is thus recommended to combine this parameter with other selection criteria to achieve unbiased detection (e.g. Brienza et al. 2017).

In this work, α_{1525}^{1400} = −1.37 ± 0.09 and Δα ≈ −0.97 ± 0.19. These spectral characteristics are comparable to those of the complete samples of remnant radio galaxies drawn by Parma et al. (2007) and Murgia et al. (2011). The former authors define a dying complete sample of remnant radio galaxies of the order of a few 10^5 yr (Marconi et al. 2004; Schawinski et al. 2015). During the quiescent AGN phase, the nuclear activity is either significantly reduced or temporarily switched off due to a shortage of material accreting on to the SMBH. The central engine of the nuclear activity will eventually reignite once a new phase of accretion on to the SMBH starts again. Such a rejuvenation of AGN activity is deemed responsible for the presence of a flat-spectrum radio core that coexists with remnant radio lobes from past nuclear activity (e.g. Saikia & Jamrozy 2009; Morganti 2017). With no direct evidence of a restarted core and/or new born jets for the current source, and based on the derived characteristics in Sections 3 and 4, we potentially classify J1615+5452 as a dying radio AGN. This implies that the radio core no longer fuels fresh particle injection. The fossil radio lobes, however, remain visible (up to ∼10^8 yr depending on the radio source environment) because of the radiating low energy particles being relatively unaffected by the fast spectral evolution.

### 6 SUMMARY AND CONCLUSIONS

We have presented in this paper the discovery of a candidate remnant radio galaxy J1615+5452 in the ELAIS-N1 field. Using low frequency GMRT observations combined with archival VLA data, we derived the source flux densities between 150 and 1400 MHz to investigate the source radio spectrum. Our main results are summarized below:

(i) The candidate remnant AGN is likely associated with an early-type elliptical galaxy at redshift of z ∼ 0.33. The potential host galaxy appears to reside in a low-density environment.

(ii) With an angular extent of ∼100 kpc, J1615+5452 has a diffuse amorphous radio emission with no evidence of compact core, jets, and hotspots. We also did not detect radio counterparts in the 1.4 GHz VLA data with a high resolution of ∼5 arcsec.

(iii) The spectral indices between 150 and 1400 MHz vary between −0.6 and −1.6 which give a high spectral curvature Δα ∼ −1. Such spectral features indicate the predominance of non-thermal synchrotron emission with strong ongoing radiative losses.

(iv) The radio spectrum is reasonably described by a Cl model with a break frequency ν_b = 384 MHz and an off component break at ν_{b, exp} ∼ 5 GHz. The computed synchrotron age is t_s = 76.0 ± 8.7 Myr with t_{dm} = 54.9 ± 7.4 Myr and t_{dm} = 21.0 ± 3.5 Myr. The source is estimated to have spent 30 percent of its total lifetime in the fading phase.

The morphological characteristics of J1615+5452 coupled with its spectral properties and synchrotron age helped us to classify the peculiar source as a dying radio galaxy. Combining such analyses is key to identify elusive remnant radio AGNs that play an important role towards a comprehensive understanding of AGN evolution in general. With new or upgraded low frequency radio interferometers such as LOFAR and the upgraded GMRT (uGMRT; Gupta et al. 2017), ongoing analyses of deep radio surveys

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DATA AVAILABILITY

The data underlying this article are available in Table 2 of the article. This publication makes use of archival GMRT data sets and VLA image available at https://naps.ncra.tifr.res.in/goa/ and https://www.cv.nrao.edu/nvss/, respectively. GMRT radio images will be shared on reasonable request to the corresponding author.

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