Nuclear Activity in Galaxies Across Cosmic Time
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A dying radio AGN in the ELAIS-N1 field

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Abstract. We use low-frequency GMRT observations and 1.4 GHz VLA archival data to study the radio spectrum of a dying radio galaxy discovered in the field of ELAIS-N1. With a linear size of ~ 100 kpc at a redshift $z \sim 0.33$, the diffuse source J1615+5452 exhibits a steep spectral index $\alpha_{612}^{1400} < -1.5$ and a convex radio spectrum. Its radio morphology also seems to lack compact features such as a nuclear core, relativistic jets and hotspots. We record a spectral curvature $\Delta\alpha \approx -1$ and a synchrotron age estimated between 34 - 70 Myr. These characteristics suggest that J1615+5452 is most likely a remnant radio AGN that has spent more than half of its total lifetime in the quiescence phase. The detection of such an elusive source is important since it represents the final phase in the evolution of a radio galaxy unless the nuclear core gets replenished with fresh particles and undergoes a restarting activity.

Keywords. galaxies: active - radio continuum: galaxies - galaxies: individual: J1615+5452

1. Introduction

Through radiation and/or jets of relativistic particles, active galactic nuclei (AGN) release large amounts of energy affecting the dynamical evolution of the surrounding interstellar and intergalactic medium (e.g. Brüggen, & Kaiser 2002; McNamara, & Nulsen 2012). Such a mechanism also plays an important role in regulating the star formation of the host galaxy. Determining the duty cycle of the nuclear activity (active vs. dormant phase) is therefore crucial for understanding the co-evolution process between the accreting supermassive black hole (SMBH) in AGN and its host galaxy (Kormendy & Ho 2013).

The active phase is typically in the range of 10 - 100 Myr (Cordey 1987). During that period, the radio galaxy morphology is characterized by the presence of a compact core, relativistic jets and hotspots besides the extended radio lobes inflated by the jets. A single power-law distribution best describes the radio spectrum over a wide range of frequencies.

On the other hand, once the quiescence phase kicks in, as the nuclear engine switches off due to a shortage of fresh particles accreting the SMBH, the compact structures fade away. This will result to a steepening of the spectral index and the appearance of a break frequency in the convex radio spectrum (Komissarov & Gubanov 1994; Murgia *et al.* 2011; Morganti 2017).

Because of the fast spectral evolution throughout the dormant phase, remnant radio AGNs remain elusive, especially in the cm wavelength regime. Low frequency observations with a relatively high sensitivity are thus required to increase their detection which are often observed as relatively bright and diffuse extended lobe emission.

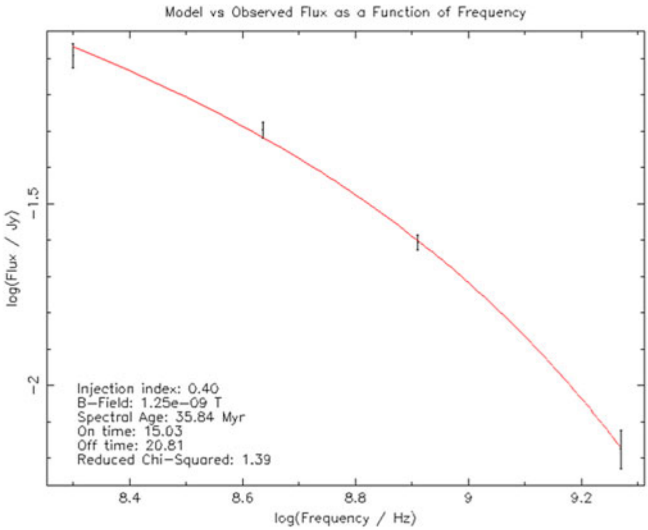

Figure 1. The radio spectrum of J1615+5452 at rest-frame frequencies fitted with a KGJP model developed by Komissarov & Gubanov (1994).

2. J1615+5452: a dying radio galaxy in EN1 field

A thorough visual inspection of the GMRT 612 MHz image of the ELAIS-N1 field (EN1, $RA = 16^h10^m$, $DEC = +54°35'$) led to the discovery of J1615+5452: a candidate remnant radio AGN. The source is likely to be hosted by an early-type elliptical galaxy, with a spectroscopic redshift $z \sim 0.32936 \pm 0.00005$ (SDSS-DR14, Abolfathi *et al.* 2018).

Observed as a fuzzy source in the radio image with a sensitivity of $\sim 40\,\mu$Jy/beam, the flux density is ~ 25 mJy and the linear size in the order of ~ 100 kpc. Although J1615+5452 is also detected at 150 MHz and 325 MHz, it is however invisible in the FIRST 1.4 GHz VLA survey. There are no signs of compact features.

An upper limit of the radio core prominence (CP $\lesssim 3.3 \times 10^{-3}$), a steep spectral index of $\alpha_{612}^{1400} < -1.5$ at high frequencies, and an estimate of the spectral curvature parameter ($\Delta\alpha = \alpha_{612}^{1400} - \alpha_{150}^{325} = -0.97 \pm 0.19$) were derived to investigate the remnant nature of J1615+5452. All the values are consistent with the radio source being dominated by non-thermal synchrotron emission. This is also reflected in the shape of the radio spectrum (Figure 1) which exhibits a break frequency between 325 and 612 MHz.

Assuming minimum energy conditions between particles and magnetic field, an estimate of the equipartition magnetic field $B_{eq} \sim 7.5\,\mu$G was used to derive a first order approximation of the synchrotron age $t_s \sim 34$ Myr. This value considers the 612 MHz radio emission. The age of the radio plasma is around 70 Myr for a reference frequency at 325 MHz.

We also fit a KGJP model (also known as CI_{off} model, Komissarov & Gubanov 1994) to the data while running BRATS (Harwood *et al.* 2013, 2015). The software returns a characteristic age of 36 Myr and a spectral break $\nu_b = 465$ MHz. The active and quiescent phases are equal to $t_{on} \sim 15$ Myr and $t_{off} \sim 21$ Myr, respectively.

The radio morphology, the synchrotron age as well as the spectral properties of the diffuse radio plasma are comparable to those of other remnant radio AGNs found in the literature (e.g. Jamrozy *et al.* 2004; Parma *et al.* 2007; Murgia *et al.* 2011; Brienza *et al.* 2016). All these factors led us to classify J1615+5456 as a dying radio galaxy.

3. Way forward: searching for dying radio AGNs with MeerKAT

This paper briefly summarizes the discovery of a dying radio galaxy in the ELAIS-N1 field (a comprehensive report on this work will be available in Randriamanakoto *et al.* 2020). Thanks to the sensitivity of low frequency GMRT observations, the diffuse radio emission from the remnant AGN could be observed. Large survey projects such as MeerKAT/MIGHTEE (rms noise level down to $\sim 10\mu$Jy at 1.4 GHz) are expected to provide an unprecedented detailed study of these elusive radio sources that are key to understanding the radio galaxy life cycle.

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