SF2A 2016
C. Reylé, J. Richard, L. Cambrésy, M. Deleuil, E. Pécontal, L. Tresse and I. Vaughlin (eds)

AGN DUTY CYCLE AND RELIC EMISSION IN THE LOW FREQUENCY SKY

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Abstract. Active Galactic Nuclei (AGNs) are amongst the brightest sources in the radio sky that deposit large amount of energy in the interstellar and intergalactic medium (ISM, IGM) via their jets. Recurrent flaring episodes in the AGN jets can terminate at large-scale faint diffuse 'relic' emission around them. These relic emissions are rare and represent the end stage of their life cycle. They show very steep spectrum giving insights of AGN duty cycle, their past activity history and surrounding environment properties. High sensitivity and arcsec scale observations at very low frequencies are needed to detect such rare relic emission and disentangle the details of their morphology. In this paper we highlight the important database provided by low frequency surveys to search for relic radio sources and discuss in particular the relic emission from the AGNs detected in the LOFAR Multi frequency Snapshot Sky Survey (MSSS) and TIFR GMRT Sky Survey (TGSS), both surveys performed with SKA pathfinder telescopes. The radio spectrum from 2 different types of relic radio galaxies (B2 0924+30 and 4C 35.06) are investigated and a correlation between the mean particle age of the relic emission and the central AGN properties is derived.

Keywords: Radio galaxies: AGNs: jets - intracluster medium: diffuse emission: relics

1 Introduction

Radio galaxies experience continuous evolution throughout their lifetimes, starting from compact, synchrotron self-absorbed sources to well evolved classical double jet radio sources. They host a bright central AGN, that may show recurrent flaring activities giving rise to kpc up to Mpc scale jet structures. Based upon the morphology of the double jets, the radio galaxies are further classified into either Fanaroff-Riley Class I (FR I with disrupted and flared jets) or Class II (FR II with collimated jets and hotspots, Fanaroff and Riley, 1974). A class of FR I and IIs towards the extreme end of their life cycle may extend upto a giant linear (Mpc) scale structure with an active or passive central AGN. As the central AGN activity shuts down in these extreme systems, the ejected plasma in their jets ages and loses energy through synchrotron radiation as well as inverse Compton (IC) scattering of electrons via cosmic microwave background (CMB) photons. This aged plasma further gives rise to relic emission or radio fossils from an earlier episode of central AGN activity. Such relic emission representing the end stage of AGN life cycle has been rarely detected, only $\sim$50 are known as of now, due to their faint nature at high radio frequencies (Shulevski et al. 2015). Further they are often detected in dense cluster environments where the losses in the energy of synchrotron emitting plasma are delayed due to the external pressure experienced via the cluster environment (Shulevski et al. 2015). Thus, they show steep spectral properties ($-2 < \alpha < -1$) and can be classified into 2 broad categories i.e. fading and restarted (Cordey et al. 1987). In the case of fading galaxies, the central AGN is inactive with no on-going feeding of the jets with new energetic radio emitting plasma. Whereas, in the case of restarted galaxies, the extended radio emission is continuously fueled via the active central core (AGN), showing multiple phase (core, lobes, relics etc.) of evolution in their morphology.

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In this paper we emphasize the importance and compare the efficiency (sensitivity and resolution) of different low frequency radio surveys like VLA-VLSSr 74 MHz (resolution= 80 arcsec and rms noise = 100 mJy/beam, Lane et al. 2012, 2014, Cohen et al. 2007), GMRT-TGSS 150 MHz (resolution= 25 arcsec and rms noise = 3.5 mJy/beam, Intema et al. 2016, Sirothia et al. 2010), LOFAR-MSSS 135 MHz (resolution= 108 arcsec and rms noise = 5 mJy/beam, Heald et al. 2015), WSRT-WENSS 325 MHz (resolution= 54 arcsec and rms noise = 3 mJy/beam, Rengelink et al. 1997) and VLA-NVSS 1420 MHz (resolution= 45 arcsec and rms noise = 0.45 mJy/beam, Condon et al. 1998), in order to discover relic radio galaxies. Radio analysis at meter-wavelength is presented for 2 different types of radio galaxies hosting relic emission, complemented with high resolution GHz-range radio observation to study their morphological and spectral properties. The low frequency radio observations (including archive) down to 74 MHz confirms the presence of relic emission around the radio jets of the 2 galaxies discussed here.

2 Relic emission in fading radio galaxy: B2 0924+30

B2 0924+30 is a relic radio source hosted by the galaxy, IC2476 that resides centrally into a group of 8 galaxies and a member of a nearby poor cluster WBL224 (Mahdavi et al. 1999, White et al. 1999, Jamrozy et al. 2004). IC2476 is associated to a bright E/S0 type galaxy located at a redshift of z = 0.0261 with no emission line indicative of a passive elliptical as shown in Fig. 1. The radio morphology from the multi-frequency radio data from 0.151-10 GHz confirms that the source is a remnant of an edge-brightened FR II type radio galaxy with no radio jet or core features (Shulevski et al. 2015, Jamrozy et al. 2004, Cordey et. al. 1987, Colla et al. 1975, Ekers et al. 1981). The relic shows bright regions in the lobes with relatively flat spectral index ($\alpha = -1$), whereas the overall spectrum is very steep ($\alpha < -1$). The radio luminosity of the source is about $L_{1.4GHz} = 10^{23.8}$ W.Hz^{-1} as normally seen in the case of low luminosity FR I radio galaxies, suggesting that the AGN had a powerful progenitor in the past but after the central AGN activity has diminished, its luminosity is fading out due to synchrotron and inverse Compton losses. Shulevski et al. (2015) mapped the low frequency emission from B2 0924+30 using the LOFAR HBA band and computed a spectral index of $\alpha = -1$ for the lobes, down to $\alpha = -1.8$ for the inner regions of the lobe in this source, confirming that it is a radio relic of a terminated FRII. There is no sign of restarted AGN activity suggesting that the relic emission is due to the fading of aged plasma. Further, the radiative ageing model suggests that, the age of the outer lobe is around 20 Myr and that towards the host galaxy is 100 Myr, the time elapsed since the AGN has turned off (Shulevski et al. 2015, Jaffe and Perola 1973).

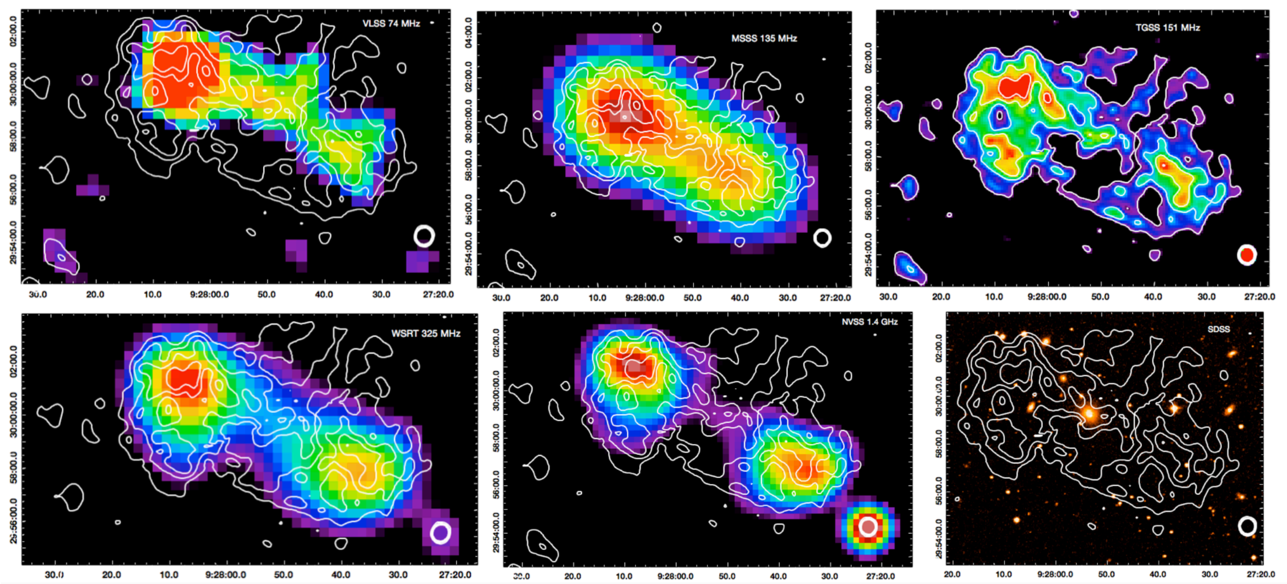

Fig. 1. Radio images of B2 0924+30 from various surveys in color scale with TGSS survey high resolution contour overlaid in white.

Low frequency surveys like, VLA-VLSSr, GMRT-TGSS, LOFAR-MSSS, WSRT-WENSS and VLA-NVSS 1420 have clearly detected the 440 kpc relic emission in B2 0924+30 down to 74 MHz (refer Fig. 1 top panel).

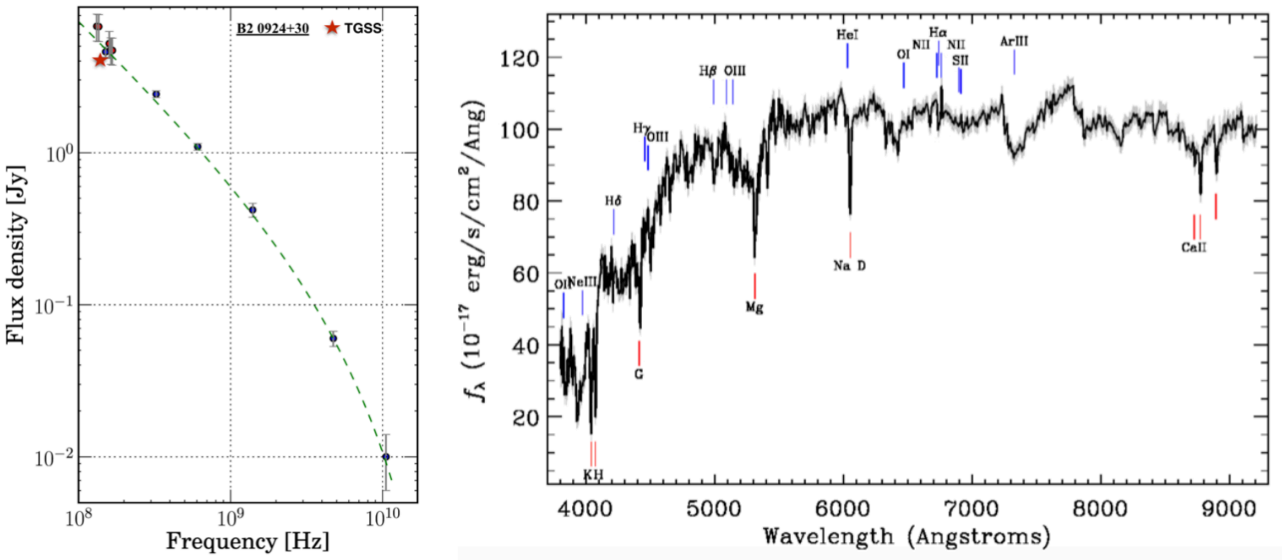

Fig. 2. Left panel shows multi frequency radio spectra extracted from Shulevski et al. (2015) with TGSS flux density marked in red and right panel with SDSS spectra of the host optical galaxy IC2476.

The radio galaxy shows a double lobe morphology with no bright core in the center in all the survey images. The TGSS survey being higher in resolution and better in sensitivity at meter wavelength regime has been able to map the morphological details like the faint central region, bended jet structures and overall diffuse radio emission in the radio lobes efficiently, giving better estimate on the source size. The VLSSr survey having lower sensitivity detects only the bright regions in the radio lobes, whereas the MSSS survey being better in sensitivity detects more diffuse emission in the lobes. The high frequency NVSS survey detects only the bright lobe regions but no diffuse extended emission (which tends to be visible only at lower frequencies). The high frequency emission from the bright regions is mainly due to young population of electrons, that tentatively age and loose energy due to adiabatic losses and finally emit mainly at lower frequencies. The integrated flux density measured in the TGSS and MSSS images are in agreement with the available data from the literature and shows that the emission from the overall relic regions dominate the spectrum rather then those from the central region (see Fig. 2).

3 Relic emission in restarted radio galaxy: 4C 35.06

4C 35.06 resides in the core of a cD galaxy UGC 2489 that lies at the center of Abell 407 cluster of galaxies (Schneider and Gunn 1982). The radio luminosity of 4C 35.06 is, $L_{1.4GHz}$ = 2.5 $\times 10^{24}$ W Hz^{-1} as typically seen in FR I, lies at a redshift of z = 0.046726 and shows no emission line in the optical spectra suggesting that the host is an elliptical galaxy (Shulevski et al. 2015, Biju et al. 2016). The SDSS optical image of UGC 2489 shows multi-component (9 galaxies) core structure with a stellar halo around the core of roughly 40 kpc in extent (see Fig. 3). High resolution VLA (Liuzzo et al. 2010), GMRT (Biju et al. 2016) and LOFAR (Shulevski et al. 2015) images shows a central unresolved core with radio emission from multiple galaxies, twisted helix dual jet structure scaling upto 435 kpc with no clear hotspots and extended diffuse relic emission at the end of the jet suggesting a FRI type radio galaxy. The twisted jet pattern suggest that the AGN has been active recently and has produced helical structure due to merger or interaction with the other AGNs in the core region (Biju et al. 2016).

The low resolution observations map the unresolved core and extended jet structure down to 74 MHz maps, as seen in Fig. 3. The GMRT-TGSS survey being higher in resolution and good in sensitivity not only maps the connected core and twisted jet morphology but also the underlying diffuse relic emission at the edge of the jets. The relic emission has a steep spectral index α = -2, indicative of a fossil of old plasma. The relic emission has been also measured with the LOFAR and GMRT at higher resolution by Shulevski et al. (2015) and Biju et al. (2016). The high sensitivity MSSS LOFAR survey not only confirms the presence of relic emission in 4C 35.06, but also shows hints of more extended diffuse relic emission at the edge of the jets than previously

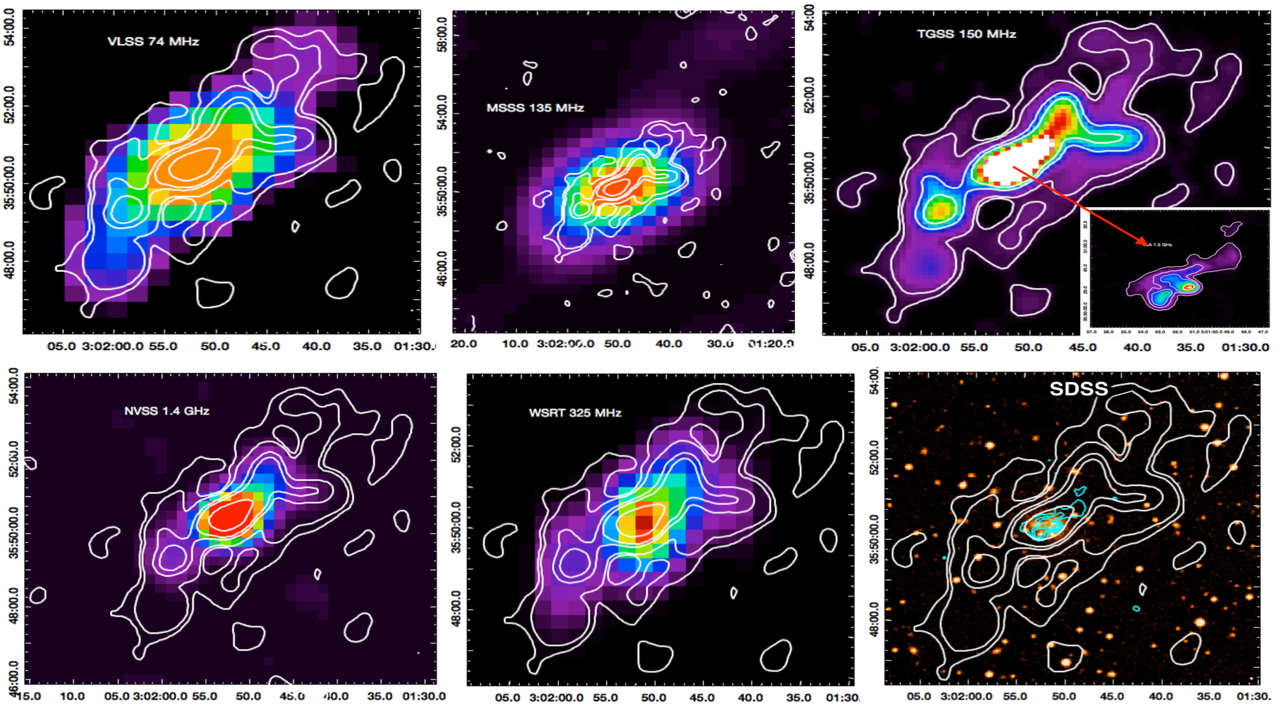

Fig. 3. Radio images from various surveys in color scale with TGSS survey high resolution contour overlaid in white. The high resolution VLA image of the core region is shown in the inset image of top 3rd panel.

measured. Deep observations with higher sensitivity below ∼300 MHz are needed to confirm this result. The radio morphology and spectral index suggest that the AGN is intermittently active as it moves in the dense cluster environment.

The broad-band radio spectra suggests that the source has a steep spectral index ($\alpha <$ -1). Integrated flux densities measured in the TGSS survey is in agreement with earlier measurements (see Fig. 4). The average flux from the MSSS survey more or less agrees with the SED. The age of the relic plasma is estimated to be

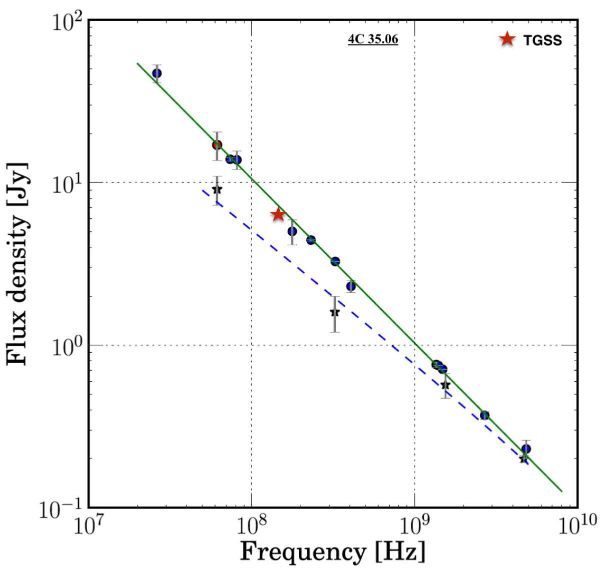

Fig. 4. Integrated flux density spectra of 4C 35.06 with TGSS flux density marked in red extracted from Shulevski et al. (2015).

∼70 Myr (elapsed time since last injection of relativistic electrons in the emission region) with 2 different phases (shutdown and restart) of AGN activity in 4C 35.06, suggesting a delay between the 2 phases of 35 Myr each (Shulevski et al. 2015).

4 Conclusions

In this paper we demonstrate the importance of database provided by new low frequency radio surveys like TGSS and MSSS to search for relic sources in the meter-wavelength sky, thanks to their unique combination of high sensitivity and resolution. Relic radio galaxies have been rarely detected (at GHz range) and expected to shine efficiently at low radio frequencies as they are sources at the end stage of their life cycle with a fossil of old population electrons. Relics in FR II type radio galaxies are longer lived due to their powerful progenitors as compared to less luminous FR I type galaxies. They show steep spectral properties and extended decay phase as compared to their active phase, due to pressure imposed by the dense cluster environment.

The LOFAR MSSS survey is efficient in detecting low surface brightness regions likes radio lobes, relics etc. however, its low resolution makes it difficult to disentangle the morphological details. The GMRT TGSS survey has better resolution and point source sensitivity than MSSS, but less surface brightness sensitivity and is equally efficient in detecting diffuse emission in AGNs. A large population of relic radio sources are yet to be discovered and the Square Kilometer Array (SKA) will be the ideal interferometer to discover such low surface brightness objects, thanks to its unique combination of high sensitivity, arcsec scale angular resolution and broad (15 MHz- 50 GHz) frequency coverage.

We thank the staff of GMRT, who made these observations possible. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. MP is thankful to the research grant received from the Franco-Indian CEFIPRA organization. This research has made extensive use of the data available from the public archive from SDSS, WSRT, VLA and GMRT observatory.

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