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Searching for remnants among young radio sources

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Abstract. The evolutionary stage of a powerful radio source originated by an AGN is thought to be related to its linear size. However, the fraction of young radio sources in flux density-limited samples is much larger than what is expected from the number counts of large radio sources, suggesting the existence of short-lived objects and/or intermittency of jet activity. Determining the incidence of young but fading radio sources is thus pivotal for improving our knowledge of the life-cycle of radio emission in radio-loud AGN. Despite its importance for constraining evolutionary models, there are no systematic studies of remnants in complete samples of young radio sources. We present results on high-resolution multi-frequency radio observations of candidate remnants selected from the B3-VLA CSS complete sample. These new observations allow us to constrain the integrated radio spectrum and unveil the presence of active regions.

1. Introduction

The radio emission of extragalactic powerful radio sources is due to synchrotron radiation from relativistic particles produced in the central active galactic nucleus (AGN). The population of powerful symmetric (double-lobed) radio sources ($L_{1.4\mathrm{GHz}} > 10^{24.5}$ W/Hz) is divided into several sub-classes, each representing a different stage in the individual source evolution in which the age is directly related to the linear size (LS). Compact symmetric objects (CSOs) have LS $<$ 1 kpc and ages $\sim 10^{2-4}$ yr, middle-sized symmetric objects (MSOs) have 1 kpc $<$ LS $<$ 20 kpc and $\sim 10^{4-6}$ yr, whereas large size symmetric objects (LSOs) have LS $>$ 20 kpc and ages $\sim 10^{7-8}$ yr (e.g., Wilkinson et al. 1994, Fanti et al. 1995). In the framework of evolutionary models CSOs will evolve into MSOs, which should be the progenitors of LSOs, i.e. the classical Fanaroff-Riley Type I/II radio sources (e.g., Fanti et al. 1995, Readhead et al. 1996, Snellen et al. 2000).

Although the onset of the radio activity is supposed to be related to merger or accretion events occurring in the host galaxy, the reason why the radio emission switches off is still largely unclear. The over-density of young radio sources in flux-limited catalogues is among the key issues in the radio source evolution (e.g., Gugliucci et al. 2005, An & Baan 2012). This suggests the existence of short-lived sources in which the radio emission turns off on short timescales (e.g., An & Baan 2012, Kiehlmann et al. 2024). So far, only a few CSOs and MSOs have been identified as "faders" (e.g., Kunert-Bajraszewska et al. 2005, Orienti et al. 2010). In case of a reactivation of the radio emission on a short timescale, a new young radio source would appear close to the relic of the earlier activity phase (Luo et al. 2007, Orienti & Dallacasa 2008, O'Sullivan et al. 2021).
The duration of the active phase is a matter of debate. Reynolds & Begelman (1997) proposed a model in which the radio emission is periodically intermittent and the activity phases last for about 10^{4-5} yr and recur every 10^{5-6} yr. In this model the radio source evolves in a self-similar way during the outbursts and then enters in a "coasting" phase. An immediate prediction of this model is the existence of a large number of MSOs in an inactive phase. On the other hand, Czerny et al. (2009) suggested a radiation pressure instability scenario which may cause an intermittent activity of the central engine on shorter time scales (less than 10^{3-4} yr), which repeats regularly every 10^{4-6} yr. In this model, a large number of CSOs is expected to be in an inactive phase. Short-lived radio sources may be not only caused by intermittency of the radio emission, but they may originate from tidal disruption events (Readhead et al. 2024, Sullivan et al. 2024). In this case, the radio emission would be "episodic" rather than "intermittent". This model predicts a large number of CSOs.

We are undertaking a systematic search for remnants objects among the sources of the B3-VLA CSS sample (Fanti et al. 2001). This will allow us to investigate, for the first time, the incidence of short-lived objects in a statistically complete sample of young radio sources, and to shed light on the life cycle of the radio emission in its early evolutionary stages after the outburst.

2. The sample

The B3-VLA CSS sample consists of 87 bright ($S_{408\mathrm{MHz}} > 0.8$ Jy) and intrinsically compact (LS $<$ 20 kpc) radio sources, which are divided into 25 CSOs and 62 MSOs, though not all the sources have a clear core identification. As a pilot project, we selected a sub-sample of 18 objects (6 CSOs and 12 MSOs) characterized by

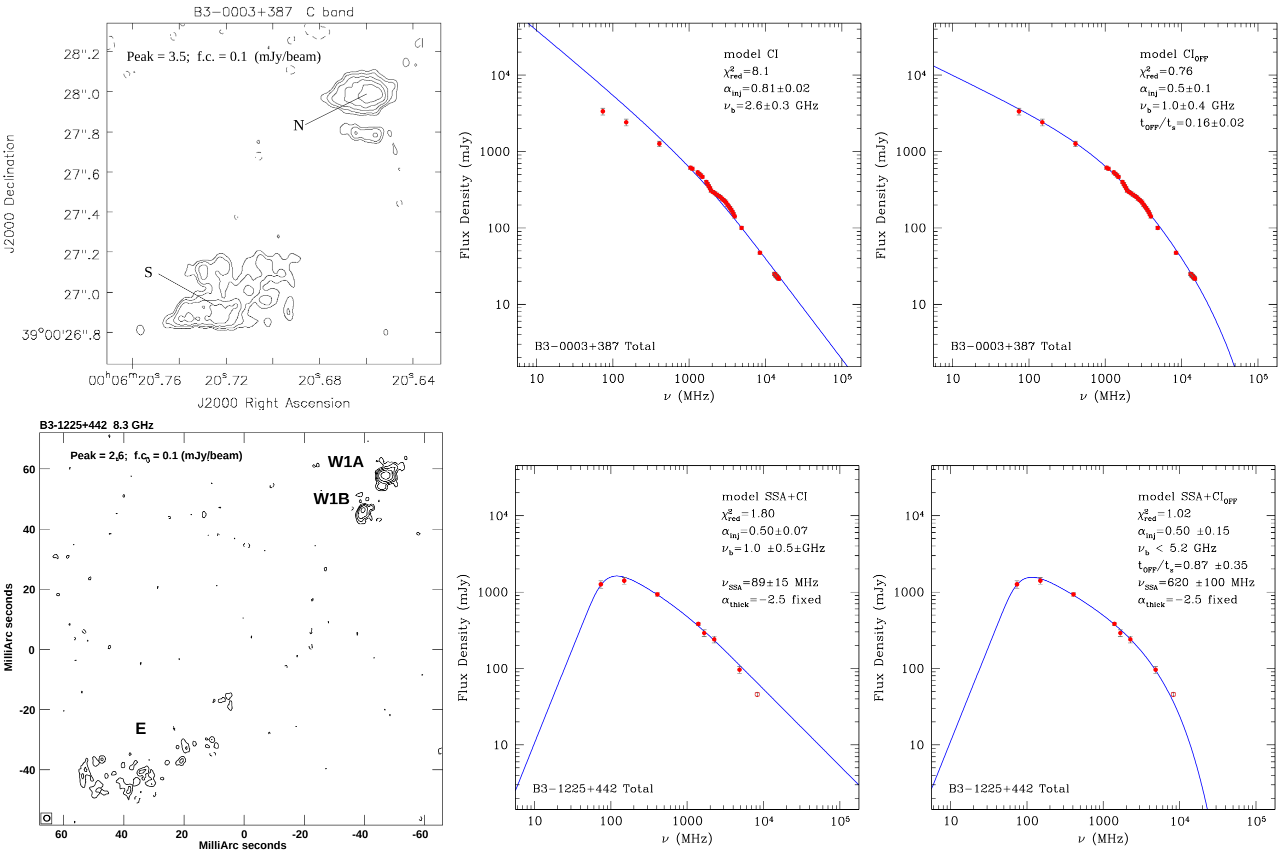

Fig. 1. Images and integrated spectra of the sources B3-0003+387 (top panel) and B3-1225+442 (bottom panel). Integrated spectra are fitted with either CI or CI OFF models. Adapted from Orienti et al. (2023).

1) a steep spectrum ($\alpha > 1.0$, $S_\nu \propto \nu^{-\alpha}$), and 2) with no core detection in earlier observations. These aspects could be considered as signatures of an aged population of relativistic electrons, with no significant contribution of newly injected/accelerated ones.

We observed the CSOs with the very long baseline array (VLBA), whereas the MSOs were observed with the very large array (VLA). Moreover, for the six most compact MSOs we got high-angular resolution e-MERLIN observations. These observations were then complemented with archival high-resolution data already published in Fanti et al. (2001), Dallacasa et al. (2002a, 2002b), Orienti et al. (2004), and Rossetti et al. (2006).

3. Results

To unveil whether a source is active or not, we investigated both the shape of the synchrotron spectrum and the radio morphology. The integrated spectra were fitted with two different models (see Murgia et al. 2011 for details): 1) assuming a continuous injection of fresh particles (CI model), 2) assuming that the injection of new particles has switched off and the source entered in a coasting phase (CI OFF model). We consider remnants those sources with an integrated spectrum that is best fitted by the CI OFF model, and do not show compact components with $\alpha < 0.8$, like core and hotspots.

Three sources, 2 MSOs and 1 CSO, follow our criteria and we classified them as bona-fide remnants (e.g., B3-0003+387, top panel of Fig. 1). Despite undetected in archival data, the high sensitivity of our new multi-frequency observations allowed us to unambiguously identify the core in 10 sources. Among them, we identified 2 CSOs and 1 MSO as restarted sources, since they do not show hotspots and their integrated radio spectrum requires a relic phase, suggesting that the activity has not been continuous during the entire source age (Orienti et al. 2023).
In the bottom panel of Fig. 1 we show how complementing the information on the source morphology with that on the radio spectrum proved to be effective in the classification of the radio source B3-1225+442 as a bona-fide restarted source. X-band VLBA observations could detect the flat spectrum core but the lobes, well detected in the L-band image presented in Dallacasa et al. (2002a), are resolved out, pointing out the lack of hotspots. On the other hand,

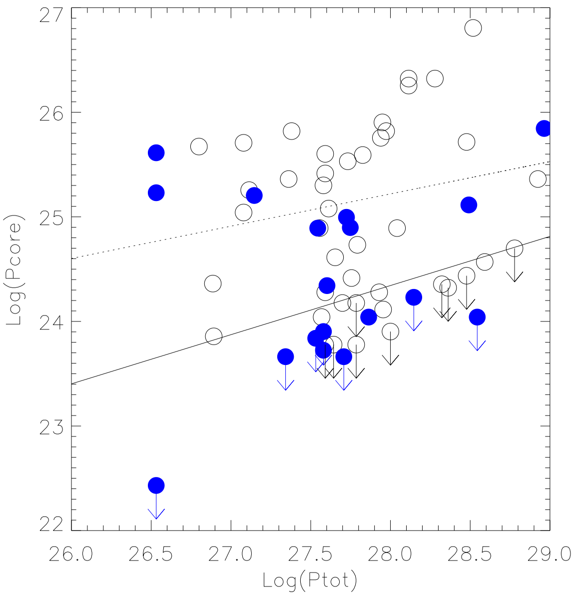

Fig. 2. Core luminosity at 5 GHz vs total luminosity at 408 MHz of the sources in the B3-VLA sample. Empty circles are CSS sources from Fanti et al. (2001), while blue filled circles are the sources from our sub-sample. The solid and dotted lines are the empirical relation for 3CR sources from Giovannini et al. (1988), and that for the B3-VLA CSS sources from Orienti et al. (2023). Downward arrows are upper limits. Adapted from Orienti et al. (2023).

the spectrum is well fitted by a CI OFF model, indicating that the radio emission has likely restarted not long ago.

4. Discussion

The discovery of remnants and restarted objects in a sub-sample of young radio sources give further evidence of short duty cycles for the radio emission. We investigated the level of core activity of the sources in our sub-sample by studying where the sources from the B3-VLA CSS sample are located in the core luminosity vs total luminosity diagram (Fig. 3). The sources from the B3-VLA CSS sample follow quite well the empirical relation found by Giovannini et al. (1988) for the 3CR galaxies. Sources with no core detection are well below the empirical relation. However, we cannot exclude that some level of core activity is always present, even if it is not able to launch powerful jets. It is worth mentioning that several sources are hosted by galaxies with jets oriented at a large angle with respect to our line of sight, and the core flux density may be Doppler diminished and undetected by sensitivity limitation (e.g., Saikia & Kulkarni 1994).

The small number of sources in our sub-sample prevented us to set strong constraints on the incidence of remnants/restarted objects in the population of young radio sources at different evolutionary stages. To improve the statistics we need to extend the study to the whole B3-VLA CSS sample.

A dominant population of short-lived radio sources is required to explain the high fraction of remnants/restarted radio galaxies, though on much larger scales, discovered by high-sensitivity deep-field observations (Shabala et al. 2020). The discovery of remnants among classical large radio galaxies with angular size $> 5-6$ arcsec, though not trivial, is not as challenging as in the case of young radio sources. In classical radio galaxies of hundreds of kpc in size, the source structure is resolved into an adequate number of resolution beams (i.e. independent regions) that allows a detailed study of the spectral index distribution across the entire source, as well as across single components (e.g., Orrú et al. 2010, Harwood et al. 2017, Quici et al. 2022). On the other hand, the (u,v)-coverage and the number of resolution beams that can be used for the spectral analysis in young radio sources are quite limited, usually preventing the investigation of spectral changes across single components (e.g., Orienti et al. 2004, Tremblay et al. 2016).

The significant improvement in sensitivity, angular resolution, and (u,v) coverage of the forthcoming facilities, such as SKA and ngVLA, will provide a step forward in the analysis of the spectral index distribution, and in the search for remnants, in particular among young radio sources.

5. Conclusions

Finding remnants and restarted objects among young radio sources is not a trivial task. No systematic searches for fading young radio sources have been performed so far. However, inferring the fraction of remnants and restarted objects in the population of young radio sources would provide important information on the time scales of the radio emission. Forthcoming facilities like SKA and ngVLA, as well as their precursors, will allow a step forward in our knowledge of the life cycle of radio sources and will provide, for the first time, the possibility to investigate the cosmological evolution of young radio sources thanks to the study of the MHz-peaked spectrum population.

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