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The GRACE project

Hard X-ray giant radio galaxies and their duty cycle

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Abstract. The advent of the new generation of radio telescopes is opening up new possibilities for classifying and studying high-energy extragalactic sources, especially the under-represented ones such as radio galaxies. Among these, Giant Radio Galaxies (GRG, larger than 0.7 Mpc) are among the most extreme manifestations of the accretion/ejection processes at supermassive black holes. Our recent studies have shown that GRGs can be up to four times more abundant in selected hard X-ray samples (i.e. from INTEGRAL/IBIS and Swift/BAT at >20 keV) and, most interestingly, most of them show signs of resurrected radio activity. This makes them an ideal test-bed for studying the unknown duty cycle of jets in active galactic nuclei. Open questions in this field include How and when do jets restart? How do jets evolve and what's their dynamics? What is the duty cycle of the jets and what triggers them? Our group has recently collected a wealth of radio data on these selected high-energy GRGs, allowing us to study their jet formation and evolution from pc to kpc scales, across different activity epochs. In particular, thanks to our large EVN programme, we have been able to probe the new radio phase in the core of these giants. We are also working to exploit new radio survey data to discover new classes of counterparts to the Fermi/LAT catalogues. In particular, we are revealing the hidden population of radio galaxies associated with gamma-ray sources.

1. Introduction

Giant Radio Galaxies (GRG, Willis et al. 1974) are among the most extreme manifestations of the accretion/ejection processes on supermassive black holes. During their ∼100 Myr time-scale evolution (Machalski et al., 2004; Jamrozy et al., 2008), they produce jets of plasma extending hundreds of kpc away from their active galactic nucleus (AGN) core. Their projected linear size, known to be between a conventional threshold of 0.7 Mpc and a maximum of 4-5 Mpc for decades (3C236, J1420-0545, and Alcyoneus, see Schoenmakers et al. 2000; Machalski et al. 2008; Oei et al. 2022), was recently extended to 7 Mpc (Porphyrion galaxy, see Oei et al. 2024). This implies that their jets are not only able to probe the intergalactic medium, but also fill voids between galaxy clusters. With such a long activity period, GRGs are the ideal testbed to study the duration of the radio phase in AGN, and its duty cycle. The recent release of new generation radio surveys (e.g. LoTSS, VLASS, RACS) is opening new possibilities for the study of radio galaxies, allowing for a deeper and sharper search, increasing their census even in the high energy domain, so far dominated by blazars.

Since early 2000s, the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) and the Neil Gehrels Swift Observatory (Swift) have been scanning the hard X-ray sky (20∼100 keV) at a sensitivity better than a few mCrab, and a point source localization accuracy of a few arcmin. The missions have produced catalogues of hard X-ray selected Active Galactic Nuclei (AGN, e.g. Malizia et al. 2023, Oh et al. 2018, and references therein) offering an unbiased view on the high-accretion regime on supermassive black holes. The samples have been the subject of several studies along years (Malizia et al., 2014; Panessa & Giroletti, 2013; Panessa et al., 2015, 2016). As expected, radio galaxies are only a fraction of these samples (∼8%). Despite their rarity, they offer the unique possibility to study at the same time ejection and accretion processes, and their connections.

2. The GRACE project

Recently, our group (GRAL - Gamma Radio Astrophysical Lab, `http://gral.iaps.inaf.it/`) has been focusing on the investigation of radio emission in such sample (Chiaraluce et al., 2020; Panessa et al., 2022), and in particular in radio galaxies. The latter show a fraction of GRG almost twice the one found in traditionally radio-selected samples (Bassani et al., 2016). Our follow-up studies on these hard X-ray GRG (HXGRG), through both a morphological and spectral analysis (see Fig. 1, revealed the presence of a restarted radio activity in the majority of objects (Bruni et al., 2019, 2020, 2021). This makes the sample the ideal testbed to study the jet duty cycle and triggering in AGN, so far still an open question for both stellar mass and supermassive black holes physics.

2.1. The jets duty cycle in AGN: open questions

We triggered a dedicated campaign involving the main radio telescopes around the globe (the GRACE project - Giant RAdio galaxies and their duty Cycle, `https://sites.google.com/inaf.it/grace/home`) securing datasets to answer the following open questions:

- **How and when jets are restarted?** Zooming into their cores by means of the VLBI techniques thanks to the collected data from our EVN and LBA large project (PI Bruni), and e-MERLIN pilot observations (PI Bruni), we aim at 1) studying the recently restarted radio phase 2) spotting any hint of jet precession, and 3) probing the possible presence of a binary supermassive black hole system (B-SMBH). Observations include a comparison sample hard X-ray *quiet* GRG (HQGRG), that will allow us to put the results in the context, understanding the selection effect and properties introduced by the HX selection. As an added value, the latter goal would be a preparatory study for the next generation of gravitational waves antennas (E.T., LISA), that will cover the low frequency domain dominated by B-SMBH.
- **How jets evolve and what's their dynamic?** Study the Mpc-scale lobes morphology to recover the information on the evolution and dynamics of these sources on the Mega-years time scale. We will make use of the already collected data from our VLA and GMRT campaign on a pilot sample of 2 HXGRG (PI Bruni), plus LOFAR survey data available for about half of the HXGRG and HQGRG comparison sample (LoTSS DR2, recently released). This will allow us to individuate the different radio phases, putting constraints on the duration of the radio activity along the AGN activity. Our collaboration includes experts in MHD simulations of jets, allowing for a comparison of the observed morphology with the simulated ones: this will lead to an estimate of the physical parameters of the plasma and environment.
- **What is the jets duty cycle?** With the same dataset, it will be possible to estimate the synchrotron ageing of the jets' plasma through a modelling of the radio SED for the different regions, allowing to date the plasma ejection time and to recover information on the radio phases temporal evolution.

As a whole, the study of the nature and evolution of the HXGRG and HQGRG samples will help understanding how the hard X-ray selection of this sample could favour the discovery of merging, restarting, and in general multiphase radio galaxies, shedding light on the radio activity of AGN.

2.2. First results from the VLBI campaign

VLBI observations of the sample started with a peculiar source showing different classification in different bands, difficult to explain in the framework of the AGN unification scheme: PBC J2333.9-2343. Indeed, while on the Mpc scale it shows extended lobes, apparently on the plane of the sky, on the pc-scale a core-jet morphology was revealed by VLBA observations. A broad-band modeling could estimated a viewing angle of just a few degrees, and a multi-wavelength monitoring could confirm the strong variability typical of Blazars (Hernández-García et al., 2017, 2023). The fact that lobes are detached from their core, led to conclusion that the inner jet in the core region is most probably a new radio phase, where the jet axis dramatically changed its direction. The reason for its $\sim 90^\circ$ reorientation is still unclear, although in such cases a merger is the main suspect.

These premises, together with the high fraction of restarted radio sources in the sample, suggested that hard X-ray selection could more easily select extreme examples of jet reactivation or reorientation. Therefore, in 2020 we carried out a combined EVN+LBA campaign to cover the entire sample at pc-scale resolution. In particular, observations at 8 and 22 GHz were designed to study the newborn radio phase in the nuclei showing a Giga-Hertz

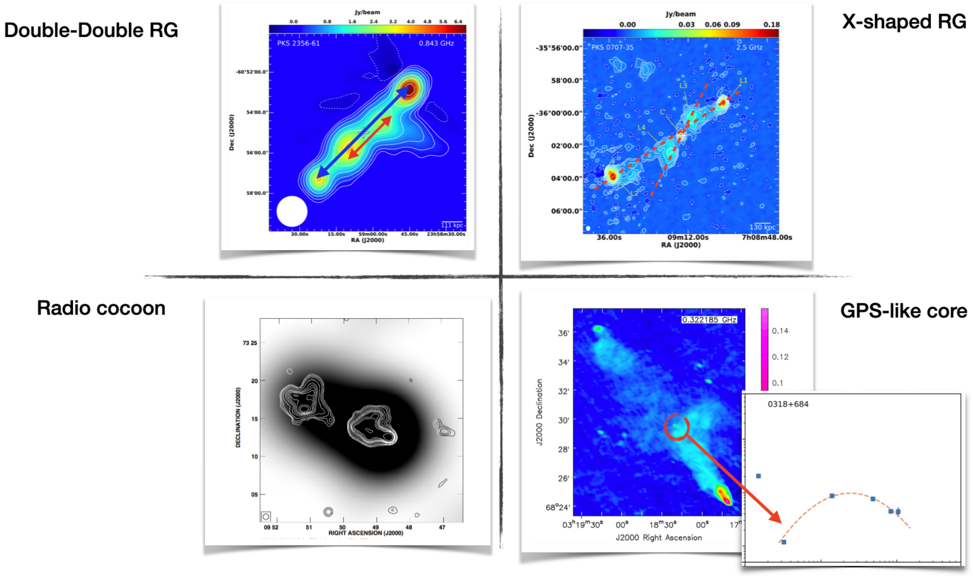

Fig. 1: Main indicators of restarted radio activity: a double-double and an X-shaped morphology, where two couples of lobes are present, even on different axes, a radio cocoon, fossil of a previous radio phase, a GPS-like core, showing a peaked spectrum.

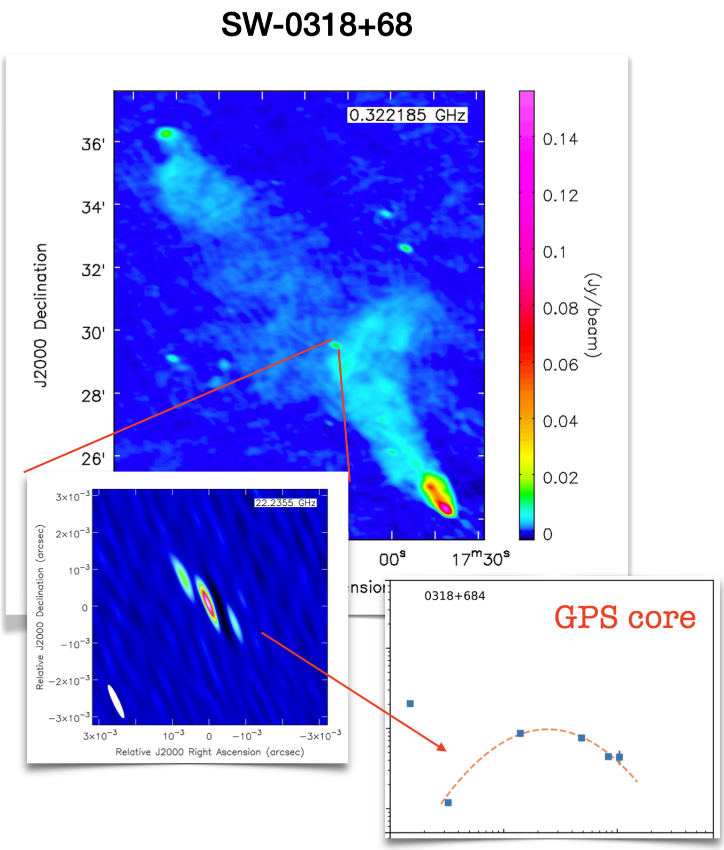

Fig. 2: Multi-scale imaging of the giant radio galaxy SW 0318+68. With a projected linear size of ∼1.6 Mpc, this is the most extended source of the sample. The Mpc-scale image is from the LoTSS survey (150 MHz, Bruni et al. 2021), and shows the extended jets and lobes. The zoom into the pc-scale core region was realized with EVN observations at 8 GHz (contours) and 22 GHz (colors). Mini-lobes and the core are visible. The radio spectrum, showing a peak similar to GigaHertz-Peaked Sources (GPS), has been built with multi-frequency Effelsberg observations plus survey data (Bruni et al., 2019).

Peaked Source (GPS) spectrum, and to estimate the angle of the new jet with respect to the Mpc-scale lobes. First results suggest that all sources with a GPS-like spectrum in their core also show pc-scale mini-lobes, confirming the resumption of the radio phase (see Fig. 2). For two other sources (non-GPS) we found evidence of jet reorientation.

Concluding, the co-presence of Mpc-scale lobes and a new radio phase (GPS) will allow us to estimate the duty cycle in these sources. First estimates via synchrotron ageing of lobes suggest a value of ∼50-70 Myr, to be compared with the one of the GPS phase, usually a few thousands years (O'Dea & Saikia, 2021).

3. The tip of the iceberg: an emerging population of high-energy radio galaxies

Beyond giant radio galaxies, new radio surveys are unveiling a growing population of radio galaxies associated with gamma-ray sources, in contrast with the common picture that sees blazar as the almost unique counterpart. Our group has recently studied a peculiar Fanaroff-Riley II INTEGRAL radio galaxy with a counterpart in the Fermi/LAT catalogue (Bruni et al., 2022). Through a broad-band spectral fitting from radio to gamma-ray, we found that the commonly invoked jet contribution is not sufficient to account for the observed gamma-ray flux. Instead, our modelling suggested that the observed emission could mainly originate in the lobes (rather than in the radio core) by inverse Compton scattering of radio-emitting electrons off the ambient photon fields. As a follow-up of this work, we have proposed to join the MeerKAT+ survey with the goal of identifying Fermi radio galaxy counterparts in the Southern hemisphere. Indeed, the survey will open a new window on the counterparts of the high-energy sky thanks to its unique combination of resolution and sensitivity. The sound statistical basis provided by the survey will allow us to extend the SED modelling of our recent pilot study to a complete sample of objects, with the goal of unveiling the production site and process of gamma-ray emission.

4. Conclusions

The multi-scale/frequency study of radio galaxies, made possible by new generation radio surveys and telescopes, is revealing details about jets duty cycle at different accretion regime, and their evolution in the Mpc-scale environment. In particular, an emerging population of high-energy radio galaxies, detected by Fermi, is suggesting that ngVLA and SKA will be able to unveil more and more of these sources. VLBI observations can provides paramount insights on the central engine, revealing cases of dramatic jet reorientation and reactivation. The GRACE project will serve as a first step in exploring synergies between different instruments to probe jets formation and evolution in different systems.

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