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## Unveiling the nature of giant radio galaxies

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### Citation

Dabhade, P. (2021, May 25). *Unveiling the nature of giant radio galaxies*. Retrieved from <https://hdl.handle.net/1887/3179453>

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**Note:** To cite this publication please use the final published version (if applicable).

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**Issue Date:** 2021-05-25

# Summary

## Giant radio galaxies

Our current understanding of Active Galactic Nuclei (AGNs) tells us that they are broadly divided into two distinct physical classes, namely the AGNs dominantly radiating at radio wavelengths with radio jets, called as radio-loud AGNs or jetted AGNs and others without radio jets called as radio-quiet or non-jetted AGNs. Radio-loud AGN are also referred to as radio galaxies (RGs) or radio quasars (RQs), which exhibit radio jets-lobes system extending beyond the galactic scales. Their formation and evolution have been studied for nearly six decades with the help of large sky radio and optical surveys along with theory and numerical simulations. This has resulted in models that explain most of their observed properties. However, some outstanding problems related to radio-loud AGNs are still under active investigation, like what are the conditions under which an AGN becomes radio-loud and why do only a small fraction of RG population grow to megaparsec (Mpc) size. RGs or RQs growing more than 0.7 Mpc in size are defined as GRGs, which were found almost two decades (1974) after RGs were discovered in the early 1950s.

Until the advent of large sky area radio surveys in the 1990s, discovering exceptional radio objects depended on the dedicated observations of bright sources selected from radio catalogues (e.g. 3CRR), containing hundreds of radio sources. The arrival of sensitive large area surveys like NVSS, WENSS, FIRST and SUMSS in the 1990s led to discoveries of interesting radio objects ranging from galactic to extragalactic; stars to AGNs to galaxy clusters. This consequently led to the possibility of carrying out studies of large samples, unveil the trends in their respective properties and also discovery of GRGs. However, most of the studies on GRGs were restricted to radio wavelengths and focused on their large scale radio properties. Therefore, the unexplored AGN properties of GRGs provides an opportunity to understand them by comparing with normal-sized RGs. The comparison will allow us to determine the distinguishing factors between them and thereby the reasons for the giant nature of some RGs/RQs. In this thesis, the work has been

carried to address the questions ( see section 1.5 of Chapter 1) pertaining to the giant nature of GRGs and to fill the remaining gaps in our understanding of their properties.

## This thesis

Until the year 2016 only about 300 GRGs were known and the studies of their properties were very limited. In order to understand the possible causes for the giant nature of GRGs and their rarity, it is essential to study their AGN as well as environmental properties. In order to carry out such a study, there is a need for a statistically large GRG sample. Hence the main focus of this thesis was to carry out large scale search in radio surveys complemented by new optical data to create large samples of GRGs to study their properties and respective trends. The studies carried out with the new samples have answered some key questions about their properties which are described in the chapter wise summary below.

Chapter 2 presents the pilot results of the project called SAGAN, which stands for ‘Search and Analysis of Giant radio galaxies with Associated Nuclei’. The aim of this project is to carry out systematic search for GRGs from available radio surveys combined with new optical surveys. As a result, new 25 GRGs were discovered from the NRAO VLA Sky Survey (NVSS) in the redshift range of  $0.07 < z < 0.67$ . Using publicly available data we studied their radio, optical and mid-infrared properties. Combining the newly discovered 25 GRGs with the known ones from literature, we created a sample of 137 GRGs and for the first time classified their AGN excitation type using mid-infrared colours. This allowed us to show that AGNs of the GRGs do not have preferred excitation state (high or low accretion rate). Also, using our 25 new GRGs and other GRG data from literature we created a sample of 82 GRGs (largest sample then) to study them with respect to Power (P) - Size (D) or P-D diagram along with a sample of smaller sized radio sources from literature (3CRR). Our analysis revealed that at 1.4 GHz the GRGs tend to be less luminous compared to RGs, which could be due to higher adiabatic expansion and radiative losses in GRGs. RG models have suggested that RGs with age evolve towards larger sizes and lower luminosities. We also found the lower right corner region of the P-D diagram to be empty, or in other words we did not find sources with very large sizes and low luminosities. These are mostly faded sources with very low surface brightness and beyond the detection capabilities of surveys like NVSS. Also, our findings suggests that GRGs with sizes greater than 2 Mpc are more rare.

In Chapter 3, results of an extensive search of GRGs from the LOFAR Two-metre Sky Survey (LoTSS) data release 1 is presented. The LoTSS covers a sky area of  $424 \text{ deg}^2$  in the northern sky at 144 MHz with a sensitivity of  $\sim 100 \mu\text{Jy}$  with images available at two resolutions of  $6''$  and  $20''$ . The low-frequency nature of the survey makes it ideal to map diffuse and steep spectrum radio emission from

sources. LoTSS with its high sensitivity and high resolution is able to resolve intricate details of the sources, allowing us to study their morphologies in great details. As a result of a hybrid method of manual and semi-automated search, a record 239 GRGs were found in the redshift range of  $0.1 < z < 2.3$ , of which 225 were new discoveries. This is the single largest sample of GRGs found to date from any survey and has almost doubled the known population of GRGs. Our new sample also has three giant radio quasars (GRQs) with  $z > 2$ , which are difficult to detect owing to the high redshift nature and rarity. Several GRGs have a very steep spectrum and are not visible in high-frequency surveys like the 1.4 GHz NVSS. About seven sources in our sample have projected linear sizes greater than 2 Mpc. We combined the LoTSS low-frequency data with NVSS high-frequency data to determine the spectral index ( $\alpha$ ) and found that the average  $\alpha$  for GRGs is 0.78 which is similar to that of normal-sized RGs. Contradictory to the prevailing assumptions, this study shows that old GRGs with diffuse relic (older) emission do not dominate the GRG population, since the spectral index distribution is similar to that RGs. Owing to our large sample size and availability of good observational data, we were able to identify GRGs with unique characteristics. Our sample has 40 GRGs hosted by quasars (GRQs), 14 with restarted AGN activity- called the double-double radio galaxies (DDRGs), 6 GRGs with hybrid radio morphology, and 20 GRGs hosted by the brightest-cluster galaxies (BCG) residing in the dense cluster environment. The large sample of GRGs also allowed us to establish that at least 16% GRGs at  $z < 0.55$  are residing in the dense cluster or group environment. This result highlights that despite the dense environment, given enough jet power combined with ongoing AGN fueling (possibly), RGs can grow to megaparsec scales.

Chapter 4 presents the first results of project SAGAN, where we report the finding of 162 new GRGs based on our search from the NVSS. The new sample of GRGs are found in the redshift range of  $0.03 < z < 0.95$  with sizes up to  $\sim 2.8$  Mpc and 23 sources powered by quasars. Combining all the GRGs reported (till March 2020) in literature since 1974 with our samples from SAGAN and LoTSS, we defined and created the largest GRG catalogue of 820 sources. To create the GRG-catalogue, all the papers reporting GRGs since its discovery in 1974 were searched from the various database and all the sources were manually inspected with updated radio survey data like NVSS, TGSS, FIRST, SUMSS, and WENSS. The optical host galaxies of each reported GRG were also re-examined using the latest optical database like SDSS, 6dF, 2MASS, 2dF, and PanSTARRS. In the absence of high-resolution maps showing entire structures, angular sizes of sources were remeasured uniformly using the NVSS. Uniform cosmology was used by adopting the latest Hubble constant value from the Planck mission to compute the projected linear sizes of GRGs. Our GRG-catalogue allowed us to create statistically significant sub samples (matched in redshift) to study its AGN and environmental properties in comparison with samples of normal-sized RGs. We carried out a multi-wavelength analysis of the AGNs of the GRGs using optical, mid-infrared and radio data. Our results show that black hole mass and radio

spectral index distribution of GRGs and RGs are similar. In contrast to the above, the average accretion rate of GRGs was found to be lower than that of RGs. We also show with larger samples that GRG AGNs do not have a preferred excitation state (low or high), which confirms the findings presented in Chapter 2. We observe GRGs in high excitation state tend to have larger sizes, radio power and accretion rate. Using the multi-wavelength data we also estimated the kinetic jet power, total radio power, magnetic field and total sizes and compared it with high and low excitation classes. Furthermore, we find that 10% GRGs reside in centres of galaxy clusters, i.e., in the dense environment and yet grow to megaparsec scales. Hence environment alone cannot be the only governing factor for the large sizes of GRGs. Using all the above results we discuss the possible factors governing the formation and growth of GRGs in detail.

Chapter 5 presents the results of our millimetre-wave study of host galaxies of GRGs. The study was carried out to understand the molecular gas content of the host galaxies of GRGs and its role in the AGN fueling. Such sample studies of GRGs are scarce and important to understand their working mechanism. Most GRGs are hosted by elliptical galaxies (with a few exceptions), which generally lack high star formation. A total of 12 GRGs were selected based on their mid-infrared colours for this study which show signs of heated dust and are likely to be in gas-accretion and star formation phase. Using our observations we report the molecular gas content and star formation efficiency. Our observations with IRAM-30m millimetre wave telescope show detection in three of the twelve selected target GRGs and report upper limits for the rest of the sample. We find two of the GRGs deficient in molecular gas content and with a short depletion time of  $\sim 200$  Myr. Two detections from our sample belong to GRGs hosted by giant gas-rich spiral galaxies which are extremely rare. We use the information available in the literature for other four GRGs in addition to our sample to discuss the observed results and trends. We find the host galaxies of the GRGs follow the main sequence of galaxies with most of them being passive galaxies. Also, GRGs with detection of molecular gas either show signs of restarted AGN activity or are a part of galaxy groups. This sheds more light on the role of environment on refuelling of the AGN. Hence, our millimetre-wave study of GRGs shows that a complex cycle of AGN fueling along with environmental factors are involved in the growth of GRGs.

In Chapter 6 the first study a peculiar ‘Barbell’ shaped GRG (GRG-J2233+1315) is presented using observations from GMRT, LOFAR and optical 4.2m William Herschel Telescope (WHT). This object was found under project SAGAN and reported for the first time in [Dabhade et al. 2017](#) (Chapter 2), where the size was estimated using photometric redshift from SDSS. In this chapter, we present its spectroscopic redshift from our optical observation with the WHT. The multi-frequency radio data was obtained at 144 MHz (LOFAR), 323 MHz, 612 MHz, and 1300 MHz (GMRT), which led to the finding of peculiar  $\sim 100$  kpc ‘kink’ structure in the western jet of the GRG. We discuss the possible reason for this peculiar structure using available results, models from Magneto-hydrodynamical (MHD)

simulations along with its comparison with other similar examples from literature. Such features in extragalactic radio objects provide the ideal laboratory for studying large scale MHD effects. We also observe a long counter-jet on the eastern side which is rare in FR-II type of GRGs. Using the radio data we have estimated the classical and revised estimates of the magnetic field of both lobes ( $\sim 5 \mu\text{G}$ ), which is consistent with the estimates of other GRGs from literature. This also allowed us to estimate the spectral ages and found them to be greater than  $\sim 110$  Myr, which shows the longevity of the AGN activity as well. Interestingly, the GRG resides in a dense cluster environment hosted by the brightest cluster galaxy (BCG) and yet has been able to grow to 1.88 Mpc in size. Using the information from the cluster catalogues, we present the galaxy cluster's virial mass ( $M_{200}$  of  $\sim 1.1 \times 10^{14} M_{\odot}$ , virial radius ( $R_{200}$ ) of  $\sim 1.02$  Mpc, and has expected X-ray luminosity of  $0.29 \times 10^{44} \text{ erg s}^{-1}$ . It is most likely that the environment of this GRG surely has had an effect on its growth and morphology.

## Future Scope

The work in this thesis has established that the GRGs are not as rare as previously thought to be. Now, with more than 800 GRGs catalogued, the next step would be to create subsamples (matched in redshift) of GRGs and study their properties also in comparison with normal-sized RGs using high resolution optical and infrared spectrographs or integral spectral unit (IFU) along with X-ray data. This will help determine the accretion state and overall AGN power of the GRG. Similarly, using optical and X-ray data, the effect of environmental densities and inhomogeneities on the GRG structure and growth will be probed.

With the rapid development in hardware and software in radio astronomy, the speed of carrying out large scale radio surveys has increased and hence surveys with LOFAR, uGMRT, MeerKAT, JVLA, and ASKAP are going to discover 100s of GRGs, which can be used for constraining RG growth and evolutionary models. Also, a large sample of GRGs can possibly be used to probe the warm-hot intergalactic medium (WHIM as described in section 1.5 of Chapter 1, by comparing their pressure balance using GRG radio observations and WHIM simulations. This particular aspect can be explored for GRGs hosted by brightest cluster galaxies or GRGs residing in a cluster environment and with the release of X-ray data from eROSITA mission in the near future it will be possible to carry out such studies.

