Unveiling the nature of giant radio galaxies
Dabhade, P.

Author: Dabhade, P.
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1 | Introduction

"Science is a way of thinking much more than it is a body of knowledge."

- Carl Sagan

The scientific framework explaining the growth and evolution of the Universe is referred to as the standard model* of cosmology or the standard Λ cold dark matter (ΛCDM) model (Peebles 2012, 2017). It successfully describes the formation and growth of structures starting from the first second to the present epoch. The ΛCDM model is widely supported by numerous high precision observations, like the measurement of the 'Cosmic microwave background radiation' (CMBR or CMB) using space based missions (e.g., Planck Collaboration et al. 2016). For the early Universe, prior to the hot Big Bang phase, the 'Cosmic Inflation' (Gorbunov & Rubakov 2011; Baumann 2009) emerges as the leading scenario and sets natural finely tuned initial conditions for the standard model. It explains the large scale observed homogeneity as a result of the rapid growth the inflation caused. There were fluctuations in the energy densities (matter) which were possibly caused by the quantum fluctuations in the early Universe. These fluctuations grew under the influence of gravity, and as the Universe expanded and cooled, it led to the formation of smaller over-densities or irregularities in the primordial Universe (after 3,80,000 years), which are observed in the CMB as anisotropies. Upon further expansion of the Universe, dark matter haloes grew, providing essential potential well for the gas clouds to settle in. The over-densities, along with gravity, triggered the collapse of dense gas clouds into the formation of very high-mass stars due to rapid adiabatic heating of gas, condensation and high accretion rate. This set the stage for the formation of the first galaxies, and the theories (Rees 1993; Barkana & Loeb 2001) suggest that these were around 100 million years after the big

*https://pdg.lbl.gov/2020/astrophysics-cosmology/astro-cosmo.html bang phase. The most sensitive observations to date have found galaxies at redshifts (z) of 10 to 11 (Bouwens et al. 2015; Oesch et al. 2016), which is ~400 million years after the Big bang phase.

Stars, dust, and gas held together by the interplay of gravity and dark matter in a system is called a galaxy. Galaxies weigh around $\sim 10^9$ to 10^{12} $\mathbf{M}_\odot$, and are often part of a bigger systems like galaxy groups or galaxy clusters. As per the standard ΛCDM cosmological model, structure formation is hierarchical, where smaller dark matter (DM) halos merge to form bigger ones, which led to the formation of the first galaxies in the Universe (Springel et al. 2005). Decades of observations combined with complex simulations in the recent years have enriched our understanding of the formation and evolution of galaxies, however, it continues to be an ongoing endeavour (Loeb 2010). The physics involved in galaxy formation is quite complex as it needs to encompass thermodynamics of gas, production energy for stars and the dynamics of stars. Galaxies are classified on the basis of their structure, and hence we have three broad categories like the elliptical, spiral and irregular type of galaxies.

As per the Hubble classification scheme, the elliptical and spiral galaxies are further sub-classified (Hubble 1926; de Vaucouleurs 1963). The elliptical galaxies are subdivided into several categories based on their ellipticity level ranging from E0 (almost spherical) to E7 (elongated). These are the largest galaxies seen at optical/infrared wavelengths, which are formed as a result of mergers over a period of giga years (Gyr). In comparison to our own galaxy - the Milky Way, ellipticals can be ten times larger and host trillion stars. Also, the giant ellipticals are often located at the centres of galaxy clusters, and quite a lot of their population emits dominantly at radio wavelengths (Valentijn & Bijleveld 1983; Bagchi & Kapahi 1994; Best et al. 2007; Hogan et al. 2015). Spiral galaxies, on the other hand exhibit spiral arms attached to the central bulge of the galaxy with a rotating disk with enhanced star formation. Under the Hubble classification scheme, the spiral galaxies were assigned a, b, and c classification based on their compactness of the spiral arms. Furthermore, spiral galaxies were sub-classified into barred spiral galaxies which show a central bar-shaped structure comprising of stars. The most abundant type of galaxy known in the Universe is the Dwarf galaxy, which owing to their low size, luminosity, and mass are difficult to observe. Galaxies with no well defined shapes are referred to as the irregular type whose masses are in the range of $\sim 10^8$ to 10^{10} $\mathrm{M}_\odot$. They are thought to be the end products of galaxy mergers or tidal interactions, leading to their peculiar shape.

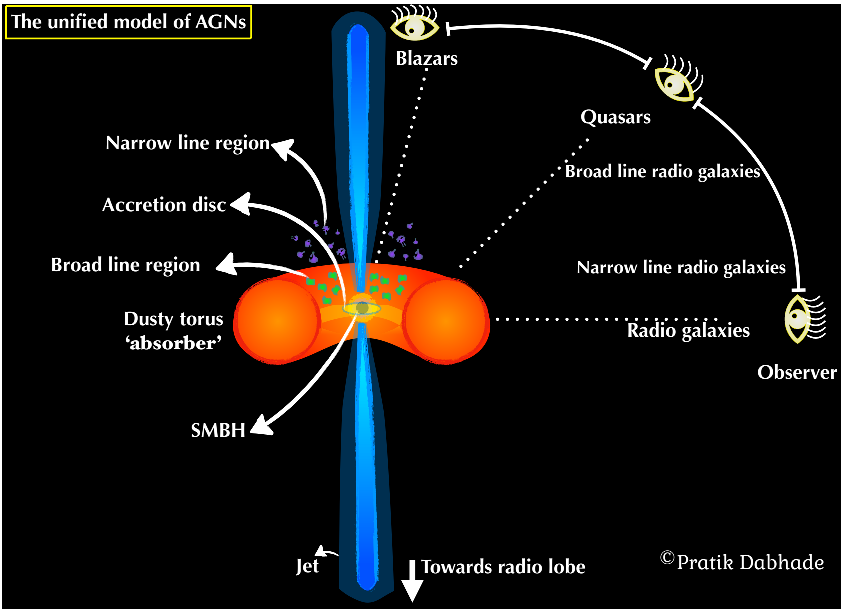

Figure 1.1: The modified version of the unified AGN model presented here in context of the radio galaxies.

1.1 Active Galactic Nuclei

Based on observational evidence, backed with theory, the mergers driving the galaxy formation is the favoured model. The model explains that the galaxy mergers initiate a sequence of events where the gas clouds collide upon mergers, triggering star formation. This, in turn, causes the gas to be pushed towards the galaxy centre, creating an active galactic nucleus (AGN) (Hopkins et al. 2008). Almost all galaxies harbour a super-massive black hole (SMBH) at their centres (Kormendy & Richstone 1995; Magorrian et al. 1998), and their masses correlate with the velocity dispersions of stars (Gebhardt et al. 2000; Kormendy & Ho 2013). Hence, the observed correlation with the central bulges and the SMBH (Ferrarese & Merritt 2000; Marconi & Hunt 2003; Gültekin et al. 2009). Therefore, it became clear that there exists a co-evolution of galaxies and AGN (Silk & Rees 1998; Kauffmann & Haehnelt 2000; Volonteri et al. 2003).

The field of AGN studies was started with the findings of broad and strong emission lines in the nuclei of spiral galaxies Seyfert (1943). These spiral galaxies were observed to show strong nuclear emission (non-stellar) as compared to other normal galaxies. Extensive studies over the years have gathered convincing proof that the AGN centre comprises of an active super-massive black hole ($\geqslant 10^6$ $M_\odot$). AGNs emit over broad electromagnetic spectrum ranging from radio to gamma-rays with 10^{48} erg s^{-1} bolometric luminosities (L_{bol}). The AGN is covered in an axisymmetric dusty structure called the 'dusty torus' as illustrated in Fig. 1.1, which is quite luminous at mid-infrared wavelengths. It has dimensions of 0.1-10 parsecs which are luminosity-dependent.

Over the years AGN have been classified into several types but essentially are characterised based on a) orientation (Antonucci 1993; Urry & Padovani 1995), and b) their accretion states (Heckman & Best 2014). The updated orientation based unification scheme of AGN (Netzer 2015) comprises of two parts, the first one unifies AGN properties observed from infrared, optical, ultraviolet and X-ray unification, and the other is exclusively about radio unification. The former unification deals with the dusty torus and explains the distinctions between type-I and type-II AGNs. The later unification of radio unifies the radio relativistic jets with the torus. Over the years these models have been constantly updated with more multi-wavelength observations of the AGNs, and it has been realized that the AGNs could differ from one another based on the properties beyond their luminosities and torus inclination. It is suggested that the AGN could differ based on the nature of the central engine and its state (e.g. RIAF or high-efficiency accretion flow) or due to absence of certain components in AGN, e.g. the broad line region (BLR) or narrow line region (NLR).

Currently, the two broad categories of AGNs which are widely accepted are the radiative-mode and jet-mode, whose properties are briefly discussed below-

1. Radiative-mode AGNs - These are efficient accretors and as a result most of their energy output is in the form of electromagnetic radiation arising from accretion through geometrically thin and optically thick accretion disk. The accretion disk emits thermal continuum emission from extreme UV to optical regime of electromagnetic spectrum. A hot corona surrounds the accretion disk which Compton up-scatters soft seed photons to high energy X-rays. This system of corona and accretion disk produces ionizing radiation which heats and photoionises dense gas clouds located close to the SMBH, and in turn produces the observed permitted emission lines in UV, optical and near IR regimes. Some gas at larger distances also produces forbidden and permitted lines with narrow widths. This mode is further

subdivided into different types (Netzer 2015) which are as follows-

- Type I AGNs : Show presence of bright central nuclei (unobscured) and broad (1000 to 20,000 km/s) permitted and semi-forbidden emission lines (as shown in Fig. 1.1). Type-I AGNs with low to intermediate luminosities have narrow emission lines of high ionization, and some population also exhibit forbidden lines. These are also referred to as Seyfert 1 galaxies or quasars.
- Type II AGNs: Show presence of strong narrow (300 to 1000 km/s) lines in near-infrared to optical regime with clear signs of photoionisation. The central region is hidden due to line of sight being near to the equatorial plane of the torus.
- LINERs (low-ionization nuclear emission-line regions) : They are characterised by low-ionization and presence of narrow emission lines from ionized gas. LINERs are further sub-divided into two classes of type-I (having broad emission lines) and type-II (having narrow emission lines). LINERs also show variation in their UV and X-ray fluxes.

2. Jet-mode AGNs- As the name indicates these AGNs produce two sided relativistic jets in which bulk kinetic energy is transported. The Eddington ratio for such AGN is much smaller than the radiative mode and the jets are likely to be produced via RIAFs. The low accretion rate and inefficient flow has been attributed to either the absence of geometrically thin accretion disk or its truncation in inner regions. It may possibly be replaced by geometrically thick disk as well, which has shorter inflow time compared to radiative cooling time (e.g., Narayan & Yi 1994; Ho 2008. Hence these are referred to as advection-dominated or radiatively inefficient accretion flows (ADAFs/RIAFs), which possibly favour launch of relativistic jets. It is further discussed in Sec. 1.2 in context of radio galaxies.

1.2 Radio-loud Galaxies and Quasars

About 90 years ago, efforts of Karl Jansky* led to the discovery (Jansky 1933) of radio waves from the Milky Way and beyond, which opened a

*Flux unit in radio astronomy is Jansky (Jy) in honour of Karl Jansky, where 1 Jy = 10^{-26} W m^{-2} Hz^{-1}.

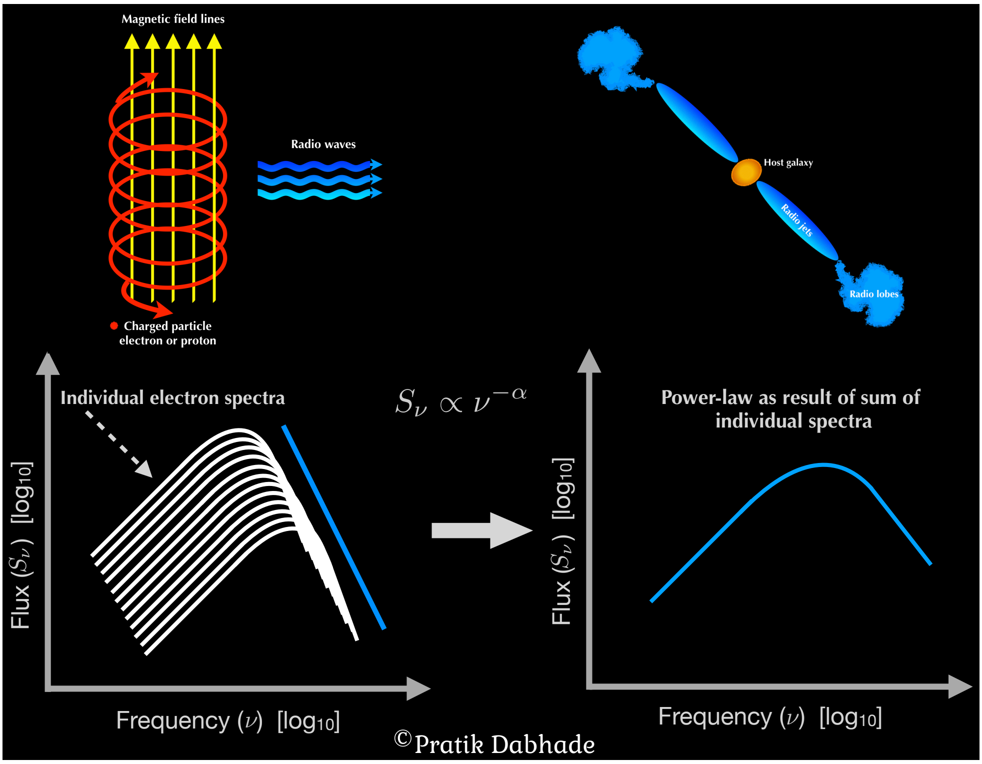

Figure 1.2: The figure illustrates the concept of Synchrotron radiation. The synchrotron emission spectrum follows a power-law decay and is constructed by adding the contributions from individual electrons, where the flux is observed to decline at higher frequencies. The slope of this distribution is called the spectral index α which usually ranges from -3 to 2 for radio sources in general and for RGs it is ~0.75.

new branch of astronomy, called radio astronomy. This paved the way for the discovery of several new objects and creation of sub-fields within astronomy, thereby enriching our knowledge of the Universe. The discovery of radio waves from outer space was taken up by Grote Reber in the 1930s, who with his meticulous work and ingenuity performed landmark research (Reber 1940, 1944, 1946, 1949) and established this field.

Following up on the work of Reber and other advancements in the field by Ryle (1952), works of Smith (1951), Jennison & Das Gupta (1953), and Baade & Minkowski (1954) established the association of radio emission from galaxies (e.g., Cygnus A) and thus, a new class of objects called 'radio galaxies' (RGs) came into existence. Works of Shklovskii (1955), Baade (1956) Burbidge (1956) based on radio spectrum and polarisation properties showed that the observed radio emission from these galaxies is produced by the process of synchrotron radiation (Ginzburg & Syrovatskii 1965, 1969). The production of this radiation is from charged particles (commonly electrons) helically moving or spiralling around magnetic field (as seen in top left of Fig. 1.2) lines at relativistic speeds (Rybicki & Lightman 1986; Shu 1991). The velocity of the charged particle directly influences the frequency of the emission. The spiralling of the charged particle in the magnetic field results in the release of energy in terms of emission of photons. Depending on the strength of the magnetic field, the charged particle loses more energy as it gyrates for a longer time. This results in the charged particle spiralling in the magnetic field at wider lengths leading it to emit radiation at low frequencies or longer wavelength (i.e. radio band of the electromagnetic spectrum). The lifetimes of the electrons in the cosmic radio sources (e.g., AGN) can range from thousands to millions of years before losing their energies via various different processes (see Longair 2011). It is evident from the shape (power law distribution, as seen in the bottom left of Fig. 1.2) of their spectra, which is obtained by observing the source at multiple frequencies covering a wide range. For an electron which is emitting via synchrotron process in a fixed magnetic field, the initial power law is given by $N(E) = N_0E^{-\delta}$, where N_0 is normalization factor and δ is the power law index of the initially injected electron energy distribution. Such a power law distribution (bottom left of Fig. 1.2) is observed in astrophysical sources with the form $S_\nu \propto \nu^{-\alpha}$, where slope of the power law distribution is the spectral index α, which depends only on δ, with $\alpha = (\delta\ \text{-}1)/2$.

The radio emission was observed to extend far beyond the optical extents ($\sim$20 to 70 kpc) of the galaxies ranging from few to hundreds of kiloparsec* scales and beyond. Such objects like RGs also later came to be known as 'radio-loud'.

In the 1960s, radio bright objects at large distances called quasars were discovered (Schmidt 1963; Greenstein & Schmidt 1964) which are the incredibly bright nuclei of distant galaxies. This opened a window to test cosmological models (Rowan-Robinson 1967; Longair & Pooley 1969; Kapahi 1975; Condon 1984; Daly 1994a; Barai & Wiita 2006). Later on, 'radio-quiet' quasars too were found which radiated dominantly at other wavelengths than radio (Sandage 1965).

Based on the observational development then, a theoretical framework (Salpeter 1964; Lynden-Bell 1969; Bardeen 1970) was put forth that the centres of the galaxies host a supermassive black hole of 10^6 - 10^{10} $M_\odot$ mass, which produces twin collimated relativistic jets (Blandford & Rees 1974; Scheuer 1974) observed at radio wavelengths. The idea of the central compact object powering the RGs shrouded in the ion torus was proposed by Rees et al. (1982), which explained their observed lower core power in radio sources compared to the power of their extended components. This model also suggested that the ion tori plays a vital role in supporting the magnetic field, leading to extracting rotational energy from the SMBH to produce the bipolar relativistic jets. Several observations have now shown the evidence of the dusty torus in AGNs (e.g., Jaffe et al. 2004, Koshida et al. 2014, and Carilli et al. 2019). Also, studies involving continuous monitoring of powerful AGNs at multiple wavelengths (especially at higher energies like X-rays and gamma rays) have established the jet connection to the accretion disk (Marscher et al. 2002; Chatterjee et al. 2009). Very recent studies of the powerful radio source M87 with earth size radio telescope called the event horizon telescope have achieved unprecedented resolution and sensitivity. Their observations, for the first time, have resolved closest possible regions near the SMBH, well inside the radio core, proving beyond doubt the existence of black holes and them powering the radio jets (Doeleman et al. 2012; Event Horizon Telescope Collaboration et al. 2019).

Studies (e.g. Marconi et al. 2004; Best et al. 2005; Saikia & Jamrozy 2009) have shown that the SMBH residing in the AGN of the galaxy is active for a limited period when compared to the galaxy's lifetime and is often re-activated or remains in a dormant phase of low activity. Factors responsible for the reactivation or restart of such AGN can be dependent on its environment and availability of accreting fuel (e.g. gas). However, it is difficult to exactly understand these factors due the different AGN

*1 Parsec ≈ 3.08×10^{16} metres modes (radiative and jet mode). The radiative mode AGNs are thought accrete via dense cold gas (Hardcastle et al. 2007) or which may be arising from a merger, whereas for the jet mode driven by radiatively inefficient AGN it has been suggested it needs hot accretion. However, some recent studies have suggested (Gaspari et al. 2013) that for jet mode AGN is driven by chaotic cold accretion. Radio-loud AGN studies (Schoenmakers et al. 2000a; Best et al. 2005; Stanghellini et al. 2005; Saikia & Jamrozy 2009) using optical and radio data have shown that the SMBH activity period is quite less compared to the lifetime of the galaxy and hence, the observations can only be explained by restarted activity of SMBH. This renewal of AGN is dependent on the modes of its nuclear activity and the galaxy's environment (Hardcastle et al. 2007; Heckman & Best 2014; Hardcastle 2018a).

The 'jet-mode' AGN are also known as low-excitation type or low-excitation radio galaxy (LERG), which are mostly prevalent in the radio domain or in RG population (Heckman & Best 2014). Despite having active relativistic jets, they do not show evidence of a luminous accretion disk as they are quite weak at X-ray energies. This possibly could be due to a presence of truncated accretion disk, where accretion could be happening with the help of a geometrically thick structure. The gas is thought to be accreted via radiatively in-efficient flows (RIAFs) or in other words advection dominated flows (ADAFs). As a possible consequence of the above scenario, observationally they do not show strong emission lines in the spectrum of their respective AGNs. These RI type AGNs are the dominant population in the local Universe as compared to the RE type (Best & Heckman 2012a), and studies (Best et al. 2005) have shown that galaxies hosting RI type AGN are quite distinct and that they occur in more dense environments with higher mass and redder colour.

RGs come in many shapes and sizes as seen in Fig. 1.3, and are also referred to as 'DRAGNS', which stands for 'double radio source associated with galactic nucleus'. RGs have been mainly divided into two classes, namely, Fanaroff-Riley type-I (FR-I) and Fanaroff-Riley type-II (FR-II) as described in Fanaroff & Riley (1974), which was mainly done on the basis of radio morphology. Around the same time, the work of Northover (1973), Turland (1975), and van Breugel & Miley (1977) provided great evidence for the existence of extragalactic AGN radio jets emanating from the central region of galaxies. This led to the understanding of the overall structure of RGs, which consists of a radio core (coinciding with the host galaxy) shooting out bipolar jets, which often ended up in cloud like structure called lobes (FR-II) as seen in the top right side of Fig. 1.2. Often high concentration of radio emission was found farther from the host galaxy, transported by jets into lobes to a region called as 'hotspot', the existence of which was shown by Mitton & Ryle 1969 first and then further confirmed by Miley & Wade 1971; Hargrave & Ryle 1974 in the famous radio source Cygnus A. The radio jets and lobes are optically thin in nature, with jets having spectral index $\alpha \sim 0.5$ to 0.8 and ~ 0.7 to 1.5 for the lobes. For the radio core which is compact and optically thick, the spectral index is flat (0 to 0.5) or inverted in some cases. The current interpretation based on the decades of observations and models (Scheuer 1974; Gopal-Krishna & Wiita 1987; Falle 1991; Kaiser & Alexander 1997; Blundell et al. 1999; Hardcastle 2018b) is that the radio jets emanating from the central region of the galaxy propagates through the interstellar medium to outer intergalactic medium for FR-I type. In FR-II type, the jet material encounters and smashes into the ambient medium and creates 'hotspots', which is a shock front with lot of particle acceleration. The region where the jet ends and impacts with external medium, a 'working surface' is developed which maintains high pressure (Blandford & Rees 1974). Here, the bulk kinetic energy of the jet converts into relativistic particles via first-order Fermi acceleration and magnetic fields through shock compression. This process results in emission of large amount of radio synchrotron radiation from high surface brightness 'hotspots'.

Jets are the collimated streams of plasma containing relativistic electrons trapped in a magnetic field, and they primarily radiate via radio synchrotron emission. The jets scaling from parsec to megaparsec scales are powered by the black holes sitting at the heart of the AGN. The leading models explaining the launching and collimation of jets are the mechanisms by Blandford & Znajek 1977 (B-Z) and Blandford & Payne 1982 (B-P). It is outlined in the former model that the jets are powered via extraction of the rotational energy of the black hole, and in the latter case, the jets are anchored by the poloidal component of the magnetic field in the accretion disc surrounding the black hole. Another interesting model is the magnetohydrodynamic (MHD) model which requires a gravitational potential hub i.e. a black hole surrounded by differentially rotating accretion disc with a poloidal magnetic field threading it (Meier et al. 2001). The complexity of the process of jet collimation and confinement increases with different processes contributing at different radii. At the very start, the jet is confined by the gas dynamical disc around the black hole. This region lies within $\sim$ 10-10^5 Schwarzschild radii (r_s) from the black hole (10^8 $M_\odot$ at $z < 0.1$)

(Junor et al. 1999; Hada 2020). If the wind happens to be hydromagnetic then the jet carries an axial current (Blandford et al. 2019) of toroidal magnetic field which is in turn balanced by gas pressure (Begelman et al. 1984). Thus, relativistic jets are mainly confined by gas pressure, and at the lobes by the backflow of particles coming from hotspots for FR-II sources. Study of AGN jets using VLBI along with other multi-wavelength facilities has enhanced our knowledge about the intricate configuration of jet magnetic fields and helped us to constrain the ejection site of highly energetic flares. Recent studies of M87 jet-base with high sensitivity arrays and Very long baseline array support the magnetically-driven (Livio 1999) jet launching model in the presence of spinning black holes.

The works of Scheuer & Readhead (1979); Kapahi & Saikia (1981); Orr & Browne (1982); Kapahi & Saikia (1982) on the relativistic beaming of quasars created the essential foundation for the standard unification scheme proposed for radio quasars and radio galaxies (Scheuer 1987; Barthel 1987, 1989) based on orientation. Under this scheme, it is proposed that (radiatively-efficient) radio-loud quasars, broad line radio galaxies (BLRGs) and narrow line radio galaxies (NLRGs) intrinsically belong to the same population (see Fig. 1.1). This model suggests that closer to the central super-massive black hole is the broad emission-line region which is shrouded in the dusty torus and further out lies the narrow-line emission region. As illustrated in Fig. 1.1, objects viewed closer to the plane of the sky are classified as NLRGs, whereas BLRGs and quasars are viewed at an angle by the observer. The low excitation radio galaxies (LERGs) are thought to be deviant to this proposed model (Barthel 1994). More details can be found in the review article of Urry & Padovani (1995) and further studies (e.g., Ishwara-Chandra & Saikia 2000 and Mullin et al. 2008) tested this model with larger samples, and their results largely support the unification scheme.

1.3 Giant radio galaxies

When the overall size of RGs grows to megaparsec (Mpc) scales, then they are referred to as Giant Radio Galaxies (GRGs). Originally, they were defined by Willis et al. (1974) as per the cosmology commonly used in those days, with the Hubble constant (H_0) $\sim$50 km s^{-1} Mpc^{-1}. These structures of unfathomable scales (Mpc) are relatively rarer than their smaller sized counterparts, i.e., the RGs. To perceive the giant scale better, a Mpc is the distance covered by $\sim$33 Milky Way galaxies (extent observed at

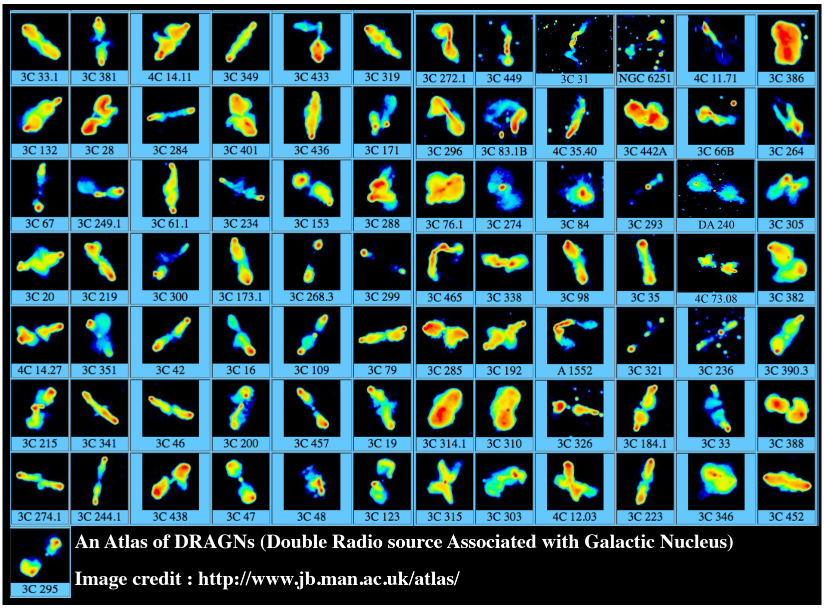

Figure 1.3: Radio images of famous radio galaxies and radio quasars from the 3C and 4C radio survey sample mapped with VLA and WSRT.

optical wavelengths ~ 30 kpc) stacked in a row (see Fig. 1.5). Sizes of the GRGs are often comparable to the sizes of the galaxy clusters, and hence they can possibly influence large scale structures, seeding magnetic fields (Kronberg et al. 2004), particle acceleration (O'Sullivan et al. 2009), and probing the intergalactic medium (Strom & Willis 1980; Gopal-Krishna et al. 1989; Subrahmanyan & Saripalli 1993). Few environmental studies (intergalactic medium or IGM) of GRGs (e.g. Malarecki et al. 2013, 2015; Peng et al. 2015) have attempted to probe the Warm-Hot Intergalactic Medium (WHIM). The study of WHIM is of particular importance with respect to the 'missing baryonic problem' (Cen & Ostriker 1999; Davé et al. 2001; Nicastro et al. 2008), which refers to the discrepancy between observed and predicted baryonic budget of the Universe. The missing baryons were then conjectured to be hiding in the low density hot plasma permeating through the Universe, whose detection has recently been claimed (Eckert et al. 2015; Nicastro et al. 2018). Also, Xu et al. (2006) used GRGs as tools to estimate magnetic field in large scale structure with the help of the Faraday rotation measurement.

In the 1970s, with the development of the aperture synthesis telescope

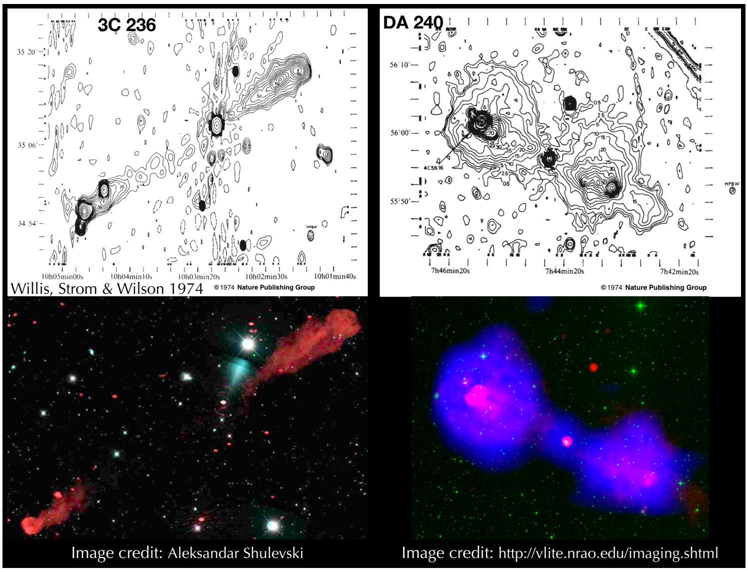

Figure 1.4: The top panel shows radio images of the first two GRGs discovered by Willis et al. (1974) made using the WSRT. The bottom panel shows improved images made recently using LOFAR for 3C 236) and combination of WSRT and VLA for DA 240.

like the Westerbork Synthesis Radio Telescope (WSRT; Baars & Hooghoudt 1974; Hogbom & Brouw 1974), the first two GRGs (3C 236 and DA240) were identified by Willis et al. (1974) using Bridle et al. (1972) ~ 98% complete 1400 MHz radio sample. Owing to the large angular sizes (>30′) and large fluxes (>5 Jy) of the two sources, Willis et al. (1974) were able to sufficiently resolve them at 610 MHz with arcminute (′) resolution (top panel of Fig. 1.4). After this, radio astronomers using aperture synthesis telescopes like the WSRT and the Very Large Array (VLA; Thompson et al. 1980; Napier et al. 1983) continued to map bright radio sources from radio catalogues like the third Cambridge radio survey (3CR; Bennett 1962; Laing et al. 1983) and Bologna radio survey (B2; Colla et al. 1970) and continued to find more GRGs. Despite this, only about 50 GRGs were found till the ~ 1990s (Ishwara-Chandra & Saikia 1999). All GRG discoveries were made using radio interferometers at high frequency, which equipped them with better resolution, with the exception of GRG 0503-286. It was identified and studied first using the Ooty Synthesis Radio telescope (OSRT; Swarup 1984) at 327 MHz by Saripalli et al. (1986).

It was only in the mid-1990s when the WSRT, the VLA, and the Molonglo Observatory Synthesis Telescope (MOST; Mills 1981) started their respective large area radio surveys, a larger number of GRGs were discovered. Therefore, it will be fair to present their work briefly:

- Schoenmakers et al. (1998, 2001) using the advantage of low-frequency survey (more sensitive to steep spectrum emission from lobes) like the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997) at 325 MHz discovered large sample (~ 30) of GRGs and performed systematic studies (Schoenmakers et al. 2000b). Here, they created a sample of 49 GRGs from WENSS and found a sharp cut off of sources above 2 Mpc in size and that no GRG exists above 10^{27} W Hz^{-1} radio power at 325 MHz in the given survey area. Studies by Schoenmakers et al. 2000b also defined a complete sub-sample of 18 GRGs, and based on their observations between 325 MHz to 10 GHz radio frequencies with acrminute resolution, they estimated the average spectral age of ~ 80 Myr, advance velocities of 0.4c and particle densities of 10^{-5} cm^{-3}. These findings were similar to that of Mack et al. 1998, who studied five GRGs in their work. The work of Schoenmakers et al. 2000b concluded that the morphology of GRGs is slightly more asymmetric than the low size RGs from the 3CRR, with their over-pressured radio lobes and GRGs are older with respect to their spectral ages. They also observed that GRGs are located in relatively sparser environments. Furthermore, their work also focused on the emission line properties of their host AGN for a small sample of 22 sources and found no differences between the properties of GRGs and RGs.

- Similarly, a radio survey at higher frequency was carried out with the VLA at 1400 MHz, which is called the NRAO* VLA Sky Survey (NVSS; Condon et al. 1998). Using the NVSS, Lara et al. (2001a) and Machalski et al. (2001) found 31 and 22 new GRGs, respectively. These were followed up with radio observations to decipher their morphology and study other radio properties (Lara et al. 2001b, 2004; Machalski et al. 2004a,c, 2006a; Machalski & Jamrozy 2006; Machalski et al. 2007a,b).

- Using the MOST, Bock et al. (1999); Mauch et al. (2003) carried out a survey called Sydney University Molonglo Sky Survey (SUMSS) at 843 MHz. Subsequently, it was used by Saripalli et al. (2005) to find more GRGs especially in the unexplored southern sky ($< -30°$

*National Radio Astronomy Observatory

declination) which was covered by SUMSS for the first time at ∼1 GHz frequencies. They defined a complete sample of 18 GRGs and observed it with other radio telescopes to study their morphology and asymmetry parameters. A subset of Saripalli et al. (2005) sample was followed up by Subrahmanyan et al. (2006) and Malarecki et al. (2013) for their respective studies on the radio morphology and probing of the IGM.

The above-mentioned dedicated searches from respective surveys still did not reveal a large population of GRGs due to lack of enough radio sensitivity and resolution (coarser resolution of WENSS: ∼ 54″, NVSS: 45″, and SUMSS: ∼ 45″) to resolve the morphologies sufficiently. Also, another reason was the lack of large sky area optical spectroscopic surveys. In order to identify GRGs, the radio images must have enough sensitivity and resolution to detect and identify the radio core, which must coincide with an optical galaxy or quasar whose redshift is needed to estimate the projected linear size.

The GRGs discovered were followed up by others, e.g. Konar et al. 2004, who studied a sample of 17 GRGs (some hosted by quasars too) at multiple radio frequencies from 240 MHz to 8 GHz to study their morphology and other radio properties. Magnetic field and spectral age estimates were also obtained by Konar et al. 2008 and Jamrozy et al. 2008 for a sample of 10 GRGs. The spectral ages of GRGs in their sample were in the range of 6 to 36 Myr with an average injection index of 0.6.

Based on the tools (telescopes+data+computational infrastructure) available at the time, above-mentioned works found a few hundred GRGs since 1974 along with their radio and associated properties. Now, with the advent of large sky area surveys in radio as well as in optical along with simulations, it is now possible to take this field further towards understanding the origin and evolution of these giant sources. The induction of several new radio telescopes which are equipped with cutting edge technology like the Jansky VLA (JVLA) and LOFAR have already shown unprecedented results (see bottom panel of Fig. 1.4).

1.4 Work in this thesis

The study of GRGs is essential with respect to understanding the growth and evolution of RGs, and their possible contributions to other processes in the Universe.

The goal of the thesis is to answer some of the following questions :

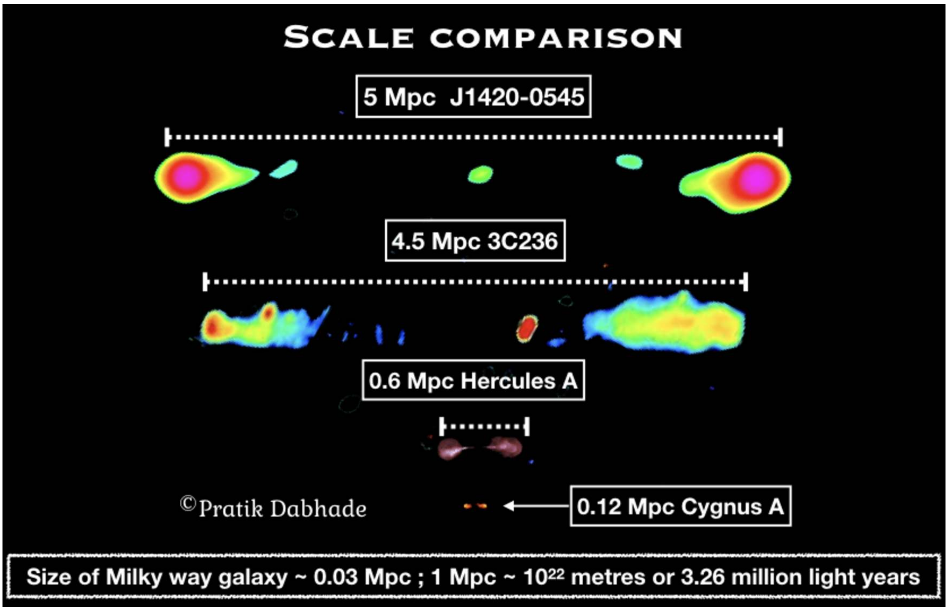

Figure 1.5: The figure shows radio images of some of the biggest GRGs and most famous RGs oriented horizontally with their respective size scales for the sake of comparison.

- What is the space density of GRGs ?
- What are the causes for their megaparsec scale sizes ?
- Do GRGs have a preferred AGN excitation state - high or low ?
- How do the radio properties of GRGs and RGs compare ?
- Are GRGs older than RGs ?
- Does the mass of GRG's SMBH outweigh the mass of RG's SMBH ?
- What fraction of the giants are powered by quasars (GRQs) ?
- Do GRGs only grow in the sparse environment ?

The work in this thesis comprises of three main broad parts-

1. Search for new samples of GRGs from existing and new radio surveys with the added help of large optical spectroscopic surveys.
2. Creating a complete and uniform database of GRGs known till date, which will be the basis of future studies for the community at large.
3. Using the newly created large database of GRGs, studying their host AGN properties systematically with statistically significant samples and exploring their environmental properties.

Below is the summary of each chapter comprising of above-mentioned work which was essentially done using data from different radio telescopes (see Fig. 1.6) and archival optical/mid-infrared data.

- Chapter 2: A dedicated project was initiated for the studies of GRGs called SAGAN, which stands for Search and Analysis of Giant radio galaxies with Associated Nuclei. In this chapter, the pilot results of the project are presented based on the initial searches from the NVSS. A total of 25 new GRGs are reported along with the mid-infrared properties of their host AGN and AGN excitation types.
- Chapter 3: Before the arrival of high sensitive low-frequency instruments like the LOFAR, very few attempts (Perley & Erickson 1979; Artyukh & Ogannisyan 1988; McGilchrist et al. 1990; Cotter et al. 1996; Nandi et al. 2010) were made to observe GRGs at low frequencies (< 200 MHz) mainly because of the lack of resolution at these frequencies provided by the telescopes before, necessary technology

and the difficulties in dealing with the turbulent ionosphere affecting the radio waves. Using the LOFAR's unique capabilities of mapping low-frequency sky at unprecedented sensitivity and high resolution, the LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2019) was conducted in the Hobby-Eberly Telescope Dark Energy Experiment Spring field region (HETDEX). It covered 424 deg^2 sky area with 6″ and 20″ resolutions, having noise levels of ∼100 μJy beam^{-1}. Based on manual and semi-automated techniques, the largest sample of GRGs (225) was discovered from the LoTSS, of which 40 are hosted by quasars. The chapter explains the procedures used for searches and the properties of the new sample. The sample also enabled to show for the first time that the spectral index of RGs and GRGs is similar.

- Chapter 4: Here, the first major results of project SAGAN are described which are as follows: hitherto creation of the largest and uniform GRG catalogue comprising of 820 objects, reported between 1974 to March 2020 (see Fig. 1.7). This was done using all the publicly available data. Another new 162 GRGs were also reported for the first time in this study. Using the GRG catalogue, the radio properties and host AGN properties were studied in detail. Also, a comparative study of properties between RGs and GRGs was carried out. The results backed by significant statistics show that the distributions of the radio spectral index and the black hole mass of GRGs do not differ from RGs. Other key physical properties like black hole mass, spin, Eddington ratio, jet kinetic power, total radio power, magnetic field, and size were compared for GRGs with low excitation AGN and GRGs with high excitation AGN. Our findings strongly suggest that statistically, the GRGs with high excitation AGN have larger sizes, stronger radio power, jet kinetic power, and higher Eddington ratio than those GRGs with low excitation AGN. We also find ∼ 10% of all GRGs reside in centres of galaxy clusters and that they tend to avoid massive clusters.

- Chapter 5: Here, we explore the millimetre wave properties of the host AGNs of GRGs by attempting to detect molecular gas, which may shed more light on their accretion properties, star formation rate and stellar mass properties. Also, how these properties compare with other objects to determine the factors making these objects giants. Such studies are very scarce, and it is thought that GRGs may not contain enough molecular and atomic gas to fuel star formation.

Using the large GRG catalogue from the SAGAN project, 12 GRGs were selected based on their mid-infrared properties to observe with the IRAM-30m millimetre telescope. Molecular gas content, star formation efficiency and depletion time information were obtained for few sources. In all, we obtained detection in three of the twelve objects with upper limits in the rest and combined the results with other GRGs from literature. The results suggests that the GRGs, in general, seem to have much longer depletion time than that of their radio emission.

- Chapter 6: As part of project SAGAN, hundreds of new GRGs were found, and a sub-sample of GRGs was observed with the Giant Metrewave Radio Telescope at multiple frequencies to obtain high resolution images to decipher their morphologies and to estimate magnetic field along with their spectral ages. Here, the study of one of the most peculiar GRGs is presented which is hosted by a galaxy in a dense cluster like environment, and exhibits $\sim$200 kpc linear jet terminating into a $\sim$100 kpc 'kink' like structure. Along with three frequency GMRT data (325 MHz to 1400 MHz), the study also benefited from the LOFAR 144 MHz low-frequency data, which allowed us to probe the source at very low frequencies with high resolution and good sensitivity. We observe that the GMRT 325 MHz and LOFAR 144 MHz maps show the maximum emission from the GRG, and also the counter jet on the eastern side is seen feeding the lobe. The detection of counter-jets (especially of such large sizes) in FR-II GRGs is not common and hence, this object provides an unique opportunity to study the large scale MHD processes. The 'kink' structure is quite bright and shows a shock front whose Mach number also has been estimated, and the possible process giving rise to it have been extensively discussed. Owing to its peculiar morphology and uncanny resemblance, it has been named as 'Barbell GRG'.

1.5 Future scope

Recently, the LoTSS, owing to its unprecedented sensitivity to low surface brightness diffuse emission has produced very interesting results as evident from the series of papers in the *Astronomy* & *Astrophysics* journal's special issue*. This enabled to the discovery of the largest GRG sample (225) to

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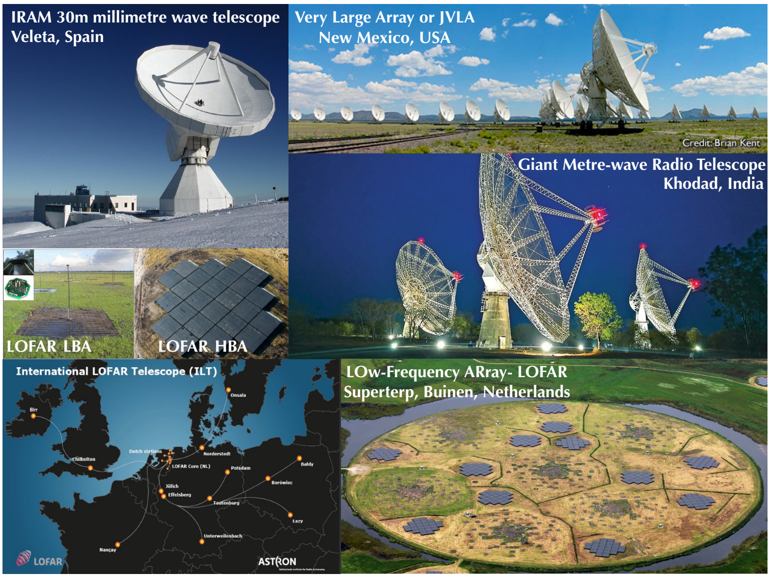

Figure 1.6: The figure shows a montage of the radio telescopes (and one millimetre-wave: IRAM) like the VLA, GMRT, and LOFAR whose data have been extensively used in the work presented in this thesis.

date from a relatively smaller part of the sky (HETDEX field of ~ 424 deg^2) and unveiled (Chapter 3 of this thesis) the hidden GRG population (Dabhade et al. 2020b). The LoTSS, which is an ongoing survey of the northern sky ($\sim 2\pi$ steradians) is expected to find at least ~ 12000 GRGs, implying that GRGs are not as rare as previously thought. It will be complemented with the ongoing optical-spectroscopic survey like the WEAVE-LOFAR survey (Smith et al. 2016). The above number is far higher than what was predicted few years back with the future survey of the Square Kilometre Survey called the SKA1$_{SUR}$, which is poised to cover $\sim 80\%$ of sky upto +48° declination at L band. Based on predicted calculations of Peng et al. 2015, the SKA1$_{SUR}$ survey should detect about 12000 GRGs from the total sky area, which is larger than what the LoTSS is going to cover.

All the above mentioned work were greatly benefited from the surge in the improvement in imaging techniques and new software packages. In the coming years, radio telescopes with their respective surveys are expected to produce data on the astronomical scale. While the challenging task of data reduction via automated pipelines has been accomplished, the task of sorting and examining the final images in an automated fashion still remains

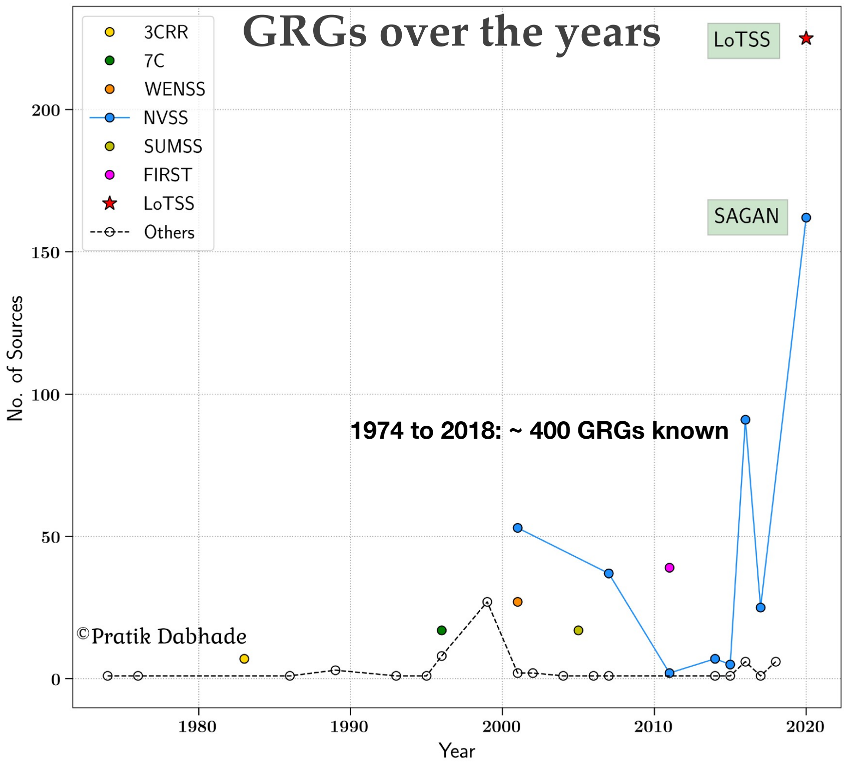

Figure 1.7: The plot shows discoveries of GRGs over the years starting from 1974 to 2020 via different radio surveys. Work done in this thesis has led to the doubling of the known population of GRGs, which in turn has enabled studies with statistically significant samples. Details of the work related to the LoTSS sample is presented in Chapter 3, followed by chapter 4, which is dedicated to the SAGAN sample.

a work in progress. Recently, there have been some promising results in this area obtained using machine learning techniques (Galvin et al. 2020).

The existence of the giant radio lobes depends on the external medium (thermal or ram pressure) which can confine them or provide a working surface. Therefore, in case of GRGs with hundreds of kpc large lobes, the external pressure on large scales can be probed. It is possible to estimate the pressure of the lobes of GRGs using X-ray observation of inverse-Compton process, where the electrons in the lobe scatter photons of the Cosmic microwave background radiation (CMB). This enables us to directly measure the electron energy density, and sheds more light on the particle content and magnetic field strength. The demonstration of the above technique has been done in the past two decades (e.g. Hardcastle et al. 2002; Croston et al. 2005) for FR-II type radio sources, which has helped constrain source dynamics by comparison of lobe internal pressure and external pressure arising from X-ray emitting hot gas. Very few GRGs till date have been studied (e.g. Konar et al. 2009; Isobe & Koyama 2015; Mirakhor et al. 2021) using this technique, and for the better understanding of GRGs and their environments it is essential to study their X-ray properties. Hence, dedicated study with Chandra and XMM-Newton X-ray telescopes of large samples of GRGs residing in cluster environment is needed. This effort will also largely be benefited from the near future data release of all sky X-ray survey of eROSITA (Basu-Zych et al. 2020).

The ongoing and the upcoming surveys at radio and other wavelengths, will not only find more GRGs but also possibly will provide definite answers related to the questions posed by their enormous sizes. There is also quite a vast scope of using GRGs as tools to probe other problems like the study of WHIM (Malarecki et al. 2013, 2015) for the 'missing baryons' problem. Old relic GRGs owing to their large sizes could also be responsible for providing necessary seed particles for giant radio relics (Rottgering et al. 1997; Bagchi et al. 2006; van Weeren et al. 2019) found near the galaxy clusters and can help in understanding their origins better.

As briefly discussed in Sec. 1.2, the RGs have been used in the past for cosmological studies and in the 1990s, brave and exciting attempts (alternative to the supernova studies) were also made to use RGs as standard candles (Daly 1994b; Gurvits et al. 1999; Sahni & Starobinsky 2000) to measure the acceleration parameter of the Universe. Now, with more data on RGs and in particular GRGs, these techniques (Daly et al. 2008; Weinberg et al. 2013) could be revisited and improved (e.g., see Turner & Shabala 2019) to use these objects as independent cosmological probes for measuring the Hubble constant and in the quest for understanding dark energy.

The respective radio surveys from LOFAR, uGMRT, ASKAP, JVLA and MeerKAT are already reaching unprecedented sensitivities and their surveys have already unearthed hundreds of objects with no optical identifications. This implies that these are mostly high redshift objects which are not visible or detected in the currently available optical and infrared surveys. Hence, optical surveys from upcoming facilities like the Large Synoptic Survey Telescope (LSST) or Vera Rubin Observatory (Ivezić et al. 2019) and EUCLID space mission (Amendola et al. 2013) will provide us optical identification for all over high redshift radio source candidates and thereby allowing us to study the high redshift Universe.