The active galactic nuclei (AGN) were first detected in optical wavelengths by E. A. Fath, a doctoral candidate at the University of California, in the year 1909. Fath was studying a few spiral ‘nebulae’ (which we now know to be galaxies) including the Andromeda nebula and NGC 1068. He found that NGC 1068 exceptionally showed five emission lines and had a diffuse nucleus that merged into the surrounding nebulosity (Fath 1909). He went on to conclude that these are star clusters surrounded by gas whose condition varies from nebula to nebula. Fath does not seem to have paid further attention to NGC 1068 but slowly more such sources were discovered and it became harder to ignore them. In 1917, Silpher found a similar source NGC4151 (Slipher 1917) and Hubble in his seminal work of 1926 made a special note of NGC 4051, NGC 1068 and NGC 4151 (Hubble 1926).

Seyfert was the first to study these sources systematically and showed that only some galaxies exhibited very broad nuclear emission lines (Seyfert 1943) and a certain class of AGN are now called Seyfert galaxies in his honour. The big push to the field, however, came from advances in the techniques of radio astronomy. The advent of radio astronomy led to the discovery of discrete radio sources which were believed to be associated with Galactic stars (e.g. Bolton, Stanley & Slee 1949).

* In his paper of 1909, Fath said:

_The only known sources of continuous spectra are luminous solids, liquids, very dense gases or possibly masses of gas of great thickness. To produce bright lines or bands we require gases or vapors rendered luminous by heat, electric discharges or chemical change... These are, for the most part, well established experimental facts..._

† In their Nature paper reporting the localisation of radio sources, Bolton, Stanley & Slee (1949) proposed that these are of Galactic origin. Decades later Bolton confessed that he had believed that these sources were extragalactic but the implied (then unbelievably) extreme energetics made him fear that the referee would put the publication of their paper on hold (Kellermann 2013).
Chapter 1

Soon enough, it was found that some of the brightest radio sources could be associated with galaxies with the first such associations including those of Cygnus A (e.g. Mills & Thomas 1951; Baade & Minkowski 1954), 3C 295 (Minkowski 1960), and 3C 273 which was associated with a star-like optical source (Schmidt 1963). This was quickly followed by the discovery of many such star-like radio sources – ‘quasi-stellar’ radio sources or quasars – including the famous 3C 48. Once the extragalactic origin of these sources was established, the enormous energy output of these sources suggested that they should be associated with very massive black holes (e.g. Salpeter 1964). Quasars turned out to be the brightest and the most distant sources known, immediately offering possibilities to address various cosmological questions (see Shields 1999 and Kellermann 2013 to learn more about the history of AGN studies). Thus it was that AGN brought about a paradigm shift in the field of astronomy and have continued to be of great interest (i) in their own right, (ii) for their role in the evolution of galaxies, as well as (iii) for being probes of various astrophysical phenomena.

In the context of this thesis, the AGN are most interesting for their role in the evolution of their host galaxies. However, it is not entirely possible to leave out many aspects of the AGN which make them equally interesting in their own right since these two aspects (in fact, all the three mentioned above, although we shall try to ignore the third one) are not completely detached from each other. For our work, we have chosen to focus on radio-loud AGN (Sect. 1.1.2) and their impact on the interstellar medium (ISM) of their host galaxies, with particular emphasis on the cold-atomic and cold-molecular gas components (Sect. 1.2). However, we will start at the beginning and try to make our way towards the main themes of interest.

1.1 What is an AGN?

We now believe that an AGN is the result of gas being accreted onto the supermassive black hole (SMBH) in the centre of galaxies. Observationally, the nucleus of a galaxy is considered active if the compact nuclear region exhibits a non-stellar radiative component and outshines the stellar component, that is, the amount of radiation arising from the nuclear region of the galaxy is higher than the rest of the galaxy put together.

1.1.1 AGN Classification schemes

Classification is one of the first things to do to understand a population better. Historically the AGN are classified based on their morphology and the properties seen in the bands they are observed at. Though this is not the best way to classify AGN, the terminology has stuck. For example, they are classified based on radio morphology as Fanaroff and Riley (FR) type I or type II sources; based on optical emission-line properties as Seyfert 1, Seyfert 2, Low Ionisation Nuclear Emission-line Region Galaxies (LINERs); as blazars in the high-energy regime (Stein, O’Dell & Strittmatter 1976). AGN emit in a broad range of the electromagnetic spectrum and hence a single source can be an FR-II-Seyfert-1 blazar!

Schemes based on unification models (e.g. Barthel 1989; Urry & Padovani 1995) pro-
1.1: What is an AGN?

Provide a more meaningful classification based on a combination of intrinsic properties of the AGN and orientation effects. In this classification scheme, an AGN is radiatively efficient (radiative-mode): the potential energy of the accreting gas is efficiently converted to electromagnetic radiation, which is the dominant form of energy output, or radiatively inefficient (jet-mode): collimated, two-sided jets comprise of the dominant energy output and the amount of radiation produced is comparatively lower.

In radiative-mode AGN, the accretion of gas onto the SMBH happens through a geometrically-thin accretion disc. The extreme conditions in this region around the accretion disc will result in high energy radiation as well as extreme ionised gas kinematics (for example, clouds with velocities of thousands of km s\(^{-1}\) that result in broad optical emission lines). In jet-mode AGN, the thin accretion disc is believed to be absent and a geometrically-thick structure is present in its place resulting in an inefficient accretion. This results in the launching of collimated, two-sided jets.

Further away, the SMBH is surrounded by obscuring structures, either dusty molecular discs or the disc of the host galaxy. Depending on the orientation of the AGN with respect to the observer, the AGN is further classified either as Type 1 (unobscured): the line of sight is close to the polar axis of the obscuring material, in which case the nucleus is directly visible, and Type 2 (obscured): where the line of sight passes through the obscuring material (see Heckman & Best 2014 and references therein for all the details).

1.1.2 Radio AGN

The focus of this thesis is on radio AGN and hence this class merits an additional description here. A fraction of the AGN are quite bright in radio wavelengths. In fact, these ‘radio-loud’ AGN are the most luminous radio sources known. The emission process is mainly the non-thermal synchrotron emission by relativistic electrons accelerated in a magnetic field. Many of them exhibit impressive radio morphologies consisting of jets, lobes and hotspots. Such radio sources span parsec to Mpc scales and happen to be the most spectacular structures imaged.

Host galaxies

Radio AGN are generally found in massive elliptical galaxies. The incidence of a radio AGN in a massive galaxy depends on the luminosity of the AGN \((L_{1.4\text{GHz}}})\) as well as the stellar mass of the galaxy \((M_*)\). The fraction of massive galaxies hosting radio AGN \((f_{\text{radio}}})\) depends on the stellar mass as \(f_{\text{radio}} \propto M_*^{2.5}\) (Best et al. 2005). While 0.01% of galaxies with \(M_* = 3 \times 10^{10} M_\odot\) host a radio AGN, this fraction goes over 30% for galaxies with \(M_* = 5 \times 10^{11} M_\odot\). For any given stellar mass bin, AGN with low radio luminosity \((L_{1.4\text{GHz}} < 10^{24} \text{ W Hz}^{-1})\) greatly outnumber their high-luminosity counterparts. This is especially pronounced in massive galaxies \(M_* \sim 10^{11} M_\odot\) where only 1% of the galaxies host such bright powerful AGN while 30% of the galaxies host low-luminosity radio sources (e.g. Best et al. 2005; Sabater et al. 2019).
Figure 1.1 – Radio images of AGN belonging to different Fanaroff-Riley types. **Left:** The famous FR II source Cygnus A. **Right:** An FR I radio source, 3C 31. (Image courtesy: NRAO)

(Further) Classification

The morphology of a radio AGN depends on factors such as the orientation of the source relative to the observer and the environment in which the radio jets are expanding. Sources that span many tens of kpc are classified based on the distance between the brightest radio features on either side of the nucleus following the Fanaroff and Riley (FR) classification scheme (Fanaroff & Riley 1974). It is an FR I source if this distance is less than half the total extent of radio emission, and is an FR II source otherwise. It has been found that FR II sources are higher in radio luminosity and the divide between the two occurs at $L_{178\text{MHz}} \sim 10^{26}$ W Hz$^{-1}$ or $L_{14\text{GHz}} \sim 3 \times 10^{25}$ W Hz$^{-1}$.

Figure 1.1 shows the examples of sources belonging to these two classes. Of course, there are sources exhibiting a hybrid morphology and this division is not as sharp.

For the more compact radio sources, the classification is more based on the shape of their radio spectral energy distribution (SED). The broad-band synchrotron spectrum of radio sources can be characterised by the power law of the form $S_\nu \propto \nu^{-\alpha}$ where $S_\nu$ is the source flux density at frequency $\nu$ and $\alpha$ is the spectral index. Sources with $\alpha < 0.5$ are called the flat-spectrum radio sources where the line of sight is very close to the radio jet axis. The compactness of these sources could either be intrinsic or the effect of orientation. Sources whose radio spectra show a turnover, that is, a spectrum peaking at a particular frequency ($\nu_p$) and falling off on either side, are collectively called the peaked-spectrum sources. Depending on where this peak is, they are further classified as giga-hertz peaked spectrum (GPS) sources ($0.5 < \nu_p < 5$ GHz), high-frequency peakers ($\nu_p > 5$ GHz) and medium-frequency peakers ($\nu_p < 1$ GHz). Further, based on their linear size and morphology they are classified as compact symmetric objects (CSOs) and compact steep spectrum (CSS) sources (see O'Dea & Saikia 2021 for an excellent review on compact radio sources). CSOs have radio lobes on both sides and
1.1: What is an AGN?

have linear sizes $< 1$ kpc. The linear sizes of CSS sources range between 500 pc and 20 kpc and additionally, they are expected to have a steep spectrum ($\alpha > 0.5$) at high frequencies.

Various hypotheses have been put forth to explain the nature of these compact radio sources. Popular scenarios include these sources being short-lived transients, young sources, sources that are frustrated due to the dense ambient interstellar medium (ISM) and sources with radio emission enhanced by high star-formation activity. However, based on the host-galaxy properties of compact sources and the extended ones, and models on the evolution of radio sources, it is clear that a sub-set of these compact radio sources are indeed young radio AGN that will go on to become large radio sources. In sources that are compact either due to frustration due to a dense ISM or due to their young age, the interaction between the jets and the ambient gas is expected to be the strongest and hence also the impact they may have on their host galaxies. We shall carry out a detailed study of one such source in this thesis. Overall, different morphologies of radio AGN represent different stages of their life cycle as (at least some of) the radio jets break out of the ambient ISM, expand through the host galaxy and enter the intergalactic medium transforming from compact pc-scale sources to huge Mpc-scale radio galaxies.

The (radio-) AGN life cycle

The fact that different stages of the life of an AGN are reflected in radio sources of different morphologies leads to the question, what is the lifespan of an AGN? This can be answered by estimating how long the matter should accrete onto the SMBH to explain the observed local black-hole mass function (e.g. Marconi et al. 2004). Such studies have found that the accretion goes on for $\sim 10^8$ to $10^9$ years.

The next question to arise is whether this accretion and hence the AGN activity happens in one instance or is episodic. At optical wavelengths, it has been possible to ‘catch’ some of the AGN when they were switched off (see, for example, Lintott et al. 2009) and thereby place a limit on the duration of the activity to be $\sim 10^4$ yr to $10^5$ yr.

In the case of radio AGN, the age of the source can be estimated from the age of the electron population. If the dominant emission mechanism in these sources is synchrotron emission, the radio SED will follow the relation $S_\nu \propto \nu^{-\alpha}$. To put it simply, the radio SED of the sources where electrons are being injected continuously is different from the SED of the source where the supply of electrons has been stopped, that is, the latter sources will show an ultra-steep radio spectrum ($\alpha > 1.2$) at high frequencies. These radio SEDs can be used by the radiative cooling models to estimate the age of the radio sources (e.g. Jaffe & Perola 1973). Such spectral ageing studies have found the life-cycle of radio AGN to be $\sim 10^7$ yr to $10^8$ yr (see Saikia & Jamrozy 2009 and Morganti 2017a for more).

The best demonstration of this episodic radio-AGN activity can be found in the so-called double-double radio galaxies where multiple pairs of radio lobes of different ages are found aligned with each other (e.g. Schoenmakers et al. 2000b; Kaiser, Schoenmakers & Röttgering 2000; Schoenmakers et al. 2000a; Saripalli, Subrahmanyan & Udaya...
Chapter 1

1.2 AGN and galaxy evolution

Given that enormous energy is given out during an AGN activity (typically an AGN outshines the entire galaxy put together) and given also the strong evidence that this activity is episodic, it is natural to expect this released energy to have an impact on the host galaxy. Theoretically, a small fraction of the energy released by the AGN activity is sufficient to remove the gas from the entire galaxy (e.g. Silk & Rees 1998). Various observational findings too seem to indicate a link between AGN and the evolution of galaxies. The existence of a tight correlation between the SMBH masses and the bulge velocity dispersion suggests a co-evolution of the SMBH and the galaxy. Powerful radio AGN in the centres of galaxy groups and clusters have been found to heat up the gas in the intra-group and intra-cluster medium (e.g. Tremblay et al. 2012; Liu et al. 2021, Shankar 2002; Konar et al. 2006; Saikia, Konar & Kulkarni 2006). Figure 1.2 shows a clear example of one such sources. More recently, in the last decade or so, with the advent of sensitive low-frequency radio instruments such as the Low-Frequency AR-ray (LOFAR), there have been many discoveries of remnant radio galaxies where the central engine has turned off and is no longer ejecting fresh electrons and the radio emission from the earlier episode is slowly fading away, and of restarted radio galaxies which consist of large-scale diffuse radio emission from the previous episode and a new bright compact radio source in the centre (e.g. Shulevski et al. 2015b,a, 2017; Brienza et al. 2018, 2020, 2021). Even more recently, studies seem to be suggesting that in these restarted radio sources, the fresh electron supply to these old lobes may not entirely be cut off as the new activity starts but instead electrons may still be flowing into those older lobes at a low level (e.g. Brienza et al. 2018; Jurlin et al. 2020; Kukreti et al. 2021). We will deal with such a restarted radio source in this thesis.

Figure 1.2 – A double-double radio galaxy J0116−473 (Saripalli, Subrahmanyan & Udaya Shankar 2002). The large diffuse radio lobes believed to arise from an earlier episode of activity while the smaller bright radio lobes are from the most recent episode of activity.
One such demonstration of the impact of radio jets at hundreds of kpc is shown in Fig. 1.3. Such findings suggest that on large spatial scales (about hundreds of kpc), the radio jets can prevent cooling and the accretion of gas onto the galaxies and thereby prevent star formation and hence their growth (e.g. McNamara & Nulsen 2007, 2012; Fabian 2012). Many quasars have been found to have radiation-driven winds with huge mass-outflow rates of a few tens to thousands of $M_\odot$ yr$^{-1}$ (e.g. Pounds & Page 2006; Tombesi et al. 2012; Maiolino et al. 2012) which can empty the host galaxy of gas.

Inspired by the amount of energy released by the AGN activity, theoretical, semi-analytical and numerical models of galaxy evolution have incorporated this AGN ‘feedback’ (e.g. Bower et al. 2006; Croton et al. 2006; Ciotti et al. 2017). These simulations primarily consider two modes of AGN feedback: quasar mode and radio or maintenance mode. In quasar mode, the radiatively efficient AGN drives winds through the host galaxy and empties it of cold gas (e.g. Springel, Di Matteo & Hernquist 2005; Di Matteo, Springel & Hernquist 2005; Choi et al. 2012; Costa et al. 2018). The radio mode feedback involves radio jets acting on many tens of kpc and keeping the gas in the intracluster medium hot thereby preventing the cooling and accretion of gas onto the galaxies. Such simulations have been able to solve some of the problems of galaxy evolution such as the cooling problem in clusters and explaining the galaxy luminosity function (Bower et al. 2006; Croton et al. 2006).

However, as has been rightly pointed out by many (e.g. Kormendy & Ho 2013), simu-
lations do not shed any new light on the exact mechanisms through which the energy transfer and hence an influence on galaxy evolution happens. Moreover, with the current spatial resolution, these simulations also do not include many other modes of impact the AGN have on their host galaxies, for example, the kpc-scale impact of the radio jets. After all, the radio jets propagate through the host galaxy before reaching the spatial scales where they do have an impact on the intergalactic medium. Moreover, most of the sources remain embedded in the dense ISM of the host galaxy for a long time. Would they not then be expected to affect the ambient ISM significantly? In the last two decades, various studies have shown that this indeed is the case. Since this interplay between radio AGN and the ambient ISM is the theme of interest for this thesis, we shall deal with it in some detail in the following section.

1.3 Radio AGN and the ISM

Over the last two decades, evidence has been piling up to show that radio jets contribute to both positive and negative feedback in their host galaxies: there have been findings of enhanced star formation in the regions where the radio jets interact with the ISM (e.g. Croft et al. 2006; Salomé, Salomé & Combes 2015; Santoro et al. 2016) and these jets have also been found to drive massive multiphase gas outflows and cause the ISM to become more turbulent (see Morganti 2017b and references therein for more). Here, we shall discuss the negative feedback effects from radio AGN with a focus on the cold atomic and molecular gas components.

1.3.1 Impact on the cold atomic gas (H\textsubscript{i})

The cold atomic gas component in radio AGN is studied primarily via the 21-cm hyperfine transition of neutral hydrogen (H\textsubscript{i}) (van de Hulst 1951). H\textsubscript{i} in galaxies tends to be distributed as large-scale discs, circumnuclear discs and also gas clouds with anomalous velocities not conforming with regular rotation. To understand the nature of the jet-ISM interaction in these sources, we should be able to trace atomic gas in the nuclear regions. This is best achieved by the H\textsubscript{i} 21-cm absorption studies (see Morganti & Oosterloo 2018 for an in-depth review).

H\textsubscript{i} absorption studies offer unique advantages over emission studies. Since the detection of gas depends only on the strength of the background radio continuum, it can be detected even at very high spatial resolutions (a few pc). Since the gas needs to be in front of the radio continuum to be detected in absorption, it is also relatively easier to constrain the kinematics of the gas. This is illustrated in Fig. 1.4. For example, in a spectrum, a blue-shifted feature indicates gas flowing towards us. In the case of emission, it is difficult to say whether that is the gas approaching us from the other side of the SMBH and hence falling towards the AGN or an outflow from the AGN towards us, a confusion that is not often encountered in absorption studies.

The strength of the 21-cm transition being low, direct detection of H\textsubscript{i} emission requires extremely long integration at higher redshifts. H\textsubscript{i} absorption, again, does not suffer from this drawback. Thus it can be used to trace a variety of phenomena such as
the blueshifted outflowing gas clouds that are driven by the radio jets, infalling gas clouds – the potential fuel for the SMBH, turbulent circumnuclear discs and large-scale quiescent gas discs. In addition, using H\text{I} absorption, such phenomena can also be studied over a range of redshifts providing insights about the evolution of the impact of radio AGN on their host galaxies over cosmic times. One of the main results from the H\text{I} absorption studies is that the AGN do impact the ambient ISM significantly and drive fast outflows, removing gas from the nuclear region of the host galaxies.

**At low redshifts**

A wealth of information about the H\text{I} in radio AGN at low redshifts has been amassed via H\text{I} 21-cm absorption studies for more than three decades (e.g. Roberts 1970; De Young, Roberts & Saslaw 1973; Mirabel 1989; Conway & Blanco 1995; O’Dea, Baum & Gallimore 1994; Morganti, Oosterloo & Tsvetanov 1998; Gallimore et al. 1999; Morganti et al. 2001; Peck & Taylor 2001; Gupta et al. 2006; Chandola et al. 2012; Geréb, Morganti & Oosterloo 2014; Gerb et al. 2015; Maccagni et al. 2017; Chandola & Saikia 2017; Chandola, Saikia & Li 2020). These studies include detailed mapping of individual sources at various spatial scales and wavelengths, studies of large samples aiming to understand the trends in the incidence and kinematics of cold gas over various classes of radio AGN.

Studies of large samples of radio AGN have shed light on the statistics of the incidence of H\text{I} and the nature of the interaction between H\text{I} and radio AGN in different classes of sources. The H\text{I} 21-cm absorption studies by Geréb et al. (2015) and Maccagni et al. (2017) form the largest sample of radio AGN searched for H\text{I} 21-cm absorption so far. Their study included 250 radio sources of compact and extended morphologies representing different stages of evolution of the radio AGN and also spanned two orders of magnitude in radio luminosity. They found an H\text{I} 21-cm absorption detection rate of $\sim 27\%$ across the entire range of radio luminosity covered. They also found that radio sources at the low-luminosity end ($L_{1.4\text{GHz}} < 10^{23}$ W Hz$^{-1}$) mostly show nar-
Figure 1.5 – Variety of H\textsc{i} structures traced by absorption. **Left**: The H\textsc{i} disc resolved in absorption (red contours) against the radio lobes of Centaurus A. **Right**: The spatially resolved blue-shifted absorption feature arising from the fast H\textsc{i} outflow in 4C12.50 driven by the radio jet. (Image courtesy: Raffaella Morganti; Struve & Conway 2010 and Morganti et al. 2013)

row absorption features indicative of gas settled in rotating discs. Broad blue-shifted absorption features, which may represent unsettled gas, were detected only in higher luminosity sources. They found that the sources with disturbed gas were also of compact radio morphology (kpc scale) and rich in heated dust (as ascertained from their mid-infrared colours). The chance of detecting H\textsc{i} was much more (∼30%) in compact radio sources compared to the older extended radio sources (∼15%).

Detailed mapping of H\textsc{i} in the nuclear regions at high spatial resolutions (kpc scales down to a few tens of pc; e.g. Conway & Blanco 1995; Taylor et al. 1999; van Langevelde et al. 2000; Struve & Conway 2010; Morganti et al. 2013; Maccagni et al. 2014; Mahony et al. 2013; Schulz et al. 2018, 2021) has found H\textsc{i} distributed in circumnuclear discs (Fig. 1.5), in the form of high-velocity outflows (Fig. 1.5), and infalling gas clouds towards the SMBH. The very long baseline interferometry H\textsc{i} absorption studies of the outflowing H\textsc{i}, in particular, have found that the ISM in the nuclear region of the radio galaxies consists of a diffuse component as well as clumpy gas clouds which interact directly with the radio jets. The H\textsc{i} mass outflow rates detected range from 0.2 to 50 M\odot yr\textsuperscript{−1}.

All these studies combined point to an interesting scenario where the impact of the radio AGN on the ISM depends on the stage of evolution of the radio AGN with the compact radio sources coupling strongly with the ISM as compared to the extended radio sources. This further suggests that a radio AGN may have a significant impact on the host galaxy over a certain period of its life span and thus contribute to this negative feedback effect. If the AGN activity is also episodic, then this impact over multiple cycles of activity could either deplete the cold gas in the nuclear region of the host galaxies or increase the turbulence of the gas sufficiently to prevent any star formation or accretion onto the SMBH.
1.3: Radio AGN and the ISM

Scenario at higher redshifts

If we are to understand the role of radio AGN in galaxy evolution, such studies are to be expanded to higher redshifts, where the galaxies are younger and the galaxy assembly is vigorous. However, the scenario at high redshifts is in stark contradiction to the results at lower redshifts. Most of the searches for H\textsc{i} 21-cm absorption have been carried out only in compact radio sources (e.g. van Gorkom et al. 1989; Uson, Bagri & Cornwell 1991; Carilli & van Gorkom 1992; Carilli et al. 1998; Vermeulen et al. 2003; Pihlström, Conway & Vermeulen 2003; Gupta et al. 2006; Yan et al. 2016; Aditya, Kanekar & Kurapati 2016; Aditya et al. 2017; Aditya & Kanekar 2018a,c; Allison et al. 2015). Thus we lack information on how the incidence and kinematics of H\textsc{i} vary in different classes of radio AGN at higher redshifts. Additionally, the number of radio sources detected in H\textsc{i} 21-cm absorption also decreases with redshift. One of the main reasons proposed for this is the selection effect, which causes radio sources studied at higher redshift to also have high restframe UV luminosity, which in turn ionises the cold gas (e.g. Curran et al. 2008), although, how UV luminosity may ionise all the gas in and around the radio galaxy is a matter of debate. Another reason could be the intrinsic decrease in the cold gas content at higher redshifts (e.g. Aditya, Kanekar & Kurapati 2016; Aditya & Kanekar 2018c). We have tried to break this degeneracy between the two causes for one class of radio AGN in this thesis. Expanding similar studies to large samples encompassing sources that are at different stages of evolution and hence presenting a clearer picture of the interplay between the radio AGN and the ISM at higher redshifts is one of the much-awaited results from the wide-field H\textsc{i} surveys in the immediate future (e.g. Chowdhury, Kanekar & Chengalur 2020b; Allison et al. 2020, 2021).

Complementing H\textsc{i} absorption with other probes

While H\textsc{i} absorption is a unique probe of the cold gas in the nuclear region of the radio AGN host galaxies, it is not without any shortcoming. The dependence on a background radio continuum to detect the foreground gas poses at least two challenges: (i) The spatial extent of the gas traced is dictated by the background continuum; thus it is usually not possible to trace the nuclear gas in its entirety but instead, the kinematics and distribution are inferred based on the observed H\textsc{i} 21-cm absorption profile. (ii) In the case of an unresolved background continuum, as usually is the case as we move to higher redshifts, it may not be straightforward to ascertain the origin of H\textsc{i} absorption; for example, if the absorption arises from a satellite galaxy along the line of sight towards a bright radio source, the absorption may still appear close to the systemic velocity mimicking a regular quiescent galactic or circumnuclear disc leading to an interpretation far from reality.

While the emission studies do not suffer from this handicap, we saw at the start of Sect. 1.3.1, that it is much more difficult to constrain the kinematics of the gas based on the observed emission profile alone in the case of disturbed gas. Moreover, in many cases, the spatial resolution that can be achieved by the H\textsc{i} absorption observations is much higher than other probes of cold gas. Thus a combination of emission and
absorption studies of different phases of gas can be employed successfully to constrain the kinematics of cold gas and hence the impact of the radio AGN on the ambient ISM. Figure 1.6 shows such an example for a combination of molecular gas traced by CO and HI detected in absorption.

1.3.2 Impact on the cold molecular gas

Cold molecular gas is of particular interest for feedback studies since it is the direct fuel for star formation. Since H$_2$, the most abundant molecule, is not easily observable in emission, different transitions of CO are some of the most commonly used tracers of molecular gas. With the advent of instruments such as the Atacama Large Millimeter Array (ALMA) and the NOrthern Extended Millimeter Array (NOEMA), the number of detailed studies of cold gas in radio AGN is rapidly increasing, providing very interesting insights into the nature of impact of the AGN on the ambient ISM (Feruglio et al. 2010; Alatalo et al. 2011; Aalto et al. 2012; Cicone et al. 2014, 2012; Viti et al. 2014; García-Burillo et al. 2014; Impellizzeri et al. 2019; Matsushita, Muller & Lim 2007; Krause, Fendt & Neininger 2007; Dasyra & Combes 2012; Combes et al. 2013; Morganti et al. 2015; Dasyra et al. 2016; Oosterloo et al. 2017; Oosterloo et al. 2019; Morganti et al. 2021; Nesvadba et al. 2021).
Firstly, these studies have shown that the cold molecular gas forms the most massive component of the AGN driven outflows (e.g. Oosterloo et al. 2017, 2019; Combes et al. 2013; Dasyra et al. 2016; Veilleux et al. 2020). The molecular-gas mass-outflow rate can range from a few to many hundreds of $M_{\odot}$ yr$^{-1}$. These studies have covered radio AGN of different luminosities, redshifts, and evolutionary stages and have traced the jet-ISM interaction over multiple transitions and species of molecules (e.g. CO, HCN, HCO$^+$).

NGC 1068 – the first AGN discovered – happens to be one of the extensively studied cases of AGN driven outflows. This source is found to have a circumnuclear disc that is strongly disturbed by the AGN which is driving a strong molecular gas outflow with a mass outflow rate of $\sim 60 M_{\odot}$ yr$^{-1}$ (García-Burillo et al. 2014; see Fig. 1.7). In another Seyfert galaxy, also hosting a radio source, IC 5063, the radio jets are found to drive fast outflows in the central region (Morganti et al. 2015; Dasyra et al. 2016; Oosterloo et al. 2017). In the case of M 51, Matsushita, Muller & Lim (2007) found that the radio jets are disturbing the rotating molecular disc in the galaxy and similarly, in NGC 4258, the magnetic field of the radio jet is found to be interacting with the rotating gas (Krause, Fendt & Neininger 2007). Young radio sources have also been observed in CO emission and prove to be interesting targets for tracing jet-ISM interactions. PKS 1549–79 is a spectacular case where there is co-existence of accretion and outflow and Oosterloo et al. (2019) found that the AGN appears to be self-regulating the flow of gas into the nuclear regions. PKS 0023–26 on the other hand shows that the feedback component that the radio jets are most famous for – maintenance mode feedback at intergalactic scales (see Sect. 1.2) – in fact, also occurs at galactic scales. In this case, the radio jets drive fast outflows at sub-kpc level, and over much larger scales, they form a cocoon in which the cold gas is heated up (Morganti et al. 2021). The outflow velocities of the gas found in many of these sources are lower than the escape velocity of their host galaxies. Thus, most of the outflows will eventually rain back on the host galaxy.

Most of these sources studied also happen to be powerful optical AGN, that is, they have high bolometric luminosities. Hence, although the radio jets certainly contribute to the observed disturbance and outflows significantly, it is not always possible to completely disentangle the contribution of the radiation winds and the radio jets towards negative feedback within the galaxy. In some cases, like IC 5063, the location of the outflow coincides with the radio jets, strongly suggesting that radio jets are the main drivers of the outflow. But the presence of a strong optical AGN makes it difficult even in such cases to clearly distinguish the impact of the radio jets from that of the radiation winds. We have addressed this aspect in one detailed case study in this thesis.

### 1.3.3 Impact on ionised gas

Although not the focus of this thesis, for the sake of completion, we briefly mention the impact of radio AGN on ionised gas. The presence of ionised gas outflows due to jet-ISM interaction are known for a long time now (see Tadhunter 2008). These outflows in radio AGN can be traced via emission lines in the optical/IR spectra. The most commonly used tracer is the [O III] $\lambda$5007 line. This line originates from the narrow-line region, very close to the SMBH and hence is a good tracer of the impact of AGN on the ambient ISM. These ionised gas outflows show up as broad (full width at half maximum
> 500 km s$^{-1}$) asymmetric features in the spectrum. Although AGN in general exhibit ionised gas outflows, studies have shown that gas with extreme kinematics is found only in radio-loud AGN (Mullaney et al. 2013). Outflows that are spatially extended are found to be driven by radio jets (e.g. Husemann et al. 2013; Nesvadba et al. 2017). Similar to cold atomic and molecular gas components, ionised gas outflows are more often seen in young or restarted radio sources. The associated mass outflow rates are usually only a few M$_\odot$ yr$^{-1}$ (e.g. Holt, Tadhunter & Morganti 2008), much lower than the atomic and the molecular gas components.

### 1.3.4 Numerical simulations

There has also been significant progress in studies seeking to model the jet-ISM interaction on kpc-scales. Numerical simulations (Sutherland & Bicknell 2007; Wagner, Bicknell & Umemura 2012; Mukherjee et al. 2016, 2018a,b) show that radio jets, despite being collimated structures, can impact the host galaxy significantly over a large volume if the ambient ISM is clumpy. This impact depends on the power of the radio jets. High-power jets ($>10^{45}$ erg s$^{-1}$) will break out of the gas more quickly compared to their low-power counterparts. The low-power jets remain trapped in the ISM while trying to break through the gas, continuously injecting their energy into the ISM and their impact over time becomes very pronounced. Also, younger radio jets that are still embedded within the host galaxy, understandably deposit more energy into the ISM than the older radio sources. They also suggest that if these expanding jets are inclined towards such a clumpy disc, their impact on the gas is stronger and they will also drive sub-relativistic outflows that can increase the velocity dispersion of the gas even beyond the physical extent of the radio jets.
Various observations over the years have been able to test some of the assumptions and predictions of these numerical simulations such as the presence of clumpy ISM, radio jets impacting the ISM even far away via shocks, and the low-luminosity jets having a stronger impact (see Sect. 1.3.2). For example, Morganti et al. (2021), Zovaro et al. (2019), Nesvadba et al. (2021) have shown that radio jets increase the turbulence of gas over large distances beyond their physical reach. Fine-tuned simulations of the cold gas outflow in IC5063 (Mukherjee et al. 2018a) have shown that the simulations now are indeed quite sophisticated and can reproduce the kinematics of fast, jet-driven outflows.

Detailed observations tracing the interaction between the multiphase gas and radio jets spanning a wide range of radio properties would help fine-tune these simulations further which could then inform large-scale cosmological simulations. This thesis combines detailed mapping of jet-ISM interaction with such simulations for this purpose.

1.4 This thesis

The earlier sections have made it clear that to understand the role of radio AGN in the evolution of their host galaxies, we need to carry out (i) a detailed study of the jet-ISM interaction over multiple ISM phases and the energetics involved; this requires high spatial resolution, multiwavelength studies which can, at the moment, be carried out only at low redshifts; (ii) studies of samples of AGN over a wide redshift range to understand how the interaction between the ISM and the radio plasma evolves; this is carried out much more easily for the cold atomic gas component via the H1 21-cm absorption especially given the low-frequency capabilities and the wide-band coverage of the new radio telescopes such as the Karl V. Jansky Very Large Array (JVLA) and the upgraded Giant Metrewave Radio Telescope (GMRT).

We have adopted a two-pronged approach in this thesis where we used relatively new highly sensitive instruments like the JVLA, upgraded GMRT and NOEMA to study the cold gas component, both atomic and molecular, in an individual source in detail and also carry out studies of samples of radio AGN over two redshift ranges: 0.26 < z < 0.4 and 0.7 < z < 1.0 to understand how the cold gas properties in radio AGN evolve with cosmic time.

Chapter 2 presents a detailed study of the jet-ISM interaction in a low-luminosity radio galaxy, B20258+35. We use the VLA and the European VLBI Network (EVN) H1 absorption observations to map the atomic gas in detail. We then compare the kinematics of H1 with the single-dish CO(1-0) observations, model the H1 absorption profile and compare our results with the numerical simulations of radio jets expanding into a clumpy medium to understand the nature of jet-ISM interaction better.

Chapter 3 is a continuation of the study of the jet-ISM interaction in B20258+35. Here we present NOEMA CO(1-0) observations of the cold molecular gas in the central few kpc of the radio galaxy. The high spatial resolution and sensitivity of the observations allow us to quantify the impact of the radio jets on the cold ISM of the host galaxy and also make a comparison with the numerical simulations to help verify
their predictions. Our findings have implications for cosmological simulations seeking to include the feedback from radio AGN.

**Chapter 4** is an $\text{H}i$ absorption study in a sample of 26 radio AGN at $0.25 < z < 0.4$ using the JVLA, a continuation of the studies by Gerêb et al. (2015) and Maccagni et al. (2017) at $z < 0.25$. Here, we investigate the rate of incidence of $\text{H}i$ absorption in different classes of radio AGN and compare it with the trends observed at lower redshifts. We also model the absorption to understand the cold gas kinematics and combine it with the kinematics of ionised gas to obtain a clearer picture of the impact of radio jets on their host galaxies.

**Chapter 5** continues the JVLA study to even higher redshifts: $0.7 < z < 1.0$ using the upgraded GMRT. Here we search for $\text{H}i$ absorption in a sample of 29 radio AGN chosen in the same way as the JVLA sample and the samples of Gerêb et al. (2015) and Maccagni et al. (2017). Here we investigate two main hypotheses proposed to explain the difference in the $\text{H}i$ absorption detection rates at low and high redshifts: (i) the selection bias leading to high-$z$ sources having high UV and radio luminosity and (ii) the cosmic evolution of the cold-gas content. The high sensitivity of the upgraded GMRT allows us to break this degeneracy for the class of extended radio sources which had not been possible for earlier studies.

**Chapter 6** presents a rare case of resolved $\text{H}i$ absorption from a faint galaxy in the same environment as the background radio source 3C 433. We use the VLA $\text{H}i$ absorption observations, the Gran Telescopio CANARIAS (GTC) optical continuum and H$\alpha$ observations to study the kinematics of cold gas in this galaxy as well as the nature of the interaction between the radio lobe and the galaxy. This study shows how faint galaxies, which would be missed even by the deep $\text{H}i$ emission surveys, could be studied via $\text{H}i$ absorption provided high spatial resolution and suitable background radio continuum are available.