Cold gas in the center of radio-loud galaxies

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CONCLUSIONS AND FUTURE OUTLOOK

In this thesis, we made an inventory of the occurrence of H I gas traced by absorption in nearby radio galaxies (Chapters 1, 2, 3). We studied the distribution and kinematics of the neutral hydrogen to investigate how the cold gas and the radio plasma interact. We found that some properties of the H I lines (e.g. width, shape and optical depth) change according to the properties of the radio AGN and the host galaxy. We also conducted a multi-wavelength study of a young radio AGN (PKS B1718–649) to understand which physical conditions of the atomic and molecular gas may trigger the radio nuclear activity (Chapters 4, 5, 6). These observations reveal that in the innermost 75 pc multiple clouds of molecular hydrogen and H I are likely fuelling the radio activity.

Results, chapter by chapter

In this section we shortly summarize the main results obtained in each chapter.

Chapter 1: The H I *absorption "Zoo"*

- We observed 101 galaxies with radio power, log $P_{1.4\,\mathrm{GHz}}\,(\mathrm{W\,Hz}^{-1}) > 24$ detecting 33 H I absorption lines associated with the sources. The complexity of the H I absorption lines, i.e. width and asymmetry, increases with the radio power of the sources.

- The H I lines can be divided in three groups based on their kinematical properties. The narrowest lines with $FWHM < 100\,\mathrm{km\ s}^{-1}$ are most likely produced by HI rotating in large scale disks or HI clouds. Relatively broad lines ($100\,\mathrm{km\ s}^{-1} < FWHM < 200\,\mathrm{km\ s}^{-1}$) may be produced by similar morphological structures with more complex kinematics. Broad lines with $FWHM > 200\,\mathrm{km\ s}^{-1}$, however, may be produced not by simple rotation, but by the most unsettled gas structures, e.g. gas-rich mergers and outflows.

- The H I absorption lines in compact sources, i.e. the radio jets are embedded in the host galaxy, often show the characteristics of unsettled gas, e.g. blue-shifted shallow wings and broad and asymmetric profiles. These properties suggest that strong interactions between the AGN and the circumnuclear cold gas are likely to occur in compact AGN, as young radio jets are clearing their way through the ambient medium.

Chapter 2: The last survey of the 'old' WSRT

- We expanded the sample of Chapter 1, observing 147 sources with radio flux densities in the interval 30 mJy beam^{-1} < $S_{1.4\,\rm GHz}$ < 50 mJy beam^{-1}, resulting in a total of 248 galaxies. The detection rate of H I absorption is 27% ± 5.5% and it does not vary across the range of redshifts (0.02 < z < 0.25) and radio powers (22.5 <log $P_{1.4\,\rm GHz}$ (W Hz^{-1})< 26.2) of the sample.

- AGN with radio-power log $P_{1.4\,\rm GHz}$ (W Hz^{-1}) < 24 only show narrow H I absorption lines ($FWHM$ < 200 km s^{-1}). Broad ($FWHM$ > 200 km s^{-1}) and asymmetric lines, which can trace a significant component of H I unsettled by the radio activity, are found only in powerful radio AGN (log $P_{1.4\,\rm GHz}$ (W Hz^{-1}) > 24).

- Additionally bright mid-infrared (MIR) sources also show H I broad lines, indicating H I with unsettled kinematics. Sources with extended radio continuum, i.e. the radio jets are likely expanding outside the host galaxy, and dust-poor sources show most of the times narrow and deep H I absorption lines. The H I profiles for these sources are mostly centred at the systemic velocity, suggesting that in these galaxies most of the H I is settled in a rotating disk.

- Stacking the spectra of 170 where the H I absorption lines were not detected directly does not reveal a detection of H I absorption down to low optical depths of $\tau \sim 0.0015$. Stacking 70 early-type galaxies of the ATLAS^{3D} sample (i.e. galaxies similar to the sample of our survey but with low radio power, log $P_{1.4\,\rm GHz}$ (W Hz^{-1}) < 22), where H I gas is not detected in the centre, suggests that the circumnuclear regions of early type galaxies may have low column density H I gas ($N_{\rm HI} \sim 2.1 \times 10^{17} (T_{\rm spin}/c_f)$ cm^{-2}). This limit has a corresponding optical depth below the detection limit of the absorption staking experiment.

- The H I gas has higher optical depths when is directly detected ($\tau \sim 0.1$) than the limit reached by the stacking experiment ($\tau \sim 0.0015$), suggesting a bi-modality in the occurrence of H I gas in early-type galaxies. Of these galaxies, 27% ± 5.5% have H I gas detectable in absorption with short targeted observations (4 – 6 hours). The other galaxies, if they are not completely depleted of it, have H I at very low column densities or higher spin temperatures.

Chapter 3: Modelling H I *absorption lines*

- `MoD_AbS` is an open source program we developed to understand if and how H I detected in absorption in radio AGN is distributed in a rotating disk.

- `MoD_AbS` simulates a disk in circular rotation around the continuum emission of a galaxy, determining which regions of the disk absorb the continuum emission and computes the integrated absorption line. Using a Markov Chain Monte Carlo algorithm, `MoD_AbS` finds the combination of parameters of the disk generating the absorption line that best fits the observed one.

- We used MoD_AbS to generate the integrated absorption line detected in a few radio sources of which we only have information about the extent of the background continuum emission. If the continuum source is not very compact (i.e. $< 5pc$) or symmetric, MoD_AbS can recover the inclination and position angle of the H I disk that best fits the observed absorption line.

Chapter 4: What triggers a radio AGN?

- We observed the young ($t_{\rm radio} \sim 10^2$ years, Tingay et al. 1997; Giroletti & Polatidis 2009; Tingay et al. 2002) radio source PKS B1718–649 with the Australia Telescope Compact Array to study the H I gas previously detected in emission and in absorption (Veron-Cetty et al., 1995).

- The study of the kinematics of the large scale H I disk detected in emission does not reveal significant deviations from regular rotation out to ~ 30 kpc from the radio source. This allows us to exclude a major interaction event or secular motions as responsible for the recent triggering of the radio AGN.

- In absorption, we detect two H I lines peaking at opposite velocities with respect to the systemic. This indicates that the lines trace distinct small clouds of gas not regularly rotating within the disk. Although these particular clouds may not have been directly involved in the triggering of the AGN, they likely belong to a larger population present within the galaxy, which may contribute to fuel it.

Chapter 5: The warm molecular hydrogen of PKS B1718–649

- We observed the innermost $8'' \times 8''$ of PKS B1718–649 in at $2.12\mu m$ using the Integral Field Unit SINFONI. These observations detect emission from the warm molecular hydrogen (H_2) assembled into two orthogonal disks.

- The outer ($r > 650$ pc) disk of H_2 is oriented in the north-south direction, and it is aligned with the stellar body of the galaxy. Its kinematics connects smoothly to that of the large-scale H I disk. At radii $r < 650$ pc, the H_2 is assembled in an inner circumnuclear disk, aligned in the east-west direction and polar with respect to the stars. The kinematics of the two disks is characterised by rotation.

- Close to the radio source, at radii $r < 75$ pc, we detect H_2 deviating from the regular rotation of the inner disk with red-shifted velocities with respect to the systemic. The properties of the circumnuclear gas and of the radio AGN suggest that this gaseous component had unsettled kinematics previous to triggering of the nuclear activity. The red-shifted velocities suggest the H_2 may be moving towards the radio source and contribute to fuel its activity.

Chapter 6: Cold molecular clouds are fuelling PKS B1718–649

- We observed the 230 GHz ^{12}CO (2–1) line in the innermost 15 kpc of PKS B1718–649 with ALMA. These observations allowed us to trace at high resolution ($0.28''$, ~ 82 pc) the distribution of the molecular gas and study its kinematics in relation to the recent triggering of the radio nuclear activity.

- The observations show the ^{12}CO (2–1) assembled in multiple clouds that are distributed in a complex warped disk. Between 7.5 kpc and 2.5 kpc from the central radio AGN, the disk is oriented edge-on ($i\sim 60^\circ - 80^\circ$) in line with as the dust lane present in the galaxy, in the north-south direction. In inner radii, the disk changes its orientation; in the innermost 700 pc the molecular gas forms a circumnuclear ring, oriented east-west, that possibly forms the fuel reservoir of the radio activity.
- Against the compact radio emission, we detect ^{12}CO (2–1) in absorption with red-shifted velocities with respect to the systemic $v_{\rm in-fall} = 365 \pm 20$ km s^{-1}. The absorption line is broad compared to the typical velocity dispersion of molecular clouds, and traces one or more clouds falling towards the radio AGN. Since the absorption is detected at the same red-shifted velocities of the warm H_2, the clouds are likely located in the innermost 75 pc of the galaxy and are accreting onto the SMBH.

Main topics, main results

In the Introduction of this thesis, we defined six main open questions that we addressed throughout the different chapters. In this section, we combine the results of this thesis to answer these questions.

What is the content of H I *in nearby radio AGN? what are the conditions of the* H I *in the central region of AGN?*

In the H I absorption survey presented in Chapters 1 and 2 we detect neutral hydrogen in $27\% \pm 5.5\%$ of the sources. In early-type nearby galaxies, the typical host of radio AGN, the detection rate of H I is $\sim 40\%$ (e.g. ATLAS^{3D}, Serra et al. 2012). Not in all of these sources H I gas is detected in the centre, where the radio AGN would be, hence the detection rate of H I in absorption is comparable to the one in emission in the same kind of galaxies.

The stacking experiments we performed on the sample of our survey (see Chapter 2 and Geréb et al. 2014), suggest that there may be a dichotomy in the properties of the H I in the central regions of early-type galaxies. Where it is detected directly, the H I gas has high optical depth while in the non-detections it has very low optical depths. Since low column density H I gas ($N_{\rm HI}\sim 2.1 \times 10^{17} (T_{\rm spin}/c_f)$ cm^{-2}) is detected in a stacking experiment of the ATLAS^{3D} early-type sources, the dichotomy may be explained by a different temperature of the H I in the detections and non-detections. Moreover, we note that orientation effects between the gas and the background radio continuum cannot be excluded.

Do the content and properties of H I *change according to redshift, power of the radio activity and characteristics of the host galaxy?*

In the survey presented in Chapter 1 and 2, we detect H I absorption in sources of all radio powers and all redshifts. This suggests that the presence of H I does not depend on these two quantities. However, the redshift interval ($0.02 < z < 0.25$) is very small compared to the redshifts over which we see a cosmological evolution of the gas content in galaxies.

The width, shape and offset of the H I absorption lines with respect to the systemic velocity changes according to the radio power of the sources. Only radio AGN with $\log P_{1.4\,\mathrm{GHz}}\,(\mathrm{W\,Hz^{-1}}) > 24$ show broad ($FWHM \gtrsim 200\,\mathrm{km\ s^{-1}}$), asymmetric lines peaking at $\pm 100\,\mathrm{km\ s^{-1}}$with respect to the systemic. These lines likely trace H I that has unsettled kinematics, possibly because of the interaction with the radio source. In sources where the radio jets have sub-kpc scales, i.e. compact sources, the H I is detected more often and it shows these traces of unsettled kinematics. Sources where the radio jets extend outside the host galaxy, i.e. extended sources, show only narrow lines, typical of a rotating disk of H I. This suggests that the expansion of the radio jets, if powerful enough ($\log P_{1.4\,\mathrm{GHz}}\,(\mathrm{W\,Hz^{-1}}) > 24$) plays an active role in disturbing the kinematics of the surrounding ISM.

Among powerful radio AGN ($\log P_{1.4\,\mathrm{GHz}}\,(\mathrm{W\,Hz^{-1}}) > 24$), sources showing absorption lines tracing H I with unsettled kinematics are also MIR-bright, indicating sources rich in dust heated either by the nuclear activity or by star formation (see Chapter 2 for further details). This further suggests that the nuclear activity may influence the conditions of the circumnuclear gas. Dust-poor sources have low detection rate of H I ($13\% \pm 5.8\%$) and the absorption lines are narrow.

What features of the H I *absorption lines indicate that gas may be interacting with the radio plasma?*

In Chapters 1 and 2 we identify three features of the H I absorption lines that can indicate that the gas is interacting with the radio plasma. If a line is broader than the rotational velocity of the host galaxy (typically with $FWHM > 200\,\mathrm{km\ s^{-1}}$), it is asymmetric and has its centroid shifted with respect to the systemic velocity of the galaxy. Such features of the lines likely trace gas with unsettled kinematics. In the H I absorption lines we detect, the asymmetry of the line is often due to the presence of a shallow blue-shifted wing. In other radio sources studied in more detail (e.g. Morganti et al. 2005b; Kanekar & Chengalur 2008; Morganti et al. 2013a; Mahony et al. 2013; Allison et al. 2015), this feature has been connected to the presence of an outflow of H I driven by the radio jets expanding through the circumnuclear regions. If the H I traced by absorption has kinematics not following regular rotation, the shift of the centroid of the line to the systemic is related to the radial motions of the gas. Since the absorbed gas is always in front of the radio source, red-shifted velocities indicate gas moving towards the radio source, while blue-shifted velocities trace gas moving away from it.

In our H I absorption survey we detected more blue-shifted lines than red-shifted ones. However, cases of red-shifted H I absorption tracing gas falling towards the radio source are known (e.g. NGC 315, Morganti et al. 2009). In this thesis we also detect a ^{12}CO (2–1) absorption line in PKS B1718–649 peaking at $+365 \pm 20\,\mathrm{km\ s^{-1}}$ with respect to the systemic velocity, which traces molecular clouds falling into the SMBH.

Can we identify H I *outflows of gas and relate their presence to the properties of the radio AGN?*

In our H I survey, we identify H I absorption lines that can trace outflows of gas only in sources with radio power, $\log P_{1.4\,\mathrm{GHz}}\,(\mathrm{W\,Hz^{-1}}) > 24$ (Chapters 1 and 2). Among these sources a lower limit on the detection rate of H I outflows is 5% (Chapter 1). If outflows are a characteristic phenomenon of all radio AGN, the relatively low detection rate would suggest that the depletion time-scale of H I outflows is short compared to the lifetime of radio AGN.

We developed a program (`MoD_AbS`) that can reproduce the integrated H I line generated by a rotating disk. If we can set enough constraints on its inclination and position angle and on the extent of the radio continuum, `MoD_AbS` can be used to understand if all or only a part of the absorption line is tracing rotating gas, and therefore can allow us to identify gas with kinematics deviating from rotation, that may be in-falling or out-flowing from the radio AGN (Chapter 3).

What triggered the young radio AGN PKS B1718–649?

In PKS B1718–649 the radio source was triggered much later ($\sim 10^9$ years) than the last major merger or interaction of the galaxy, that from the dynamical time of the H I disk detected in emission.

In PKS B1718–649 we do not detect neutral hydrogen in emission that deviates from the kinematics of the large scale disk, we exclude that large clouds of gas ($M_{\rm H_I} < 4 \times 10^7 {\rm M}_\odot$) may fall towards the AGN.

The two absorption lines detected at opposite velocities with respect to the systemic velocity of PKS B1718–649 suggest the presence of a population of clouds in the innermost regions of the radio source. These clouds are small, otherwise they would have been detected in emission, have low optical depth ($\tau_{\rm peak} \sim 0.002 - 0.004$), and their kinematics deviate from the regular rotation of the large scale disk. This suggests they may be involved in triggering and fuelling the newly born radio AGN.

Do we see signature of the cold gas contributing to the fuel the AGN and which component contributes the most?

The observations of the H_2 1-0 S(1) line with SINFONI (Chapter 5), and of the ^{12}CO (2–1) with ALMA (Chapter 6), show that the circumnuclear regions are rich in molecular gas that is distributed in a rotating structure, likely forming the fuel reservoir of the radio activity. In the centre of the galaxy ($r < 75$ pc), we detect H I H_2 1-0 S(1) and ^{12}CO (2–1) with deviating kinematics tracing a population of clouds of neutral and molecular hydrogen contributing to fuel the radio activity. In particular, the carbon monoxide detected in absorption has red-shifted velocities with respect to the systemic velocity ($v_{\rm peak} \sim 365 \pm 20\,{\rm km\ s^{-1}}$), similar to the H_2 component. It is likely that the multiple clouds traced by these components are falling into the SMBH.

The mass of the hydrogen clouds as well as the one of the warm H_2, with red-shifted velocities with respect to the systemic, cannot alone sustain the radio activity of PKS B1718–649. We estimate an upper limit on the masses of the cold molecular clouds traced by the ^{12}CO (2–1) absorption that suggests accretion of these clouds onto the SMBH may sustain the jet mode activity of PKS B1718–649. This agrees with what is observed in other young radio AGN, where the molecular gas is the dominant gas phase in their central regions (e.g. IC 5063, Morganti et al. 2015; Dasyra et al. 2016; NGC 1433, Combes et al. 2013; NGC 1466, Combes et al. 2014; 3C 293, Labiano et al. 2013; NGC 1068, (García-Burillo et al., 2014; Viti et al., 2014; García-Burillo et al., 2016); NGC 1097, Martín et al. 2015).

Which accretion mechanism triggered and is feeding PKS B1718–649?

The radio, optical and X-ray properties of PKS B1718–649 suggest it is a jet mode radio AGN (Tingay et al., 1997, 2002; Filippenko, 1985; Siemiginowska et al., 2016). Its accretion mechanism is radiatively inefficient and most energy is expelled by the compact radio jets. Among various models of radiatively inefficient accretion, different numerical simulations suggest that in jet mode radio AGN chaotic accretion of clouds of cold gas may sustain the radio activity (Nayakshin & Zubovas, 2012; Gaspari et al., 2013; King & Nixon, 2015; Gaspari et al., 2015, 2016). This model of accretion could be the triggering and fuelling mechanism of PKS B1718–649. It provides an explanation for the accretion rate of PKS B1718–649, and well describes the properties of its circumnuclear ring, in-falling clouds, and the radio emission that we observe. Moreover, the numerical simulations on chaotic cold accretion predict that structures falling onto radio AGN should appear as H I or CO absorption features, and they predict the formation of a circumnuclear disk of about 500 pc of diameter within which turbulent clouds may generate, and fall towards the nucleus, triggering and fuelling the radio activity.

Future outlook

The H I absorption surveys of the SKA precursors and pathfinders

Neutral hydrogen is the most abundant element in the Universe. Detailed knowledge about its content, distribution and physical conditions in galaxies is crucial to understand how galaxies evolve, change their star formation history and trigger different modes of nuclear activity. In this thesis, we showed that H I absorption studies allow us to successfully investigate the content and kinematics of the H I in early-type galaxies with radio flux density as low as ($S_{1.4\,\rm GHz}\sim$ 30 mJy). The detection rate of H I does not seem to depend on the radio power of the sources. This suggests that H I absorption studies can be expanded to all kinds of galaxies with radio continuum emission detected at 1.4 GHz. The study of H I in absorption is one of the science goals of the SKA precursors and pathfinders; Apertif Oosterloo et al. 2010b, MeerKAT Jonas 2009 and ASKAP Johnston et al. 2008, as well as of SKA Phase 1 (Morganti et al., 2006b).

In Chapter 2, we presented the dedicated H I surveys of the SKA precursors and pathfinders, the Search for H I with Apertif (SHARP), the MeerKAT Absorption Line Survey (MALS) with the South African SKA precursor MeerKAT, and two surveys with the ASKAP, i.e. the Wide-field ASKAP L-band Legacy All-sky Blind surveY (WALLABY) and the First Large Absorption Survey in H I (FLASH). One of the goals of these surveys is to blindly look for associated H I absorption among all sources detected in the radio continuum at 1.4 GHz. As shown in Fig. 10 of Chapter 2, these surveys are complementary. Only by combining the results of all surveys it will be possible to obtain a complete picture of the H I content in galaxies between redshift $z = 0$ and $z \sim 1$. Based on the results of our and other previous H I surveys (Chapters 1, 2 and e.g. Vermeulen et al. 2003; Pihlström et al. 2003; Gupta et al. 2006; Emonts et al. 2010; Allison et al. 2012; Chandola et al. 2013; Allison et al. 2014; Geréb et al. 2014; Chandola & Saikia 2017; Glowacki et al. 2017; Curran et al. 2017), we are confident that the upcoming surveys will detect H I absorption in radio galaxies of powers in the interval $22 < \log P_{1.4\,\rm GHz}\,(\rm W\,Hz^{-1}) < 27$. The detection of H I in sources of lower radio power, mainly at low redshifts, should not be excluded.

SHARP and WALLABY will look for H I at low redshifts ($z < 0.26$), and it will be sensitive to the broader range of radio powers (22 <log $P_{1.4\,\mathrm{GHz}}$ (W Hz^{-1})< 27), FLASH will look for H I absorption out to redshift of $z \sim 1$, even though it will mainly detect H I in the most powerful radio sources (24.5 <log $P_{1.4\,\mathrm{GHz}}$ (W Hz^{-1})< 27). MALS will bridge the gap between the local and the nearby Universe since it will be sensitive to detect H I absorption in sources with radio power in the interval 24 <log $P_{1.4\,\mathrm{GHz}}$ (W Hz^{-1})< 27 at redshifts between $z = 0.25$ and $z = 0.57$.

In this thesis, we also developed a set of tools for the upcoming dedicated H I absorption surveys. To analyse the observations presented in Chapters 1 and 2, we developed a strategy of data reduction and flagging of radio frequency interference that will be part of the data reduction pipelines of the SHARP survey. The program we developed to infer the distribution of H I from the integrated absorption line and a few assumptions on the radio continuum and the host galaxy (`MoD_AbS`, Chapter 3) is also another useful tool for the upcoming surveys. Since it will not be possible to follow up every source where H I is detected in absorption with high resolution observations, `MoD_AbS` will allow us to relate the properties of the H I lines to the radio nuclear activity and the properties of the host galaxy in a sample of hundreds of sources, even though information on the host galaxy and the radio continuum emission is limited.

Studying the molecular gas in AGN and feedback effects at all redshifts

The study of the young radio source PKS B1718–649, as well as many other multi-wavelength studies of AGN of different kinds (e.g. IC 5063, Morganti et al. 2015; Dasyra et al. 2016; NGC 1433, Combes et al. 2013; NGC 1466, Combes et al. 2014; 3C 293, Labiano et al. 2013; NGC 1068, (García-Burillo et al., 2014; Viti et al., 2014; García-Burillo et al., 2016); NGC 1097, Martín et al. 2015) have shown that molecular gas is a key ingredient for the fuelling of the nuclear activity, and that sometimes radio AGN show an outflow of molecular gas that is associated to either the expansion of the radio jets or to the radiative winds of the AGN. Near infra-red Integral Field Unit spectrometers and millimetre and sub-millimetre telescopes are the ideal instruments to study at high resolution the molecular gas in the circumnuclear regions of AGN and investigate how their physical conditions are influenced by the nuclear activity.

One of the fundamental questions of galaxy evolution studies is how galaxies form at high redshifts and evolve to be the galaxies that we observe in the nearby Universe. The most important characteristics of this evolution is that the Specific Star Formation Rate of galaxies at $z = 0$ is much lower than the one of galaxies at $z > 2$. Different numerical simulations of galaxy evolution (e.g. Di Matteo et al. 2005; Springel et al. 2005a; Springel 2005; Springel et al. 2005b; Schaye et al. 2014; Schaller et al. 2015) suggest that negative feedback effects from AGN at high redshifts may be able to displace great amounts of gas outside of the galaxies and therefore quench their star formation. In galaxies at high redshift, it is very difficult to investigate at high resolution the physical conditions of the ISM that is influenced by the nuclear activity. Nevertheless, different effects of feedback from AGN have been detected in a few high redshift galaxies, i.e. fast outflows of gas expelled out of the galaxy for several kilo-parsecs, possibly because of the radiative winds or the radio jets of the AGN (e.g. Alexander et al. 2010; Bradshaw et al. 2013; Maiolino et al. 2012; Cicone et al. 2013; Maiolino et al. 2017). To obtain a complete understanding of feedback from AGN and its role in galaxy evolution, it is crucial to connect the knowledge we have on their physical conditions and influence on the ISM in nearby galaxies to high redshift galaxies.

In this scenario, ALMA and the NOrthern Extended Millimeter Array (NOEMA) are crucial instruments since its spectral coverage allows us to study the physical conditions of molecular gas in galaxies out to redshift $z \sim 6$, as well as image at high spectral and spatial resolution the same molecular gas in galaxies of the local Universe. This will allow us to expand, in the near future, the study of the molecular gas in AGN from the observations of a few objects to high resolution observation of many types of AGN at different redshifts, thus connecting the effects of nuclear activity on galaxies throughout the evolution of the Universe.