The role of neutral hydrogen in the life of galaxies and AGN
Gereb, Katinka

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6 HI, radio continuum, and optical properties of radio galaxies

– K. Geréb, R. Morganti, T. Oosterloo, P. Best –
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6.1 Abstract
We use WSRT observations to study the HI gas properties of nine Sloan Digital Sky Survey (SDSS) radio AGN at redshifts $z < 0.1$. Neutral hydrogen absorption is detected towards the optical core of a compact and a Fanaroff-Riley II type extended radio source. In a third source we find a tentative detection at low optical depth upper limit $\tau < 0.008$.

We detect diffuse extended emission around both sources with certain HI absorption. We argue that the faint diffuse structure is the residual emission from a previous cycle of AGN activity. The presence of cold gas in restarted radio sources suggests that HI is (one of) the main fuel for triggering or even rejuvenating the nuclear activity. Thus, signatures of restarted activity, e.g. faint relic structures, seem to be a good indicator for finding HI absorption in radio galaxies.

In order to increase the statistical significance of our results, based on a literature search we construct a larger dataset of radio sources with available HI observations and optical spectra from SDSS. Galaxies with young stellar populations tend to show high HI detection rate, suggesting that star formation in radio galaxies is connected with the presence of an HI-rich medium. If gas accretion is a periodic event in radio galaxies, then perhaps the new gas supply can continuously contribute to the AGN and star formation fuelling processes.

6.2 Introduction
Gas accretion onto the central black hole (BH) of galaxies is thought to provide the necessary fuel supply for (radio) AGN activity. The availability of cold gas in the circumnuclear region is crucial for the evolution of the galaxy as a whole for the following reasons. Apart from ‘feeding the monster’, the infalling gas may also trigger a central
starburst and produce young stellar populations. Furthermore, interactions between the radio jets and the ambient medium are likely to result in highly energetic feedback mechanisms, releasing substantial amounts of energy back into the ISM. Such interactions often produce high velocity gas outflows (Morganti et al. 1998, 2005, 2013; Dasyra et al. 2014), which may lead to depletion of cold gas reservoirs. Given the importance that the interplay between the energy released by the active black hole and the gas is considered to have, it is important to explore the presence of gas and its relation to other properties of AGN.

H I absorption offers key diagnostics to study the physical and kinematical condition of the gas in the circumnuclear region of radio galaxies. The study of the H I has given in the last years interesting view of the gas properties in one particular type of AGN: the radio loud. Although most of the H I observations were done in quite powerful AGN (i.e., relatively rare AGN) these studies have provided relevant information on the characteristics of the radio sources and their relation with the gas content. In particular, a close connection between the evolutionary stage of the radio source and the H I content has been pointed out by several studies (van Gorkom et al. 1989; Pihlström et al. 2003; Gupta et al. 2006; Emonts et al. 2010; Chandola et al. 2011). The detection rate of H I seems to be particularly high in young radio sources (compact steep spectrum and gigahertz peaked spectrum sources), and this has been interpreted as a signature that cold gas plays a prime role in the AGN triggering processes.

H I observations can also help to time AGN triggering events in the following way. Some of the young radio sources were found to contain large amounts of H I ($\sim 10^{10}$ M$_\odot$), distributed in many cases in the form of regular structures (e.g. large discs and rings with sizes up to 200 kpc (Struve et al. 2010; Emonts et al. 2010). These discs are believed to form by galaxy mergers or by accretion of cold gas from the intergalactic medium, which processes are also considered to be involved in the triggering mechanism of nuclear activity (Smith & Heckman 1989; Tadhunter et al. 1989; van der Hulst et al. 2004). The time scale for the formation of such large discs is about 1 Gyr, whereas AGN activity in the largest radio-loud galaxies is relatively short, $10^7 - 10^8$ years. Therefore, the timescales suggest that either there is a reasonable time delay between the formation of these structures and the triggering of AGN, or the two processes are not related. The latter case may suggest that radio activity is a common, sometimes recurrent period in the evolution of (all) early-type galaxies.

One important questions regarding our understanding of active nuclei is whether AGN activity is usually episodic and if so, what is the cycle of the activity. After the central nucleus switches off, for lack of fuelling the lobe structure will fade away, however for a limited time we can identify these sources through their relic radio emission. Periodic gas accretion may lead to episodic activity of the BH and, interestingly, cold gas seems to be frequently present also in restarted radio sources. This is a rather puzzling result, as it is expected that cold gas reservoirs are depleted by feedback effects during the previous cycle of activity. The main limitation of these studies is that at the moment only a handful of such radio relics have been found, and even fewer cases are known where both continuum and spectral line measurements are available.

As the rejuvenation of the nuclear activity is likely connected with the presence of new gas supply, it is also interesting to investigate whether H I has also other roles in the evolution of radio galaxies. Earlier studies suggest that about 30% of powerful radio sources show the presence of young stellar populations (Lilly & Longair 1984; Smith & Heckman
Therefore, it is interesting to probe the presence of H\(_1\) in connection with star formation and AGN triggering processes in radio galaxies.

An indicator of the presence of young stars in addition to the passively evolving old (12.5 Gyr) component is the 4000 Å break (Tadhunter et al. 2002, 2005). Kauffmann et al. (2003) showed that values of this break in the range D(4000) ~ 1.4 – 1.5 are indicator of the presence of a stellar component with ages less than ~ 1 Gyr. If the star-formation activity is triggered by the same event as the AGN, then the age of the stellar populations can provide important information on the evolution of radio sources and the timescales of reactivation.

It is clear that the picture of galaxy evolution, including the onset and cycle of nuclear activity, is not complete without our knowledge of the presence and distribution of gas. Given the growing interest in the role of the cold gas as tracer of AGN feeding and feedback processes, it is important to explore the relation of H\(_1\) to other properties, e.g. the cycle of AGN activity, presence of young stellar populations. However, it is also clear that H\(_1\) alone cannot give the full view. Sensitive, high resolution continuum observations are needed for tracing the signatures of past activity. Furthermore, complementary optical information needs to be available to characterize the presence of ionized gas and the stellar properties of galaxies for identifying young stellar populations associated with gas accretion events. Therefore, the next step is the systematic investigation of the gas content of different types of AGN based on their radio and optical characteristics.

A way to do this, is to use radio sources obtained from the cross-correlation with optical, spectroscopical catalogs. Best et al. (2005) created a sample of ~ 3000 radio-luminous galaxies (2215 radio-loud AGN, and 497 star-forming galaxies) brighter than 5 mJy by cross-comparing NVSS (National Radio Astronomy Observatories (NRAO) Very Large Array (VLA) Sky Survey) and FIRST (Faint Images of the Radio Sky at Twenty centimeters) surveys with the Sloan Digital Sky Survey (SDSS, York et al. 2000) second data release.

In this paper we present H\(_1\) studies of a pilot sample of nine galaxies selected from the sample of Best et al. (2005). We explore H\(_1\) absorption in relation to the radio continuum and optical characteristics of the host galaxy. In particular, we focus on the connection of H\(_1\) with relic radio structures, optical line ratio diagnostics, presence of young stellar populations. To increase the significance of our conclusions, we also collect a sample of radio sources which have available H\(_1\) observations in the literature. With this study we aim to understand in advance what are the relevant parameters to be explored with future H\(_1\) absorption surveys.

Throughout this paper the standard cosmological model is used, with parameters of \(\Omega_m=0.3\), \(\Lambda=0.7\) and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\).

### 6.3 Sample selection

For this study we have selected a sample of compact and extended sources. The radio classification of extended sources in the dataset by Best et al. (2005) is based on the standard FR classification scheme (Fanaroff & Riley 1974). FR II - s are powerful radio sources with relativistic jets and edge-brightened lobes. A source is classified as an FR II if the peak radio flux compared to the flux at the end of the radio lobe is > 50 \%. This type of radio galaxy is usually found at relatively high redshifts and, therefore, they
<table>
<thead>
<tr>
<th>Source number</th>
<th>Other name</th>
<th>Right ascension $h^m^s$</th>
<th>Declination $\degr'&quot;'$</th>
<th>$z$</th>
<th>log $P_{1.4\text{GHz}}$ (W/Hz)</th>
<th>Radio classification</th>
<th>log(NII/H$\alpha$)</th>
<th>log(OIII/H$\beta$)</th>
<th>D($\text{kpc}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS1 B2 0828+32</td>
<td>08 31 27.49</td>
<td>+32 19 26.6</td>
<td>0.05115</td>
<td>22.75</td>
<td>FR II</td>
<td>0.20</td>
<td>0.59</td>
<td>1.86</td>
<td></td>
</tr>
<tr>
<td>SDSS2 -</td>
<td>11 50 11.28</td>
<td>+53 43 20.7</td>
<td>0.06032</td>
<td>23.23</td>
<td>FR II</td>
<td>-0.99</td>
<td>-99</td>
<td>2.07</td>
<td></td>
</tr>
<tr>
<td>SDSS3 -</td>
<td>08 46 32.44</td>
<td>+29 35 55.2</td>
<td>0.07010</td>
<td>23.53</td>
<td>FR II</td>
<td>0.28</td>
<td>0.18</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td>SDSS4 -</td>
<td>10 22 00.78</td>
<td>+44 51 44.1</td>
<td>0.08295</td>
<td>24.40</td>
<td>Interm.</td>
<td>0.28</td>
<td>0.24</td>
<td>1.98</td>
<td></td>
</tr>
<tr>
<td>SDSS5 -</td>
<td>11 45 06.52</td>
<td>+53 38 52.8</td>
<td>0.06901</td>
<td>23.11</td>
<td>Interm.</td>
<td>0.23</td>
<td>-0.03</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>SDSS6 4C 29.30</td>
<td>08 40 02.35</td>
<td>+29 49 02.6</td>
<td>0.06485</td>
<td>23.35</td>
<td>FR II</td>
<td>0.06</td>
<td>0.93</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>SDSS7 -</td>
<td>15 42 28.35</td>
<td>+52 59 50.7</td>
<td>0.06904</td>
<td>23.45</td>
<td>Compact</td>
<td>-0.04</td>
<td>0.34</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>SDSS8 -</td>
<td>13 17 39.19</td>
<td>+41 15 45.6</td>
<td>0.06616</td>
<td>24.42</td>
<td>Compact</td>
<td>0.20</td>
<td>0.14</td>
<td>2.03</td>
<td></td>
</tr>
<tr>
<td>SDSS9 -</td>
<td>15 18 38.89</td>
<td>+40 45 00.2</td>
<td>0.06516</td>
<td>23.65</td>
<td>Compact</td>
<td>0.11</td>
<td>0.28</td>
<td>1.68</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6.1:** Optical identification and radio characteristics of the observed sample. The radio power of the sources presented in Col. 6 is taken from the NVSS catalog. Optical line ratios in Col. 7 and Col. 8 extracted from the SDSS catalog. In case a line has S/N < 3, the ratio is set to -99.
6.3: Sample selection

Figure 6.1: Continuum images of the observed sample extracted from the FIRST survey, overlaid with 3σ contours of our WSRT observations. In case of SDSS6, the contour levels are adjusted to get a better definition of the extended emission. In the first row we show SDSS1, SDSS2, and SDSS3 from the left to the right. The other images follow accordingly in increasing order.

tend to be underrepresented in studies of HI in radio sources. To facilitate the inclusion of FR II galaxies, we selected our objects at relatively high redshifts $0.05 < z < 0.09$. Other selection criteria were: $10^{11} M_\odot < \text{stellar mass} < 5 \times 10^{11} M_\odot$, and $\delta > 25^\circ$. The radio sources are brighter than $S_{1.4\text{GHz}} > 30$ mJy.

According to this classification scheme, our sample contains four FR II, and two intermediate type sources with only one hotspot. The remaining three sources show compact morphology. The continuum images of the sources are presented in Fig. 6.1. The targets of the observations and some of their characteristics (including radio morphology classification) are listed in Table 6.1.
## 6.4 Observations and data reduction

The observations were obtained with the Westerbork Synthesis Radio Telescope (WSRT). The nine sources were observed in April 2006, with 12 hour exposure times for every source. The observational setup consists of 20 MHz bandwidth covered by 1024 frequency channels. All cubes were made by adding 4 channels together, yielding a velocity resolution of 15.6 km/s before, and 27 km/s after Hanning smoothing.

The data was reduced using the MIRIAD package. After initial flagging and bandpass calibration, the continuum was subtracted by fitting a first or second order polynomial to the line-free channels. In case an \( \text{H} \text{I} \) detection was found, the cubes were cleaned, restored, Hanning smoothed, and the velocity was set to optical. If no sign of \( \text{H} \text{I} \) was found, the cubes were only Hanning smoothed but not cleaned.

For the line cubes different weights were used in order to obtain the best sensitivity for detecting absorption/emission. In order to detect \( \text{H} \text{I} \) in absorption we used robust weighting. To search for emission in the environment of the central sources (see Section 6.5) we used natural-weighted cubes corresponding to the highest S/N ratio.

The continuum images of the sources were created using the line-free channels, later cleaned and self-calibrated in order to obtain a satisfactory map. Table 6.2 contains the parameters of the continuum images and line cubes.

### Table 6.2: Parameters of the continuum images and line cubes. Col. 1 refers to the serial number of the sources in our sample.

<table>
<thead>
<tr>
<th>Source number</th>
<th>Beam Size ( (&quot;) )</th>
<th>PA ( (\degree) )</th>
<th>rms continuum (mJy/beam)</th>
<th>rms linecube (mJy/beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS1</td>
<td>27.80 × 13.95</td>
<td>1.1</td>
<td>0.059</td>
<td>0.315</td>
</tr>
<tr>
<td>SDSS2</td>
<td>17.28 × 13.15</td>
<td>0.7</td>
<td>0.049</td>
<td>0.322</td>
</tr>
<tr>
<td>SDSS3</td>
<td>30.80 × 13.77</td>
<td>0.8</td>
<td>0.054</td>
<td>0.322</td>
</tr>
<tr>
<td>SDSS4</td>
<td>17.35 × 10.74</td>
<td>0.1</td>
<td>0.063</td>
<td>0.325</td>
</tr>
<tr>
<td>SDSS5</td>
<td>19.47 × 14.80</td>
<td>0.8</td>
<td>0.064</td>
<td>0.375</td>
</tr>
<tr>
<td>SDSS6</td>
<td>32.27 × 13.95</td>
<td>-2.5</td>
<td>0.058</td>
<td>0.351</td>
</tr>
<tr>
<td>SDSS7</td>
<td>19.75 × 14.90</td>
<td>0.9</td>
<td>0.050</td>
<td>0.315</td>
</tr>
<tr>
<td>SDSS8</td>
<td>26.49 × 11.19</td>
<td>11.5</td>
<td>0.065</td>
<td>0.331</td>
</tr>
<tr>
<td>SDSS9</td>
<td>23.65 × 14.02</td>
<td>1.2</td>
<td>0.037</td>
<td>0.339</td>
</tr>
</tbody>
</table>

### 6.5 Results

We detect \( \text{H} \text{I} \) absorption towards the optical core in two sources. For a third source we have a tentative detection, in which case the \( \text{H} \text{I} \) profile appears towards the northern lobe. We also detect an emission feature South-East from the core. The \( \text{H} \text{I} \) profiles and parameters of the detected lines are presented in Fig. 6.2, 6.3 and Table. 6.3.

One of the detected sources (SDSS6, 4C29.30) has been reported in the meantime by Chandola et al. (2010). The other detections are new. The second detection is found in SDSS8, a compact source. Interestingly, both detected sources show extended low surface brightness emission, that will be discussed in Sec 6.6. The tentative detection
### Table 6.3: Parameters of the H\(I\) absorption in the observed sample.

The \(S_{1.4\text{GHz,core}}\) flux density is measured in the optical core of the sources. In case of SDSS4, the tentative detection appears against the northern lobe, therefore the flux density of the lobe at the position of the absorption is also indicated with the corresponding parameters. The upper limits in Col. 5 are calculated from \(3\sigma/S_{1.4\text{GHz,core}}\).

<table>
<thead>
<tr>
<th>Source number</th>
<th>(S_{1.4\text{GHz,core}}) (mJy)</th>
<th>(S_{1.4\text{GHz,lobe}}) (mJy)</th>
<th>HI detection</th>
<th>(\tau) (10^{18}) ((T_{\text{spin}}/c_1)) cm(^{-2})</th>
<th>(N(H I)) ((\text{mJy}))</th>
<th>(\Delta V) (km/s)</th>
<th>FWHM (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS1</td>
<td>9.16</td>
<td>-</td>
<td>&lt; 0.103</td>
<td>&lt; 0.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDSS2</td>
<td>19.72</td>
<td>-</td>
<td>&lt; 0.049</td>
<td>&lt; 0.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDSS3</td>
<td>28.80</td>
<td>-</td>
<td>&lt; 0.033</td>
<td>&lt; 0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDSS4</td>
<td>149.83</td>
<td>-</td>
<td>&lt; 0.006</td>
<td>&lt; 0.01</td>
<td>94.03</td>
<td>0.008</td>
<td>0.85</td>
</tr>
<tr>
<td>SDSS5</td>
<td>11.12</td>
<td>-</td>
<td>&lt; 0.101</td>
<td>&lt; 0.183</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDSS6</td>
<td>221.8</td>
<td>+</td>
<td>0.065</td>
<td>16.3</td>
<td>24.43</td>
<td>0.038</td>
<td>0.06</td>
</tr>
<tr>
<td>SDSS7</td>
<td>24.43</td>
<td>-</td>
<td>&lt; 0.038</td>
<td>&lt; 0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDSS8</td>
<td>251.05</td>
<td>+</td>
<td>0.032</td>
<td>7.39</td>
<td>44.36</td>
<td>0.022</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>SDSS9</td>
<td>44.36</td>
<td>-</td>
<td>&lt; 0.022</td>
<td>&lt; 0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.2: H\textsc{i} detections. The figures show the H\textsc{i} absorption from the nuclear region of SDSS6 (above) and SDSS8 (below). The systemic velocity is marked by a vertical solid line in both figures.

of H\textsc{i} absorption is found in SDSS4. The optical depth of the absorption is 0.0065 in SDSS6 and 0.022 in SDSS8. The optical depth of the tentative detection in SDSS4 is 0.008 at the 2.5-\textsigma limit (Table. 6.3).

For the calculation of column densities (Table 6.3) we used the formula:

$$N(\text{H} \textsc{i}) \, (\text{cm}^{-2}) = 1.8216 \cdot 10^{18} \times T_{\text{spin}} \times \int \tau(v)dv$$

where $v$ is the velocity, $\tau(v)$ is the optical depth (or in case of non-detections the 3\textsigma upper limit), and $T_{\text{spin}}$ is the spin temperature. The latter temperature can be effected by three factors: collisions, Ly\alpha photons, and the absorption of 21 cm continuum radiation. If
the HI absorption arises from cold, dense, atomic regions, the spin temperature should be very similar to the kinetic temperature of such a medium $T_{\text{spin}} \approx T_{\text{kinetic}} \sim 100$ K.

Table 6.3 shows that HI spans a broad range of column densities between $\text{few} \times 10^{17} - 10^{19} \left(\frac{T_{\text{spin}}}{c_f}\right) \text{cm}^{-2}$, where $c_f$ is the covering factor of the gas. Similar HI column densities were detected by previous studies of larger radio galaxy samples (Allison et al. 2012; Gereb et al. 2014). This is likely related to the fact that radio AGN are typically hosted by early-type galaxies. HI emission studies of SAURON (Morganti et al. 2006; Oosterloo et al. 2010a) and ATLAS$^3$D (Serra et al. 2012) early-type galaxies show a broad range of HI masses, column densities, and kinematics, accounted for the fact that HI in ETGs is of external origin. HI can be transported by accretion from the intergalactic medium or by merger events, and this observational result is also in good agreement with AGN triggering theories.

The Full Width Half Maximum (FWHM) of the detected lines is $72 - 112 \text{ km s}^{-1}$ (see Table 6.3). The absorption peak in SDSS4 and SDSS6 is detected close to the systemic velocity, with velocity offsets similar or lower than the 3-$\sigma$ error on the SDSS redshift ($\sim 60 \text{ km s}^{-1}$). As it is explained in Gereb et al. (2014a, 2014b submitted), such narrow lines of the order of $100 \text{ km s}^{-1}$ at the systemic velocity are likely produced by rotating HI disks. In SDSS8, the peak is redshifted by $136 \text{ km s}^{-1}$, suggesting that an HI cloud is falling in toward the core of this source.

In the remaining sources no HI absorption has been detected optical depth upper limits around a few percent (see Table 6.3). However, the optical depth upper limit in SDSS1 and SDSS5 is relatively high, 10%. The high upper limits in these sources are due to the weak cores revealed once imaged at higher spatial resolution than NVSS, see Table 6.3. This is an important consideration to keep in mind for future studies.

Among the sources undetected in HI, two are worth a few extra comments. The
lobe structure of SDSS1 (B2 0828+32) has been studied in more detail in previous works (Ulrich & Ronnback 1996). SDSS1 is one of the few X-shaped galaxies found so far, with two radio lobes of different ages and orientation. As a possible explanation for the X-shape, Ulrich & Ronnback (1996) suggest a change in the orientation of the jets, the age of the older lobes being 70 Myr. No sign of H\textsc{i} absorption or emission was found neither in the nuclear region, nor in the other parts of the galaxy. However, we remind the reader that high H\textsc{i} detection limit is set in this source by the weak AGN core.

SDSS9 is a flat-spectrum compact radio source selected by Caccianiga et al. (2001) to investigate the hypothesis that low-power AGN, usually classified as radio-quiet, can produce relativistic jets. They suggest that SDSS9 could be a radio AGN whose relativistic jets are viewed close to end-on. Their finding of a high-brightness temperature core partly support this hypothesis. No signs of H\textsc{i} absorption was found in this source, but two companion galaxies contain H\textsc{i} emission (see Sec 6.5.4 and Table 6.4).

Below we briefly comment on the detections.

\subsection*{6.5.1 SDSS6: 4C 29.30}

In our sample the extended SDSS6 source is detected with an optical depth of \( \sim 0.06 \), well above the 3\( \sigma \) detection limit. Apart from the H\textsc{i} we detect diffuse continuum emission around this source. The diffuse feature was previously observed by Jamrozy et al. (2007), who suggest that 4C 29.30 is a restarted FR II radio source, where the relic emission is the signature of the past activity cycle. Previously, Chandola et al. (2010) reported the detection of a redshifted H\textsc{i} component in this source, and they suggest that infalling H\textsc{i} clouds provide fresh supply to rejuvenate the activity of the AGN. The redshifted line is tentatively detected at low significance in our observations.

SDSS6 has the highest column density H\textsc{i} in our sample (see Table 6.3). The low D(4000) index (see Table 6.1) and the presence of strong optical lines in the spectrum of SDSS6 (see Fig. 6.10) indicate that the host galaxy is actively forming stars. The presence of young stellar populations (YSPs) in this source suggest that in SDSS6 stars are likely to form in dense regions of cold gas, rich in H\textsc{i} similarly to what has been found in SAURON and ATLAS\textsuperscript{3D} early-type galaxies.

\subsection*{6.5.2 SDSS8}

SDSS8 is the second detection and, again, we detect low brightness radio emission around the central compact source. In SDSS8 the peak is redshifted by 136 km s\(^{-1}\). This can suggest that H\textsc{i} in this source is being accreted through gas infall, and this process transports new supply of gas to reanimate the nucleus.

The host galaxy shows an edge-on stellar disk in the SDSS optical image, and along with the lenticular appearance of the host, it is likely that SDSS8 belongs to the S0 morphological class. The column density of the H\textsc{i} is relatively high, although no clear signature of YSPs is detected in this source. However, in red galaxies like the host of SDSS8 it is also possible that the light of young stars is masked by more luminous old stellar populations (Tadhunter et al. 2002).
6.5.3 SDSS4

The source with tentative detection (SDSS4) is an intermediate radio galaxy with only one hot spot. In this AGN the HI absorption is seen against the northern lobe (the lobe of the hot spot). Even though smaller patchy structures (e.g. clouds) could produce such absorption at larger distances from the nucleus, here we consider the existence of an extended (∼40 kpc diameter) gaseous circumnuclear disc more likely: HI in this galaxy is detected at the systemic velocity, suggesting co-rotation of the HI with the host. Such extended discs are quite rare, there are only a few cases reported. Morganti et al. (2002) detected a similar absorption feature against the lobes in Coma A. They explain the occurrence of HI absorption at such large distances from the central region as being produced by a gaseous disk-like structure of at least 60 kpc in diameter, made up by neutral and ionised gas. Similar neutral gas distribution extending up to tens of kpc was detected in the source 3C 234 by Pihlström (2001).

We also detect tentative HI emission in this source at the ∼3-sigma level South-East from the core. The emission line is redshifted by +490 km s$^{-1}$, suggesting that the source of HI emission is possibly not associated with the galaxy.

6.5.4 Galaxies detected in HI emission

In several cases we detect galaxies with HI emission in the environment of the SDSS sources. The properties of these galaxies are presented in Table 6.4. The presence of HI-rich companion galaxies interacting with the central source is considered in some cases to be responsible for triggering the AGN activity (see e.g. Keel et al. 2006; Emonts et al. 2008a for some examples).

For distances larger than 350 kpc the timescale of interactions between sources is $\gtrsim 10^9$ year. The timescale of the radio loud phase is instead shorter, $\lesssim 10^8$ years. Thus, galaxies above this distance can not be responsible for triggering the nuclear activity, and only surrounding galaxies within 350 kpc are considered as companion in our sample. Only one galaxy can be classified a real companion based on the above criteria. This galaxy is observed in the environment of SDSS3 within only 32 kpc distance, although no sign of interaction with SDSS3 is seen in HI. The other galaxies with HI emission are at distances larger than 400 kpc (see Table 6.4).

6.6 Rejuvenated radio AGN

We used our relatively deep WSRT continuum images to search for relic radio emission. Interestingly, the two HI-detected sources in our sample show diffuse emission features around their central radio galaxy (Fig. 6.1).

The presence of the faint continuum feature in SDSS6 is confirmed by other observations (Jamrozy et al. 2007; Chandola et al. 2010). The angular size of the extended structure is 520 arcsec (639 kpc), inside which a 29 arcsec (36 kpc) double-lobed FR II galaxy is embedded. Jamrozy et al. (2007) consider this source a rejuvenated radio galaxy, with the diffuse halo being the residual of an earlier cycle of activity. The inner radio source has an estimated spectral age of $\lesssim 33$ Myr, while the spectral age of the diffuse extended emission is $\gtrsim 200$ Myr (Jamrozy et al. 2007). Although we do not have the
### Chapter 6: HI, Radio Continuum, and Optical Properties of AGN

#### Table 6.4: Parameters of H I emission detections in the environment of the SDSS galaxies

<table>
<thead>
<tr>
<th>Associated galaxy</th>
<th>RA (h m s)</th>
<th>Dec (° ′ ″)</th>
<th>z</th>
<th>∆V (km/s)</th>
<th>H I mass (10^9 M⊙)</th>
<th>Distance from central source (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS3</td>
<td>08 46 28.1</td>
<td>29 35 27.1</td>
<td>0.070862</td>
<td>+18.24</td>
<td>8.4</td>
<td>32.08</td>
</tr>
<tr>
<td>SDSS7</td>
<td>15 42 7.7</td>
<td>53 05 14</td>
<td>0.07094</td>
<td>-315.17</td>
<td>6.1</td>
<td>412.06</td>
</tr>
<tr>
<td>SDSS8</td>
<td>13 17 47</td>
<td>41 09 17</td>
<td>0.067379</td>
<td>-7.56</td>
<td>2.4</td>
<td>480.91</td>
</tr>
<tr>
<td>SDSS9</td>
<td>15 19 19</td>
<td>40 51 46.7</td>
<td>0.065252</td>
<td>-28.16</td>
<td>-</td>
<td>490.72</td>
</tr>
<tr>
<td></td>
<td>15 18 30.8</td>
<td>40 36 52</td>
<td>0.06555</td>
<td>-85.65</td>
<td>12.3</td>
<td>578.11</td>
</tr>
</tbody>
</table>

The same wealth of information for SDSS8, from the morphology of the diffuse, low surface brightness continuum we suggest that it has a similar, relic-like origin.

The D(4000) index of SDSS6 is \( \sim 1.4 \), corresponding to \( \sim 1 \) Gyr in stellar age (Kauffmann et al. 2003). This suggests that apart from feeding the black hole, cold gas also can contribute to the evolution of powerful radio galaxies by producing young stars. If new stars are produced by the same effect as the triggering of the AGN activity, then the timescales (compared to the estimated age of the lobes) suggest that the YSP in SDSS6 was formed in the previous cycle of activity. In this case, the detection of H I in SDSS6 would suggest that new supply of cold gas has been accreted over the last 1 Gyr.

The detection of H I in both sources with relic diffuse emission supports the suggestion made by Saikia & Jamrozy (2009); Jamrozy et al. (2007); Chandola et al. (2010); Shulevski et al. (2012) that episodic activity in radio AGN is connected with the presence of cold gas. Considering previous results (Chandola et al. 2010; Fernández et al. 2010; Shulevski et al. 2012), relic structures could be good indicators for the presence of H I with the possibility that H I gas is connected to the fuelling of the recent phase of activity. The number of known sources with similar properties is still low, and in order to understand the role of H I in the life cycle of radio AGN, large systematic studies are needed with available H I and sensitive continuum measurements at high resolution.

### 6.7 H I and Optical Properties

To complement the information about the H I, we have also explored the optical properties of the sources. The SDSS database contains information which can be used to investigate the stellar populations, star-formation properties of the objects, or to distinguish between normal star-forming galaxies and optical AGN. The SDSS optical images and spectra of each object are presented in Fig. 6.9, 6.10 and in Table 6.1.

Fig. 6.4 shows the location of our galaxies in the BPT diagram (Baldwin, Philips & Terlevich 1981). The dashed line marks the theoretical limit between AGN and normal star-forming galaxies, as above this line AGN provide a substantial contribution to the line fluxes (Kewley et al. 2001). The horizontal and vertical solid lines separate high ionization galaxies from LINERs (low-ionization nuclear emission region) (Kauffmann et al. 2003). The objects from the observed sample are marked in
Figure 6.4: BPT line ratio diagram. Our sample is marked by red symbols, sources which were collected from the literature are indicated in black (see Sec 6.8). Filled symbols indicate HI detections (certain and tentative), whereas empty symbols mark HI non-detections. SDSS5 is marked by an empty triangle in this plot because we only have an upper limit on the \([\text{NII}]/\text{H}\alpha\) ratio of this galaxy. Filled triangles mark tentative HI detections.

red, while the black symbols are objects taken from the literature and will be discussed in the next session.

For lines with S/N < 2, the line ratios are very poorly constrained, therefore should be completely ignored, or used with precaution. For SDSS2 none of the four emission lines are detected with S/N > 2, therefore this object is not included in the BPT diagram. In case of SDSS5, the \([\text{NII}], \text{H}3\) and \([\text{OIII}]\) lines are all detected with a S/N > 2, and although its H$\alpha$ line has S/N just below 2, in the SDSS catalog one can find an upper limit of 0.23 set for its \([\text{NII}]/\text{H}\alpha\) line ratio. This way SDSS5 belongs to LINER galaxies in the BPT diagram, though the low value of \([\text{OIII}]/\text{H}3\) already indicated its type. According to the diagram, SDSS1 and SDSS6 are high ionization AGN belonging to the Seyfert group, the rest are LINERs. It is worth mentioning that at the lower resolution of NVSS, SDSS1 and SDSS6 are the most powerful radio sources in our sample (with log($P_{1.4\,\text{GHz}}$) = 25.09 and 24.77 W Hz$^{-1}$ respectively). This is consistent with the known correlation between radio continuum and optical line luminosity (Tadhunter et al. 1998). According to the radio power (Table 6.1) and optical SDSS spectra of the sources, SDSS2 and SDSS3 appear less powerful with fluxes relatively low for FR II-s, and with optical line strengths more characteristic for FR I-s. These could be examples of weak emission line radio galaxies, i.e. powerful sources (FRII) with weak lines (like FRI) (Hardcastle et al. 2006; Buttiglione et al. 2010).
Figure 6.5: D(4000) index as function of redshift. Symbols are the same as in Fig. 6.4. The three horizontal lines represent the values of the break for which 100, 50 and 10 percent (in order solid, dashed, dotted line) of the light below a rest-frame wavelength of 4000 Å arises from young stars (Tadhunter et al. 2002).

Signatures of star formation activity are often found in HI-detected early-type galaxies. For example, in a sample of powerful 3CR radio sources Tadhunter et al. (2002) found that about 30% of the galaxies contain a young stellar component. Low-luminosity AGN are mostly found to have stellar populations similar to normal early-type galaxies, while high-luminosity AGN have younger stellar populations (Kauffmann et al. 2003). SDSS provides the D(4000) index for our nine sources, and we use this parameter to investigate the YSPs in our galaxies in Fig. 6.5 (red symbols). Above the solid line one can only find old stars, at the limit of the dashed line only 50% of the light is produced by old stellar populations, while below the dotted line only 10% is represented by old stars.

All our galaxies show UV excess compared to passively evolving elliptical galaxies, SDSS6 having the lowest D(4000) index. Since the high UV excess of SDSS6 indicates the presence of YSPs in this source, and along with the detections of HI this result supports a connection between starburst activity and the presence of HI gas. However, not all galaxies with HI detections show the presence of starbursting YSPs. This is, again, in good agreement with SAURON and ATLAS3D results. In the latter studies it was suggested that high column density gas is needed for star formation to occur in early-type galaxies and, in fact, SDSS6 shows the highest column density in our sample in Table 6.3.
6.8 Results from the literature

In order to better investigate the relation between H$_I$, AGN and the host galaxy, we have constructed a database of radio galaxies with available H$_I$ absorption observations. The data are collected from works by Briggs et al. (1993); Conway & Blanco (1995); Dwarakanath et al. (1995); Emonts et al. (2008a,b, 2010); van Gorkom et al. (1989); Gupta et al. (2007); Jaffe (1991); Kanekar & Chengalur (2008); van Langevelde et al. (2000); Orienti et al. (2006); Pihlström et al. (2003); Struve et al. (2010b); Vermeulen et al. (2003); Morganti et al. (2001, 2009); Véron-Cetty et al. (2000) and Privon in prep. The collection includes information about the optical depth, flux density, optical ionization lines, star-formation properties of compact, extended sources. From the collected sample, 19 sources have available line flux and D(4000) index measurements in the SDSS spectroscopic database.

6.8.1 H$_I$ and radio properties

In Fig. 6.6 we show the optical depth histograms for compact, extended sources. For this work only the optical depth of the deepest H$_I$ components is considered for every radio source. The histogram of compact sources shows a wide range of optical depths, revealing sources with certain detection even at very low values (below $\tau \sim 0.001$). Extended sources show a distribution with H$_I$ detections only above the typical detection limit ($\tau \sim 0.01$) of present-day radio telescopes (see Section 6.5), below this limit one can only find non-detections.

In Fig. 6.7 we plot the flux density distribution against the optical depth for detections and non-detections. Compact sources seem to be systematically brighter, allowing for the detection of faint H$_I$ structures at low optical depth. This suggests that the low core brightness may represent a bias against H$_I$ detections in the central region of extended sources.

Non-detections show a similar flux density distribution as detections. In the figure of non-detections, compact sources – despite being stronger in flux density – appear with rather high upper limits. These compact sources were selected from a study at higher redshift (Vermeulen et al. 2003), where insufficient sensitivity could yield increased upper limits, resulting in a strong bias for non-detections. Taking this in consideration, one can not make certain conclusions about the lack of H$_I$ in these sources. In compact sources the detection rate of H$_I$ is $\sim$37%, however the actual detection rate could be even higher. Although, this could only be tested by more sensitive observations.

6.8.2 Optical properties

In Fig. 6.4, the new collection of galaxies for which optical data is available (black symbols) are added to the BPT diagram of our observations. Among LINERs we find a mix of detections and non-detections. Galaxies with highly ionized lines in the region $\log([NII]/H\alpha) > -0.22$ and $\log([OIII]/H\beta) > 0.47$ show a high, 66% H$_I$ detection rate (4 out of 6). This is similar to the H$_I$ emission detection rate obtained by Ho & Ulvestad (2001) in a sample of type 1 AGN (broad-line) with Seyfert nuclei, which galaxies are usually located in the same region of the BPT diagram. Ho & Ulvestad (2001) concluded that type 1 AGN possess a normal H$_I$ gas content, as expected from scaling relations. From our plot, this seems to be the case for AGN with highly ionized lines.
Figure 6.6: Comparison between the optical depth histograms of compact (top), extended (bottom) sources.
Figure 6.7: Flux density vs. optical depth for HI detections (top) and non-detections (bottom) collected from the literature. The solid, dotted and hashed line represent the 3σ limits in the absorption line signal corresponding in order to $1\sigma=0.2, 0.4, 2\text{ mJy}$
In Fig. 6.5 we also show the D(4000) index of the galaxies. We find that YSPs at D(4000) < 1.6 are predominantly found in AGN with H I detections, whereas the majority of AGN with H I non-detections have older stellar populations. This is in good agreement with our results obtained for SDSS6, supporting the possibility that star formation in radio galaxies is connected with the presence of cold gas. If gas accretion is a common process as it is suggested by the rejuvenation theory of AGN, it is likely that the same event can also periodically provide fuel for the production of new stars. The fact that most of the radio galaxies with young stellar populations also show H I detection suggests that cold gas plays a major role in both AGN and star formation fuelling processes.

6.9 Conclusions, and future perspectives

We have explored the presence of H I in radio sources typically not considered very powerful. We detect H I in the two brightest galaxies, a compact, and an FR II radio source. Furthermore, we find a tentative detection in an intermediate type radio galaxy. We have not explored the significance of the upper limits because the cores turned out to be weak when imaged at higher resolution.

We observe diffuse extended emission around both detected sources, likely due to residual of a previous cycle of AGN activity. The detection of H I absorption in restarted sources suggests a link between neutral hydrogen gas and rejuvenation of nuclear activity, where possibly H I is the main fuel for feeding the central black hole. Considering also previous studies, restarted activity seems to be a better indicator of H I absorption than the radio morphology, e.g. FR I or FR II type.

Furthermore, recent star formation events also show a close connection with the presence of H I. Galaxies with young stellar populations tend to show high H I detection rate, suggesting that stars are likely to form in H I-rich gas regions in radio AGN. If gas accretion is a periodic event in radio galaxies, perhaps this effect will leave an imprint on the star formation history as well.

Our results are based on datasets with small number of galaxies, which are therefore statistically not representative. We expect that future surveys will provide much larger samples to study, statistically, the H I gas properties of radio galaxies. We use a semi-empirical simulation of the extragalactic radio continuum sky (Wilman et al. 2008) to predict the number of galaxies that will be observed by future surveys. For example, an all-sky survey of 10000 deg$^2$ in the redshift range $0 < z < 0.1$ would provide $\sim$500 sources brighter than 30 mJy. Based on our results we expect 20 – 30% of these sources to be detected, namely 100 – 150 sources. If we push the redshift limit out to $z < 1$, one can get the same result with observing only $\sim$200 deg$^2$. It is clear that in order to get large datasets with a desired brightness limit, we need to observe large areas of sky at shallow redshifts, else the same result could be obtained on smaller areas but reaching to higher redshifts.

Considering the results of simulations, one can understand that future instruments e.g. Apertif with observations in the redshift range $z < 0.2$, or, eventually, SKA will significantly increase the number of sources available for H I studies. For example, the ASKAP-FLASH (The First Large Absorption Survey in HI) all-sky survey is expected to yield $\sim$1000 intervening absorbers (along the line of sight to the background continuum source), and several hundred H I absorption systems with associated neutral gas in the redshift range $0 < z < 1$. The increased number of H I absorption detections with the
Figure 6.8: Redshift histogram of radio sources brighter than 30 mJy distributed on a 100 deg$^2$ area of sky, based on extragalactic radio continuum sky simulations (Wilman et al. 2008)

next generation of radio telescopes will provide enough sources interpret our HI results on a much higher confidence level.

As a conclusion we can say that future large HI surveys reaching to cosmologically high redshifts will represent the key to statistically analyse large samples of radio sources. These surveys will provide large datasets to trace the distribution of neutral hydrogen gas in AGN, and to find the link between HI, the evolution of radio sources, and star formation properties.

6.10 Appendix

6.10.1 SDSS images and spectra
Figure 6.9: SDSS optical images of the host galaxies in our sample. In the first row we show SDSS1, SDSS2, and SDSS3 from the left to the right, and the other images follow accordingly in increasing order as in Fig. 6.1.
Figure 6.10: SDSS optical spectra of our galaxies. The order of the objects is the same as in Fig. 6.1 and Fig. 6.9.
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