Parsec-scale HI outflows in powerful radio galaxies

R. Schulz1, R. Morganti1,2, K. Nyland3, Z. Paragi4, E. K. Mahony5, and T. Oosterloo1,2

1 ASTRON, Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands e-mail: r.f.schulz@issc.leidenuniv.nl, morganti@astron.nl
2 Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands
3 National Research Council, Resident at the U.S. Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375, USA
4 Joint Institute for VLBI ERIC, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
5 Australia Telescope National Facility, CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia

Received 6 February 2020 / Accepted 21 September 2020

ABSTRACT

Massive outflows of neutral atomic hydrogen (H I) have been observed in absorption in a number of radio galaxies and are considered a signature of active galactic nucleus (AGN) feedback. These outflows on kiloparsec scales have not been investigated in great detail as they require high-angular-resolution observations to be spatially resolved. In some radio AGN, they are likely to be the result of the radio jets interacting with the interstellar medium. We have used the global very-long-baseline-interferometry (VLBI) array to map the H I outflow in a small sample of young and restarted radio galaxies that we previously observed with the Very Large Array and the Westerbork Synthesis Radio Telescope at a lower resolution. Here we report on our findings for 4C 12.50 and 3C 236. For 4C 52.37, we present the first ever H I VLBI observations, which recovered the majority of the outflowing H I gas in the form of clouds toward the central 100 pc of the AGN. The clouds are blueshifted by up to $-600$ km s$^{-1}$ with respect to the systemic velocity. 3C 293 is largely resolved out in our VLBI observation, but toward the VLBI core we detect some outflowing H I gas blueshifted with respect to the systemic velocity by up to $-300$ km s$^{-1}$. We also find indications of outflowing gas toward the other parts of the western lobe suggesting that the H I outflow is extended. Overall, we find that the fraction of H I gas recovered by our VLBI observations varies significantly within our sample, ranging from complete (4C 12.50) to marginal (3C 236). However, in all cases we find evidence for a clumpy structure of both the outflowing and the quiescent gas, consistent with predictions from numerical simulations. All the outflows include at least a component of relatively compact clouds with masses in the range of $10^4$–$10^5 M_\odot$. The outflowing clouds are often already observed at a few tens of parsecs (in projection) from the core. We find indications that the H I outflow might have a diffuse component, especially in larger sources. Our results support the interpretation that we observe these AGNs at different stages in the evolution of the interaction between the jet and the interstellar medium and this is reflected in the properties of the outflowing gas as predicted by numerical simulations.

Key words. galaxies: active – galaxies: jets – galaxies: general – galaxies: nuclei – techniques: high angular resolution – ISM: jets and outflows

1. Introduction

Active galactic nuclei (AGNs) produce tremendous amounts of energy through the accretion of matter onto the super-massive black hole (SMBH). The release of this energy can heat and expel gas that would otherwise be available for star formation and for the growth of the SMBH. Thus the energy release can have a direct impact on the interstellar medium (ISM) of the host galaxy and this interplay, or feedback, links the evolution of the galaxy to the activity of the SMBH (e.g., Silk & Rees 1998; Di Matteo et al. 2005; Croton et al. 2006; McNamara & Nulsen 2007; Heckman & Best 2014; Harrison 2017). Among the clear observational pieces of evidence of this interaction are outflows of gaseous matter observed in all phases of the ISM. Outflows of hot and warm ionized gas have been found in many AGNs over a range of redshifts suggesting that they could be a general feature (e.g., Veilleux et al. 2005; Tadhunter 2008; King & Pounds 2015; Morganti 2017). In addition, several studies have shown outflows of matter from the cold ISM, which consists of molecular and atomic gas. Interestingly, the outflows of cold gas appear to carry higher mass outflow rates than their counterparts of ionized gas (e.g., Morganti et al. 2005a; Cicone et al. 2014; Morganti 2017; Fiore et al. 2017; Veilleux et al. 2020). There are different possible driving mechanisms capable of producing these outflows: radiative winds from the accretion disk, radiation pressure on dust, and radio jets. Observational evidence has been found for all of them with one being more likely than another depending on the type of host galaxy and nuclear activity mode (e.g., McNamara & Nulsen 2012; King & Pounds 2015; Morganti 2017).

In a number of cases, radio jets appear to be the most likely mechanism capable of accelerating the gas and producing outflows (e.g., Morganti et al. 1998, 2005a, 2005b, 2013, 2016; Oosterloo et al. 2000; Mahony et al. 2013; Gerèb et al. 2015; Aditya & Kanekar 2018; Aditya 2019). In particular, one of the findings supporting this is the higher fraction of outflows observed in young and restarted AGNs and, in some cases, the close morphological association of the region of the outflow and the radio jet (e.g., Holt et al. 2008).
Radio galaxies in their young phase are often characterised as compact steep spectrum (CSS) or GHz-peaked spectrum (GPS) sources based on the shape of the radio spectrum (e.g., O’Dea 1998; Orienti 2016). The radio continuum emission of these sources extends to a few kiloparsecs or less and it is still contained within the host galaxy. They are often hosted in galaxies with a richer ISM (Calinghuan et al. 2017; Holt 2009), which has also been confirmed by the study of H I gas (Gérèb et al. 2015; Gupta et al. 2006; Chandola et al. 2011).

In restarted AGNs, the CSS or GPS source stems from the most recent or current cycle of AGN activity and is embedded in larger radio galaxies where the large-scale radio emission reflects previous cycles of AGN activity. The expected coupling of the jet with the ISM depends on the properties of the gas. In particular, in recent numerical simulations (Wagner & Bicknell 2011; Wagner et al. 2012; Mukherjee et al. 2016, 2018a; Cielo et al. 2018) the ISM is now modelled much more realistically (e.g., clumpy instead of smooth). An important result is that a clumpy ISM has a much stronger impact on the propagation of newly (re-)born jets: the jet interacts with dense clumps of the ISM, temporarily blocking its progress, which results in an over-pressured cocoon in the ISM that affects a much larger region of the host galaxy than the jet itself. Investigating whether this scenario is confirmed by the observations requires a high spatial resolution to resolve the distribution and kinematics of the outflowing gas and to compare it with the predictions of the simulations. Such a comparison has already been successful in some cases, for example, Mukherjee et al. (2018a) and Zovaro et al. (2019), but the number is still limited.

In this work, we focus on deriving the properties and structure of outflows of neutral atomic hydrogen (H I) gas observed in absorption in young or restarted radio galaxies. In order to resolve the outflows on sub-arcsecond angular resolution, we carried out Very Long Baseline Interferometry (VLBI) observations. This paper is a continuation of the work presented in Morganti et al. (2013) on 4C 12.50 and in Schulz et al. (2018) on 3C 236, both of which are restarted radio sources. Here, we present results from the remaining two sources of our initial sample, 4C 52.37 and 3C 293, and compare the properties of the H I outflows in all four sources in particular with respect to the evolution of the radio AGNs.

The paper is structured as follows: we first describe the sample and in particular the properties of 4C 52.37 and 3C 293. This is followed by a description of the VLBI observation and data reduction in Sect. 3. This is followed by the presentation of our results on the line and continuum in Sect. 4. We discuss in Sect. 5 the results of the two new objects and we also discuss some general results obtained by combining the findings for the full sample. We conclude this paper with a summary in Sect. 6 and provide additional plots in Appendix A. Throughout this paper, we use a ΛCDM cosmology of \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} \), \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \).

2. Sample

The four sources 4C 12.50, 3C 236, 4C 52.37, and 3C 293 have been selected because they exhibit fast H I outflows, they are powerful radio sources, and they are likely to be young or restarted AGNs, but they are potentially at different stages in their AGN evolution. Based on their optical properties, 4C 52.37, 3C 236, and 3C 293 have been classified as low-excitation radio galaxies (Buttiglione et al. 2010; Best & Heckman 2012; de Gasperin et al. 2011), which makes the radio jet the most likely driving force behind the outflowing gas. Even though 4C 12.50 is classified as a high-excitation radio galaxy (Holt et al. 2011), Morganti et al. (2013) concluded that the H I outflow is jet-driven based on the location of the H I outflow. The VLBI observations revealed all of the H I outflow concentrated in a slightly extended cloud toward the hot spot of the southern radio jet. In 3C 236, part of the H I outflow was detected in the form of unresolved clouds towards the center of the AGN and as an extended cloud located towards the hot spot of the southeast radio lobe, but the VLBI data did not recover all of the outflow and suggested that part of the outflow might be in the form of a diffuse component.

Galaxy 4C 52.37 is a radio galaxy located at a redshift of 0.106 based on the Sloan Digital Sky Survey (SDSS; Abolfathi et al. 2018). The SDSS redshift corresponds to a systemic optical velocity of 31688 km s\(^{-1}\) and a linear scale of 1 mas \( \approx 1.9 \) pc. The optical spectrum is characterized by strong broad permitted and forbidden emission lines. 4C 52.37 is included in the Compact Radio sources at Low Redshift (CORALZ) sample of compact and young radio sources (Snellen et al. 2004). The sub-arcsecond radio morphology has been classified as a compact symmetric object by previous VLBI observations (de Vries et al. 2009). So far, it is not clear whether there have been previous cycles of radio activity. The main H I absorption feature was first reported by Chandola et al. (2011) using the Giant Metrewave Radio Telescope (GMRT). The H I outflow was discovered by observations with the Westerbork Synthesis Radio Telescope (WSRT, Gérèb et al. 2015; Maccagni et al. 2017) and covers more than 600 km s\(^{-1}\). For 4C 52.37, this study represents the first detailed investigation of the H I absorption with VLBI.

The radio galaxy 3C 293 is located at a redshift of 0.045 (Abolfathi et al. 2018). At this redshift an angular scale of 1 mas corresponds to 0.96 pc. Optical observations show a complex system of dust lanes and a companion galaxy (Heckman et al. 1986; Martel et al. 1999; Evans et al. 1999). The host galaxy of 3C 293 has undergone at least one merger event, but it is unclear whether the companion galaxy is connected to this (Evans et al. 1999; Capetti et al. 2002; Floyd et al. 2006). Star formation and radio activity are considered to be linked to the merger event (Tadhunter et al. 2005; Labiano et al. 2014). The large-scale radio emission extends over 2’ with a bright central region comprising two strong features extending about 2’’ in size and oriented in an east-west direction (e.g., Haschick & Baan 1985; Beswick et al. 2002). Strong H I absorption has been detected from both features of the central region (Baan & Haschick 1981; Haschick & Baan 1985; Beswick et al. 2002) and a shallow, broad (~1200 km s\(^{-1}\)) blue wing corresponding to an H I outflow towards the western feature (Morganti et al. 2003, 2005a; Mahony et al. 2013). VLBI observations by Beswick et al. (2004) reveal a complex, extended radio morphology of the central region with H I absorption corresponding to the dust lane detected over most of the radio emission. However, the available bandwidth of the observations by Beswick et al. (2004) was insufficient to detect the outflow. Cold molecular gas in the form of CO has been detected in absorption and emission (Evans et al. 1999; Labiano et al. 2014) and associated with an asymmetric, warped disk rotating around the AGN. Labiano et al. (2014) did not detect a high-velocity molecular outflow associated with 3C 293 based on their CO observation.

3. Observation and data reduction

3.1. 4C 52.37

Galaxy 4C 52.37 was observed with a global VLBI array comprising the European VLBI Network (EVN), the Very Long
Baseline Array (VLBA), and the Arecibo radio telescope on 2015 Oct 15 (project code: GN002C). The data were correlated at the Joint Institute for VLBI ERIC (JIVE) producing two data sets: a ‘continuum pass’ with four intermediate frequencies (IFs) each with 32 channels and 16 MHz bandwidth and a ‘spectral-line pass’ with one IF of 16 MHz bandwidth and 512 channels (see Table 1). We used J1545+5400 and J1638+5720 as the reference source and fringe finder (and bandpass) calibrator, respectively.

The data reduction process is similar to Schulz et al. (2018). We processed both the continuum and the spectral-line pass in the Astronomical Image Processing System (AIPS, version 31DEC16, Associated Universities, Inc. 1999), using the a-priori amplitude calibration and flag tables provided by the EVN calibration pipeline. We first started with the calibration of the continuum pass. We flagged the data if the station elevation was below 15°. Next, we corrected for the instrumental delay using the task FRING and J1638+5720. Due to the nature of the VLBI array, a single scan of J1638+5720 from all stations was not available. Therefore, we used two scans for the manual phase calibration. In the next step, we corrected for the phase, delay, and rate of both calibrators using a global fringe fit. The solutions for each calibrator were applied to themselves. In addition, the solution of the phase calibrator J1545+5400 was applied to our target source (4C 52.37). Finally, we performed the bandpass calibration using J1638+5720 and applied the solutions to all sources. Because the global fringe fit assumes a point source model, we imaged the calibrators and found them to be slightly extended. Therefore, we used the image of the calibrators as an input model for the global fringe fit and repeated the process up to the bandpass calibration.

For the spectral-line pass, we used the amplitude calibration provided by the EVN calibration pipeline and the calibration of the continuum pass. We first applied the solutions from the manual phase calibration of the continuum pass to the spectral-line pass. Afterwards, we took the solutions of the calibration from the continuum pass and applied them to the calibrator and target source of the spectral-line pass. In the last step, we performed the bandpass calibration. Afterwards, we produced a continuum and a spectral-line visibility data file of 4C 52.37. For the continuum data, we averaged all channels together, while the spectral-line data contains the full cube.

Flagging bad visibilities, imaging and self-calibration of the continuum data of 4C 52.37 was performed with DIFMAP (Shepherd et al. 1994; Shepherd 2011). We used natural weighting and set CLEAN windows to allow for better convergence of the CLEAN algorithm. Once a sufficiently good model was achieved, we performed phase self-calibration and imaged the data again. This process was repeated with smaller time intervals for the phase self-calibration as long as the solutions stayed smooth. Then, a constant gain correction factor over the entire observing time was determined with amplitude self-calibration and applied to the data. After flagging bad solutions, we repeated the smaller cycle of imaging and phase-self-calibration and performed another amplitude self-calibration with a smaller time interval. We repeated this process with decreasing time intervals for amplitude self-calibration. The noise level of the final continuum image is above the theoretical thermal noise level that is expected in phase referencing VLBI. Also, radio frequency interference in this frequency band can contribute to an increase in noise level.

For further processing of the spectral-line visibility data of 4C 52.37, we first inspected the data in detail and flagged bad visibilities. In order to keep the visibilities as uniform as possible across channels, we generally flagged entire scans or channels of a specific telescope instead of single visibilities. Next, we loaded the continuum image into AIPS and used it to perform a single phase self-calibration of the spectral-line visibility data. To improve sensitivity and consistency with the continuum data, we time-averaged data within 30 s. In the next step, we subtracted the continuum in the visibility domain using a fit to the first and last 100 channels. Because we are primarily interested in the broad absorption and in order to increase the sensitivity, we averaged the spectral-line data also in frequency. This reduced the velocity resolution by a factor of 3 to 20.7 km s⁻¹. The resulting velocity cube was manually imaged in AIPS using robust weighting 1, a visibility taper of 0.3 at 10 Mλ, and a restoring beam of 20 mas. Like in Schulz et al. (2018) we found this combination of parameters to be sufficient. We only cleaned those channels of the cube that showed significant absorption in the area of the radio continuum. The imaged cube was Hanning-smoothed to further improve the sensitivity which reduces the effective velocity resolution by an additional factor of 2. The cube was de-redshifted in order to gain relative velocity information in the source rest frame. The full list of image parameters is given in Table 2.

### 3.2. 3C 293

Galaxy 3C 293 was observed with a global VLBI array on 2015 March 2 (project code: GN002A). J1350+3034 and J1407+2827 served as phase reference source and bandpass calibrator, respectively. Correlation and data processing were done following the procedure outlined for 4C 52.37.
Unfortunately, an issue in the frequency setup of the observation resulted in a shift in the center frequency. As a result a significant part of the blueshifted wing observed in previous observations was shifted out of the band. Therefore, only a linear fit using the outer 200 channels on the high-frequency side of the spectrum could be used for the subtraction of the continuum in the visibility domain. We used a restoring beam of 25 mas for the continuum image and spectra-line cube instead of the highest angular resolution due to the large extent of the radio emission.

3.3. Archival radio data

We make use of archival Very Large Array (VLA) and WSRT data for all four sources in this paper. The VLA data of 3C 236 and 3C 293 were presented in Schulz et al. (2018) and Mahony et al. (2013), while the WSRT data on 4C 12.50 and 4C 52.37 were taken from Morganti et al. (2013) and Geréb et al. (2015). We also made use of VLBI data from 4C 12.50 (Morganti et al. 2013) and 3C 236 (Schulz et al. 2018).

In Appendix A we present the H1 profiles of these objects, which have been fitted with Gaussian distribution (using the Python package LMFIT; Newville et al. 2014) to characterize the absorption spectrum. The fit parameters are listed in Table A.1 and plots of the fits are shown in Figs. A.2–A.4. These parameters are slightly different from Maccagni et al. (2017) because that study used the busy function (Westmeier et al. 2014) to fit the spectrum. In order to be consistent, we use Gaussian distribution for all our objects for an easy comparison.

4. Results

4.1. 4C 52.37

As we will describe in the sections below, in 4C 52.37 we have succeeded in imaging the radio continuum on scales between ~10 and 40 pc, and we have recovered a large fraction of the H1 absorption and, in particular, most of the outflowing gas. The outflow appears to be located mostly in the central regions, specifically in the central ~120 pc.

4.1.1. VLBI continuum

The top panel of Fig. 1 shows the continuum VLBI image of 4C 52.37 at a resolution of 20 mas and a zoom-in into the central 200 pc at 6 mas. At the higher angular resolution, the central region is clearly resolved into two distinct features, E1 and W1. They are located about 20 mas apart and are separated by a small drop in surface brightness. The western feature W1 represents the peak of the radio emission and is compact while the eastern one (E1) is marginally resolved at 6 mas resolution. Additionally, there are two prominent radio lobes, E2 and W2. The overall radio morphology is asymmetric and spans a projected linear size of ~280 mas, which corresponds to ~530 pc.

The majority of the integrated flux density stems from extended radio emission of W2 and E2 with W2 accounting for almost 50%. The central features E1 and W1 contain about 25% of the total flux density. In total, we measure a flux density of 429 mJy, which is about 20% below the value obtained, at lower resolution, by Geréb et al. (2015) and Maccagni et al. (2017) with the WSRT (577 mJy) and from the VLA survey FIRST at 1.4 GHz (575 mJy, Helfand et al. 2015). Even considering our conservative flux density uncertainty of 15%, this suggests that there is a small amount of extended low-surface brightness emission that is either below our sensitivity or resolved out or both. The shortest baseline of the VLBI array, which is about 460 Mλ, implies that extended emission larger than about 550 mas cannot be recovered.

The EVN observations at 1.659 GHz by de Vries et al. (2009) provide the best comparison on VLBI scales to our observations in both frequency and resolution. Our measured VLBI flux density is consistent, within the uncertainty, with the value obtained by de Vries et al. (2009) of 448.3 mJy ± 1.1 mJy. Also, the morphology of the source recovered by these two observations matches very well.

4.1.2. VLBI H1 absorption

The H1 absorption profile from the archival WSRT observations (Geréb et al. 2015) and the integrated spectrum from the new VLBI H1 are shown in Fig. 2. Because of the lower spatial resolution of the WSRT observation, we can use this absorption spectrum as a reference of the total absorption that should have been recovered. The WSRT spectrum comprises of two main features: a narrow, deep absorption close to the systemic velocity and a broad, shallower feature blueshifted with respect to the systemic velocity. The latter has been interpreted in previous studies as outflowing H1 gas (Geréb et al. 2015; Maccagni et al. 2017).

The spatially integrated VLBI H1 absorption spectra have been extracted using the same method as in Schulz et al. (2018). First, we created a mask based on the continuum image using only those pixels with a value above three times the continuum noise level (σ_{VLBI,cont}). Second, for each channel we applied the mask and integrated either all remaining pixels of the channel.
Most interestingly, in 4C 52.37 we have been able to trace the location of the outflowing H\textsc{i} gas. The central panel of Fig. 3 shows the integrated optical depth of the H\textsc{i} gas, \( \int \tau dv \), detected by our VLBI observation with respect to the continuum source. To calculate \( \int \tau dv \), we used the same clipping method as described in the previous section, which is a 3\( \sigma \) cut in the continuum and in the cube. The map shows a large concentration of H\textsc{i} gas toward the central region, over an elongated region of \( \sim 140 \) pc, partly overlapping with the eastern component E1, but not W1. In addition, there are smaller clouds of H\textsc{i} gas distributed over the extent of the continuum emission.

In order to characterize the H\textsc{i} gas further, we extracted position-velocity diagrams along different position angles. Figure 3 shows slices along the extent of the H\textsc{i} gas in the central region (panel a) and along the position angle of the radio emission in the central region (panel c). The position-velocity plots show that the gas in the central region covers the full range of velocities seen in the spatially integrated absorption spectrum of Fig. 2. Three features, labeled S1, S2, and S3, can be seen at increasing (blueshifted) velocity from the systemic velocity. All three features are located within the central 100 pc of the source. While S2 and S3 are unresolved, S1, which corresponds to the gas close to the systemic velocity, is extended (Fig. 3a). From Fig. 3 we can therefore derive the location of the outflowing H\textsc{i}. The gas does not cover the entire central region but it is concentrated towards E1. Since E1 and W1 are of comparable brightness, it would have been possible to detect against the latter a more extended distribution of gas of a similar column density if it were present in front of the continuum.

Figure 2 shows that there is a significant fraction of absorption missing close to the systemic velocity in the VLBI extracted around E1, in the velocity range of S1. The patches of absorption that are depicted in Fig. 3b cannot account for the undetected gas. Because they are weak absorption features, we are cautious in interpreting them, but we might be seeing the presence of regular rotating gas distributed across the radio source. However, we do not reach the optical depth across the radio source to fully recover the gas at the systemic velocity. In comparison, most of the absorption in the velocity range of S2 and S3, which is the blueshifted component, is recovered in the region around E1. Therefore, clouds of outflowing gas of a similar optical depth to S2 and S3 are unlikely to exist anywhere else toward the radio source and the undetected absorption at the systemic velocity must be in the form of compact clouds or diffuse gas of a lower optical depth. The only possible exception may be the small absorption feature (S4) at the edge of E2 (see Fig. 3). This absorption is also blueshifted with respect to the systemic velocity by about 300 km s\(^{-1}\). S4 is much fainter than S2 and S3 and located toward the edge of the radio continuum of E2 rather than the brighter parts. That is why we are cautious in interpreting this feature, but it could be a sign of outflowing clouds outside the central region.

The peak brightness of the continuum and the noise level of the cube imply an optical depth limit of about 0.035 at 3\( \sigma_{\text{VLBI cube}} \). The optical depth limit toward the peak of the western radio lobe (W2) is only slightly higher. W2 has a peak brightness of about 42 mJy beam\(^{-1}\), which corresponds to an optical depth limit of 0.042 at 3\( \sigma_{\text{VLBI cube}} \). At the location of E1 the peak optical depth of the absorption feature is about 0.06. Therefore, we would have been able to detect clouds such as S1 at the peak of the western radio lobe (W2) unless the gas clouds have a lower optical depth or the gas is diffuse. This is an indication that the missing H\textsc{i} absorption is in part due to low-column density gas that is distributed across the continuum source (see Sect. 4.1).
Figure 4 shows the H\textsubscript{i} absorption spectrum from the VLBI observations over-plotted to the spectrum obtained with the VLA with 1\arcsec resolution by Mahony et al. (2013). At this lower resolution, the structure of the source is made of two – barely resolved – components, the eastern and western radio lobes. Mahony et al. (2013) extracted H\textsubscript{i} absorption spectra for the eastern and western part, separately. For comparison, we provide spatially integrated H\textsubscript{i} absorption spectra from our VLBI data for the eastern and western part.

Given the much larger spatial scale, we managed to recover only a relatively small part of the continuum structure of 3C 293. Similarly, a small fraction of the H\textsubscript{i} absorption is also recovered. This is particularly the case for the H\textsubscript{i} outflow. However, the data show that at least a small fraction of the outflow can be seen against the central (∼50 pc) region.

### 4.2. 3C 293

The bottom panel of Fig. 1 shows the VLBI continuum emission recovered by our observations. The radio emission from the eastern and western structure spans over 2\arcsec as seen in other high-resolution radio images (e.g., Beswick et al. 2004; Mahony et al. 2013). The total flux density from our image is about 539 mJy, which is about 17% of the total flux density recovered by Beswick et al. (2004) at a resolution of 30 mas. The difference can be best explained by the spatial filtering. The shortest baseline of our VLBI array is 400 M\textsubscript{L}, which means that any extended emission on scales larger than about 630 mas is resolved out. In contrast, Beswick et al. (2004) combined a global VLBI array similar to ours with the Multi-Element Radio Linked Interferometer Network (MERLIN) and VLA data. This has provided significantly shorter baselines, which improves the sensitivity for diffuse extended emission.

The brightest feature in our image matches the location of the VLBI core identified in Beswick et al. (2004). Interestingly, we find the peak brightness to be a factor of 4.1 brighter than in Beswick et al. (2004). This cannot be explained by the difference in resolution, because the synthesized beam is similar: 25 mas in our case, compared to 30 mas in Beswick et al. (2004). A frequency-dependent effect can also be excluded, because the frequency setup of both studies is chosen to investigate H\textsubscript{i} absorption. This suggests that the emission from the radio core is variable and the VLBI core is brighter in our observation compared to previous observations. Our data do not allow us to test whether the radio emission extending from the core also shows changes in brightness or distribution. However, this result warrants caution when comparing observations.

### 4.2.2. VLBI H\textsubscript{i} absorption

Figure 4 shows the H\textsubscript{i} absorption spectrum from the VLBI observations over-plotted to the spectrum obtained with the VLA with 1\arcsec resolution by Mahony et al. (2013). At this lower resolution, the structure of the source is made of two – barely resolved – components, the eastern and western radio lobes. Mahony et al. (2013) extracted H\textsubscript{i} absorption spectra for the eastern and western part, separately. For comparison, we provide spatially integrated H\textsubscript{i} absorption spectra from our VLBI data for the eastern and western part.

Overall, we recover a relatively small fraction of the VLA-detected absorption. In particular, we recover absorption from the narrow, deep absorption on both lobes. We also marginally detect, on the western side of the source, clouds blueshifted by up to ∼300 km s\textsuperscript{-1} with respect to the systemic velocity (see solid blue line in Fig. 4). We do not consider any features below a relative velocity of ∼450 km s\textsuperscript{-1}. The issue with the frequency setting of our observation mentioned in Sect. 3.2 strongly affected our ability to perform an optimal continuum subtraction at the corresponding frequencies. As a result, our effectively usable bandwidth is comparable to that of Beswick et al. (2004).

The spatial distribution of the H\textsubscript{i} absorption obtained by our VLBI observation is shown in Fig. 5. On the eastern side, we detect H\textsubscript{i} gas distributed in three connected regions. The kinematic of the gas in this part of the source is mostly consistent with quiescent gas like the one originating from the narrow, deep absorption feature. On the western side, the H\textsubscript{i} distribution is more patchy. Most of the broad absorption is located toward the core and shows kinematics deviating from that of the regularly rotating gas (as described in Beswick et al. 2004).

We identify two kinematic components (S1 and S2). S1 is likely to be part of the narrow absorption feature similar to the gas recovered on the eastern side and also traced by the observations of Beswick et al. (2004). S2 is broader in velocity than S1 and blueshifted by up to ∼300 km s\textsuperscript{-1} with respect to the systemic velocity. Interestingly, S2 appears to be broader than what was detected by Beswick et al. (2004) at the location of the core (see their Fig. 8). Thus, this suggests that the gas originating the S2 absorption has a highly disturbed kinematics and could be part, as suggested by Haschick & Baan (1985), of the broad H\textsubscript{i} outflow observed by Morganti et al. (2005a) and Mahony et al. (2013). If this is the case, in 3C 293 also the outflow can already be observed in the inner nuclear region (≤40 pc).

We also tentatively detect gas clouds of a similar velocity to S2 at other locations in the western part of the source (see Fig. 5). They are at the edges of the recovered radio emission, which is why we are cautious in interpreting them. However, if confirmed they would indicate that the outflow is extended, as suggested by Mahony et al. (2013), and clumpy.

The gas related to S1 has a peak optical depth of about 0.1 while the gas of S2 peaks at an optical depth of about 0.024. Only at the location of the core are we able to reach the necessary optical depth of about 0.005 and 0.014 at 1\arcsec of the VLA cubes and 3\arcsec of the VLBI cubes, respectively, to detect S2. We cannot detect clouds such as S2 toward the eastern part of the source. The tentatively detected gas cloud at the edge of the western lobe has a peak
5. Discussion

In both radio galaxies, 4C 52.37 and 3C 293, we were able to recover (at least partly) and trace the H\textsc{i} outflows known from previous observations on scales of about 20 pc. We discuss below their structure as revealed on a few tens of parsec scale, their properties, and their location. We then compare them with already published H\textsc{i} VLBI results (see Sect. 5.4).

5.1. Properties of the H\textsc{i} gas and the outflow in 4C 52.37

As described in Sect. 3.1, in 4C 52.37 we recover most of the H\textsc{i} outflow and only part of the H\textsc{i} close to the systemic velocity. The outflowing gas is mainly concentrated in the central region (see Fig. 3) and largely contained within two clouds, S2 and S3, detected toward E1 (see Fig. 1), the eastern component of the central region. The location of the core in 4C 52.37 is still unclear and this has implications for understanding the origin of the outflow. This will be further discussed in Sect. 5.2. However, it is reasonable to assume that the active black hole is located either in E1 or W1, which are separated by about 40 mas (∼76 pc) in projected size. Table 3 lists the properties of H\textsc{i} gas in 4C 52.37 based on our observations and using the same clipping as for the absorption profile. We determine the spin temperature (\(T_{\text{spin}}\)) and normalized column density (\(N_{\text{HI}}\)) of the outflow by integrating over S2 and S3. In order to calculate any subsequent parameters, we assume \(T_{\text{spin}} = 1000\) K, which is reasonable considering the proximity of the gas to the AGN. This suggests a column density of \(\sim 2 \times 10^{22}\) cm\(^{-2}\). For a spherical geometry, this yields an H\textsc{i} mass of \(1 \times 10^5\) M\textsubscript{☉}. Following Heckman (2002), we estimate the mass outflow rate to be \(\sim 4.3\) M\textsubscript{☉} yr\(^{-1}\) with

\[
M_{\text{HI}} \sim 30 \frac{r_*}{\text{kpc}} \frac{N_{\text{HI}}}{10^{21}\text{ cm}^{-2}} \frac{v}{300\text{ km s}^{-1}} \frac{\Omega}{4\pi} M_{\odot}\text{ yr}^{-1}
\]

where \(r_*\) is the deprojected distance of the cloud, \(v\) its velocity, and \(\Omega\) its solid angle, which is assumed to be \(\pi\) (see Table 3). We take the synthesis beam as an upper limit on the radius of the clouds because S2 and S3 are both unresolved (see Fig. 3).
The gas detected with velocities close to the systemic (S1) represents a fraction of what has been detected by the WSRT. Assuming also for this gas that $T_{\text{spin}} = 1000$ K, given the proximity to the AGN, we estimate an average column density of $1.0 \times 10^{22}$ cm$^{-2}$. Based on our VLBI data, we describe S1 by an ellipsoid that is resolved in one direction (95 pc $\leq$ 38 pc) and estimate a lower limit on the mass of the HI gas of $\sim 2.3 \times 10^5 M_\odot$. In the kinematics of this gas, we do not detect signatures of rotation. However, we cannot fully rule out the presence of a circumnuclear HI disk, for example, given the large fraction of missing absorbed flux. Circumnuclear disks of HI gas have been traced in the center of a number of radio galaxies such as 3C 236 (Schilizzi et al. 2001; Tremblay et al. 2010), Cygnus A (Struve & Conway 2010), NGC 4261 (Jones et al. 2000), and Centaurus A (van Gorkom et al. 1.990; Morganti et al. 2008).

Our observations are limited by the optical depth that we can probe. While we are only able to probe an optical depth similar to E1 toward the peak of the western lobe (W2), S1 is extended and detected against fainter parts around E1. If there is a disk made of clouds like S1, we should have detected it against W1. Therefore, it is possible that the missing absorption comes from an extended, diffuse component of the systemic gas or lower column density clouds. The patches of absorption observed across the radio source could be related to this.

If an HI disk is present, the absorption recovered in the central region of the radio source would correspond to gas in an inner denser disk, while the undetected absorption would be related to the extended (and lower column density) outer part of the disk. It is possible that the radio jets are drilling into this gas disk. This could explain the asymmetric morphology of the radio emission. Radio jets that are expanding into the ISM have been observed for example in IC 5063 (Oosterloo et al. 2017) and NGC 1167 (Murthy et al. 2019). In both objects VLBI observations were only able to recover a small fraction of the absorption.

5.2. Origin of the HI outflow in 4C 52.37

The fact that most of the HI outflow in 4C 52.37 is concentrated in a very small region in the center of the radio source is important for understanding the driving mechanism of the outflow and the evolution of the radio source. As mentioned in Sect. 1, 4C 52.37 is classified as a low-excitation radio galaxy. As such, the most likely drivers of the outflow are the radio jets rather than
radiative winds from the AGN. It is worth taking a closer look at the region of E1 and W1 where the AGN is likely to be located. We compare the location and spectral index of W1 and E1 (Fig. 1) using the Gaussian model components fitted to the visibility data at 1.659 GHz and 4.99 GHz by de Vries et al. (2009).

We find that the position of the model components at 1.659 GHz and 4.99 GHz match for W1 and E1. We also fit Gaussian components to W1 and E1 of our VLBI observation and find no difference in location with respect to the components from de Vries et al. (2009) at 1.659 GHz. In addition, we determine the spectral index \( \alpha \) between the two frequencies for W1 and E1 to be 0.17 and −0.16, respectively. Both features seem to have a flat spectral index \( |\alpha| < 0.5 \). Due to the time span between our observation and the data from de Vries et al. (2009), we do not determine the spectral index between these data sets.

As the radio jets of 4C 52.37 seem to be oriented in the plane between our observation and the data from de Vries et al. (2009), we expected our measurements of \( E_1 \) to be consistent with the resolution VLA observations. The study concluded that the outflow is largely extended across the western lobe. The authors state that it is unlikely that all of the outflow is concentrated within the VLBI core because of the implied high optical depth in the latter features, which is why we only derive physical values.

### Table 3. Properties of the kinematically disturbed HI gas.

<table>
<thead>
<tr>
<th>Source (a)</th>
<th>Component (b)</th>
<th>( \text{N}<em>\text{HI}/T</em>{\text{spin}}^{-1} ) (c)</th>
<th>( \text{N}_\text{HI} ) (d)</th>
<th>( d ) (e)</th>
<th>( \text{N}_\text{HI} ) (f)</th>
<th>( m_{\text{H}_2} ) (g)</th>
<th>( \nu ) (h)</th>
<th>( r_e ) (i)</th>
<th>( M_{\text{out}} ) (j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C 12.50 4C 52.37</td>
<td>Outflow</td>
<td>4.6 2.0</td>
<td>460 1000</td>
<td>50 1.0</td>
<td>150 3.0</td>
<td>1.6 3.0</td>
<td>1000 450</td>
<td>– 23</td>
<td>– 10</td>
</tr>
<tr>
<td>3C 326 3C 293</td>
<td>Outflow (Core)</td>
<td>0.78 0.4</td>
<td>780 400</td>
<td>36 24</td>
<td>20 15</td>
<td>1.0 1.5</td>
<td>640 300</td>
<td>– 14</td>
<td>– 36</td>
</tr>
<tr>
<td>4C 12.50 3C 236</td>
<td>Systemic</td>
<td>1.0 1.0</td>
<td>1000 1000</td>
<td>95 85</td>
<td>170 23</td>
<td>1.0 1.5</td>
<td>640 300</td>
<td>– 14</td>
<td>– 36</td>
</tr>
<tr>
<td>3C 293 Outflow</td>
<td>0.4</td>
<td>400</td>
<td>24</td>
<td>15</td>
<td>300</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C 293 Systemic (Core)</td>
<td>2.0</td>
<td>2000</td>
<td>33 33</td>
<td>196</td>
<td>1.4</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. (a) Values for 4C 12.50 from Morganti et al. (2013), for 3C 236 from Schulz et al. (2018), and for 4C 52.37 and 3C 293 from this paper. For 4C 12.50 and 3C 236, we focus on the kinematically disturbed H I gas. (b) For 4C 52.37, the values for ‘Outflow’ after integrating over S2 and S3. (c) Mean H I column density normalized by spin temperature. (d) Mean H I column density. \( T_{\text{spin}} = 1000 \) K is assumed except for 4C 12.50 for which Morganti et al. (2013) assumed \( T_{\text{spin}} = 100 \). (e) Projected size of the components. For the outflow, a spherical geometry is assumed with an upper limit of the diameter based on the synthesized beam. For S1, an ellipsoidal geometry is assumed, with the major and minor axis given. (f) Density of the H I clouds. The same \( T_{\text{spin}} \) values as for the column density are assumed here. (g) Mass of the H I clouds for the chosen \( T_{\text{spin}} \) values. (h) Peak velocity of the H I clouds relative to the peak velocity of S1. (i) Deprojected distance of the H I clouds. (j) Mass outflow rate following Heckman (2002) for the chosen \( T_{\text{spin}} \) values.

5.3. H I outflow in 3C 293

In Sect. 4.2 we have shown that, unlike for 4C 52.37, our VLBI observation of 3C 293 recovers a relatively small fraction of the H I absorption and, in particular, of the broad, blueshifted component. We strongly detect signatures of this component against the VLBI core and we tentatively detect clouds against other parts of the western radio lobe. We are cautious in interpreting the latter features, which is why we only derive physical values for the absorption against the VLBI core. At this location, we detect unresolved clouds of outflowing H I gas with velocities blueshifted and deviating up to 300 km s\(^{-1}\) with respect to the systemic velocity (S2). The clouds have column densities of \( 4 \times 10^{13} \) cm\(^{-2}\). If we take the beam as an upper limit on the size and assuming a spherical geometry, we derive an H I mass of the clouds of \( 1.5 \times 10^5 \) \( M_{\odot} \) and a mass outflow rate of \( \sim 0.36 \) \( M_{\odot} \) yr\(^{-1}\). Mahony et al. (2013) investigated the H I outflow using high-resolution VLA observations. The study concluded that the outflow is largely extended across the western lobe. The authors state that it is unlikely that all of the outflow is concentrated within the VLBI core because of the implied high optical depth and the location of the H I outflow in the VLA image. Our findings support and are complementary to these results. The mass outflow rate of S2 is a fraction of the total rate estimated by Mahony et al. (2013) to be \( 8-50 \) \( M_{\odot} \) yr\(^{-1}\). We recover only a fraction of the radio emission from the lobe and, at the high spatial resolution of our observations, the core appears to be the brightest component in the western lobe. This suggests we are limited in our sensitivity to trace the outflow in the western lobe. However, our observations show that a fraction of the outflow exists on nuclear scales close to the AGN. Furthermore, we also find clouds at other locations that could be part of the outflow (see bottom right panel of Fig. 5) indicating that the outflowing
gas might be extended and clumpy. The optical depth of these tentative detections suggests that we should have been able to find absorption against other parts of the western radio continuum emission, if distributed in clouds with similar properties. The lack thereof suggests that the outflow might have a diffuse component.

The cold ISM gas in 3C 293 is not the only ISM phase that has an outflowing gas component: Emonts et al. (2005) and Mahony et al. (2016) reported outflowing ionized gas. The latter study showed that disturbed ionized gas is also observed for a few kiloparsecs in the direction perpendicular to the radio jet. This has been interpreted as the result of a cocoon of shocked gas produced by the radio jet, expanding perpendicular to the jet propagation into the gas disk aligned with the dust-lane known to be present in the host galaxy of 3C 293. Such cocoons have been predicted in numerical simulations describing the interaction between a newly formed radio jet and the surrounding, clumpy medium (e.g., Wagner & Bicknell 2011; Mukherjee et al. 2016, 2017).

Our results are consistent with this scenario, which predicts that the interaction between jet and ISM begins as soon as the jet starts expanding into the gas and it occurs along and perpendicular to the jet propagation. Additionally, the longer the jet expands into the ISM the more the gas can get dispersed. The detection of clouds of outflowing H\textsc{i} toward the core, in addition to outflowing gas distributed across the western lobe, further supports this scenario.

### 5.4. Properties of H\textsc{i} outflows in our sample

We now compare the results on the properties of the H\textsc{i} outflows presented here for 4C52.37 and 3C293 with the other two objects (4C 12.50 and 3C 236) presented in Morganti et al. (2013) and Schulz et al. (2018). These four radio galaxies are the only objects for which fast outflows in H\textsc{i} absorption on milliarcsecond scales have been studied.

We can summarize the main results we have obtained as:

1. We recover at least part of the H\textsc{i} outflow on the VLBI (20\text{pc}) scale in all objects.
2. This indicates that all the outflows include at least a component of relatively compact clouds (with masses in the range of $10^5-10^6\ M_\odot$).
3. We suggest that the clouds might be embedded in a more diffuse component. We detect this in 4C 12.50 (Morganti et al. 2013). Also in 3C 236 we concluded that at least part of the undetected outflow is made of a diffuse, lower column density component (Schulz et al. 2018). This could also be the case in 3C 293 since the outflow must be extended over the western lobe.
4. The data alone provide only limited additional insight into the understanding of the driving mechanism. As already mentioned in the introduction, we remark that the radio galaxies are low luminosity optical AGNs (with the exception of 4C 12.50), and are all young or restarted radio galaxies. Therefore, the radio jet is a very likely mechanism for driving the outflows. The properties of the outflows we derive are consistent with what is predicted by the simulation of jet-driven outflow. The derived density of the clouds is also similar to that used in the simulations (e.g., Wagner & Bicknell 2011; Wagner et al. 2012; Mukherjee et al. 2016, 2018b).

In all four sources we find evidence for a clumpy distribution of the outflowing H\textsc{i} but at different levels. This is shown in the spatial and velocity distribution of the gas as well as the difference between the blueshifted H\textsc{i} absorption recovered at low and high angular resolution. Here, we attempt to explore whether our results show an evolutionary sequence as expected from numerical simulations by considering the age of the sources and the characteristics of the H\textsc{i} outflow both in the integrated spectrum as well as in the spatially resolved distribution of the outflowing gas. Numerical simulations (see, e.g., Wagner & Bicknell 2011; Wagner et al. 2012) have shown that radio jets will accelerate and disperse gas along their direction of propagation, but also transversal to it when they expand into a clumpy medium. With time, more and more of the ISM gas will be dispersed (Mukherjee et al. 2018b) leading to changes in the properties of the ISM and outflowing gas.

In Sect. 5.2, we have estimated a minimum age of the radio source of 4C 52.37 of $t_{\text{min}} \approx 2 \times 10^5\ yr$ based on the size of the radio continuum emission. This is of the same order as the minimum age estimated for 4C 12.50 (Morganti et al. 2013). In 4C 12.50, all of the H\textsc{i} outflow has been recovered with VLBI in the form of a slightly extended gas cloud toward the southern jet, while in 4C 52.37 most of the outflow is recovered and located toward the inner region of the radio source. It is still mostly compact in 4C 52.37, but the undetected absorption in this source suggests that a fraction of the outflowing gas is located elsewhere. Based on this, 4C 12.50 would be consistent with an early evolutionary stage of the jet-ISM interaction and 4C 52.37 would be at a slightly more advanced stage compared to 4C 12.50.

The minimum age of 4C 12.50 and 4C 52.37 is an order of magnitude lower than the age estimated for 3C 236 (O’Dea et al. 2001; Tremblay et al. 2010). In 3C 236, only a fraction of the H\textsc{i} outflow was recovered, mostly toward the nuclear region of the radio source, but also toward the hot spot of the southeast jet in the form of an extended cloud. This would be consistent with a later stage in the evolution of the radio source where the jet had significant time to disperse most of the gas. In agreement with this, also in the case of 3C 293 we recover only a fraction of the outflow, mostly at the location of the core.

In order to characterize H\textsc{i} spectra in more detail, we fitted between one and three Gaussian distributions to the low and high resolution spectra. The spectra and fit parameters are provided in Table A.1, respectively. While Gaussian functions do not represent a physical model, they provide a simple and consistent approach. The fits to the VLAspectra of 3C 236 and 3C 293 are consistent with the fits presented in Labiano et al. (2013) and Mahony et al. (2013). In the case of 4C 12.50 we only performed a fit of the WSRT spectrum, because the VLBI spectrum is consistent with it as shown in Morganti et al. (2013). For 4C 52.37 our fit parametrization is different from Maccagni et al. (2017), because this study used the busy function of Westmeier et al. (2014) to fit the spectrum.

The shape of the blue wing in the absorption spectra differs greatly among the four sources. In the case of 4C 12.50 and 4C 52.37 it is more detached from the systemic gas than in 3C 236 and 3C 293. In the latter two sources, the blue wing is shallow and smooth, including a smooth transition from the systemic H\textsc{i}. The difference in the blue wing is reflected by the properties of the Gaussian components that describe that part of the spectrum. The FWHM of 3C 236 (VL A component 3) is larger by factor of 2 than 4C 12.50 (WSRT component 2) and 4C52.37 (WSRT component 3). The component describing the wing of 3C 293 (VL A component 2) has a FWHM similar to that of the latter two sources, but the uncertainty of the fit result is very high most likely due to correlation with the parameters of component 3. It is therefore possible that the shape of the blue
wing in the H I spectrum is a signature of the compactness of the H I outflow. It is clear that the actual situation is more complicated, because the above arguments do not consider individual differences in the gas distribution and evolution of the system, such as merger activity (3C293) and previous cycles of activities (4C 12.50, 3C 236, and 3C 293). The ages of the radio sources provide only limited information as these are lower limits. Also, 4C 12.50 is the only source in our sample where no absorption is detected toward the VLBI core. Interestingly, the density of the detected outflowing gas clouds is relatively similar among the four sources and the VLBI observations probe similar spatial scales in all of them. Therefore, it is intriguing that a connection can be drawn in the form of an evolutionary scheme for these sources and it shows the need for further studies of H I outflows in other systems in combination with numerical simulations.

6. Summary and conclusion
In this paper, we have presented results, using global spectral-line VLBI, for two additional sources from our investigation of the parsec-scale H I outflow in four radio galaxies. In the case of 4C 52.37, this is the first such VLBI study of the H I gas distribution. We recovered the majority of the H I absorption related to the outflowing gas and a significant fraction of the systemic H I gas with a resolution of 20 mas. We detected the outflow in the form of two unresolved clouds toward the central region of the radio source. They have a combined mass outflow rate of less than 4.3 M⊙ yr⁻¹ and cover about 600 km s⁻¹. The recovered systemic gas is extended and largely concentrated toward the central 100 pc, but it also shows signs of being clumpy and distributed across the radio source. We find signs that the radio jet of 4C 52.37 expands into the gas disk, but further observations are necessary.

In the case of 3C 293, our VLBI observation resolved out most of the extended radio emission and it suffered from technical difficulties limiting the frequency range over which we could probe the broad H I outflow. Nevertheless, we recovered a fraction of the H I gas over a velocity range of 300 km s⁻¹ in the form of distinct gas clumps. Some of the clumps are located toward the VLBI core, close to the AGN, and are likely signs of the outflow in this source. As both 4C 52.37 and 3C 293 are low-luminosity galaxies, it is reasonable to assume that only the radio jets are capable of driving the H I outflows.

All four sources (4C 12.50, 4C 52.37, 3C 236, 3C 293) in our sample have in common the fact that the outflowing H I gas is clumpy and that some of the gas is located toward the innermost region (<50 pc) of the radio source. For 4C 12.50 and 4C 52.37 we find that almost all of the outflowing H I gas is concentrated in a small number of compact clouds, whereas for the other two sources our data implies that the H I outflow is more extended and might have a diffuse component. Taking into account our observational limitations, we can interpret the properties of the H I outflow as a sign of different stages of jet-ISM interaction in these sources. This would be consistent with numerical simulations that have shown that the radio jets would disperse more and more of the ISM gas while they are expanding over time.

Our results highlight the importance of high-angular-resolution observations to understand the gas properties and dynamics in connection to AGN activity. Upcoming facilities such as the Square Kilometre Array and its pathfinders such as Apertif, MeerKAT, and ASKAP (Braun et al. 2015; Morganti et al. 2015; Oosterloo et al. 2010; Gupta et al. 2016; Johnston et al. 2007) and the Deep Synoptic Array 2000 (DSA-2000, Hallinan et al. 2019) will produce blinder large-scale surveys of H I absorption that will increase the number of radio AGN with H I absorption, particularly at low radio powers. In addition to large-scale H I surveys to be conducted over the next decade, follow-up VLBI observations with new telescopes such as the next-generation Very Large Array (Murphy et al. 2018) and the Square Kilometre Array (SKA, Paragi et al. 2015), will be crucial for spatially resolving H I absorption against radio jets in order to quantify the impact of jet-ISM feedback on host galaxy properties (Nyland et al. 2018). The results from future H I absorption studies of much larger samples will ultimately inform numerical simulations of jet-ISM interactions (e.g., Wagner et al. 2012; Mukherjee et al. 2016, 2018a, b; Bicknell et al. 2018), thereby providing new insights into the role of jet-driven feedback in the broader context of galaxy evolution.

Acknowledgements. We thank the referee, Bjorn Emonts, for the insightful comments which helped to improve the manuscript. RS gratefully acknowledges support from the European Research Council under the European Union’s Seventh Framework Programme (FP/2007-2013)/ERC Advanced Grant RADIOLIFE-320745. Basic research in radio astronomy at the US Naval Research Laboratory is supported by 6.1 Base Funding. The European VLBI Network is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. Scientific results from data presented in this publication are derived from the following EVN project code: GN002. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Long Baseline Observing Facility is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Arecibo Observatory is a facility of the National Science Foundation (NSF) operated by SRI International in alliance with the Universities Space Research Association (USRA) and UMET under a cooperative agreement. The Arecibo Observatory Planetary Radar Program is funded through the National Aeronautics and Space Administration (NASA) Near-Earth Objects Observations program. Based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSSA). This research has made use of NASA’s Astrophysics Data System Bibliographic Services. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration 2013). This research made use of APLPy, an open-source plotting package for Python (Robitaille & Bressert 2012).

References
Braun, R., Bourke, T., Green, J. A., Keane, E., & Wagg, J. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 174
Appendix A: Fits to HI absorption spectra

Fig. A.1. Fits of Gaussian functions to inverted HI absorption spectra of 4C 52.37. The fit parameters are given in Table A.1. Top: WSRT spectrum from Fig. 2 with two Gaussian functions fitted to it (red and yellow dotted lines). The combination of the two fit functions is shown as the black dashed line. The data is colored in gray. Bottom: clipped integrated VLBI spectrum from Fig. 2. Three Gaussian components were fitted to it (colored dotted lines) and their combination is shown as the black dashed line.

Fig. A.2. Inverted VLA HI absorption spectrum of 3C 293 of the western component from Fig. 4. Data from Mahony et al. (2013). Three Gaussian components were fitted to it (colored dotted lines) and their combination is shown as the black dashed line. Fit parameters are listed in Table A.1.
Fig. A.3. Fits of Gaussian functions to inverted H\textsc{i} absorption spectra of 3C 236. Data are taken from Schulz et al. (2018). Fit parameters are listed in Table A.1. Top: VLA spectrum with three Gaussian components fitted to it (coloured dotted lines). Their combination is shown as the black dashed line.

Fig. A.4. Inverted WSRT H\textsc{i} absorption spectrum of 4C 12.50 from Morganti et al. (2013). Three Gaussian components were fitted to it (coloured dotted lines) and their combination is shown as the black dashed line. Fit parameters are listed in Table A.1.

Fig. A.3. Fits of Gaussian functions to inverted H\textsc{i} absorption spectra of 3C 236. Data are taken from Schulz et al. (2018). Fit parameters are listed in Table A.1. Top: VLA spectrum with three Gaussian components fitted to it (coloured dotted lines). Their combination is shown as the black dashed line. Bottom: clipped integrated VLBI spectra for the core and lobe region of 3C 236.
Table A.1. Parameters of the Gaussian fit to the HI absorption spectra.

<table>
<thead>
<tr>
<th>Source</th>
<th>Instr.</th>
<th>Comp.</th>
<th>$N_{\text{free}}$</th>
<th>$\chi^2$ (c)</th>
<th>$\chi^2_{\text{red}}$ (f)</th>
<th>Center (g)</th>
<th>FWHM (h)</th>
<th>Peak (i)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[km s$^{-1}$]</td>
<td>[km s$^{-1}$]</td>
<td>[mJy]</td>
</tr>
<tr>
<td>4C 12.50</td>
<td>WSRT</td>
<td>1</td>
<td>357</td>
<td>723.235</td>
<td>2.03</td>
<td>84.0 ± 0.8</td>
<td>135 ± 3</td>
<td>41.9 ± 0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>110 ± 0.010</td>
<td>850 ± 40</td>
<td>7.0 ± 0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>−880 ± 10</td>
<td>340 ± 20</td>
<td>6.4 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>4C 52.37</td>
<td>WSRT</td>
<td>1</td>
<td>179</td>
<td>61.849</td>
<td>0.35</td>
<td>1 ± 3</td>
<td>136 ± 8</td>
<td>7.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>−309 ± 9</td>
<td>330 ± 30</td>
<td>3.9 ± 0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VLBI</td>
<td>1</td>
<td>105</td>
<td>3.021</td>
<td>0.03</td>
<td>−48 ± 1</td>
<td>64 ± 3</td>
<td>3.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>−231 ± 2</td>
<td>76 ± 6</td>
<td>2.1 ± 0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>−396 ± 2</td>
<td>100 ± 5</td>
<td>2.7 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>3C 236</td>
<td>VLA</td>
<td>1</td>
<td>148</td>
<td>943.735</td>
<td>6.38</td>
<td>66 ± 1</td>
<td>78 ± 4</td>
<td>67 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>52 ± 4</td>
<td>270 ± 20</td>
<td>42 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>−210 ± 80</td>
<td>700 ± 100</td>
<td>6 ± 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VLBI (Core)</td>
<td>1</td>
<td>134</td>
<td>25.049</td>
<td>0.19</td>
<td>−103.0 ± 0.5</td>
<td>60 ± 1</td>
<td>2.91 ± 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>−327 ± 1</td>
<td>86 ± 2</td>
<td>1.89 ± 0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>−544 ± 2</td>
<td>62 ± 4</td>
<td>0.92 ± 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VLBI (Lobe)</td>
<td>1</td>
<td>134</td>
<td>0.528</td>
<td>0.004</td>
<td>61 ± 1</td>
<td>88 ± 3</td>
<td>54 ± 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>130 ± 70</td>
<td>130 ± 70</td>
<td>4 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>−99 ± 3</td>
<td>38 ± 6</td>
<td>2.8 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>3C 293</td>
<td>VLA (west)</td>
<td>1</td>
<td>110</td>
<td>776.292</td>
<td>7.06</td>
<td>−55 ± 2</td>
<td>165 ± 5</td>
<td>79 ± 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>−400 ± 70</td>
<td>400 ± 200</td>
<td>4 ± 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>210 ± 20</td>
<td>120 ± 40</td>
<td>6 ± 2</td>
<td></td>
</tr>
</tbody>
</table>

Notes. (a) Name of the source. (b) Instrument used to obtain the spectrum. (c) Components used to fit the spectrum. (d) Number of degrees of freedom for the fit. (e) Chi-squared of the fit. (f) Reduced chi-squared of the fit. (g) Velocity of the center of the Gaussian component. (h) Full-width at half maximum of the Gaussian component. (i) Peak of the Gaussian component.