Outflows of neutral (and ionized) gas in radio galaxies

R. Morganti, T. Oosterloo

Netherlands Foundation for Research in Astronomy, Postbus 2,
NL-7990 AA, Dwingeloo, The Netherlands

C.N. Tadhunter
Dep. Physics and Astronomy, University of Sheffield, S7 3RH, UK

Abstract.
Outflows up to 1500 km s$^{-1}$ of atomic neutral hydrogen are detected in a growing number of radio galaxies. Outflows with similar velocities are also detected in ionized gas, suggesting a common origin for the extreme kinematics of these two phases of the gas. The high detection rate of such outflows in young (or restarted) radio sources appears to be related to the existence of a dense ISM around these objects. Such a dense ISM can have important consequences for the evolution of the radio source and the galaxy as a whole. Here we summarize the recent results obtained and the characteristics derived so far for these outflows. We also discuss possible mechanisms (e.g. interaction between the radio plasma and the ISM and adiabatically expanding broad emission lines clouds) that can be at the origin of these phenomena.

1. Introduction

The presence of neutral hydrogen in the central regions of active galaxies is often explained as being due to gas in circumnuclear tori/disks, i.e. with gas relatively settled and regularly rotating (see e.g. Pihlström, Conway, Vermeulen 2003, Mundell et al. 2003 and Morganti et al. 2004a for a review). However, the conditions of the H I are often more complex and disturbed kinematics of the atomic neutral hydrogen is observed in a growing number of radio sources. The presence of this “unsettled” gas can now be detected thanks to the possibility of performing, with sensitive systems, H I-21 cm observations using broad spectral bands (e.g. bands that can cover up to $\sim 4000$ km s$^{-1}$ in the case of the recently upgraded WSRT).

The presence of gas with extreme kinematics in the central regions of active galactic nuclei (AGN) has recently attracted particular attention, in particular on the presence and occurrence of fast gas outflows. Fast nuclear outflows of ionized gas appear to be a relatively common phenomena in active galactic nuclei (see e.g. Crenshaw et al. 2000, Kriss et al. 2004, Capetti et al. 1999, Krongold et al. 2003, Veilleux et al. 2002, Tadhunter et al. 2001 Elvis 2000 and ref. therein). They are mainly observed in optical, UV and X-ray observations. Gas outflows associated with AGN provide energy feedback into the interstellar medium (ISM) that can profoundly affect the evolution of the central engine as well as that of the host galaxy. The mass-loss rate from these outflows can
be a substantial fraction of the accretion rate needed to power the AGN. Thus, the physics of these phenomena needs to be understood in order to understand AGN. It is not too surprising to find such outflows also in radio galaxies (see Tadhunter et al. 2001, Holt et al. 2003 and Morganti et al. 2003a for a summary of recent results). However, it is extremely intriguing that is several radio sources fast outflows of neutral hydrogen (up to 2000 km s$^{-1}$) have been discovered. The physical conditions of this gas provide new and important clues on the mechanism responsible for AGN-related outflows. Here, we summarize the cases found so far and the characteristics of the neutral hydrogen associated with such outflows. We also discuss some of the possible mechanisms that can be at the origin of this phenomenon.

2. Characteristics and occurrence of the broad H\textsc{i} absorption

The first case of H\textsc{i} outflow has been found in a radio loud Seyfert galaxy, IC 5063 (Morganti et al. 1998). The identification of the broad H\textsc{i} absorption with an outflow has been possible because of the accurate value of the systemic velocity available for this galaxy. This object is one of the best studied so far. It has been followed up with the Australian LBA and these high resolution observations have confirmed that the location of the absorption is against the brighter (eastern) radio lobe, few hundred pc from the nucleus (Oosterloo et al. 2000). More recently, an optical spectroscopic study (using the NTT) has shown that, at the same location, also the ionized gas has very complex kinematics indicating an outflow of similar velocity as for the neutral gas (Morganti et al. 2003b).

In radio galaxies, we have detected so far 8 cases of broad (up to 2000 km s$^{-1}$) H\textsc{i} absorption. In all but one of these objects (see Sec. 2.1), most of the absorption appears blueshifted compared to the systemic velocity and therefore associated with outflowing gas. The outflow velocities are up to 1500 km/s. The column densities of these broad absorption are very low, typically $\tau \sim 0.001 - 0.005$. With the sensitivity of present-day radio telescopes, this limits the detection of such absorption to very strong radio sources. These broad H\textsc{i} absorption features have been mainly detected using the broad band (20 MHz) receiver now available at the WSRT. However, given the limited spatial resolution of these observations ($\sim 10$ arcsec), the exact locations of the absorption is not known. Indeed, most of these sources have a relatively complex continuum structure on the sub-arcsec and sometimes milliarcsec scale. In the case of the nearby radio galaxy 3C 293, described in detail in Emons et al. (this Volume), the H\textsc{i} absorption could be located as far as $\sim 1$ kpc from the nucleus, similar to what found in the Seyfert galaxy IC 5063. However, there are also cases where the broad H\textsc{i} absorption can be located much closer to the nucleus. An interesting example is the Compton-thick, broad-line and GigaHertz Peaked (GPS) radio galaxy OQ 208. This source is only 10 pc in size (Stanghellini et al. 1997) and the H\textsc{i} spectrum is shown in Fig. 2. More cases where the broad H\textsc{i} absorption occurs close to the nucleus may exist. However, high resolution follow-up observations are needed to investigate this.

The lack of detailed information about the location of the broad H\textsc{i} absorption implies an uncertainty in deriving the physical parameters of the gas outflows. Assuming that the absorption uniformly covers the radio source and
Gas outflows in radio galaxies

Figure 1. Examples of broad H I absorption has been detected in radio galaxies. The systemic velocity as derived from optical emission lines is also indicated. In two cases (3C 459 and PKS 1814-637) we have marked both the systemic velocity (corresponding to the velocity of the narrow lines) as well as the velocity of the broad component also detected in the optical emission lines (Holt et al. in prep.). See text for details.
Figure 2. Broad HI absorption detected (using the WSRT) against the compact source OQ 208. The systemic velocity derived by Marziani et al. (1997) is also indicated. The VLBI radio continuum (that is only \(\sim 10\) pc in size) is taken from Stanghellini et al. (1997).

a \(T_{\text{spin}} = 100\) K, the column density associated with the absorption is typically around few times \(10^{20}\) cm\(^{-2}\). These values can easily go up to few times \(10^{21} - 10^{22}\) cm\(^{-2}\) if the absorption is instead localized in a small area. Moreover, the \(T_{\text{spin}}\) can have much higher values (1000 K or more) if the absorption occurs very close to the nucleus. The density of the HI (still very dependent on the location and size of the absorption) ranges from \(\sim 0.2\) cm\(^{-3}\) (this could be the case in 3C 293) to \(\sim 30\) cm\(^{-3}\) (in the case of OQ 208). The HI mass associated with the outflows ranges from \(\sim 10^{3}\) up to \(10^{6}\) \(M_\odot\). The energy flux associated with the HI outflows is of the order of \(10^{40} - 10^{41}\) erg/s.

It is interesting to notice that, although in the cases described above (and shown in Figs. 1 and 2) most of the broad HI absorption is associated with blueshifted gas (indicating an outflow), indication of redshifted wings are also seen in some objects although with much smaller amplitude. One exception to this is the case of the compact radio galaxy 4C 37.11 where the new WSRT observations show a broad HI absorption of about \(\sim 1500\) km s\(^{-1}\) (see Fig. 3) symmetrical around the systemic velocity. Interestingly, VLBA observations (Maness et al. 2003) recover only part of the HI absorption detected by the low resolution WSRT spectrum.

3. Combining neutral and ionized gas

As mentioned above, direct evidence for fast outflows has been found also in the near-nuclear ionized gas from the detailed analysis of the strong optical emission lines characteristic of powerful radio galaxies. These studies further show how complex are the conditions of the gas in the circum-nuclear regions by revealing the presence of high ionization [OIII] emission lines with very broad (1000 to 2000 km/s) and blueshifted by 400-2000 km/s relative to the extended, quiescent gaseous halos (Tadhunter et al. 2001, Holt et al. 2003). The presence of more than one kinematic component of the ionized gas (a narrow and a broad component detected in the emission lines) is indicated for two objects in Fig. 1 but more cases have been found (see below). The difference in velocities between these two components can be substantial and it is therefore important to derive
the systemic velocity from the component associated with the more quiescent (i.e. narrower line profile) gas. The accurate value of the systemic velocity is, of course, crucial for the interpretation of the kinematics of the gas (both ionized and neutral). It is, therefore, clear how important these combined studies of the neutral and ionized gas are for a comprehensive interpretation of gas conditions around AGN. Accurate values of the systemic velocity are now available for all the galaxies for which broad H I absorption has been found.

The most extreme case of complex kinematics of the ionized gas has been observed in the compact radio galaxy 4C 12.50 (see Holt et al. 2003 for details). In this object, complex optical emission line profiles – with at least three kinematical components, as broad as 2000 km s$^{-1}$ and blueshifted $\sim$ 2000 km s$^{-1}$ – have been found at the position of the nucleus. These components have been identified - through measurement of density, reddening and the association with the neutral hydrogen components - as coming from different regions. These regions range from a large-scale quiescent halo to an inner region strongly affected by the radio jet (and associated with the most kinematically disturbed component). All this supports the idea that 4C 12.50 is a young radio source with the nuclear region still enshrouded in a dense cocoon that is in the process of being swept away (see also Sec. 5). We may be looking, therefore, at the first stage of the evolution of the newly born (or restarted) radio jet that will evolve into a Cygnus A-like object (Tadhunter et al. 1999) where the result of the outflows in the form of hollowed out biconical structures can be seen.

Interestingly in 4C 12.50 some similarities can be seen between the kinematics of the neutral and ionized gas. Another similar case is 3C 293 (see Emonts et al. this Volume). The similarities between the two phases of the gas may indicate that both outflows are originating from the same mechanism and could be co-spatial. If confirmed for other galaxies it would provide further constrains for the models that should describe these phenomena.
Figure 4. Left VLBI continuum image (grey scale and thin contours) of 4C 12.50 superimposed onto the total intensity of the (narrow) HI absorption (thick contours). See Morganti et al. (2004b) for more details. The position of the radio core is also indicated. Right HI absorption profile observed with the WSRT (black) and VLBI (red). A broad, shallow HI absorption is detected in the WSRT observations (see also Fig. 1). Due to the narrower band, this broad absorption is not detected in the VLBI observations.

4. Origin of the HI outflows

The central question is how neutral gas can be associated with such fast outflows. As discussed in Morganti et al. (2003c) for the case of 3C 293, a number of possible hypotheses can be made. They include: starburst winds (Veilleux et al. 2003), radiation pressure from the AGN (Dopita et al. 2002), jet-driven outflow and adiabatically expanding broad emission line clouds (Elvis et al. 2002). For the cases where the broad absorption seem to happen far away (few hundred pc) from the nucleus (e.g. 3C 293), the model that we favour is jet-driven outflow. The energy flux associated with the HI outflows (although uncertain) can be easily accounted for by the energy carried by the radio plasma, that in the case of the radiogalaxies studied so far it is at least of the order of $10^{42}$ erg/s. However, regardless the energetics, the neutral gas needs to be accelerated to velocities many times its local sound speed: how this is done is not yet clear. A possibility is that the radio plasma jet hits a (molecular) cloud in the ISM. As a consequence of this interaction, the kinematics of the gas are disturbed by the shocks. Once the shock has passed, part of the gas may have the chance to recombine and become neutral while it is moving at high velocities. The possibility that cool gas clouds will be formed in this way has been explored via numerical simulations with the main aim of investigating whether star formation can be produced via jet-cloud interaction (see Mellema et al. 2002 and Fragile et al. 2004). Although it seems to be possible to form cool gas (and HI) this way, it is still unclear whether it is also possible to accelerate the gas clouds to the high velocities that we observe.

However, in other cases (like e.g. OQ 208) the outflows appears to happen on much smaller scales. In these cases the outflows could originate from radiation...
pressure for example from adiabatically expanding broad line clouds. Elvis et al. (2002) have investigated the evolution of such clouds and they derive these cloud would reach temperatures of $\sim 1000$ K at distances of the $\sim 3$ pc from the nucleus. When they reach that phase they would be able to form dust. If the clouds can expand further, they will also cool enough to produce H\textsc{i}.

While for the jet/cloud interaction we may expect to find the broad H\textsc{i} absorption in the vicinity of strong radio continuum structure, in the case of radiation pressure this does not have to be the case and the accelerated gas may be found mainly close to the nucleus. These scenarios can be further tested with high-resolution observations. Whatever mechanism is responsible to produce the outflow of atomic hydrogen, the presence of such a component will put some tight constrain on the models that have to describe such a phenomenon.

5. Relevance for the evolution of the radio sources

A particularly high detection rate of broad H\textsc{i} absorption has been found in radio galaxies considered to be either in the early-stage of their evolution (like 4C 12.50) or in a phase of re-started activity (perhaps the case for 3C 293). This is suggested, e.g., by the detection in these objects of a “young” ($\sim 1$ Gyr old) stellar population (Tadhunter et al. 2004). These objects appear to have a particularly rich medium – they are often detected in CO and are typically far-IR bright, Evans et al. (2004) – likely resulting from a (major) merger that happened in their recent past. The H\textsc{i} can be a further tracer of this rich medium and the complex kinematics of the H\textsc{i} and ionized gas results from the interaction between the energy released by the AGN and the dense ISM.

The case of 4C 12.50 is again particularly interesting. This radio galaxy has often been suggested to be a prime candidate for the link between ultraluminous infrared galaxies and young radio galaxies. In this object, even the deep and relatively narrow H\textsc{i} absorption (observed at the systemic velocity) has been found to be associated with an off-nuclear cloud ($\sim 50$ to $100$ pc from the radio core) with a column density of $\sim 10^{22} \frac{T_{\text{spin}}}{(100 \text{ K})} \text{ cm}^{-2}$ and an H\textsc{i} mass of a few times $10^5$ to $10^6 M_\odot$ (see Fig. 4 and Morganti et al. 2004b). There are more examples of objects where the H\textsc{i} traces the rich medium surrounding the active nucleus. Examples of off-nuclear H\textsc{i} absorption are found in 3C 236 (Conway & Schilizzi 2000) and, more recently, against the southern hot-spot of the CSO 4C 37.11 (Maness et al. 2004, see also Fig. 3). This may have important implications for the evolution of the radio jets. Although this gas will not be able to confine the radio source, it may be able to momentarily destroy the path of the jet as shown also by numerical simulations (Bicknell et al. 2003). Thus, this interaction can influence the growth of the radio source until the radio plasma clears its way out. A similar situation may occur in the case of OQ 208. Guainazzi et al. (2004) suggest that in this source we could be seeing the jets piercing their way through a Compton-thick medium pervading the nuclear environment. The outflow detected in H\textsc{i} (see Fig. 2) would be an other indication of this process. Guainazzi et al. (2004) also suggest that if the jets have to interact with such a dense medium, one could largely underestimating the radio activity dynamical age determinate for this kind of sources from the observed hot-spot recession velocity.
References

Bicknell G. et al. 2003, New Astronomy Reviews, Volume 47, Issue 6-7, p. 537-544
Capetti et al. 1999, ApJ 516, 187
Crenshaw D.M. et al. 2000, AJ 120, 1731
Conway J.E. & Schilizzi R.T. 2000, in 5th European VLBI Network Symposium, Eds.: J.E. Conway et al., Onsala Space Observatory, p. 123
Dopita M.A. et al. 2002, ApJ 572, 753
Elvis M., 2000 ApJ 545, 63
Elvis M., Marengo & Karovska, 2002, ApJ 576, L106 [astro-ph/0202002]
Evans A.S. et al. 2004 in "Neutral ISM in Starburst Galaxies", eds. Aalto et al., PASP in press
Fragile P.C., Murray S.D., Anninos P., van Breugel W. 2004, ApJ 604, 74
Guainazzi M. et al. 2004 A&A in press [astro-ph/0402639]
Holt J., Tadhunter C., Morganti R., 2003 MNRAS 342, 227
Kriss G. 2004, in IAU Symposium 222 The Interplay among Black Holes, Stars and ISM in Galactic Nuclei, eds Storchi-Bergmann et al. in press [astro-ph/0403685]
Krongold et al. 2003, ApJ 597, 832
Maness H.L., Taylor G.B., Zavala R.T., Peck A.B. & Pollack L.K. 2004 ApJ 602, 123
Marziani P., Sulentic J.W., Calvani M. et al. 1997 ApJ 410, 56
Mellema G., Kurk J.D., Röttgering H.J.A. 2002, A&A 395, L13
Morganti R., Greenhill L.J., Peck A.B., Jones D.L., Henkel C. 2004a, in "Science with the Square Kilometer Array" eds. C. Carilli and S. Rawlings, New Astronomy Reviews (Elsevier: Amsterdam) in press [astro-ph/0409501]
Morganti R. et al. 2004b A&A 424, 119
Morganti et al. 2003a, in Recycling Intergalactic and Interstellar Matter, IAU Symposium 217, eds. P.-A. Duc et al., p. 332 [astro-ph/0310629]
Morganti R., Oosterloo T., Holt J., Tadhunter C., van der Hulst J.M., 2003b ESO Messenger 113, 69 [http://www.eso.org/gen-fac/pubs/messenger/]
Morganti R., Oosterloo T.A., Emonts B.H.C., van der Hulst J.M., Tadhunter C.N. 2003c, ApJLetter 593, L69
Morganti R., Oosterloo T., Tsvetanov Z. 1998, AJ, 115, 915
Mundell C.G., Wrobel J.M., Pedlar A., Gallimore J.F. 2003, ApJ 583, 192
Oosterloo T.A., Morganti R., Tzioumis A. et al. 2000, AJ 119, 2085
Pihlström Y.M., Conway J.E., Vermeulen R.C. 2003 A&A 404, 871
Stanghellini et al. 1997 A&A 318, 376
Tadhunter C., Robinson T.G., Gonzalez-Delgado R.M. et al. 2004 MNRAS in press [astro-ph/0410108]
Tadhunter C., Wills K., Morganti R., Oosterloo T., Dickson R. 2001 MNRAS 327, 227
Tadhunter C.N., Packham C., Axon D.J., Jackson, N.J. et al. 1999 ApJ 512, 91
Veilleux et al. 2002 in Emission lines from Jet Flows, eds. Henney et al. RevMex AA 13, 222 [astro-ph/0101075]
Veilleux et al. 2003, in "Neutral ISM in Starburst Galaxies", eds. Aalto et al., PASP in press [astro-ph/0309119]