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## Fast neutral outflows in nearby radio galaxies: a major source of feedback

Raffaella Morganti<sup>1,2</sup>, Clive Tadhunter<sup>3</sup>, Tom Oosterloo<sup>1,2</sup>,  
 Joanna Holt<sup>3</sup>, Bjorn Emonts<sup>4</sup>

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

2) *Kapteyn Astronomical Institute, University of Groningen, P.O. Box  
 800, 9700 AV Groningen, the Netherlands*

3) *Dep. Physics and Astronomy, University of Sheffield, Sheffield, S7  
 3RH, UK*

4) *Dep. of Astronomy, Columbia University, 550 W 120th Street, NY  
 10027, USA*

**Abstract.** Fast ( $\sim 1000 \text{ km s}^{-1}$ ) outflows of neutral gas (from 21-cm HI absorption) are detected in strong radio sources. The outflows occur, at least in some cases, at distances from the radio core that range between few hundred parsecs and kpc. These HI outflows likely originate from the interaction between radio jets and the dense surrounding medium. The estimated mass outflow rates are comparable to those of moderate starburst-driven superwinds. The impact on the evolution of the host galaxies is discussed.

### 1. Introduction

Huge amounts of energy are produced through the accretion of material on to the super-massive black hole situated in the centre of an Active Galactic Nucleus (AGN). This energy is released into the surrounding medium in a number of different ways, ranging from collimated radio-plasma jets to UV and X-ray emission. The regions around an AGN are, therefore, highly complex and host a wealth of physical processes. Gas in different phases (atomic, molecular and ionised) is observed in this very hostile environment. This gas - in particular its kinematics and ionisation - can bear the signature of the effects of the AGN on its surrounding medium. For example, the energy released from the nucleus can produce gas outflows of very high velocities (thousands  $\text{km s}^{-1}$ ).

Gas outflows have a wide range of effects, including clearing the circum-nuclear regions and halting the growth of the supermassive black-holes (see e.g. Silk & Rees 1998, Di Matteo et al. 2005). These effects can be at the origin of correlations found between the masses of the central super-massive black-hole and the properties of the host galaxies. They can also prevent the formation of too many massive galaxies in the early universe. In addition, outflows can inject energy and metals into the interstellar and intergalactic medium. It has been suggested that AGN-driven outflows are a major source of feedback in the overall galaxy formation process.

Outflows of *ionised* gas have been observed in many AGN, from Seyfert galaxies to quasars (see e.g. Crenshaw, Kraemer & George 2003 and Crenshaw these proceedings). In addition to this, we have recently discovered fast and massive outflows of *neutral hydrogen* detected as 21-cm HI absorption against the central regions of radio-loud galaxies (Morganti, Tadhunter & Oosterloo 2005). The characteristics and the possible effects of these outflows are summarised in this contribution.

## 2. Fast HI outflows

Using the Westerbork Synthesis Radio Telescope (WSRT) we have detected very broad HI absorption components in 6 radio galaxies. Three examples of the detected HI absorption are shown in Fig. 1. The broad absorption is observed against the strong nuclear radio continuum. This broad HI component has been also found in a radio-loud Seyfert galaxy (IC 5063) observed with the Australia Telescope Compact Array (ATCA). These objects are characterised by the presence of a rich ISM surrounding the AGN, e.g. strong CO or far-IR emission, and/or known to have undergone a major episode of star formation in the recent past (Tadhunter et al. 2005). Some of them have strong, steep-spectrum core emission (on a scale  $<10$  kpc, i.e. unresolved at the resolution of the WSRT 21-cm observations). These objects are considered to be young or recently restarted radio sources. In many of the objects the presence of a deep *but narrow* HI component was already known and studied, but the *shallow broad* component was discovered only by the new observations (thanks to the broad band that the upgraded WSRT could offer).

The broad HI component is typically very shallow (peak optical depth as low as  $\tau \sim 0.0005$ ), with the full width at zero intensity (FWZI) of the absorption ranging between  $600 \text{ km s}^{-1}$  and almost  $2000 \text{ km s}^{-1}$  — perhaps the broadest found so far in HI 21-cm absorption in any class of astronomical objects. A large fraction of the HI absorption is blueshifted relative to the systemic velocity of the galaxy. Because the gas producing the absorption must be in front of the radio source, this provides unambiguous evidence that the bulk of gas is outflowing. The typical column densities found for the broad absorption are 1 to  $10 \times 10^{21} \text{ cm}^{-2}$  (for a  $T_{\text{spin}} = 1000 \text{ K}$ ). More details can be found in Morganti et al. (2003, 2005a,b), Emons et al. (2003).

In order to understand the origin of such outflows and quantify their effects it is crucial to know their location as well as obtain a complete as possible view of what are the characteristics of the gas in other phases (e.g. ionised gas).

## 3. What is the origin?

Understanding the driving mechanism(s) of the outflows is crucial for understanding more about the physical mechanisms at work in the central regions of AGN. Radiation or wind pressure from the regions near the active super-massive black hole (i.e. a quasar wind) are the likely drivers of the gas outflows detected in X-ray and UV. However, in radio-loud objects, an other possible mechanism for driving the outflows is the interaction of the radio plasma with the (rich) gaseous medium in the direct vicinity of the active nucleus (Tadhunter 2007).

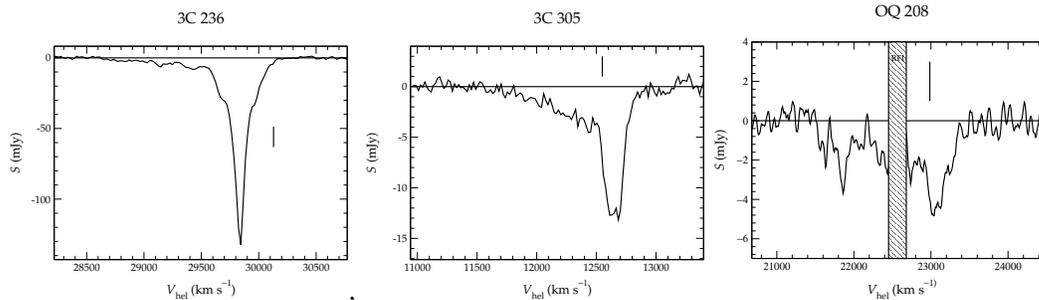


Figure 1. 21 cm - HI absorption profiles detected against three radio galaxies. The observations of the radio galaxies were done using the upgraded WSRT. The vertical line indicates the systemic velocity.

In the case of the fast HI outflows presented here, there is now strong evidence that this is likely to be the case. This evidence comprises follow-up observations at higher resolution of two of the objects in our sample (IC 5063 and 3C 305, Oosterloo et al. 2000 and Morganti et al. 2005 respectively) that demonstrate that the outflow regions are resolved on a scale of 200 pc (IC 5063) and 1.6 kpc (3C 305), and spatially associated with both the extended, bright radio lobes and the outflows of ionised gas detected at the same locations in optical observations. In a third case (3C 293), the evidence that the outflow is located at  $\sim 1$  kpc is more indirect (Morganti et al. 2003, Emonts et al. 2005). The presence of neutral atomic gas accelerated to such high velocities is in itself intriguing. It indicates that after a strong jet-cloud interaction the gas can cool very efficiently. Such rapid cooling is indeed predicted by recent numerical simulations of jets impacting on gas clouds (Mellema et al. 2002, Fragile et al. 2004, Krause 2007).

### 3.1. Effects on the galaxy

The main result of this study is that the neutral outflows occur, in at least some cases, at kpc distance from the nucleus, and they are most likely driven by the interactions between the expanding radio jets and the gaseous medium enshrouding the central regions. We estimate that the associated mass outflow rates are up to  $\sim 50 M_{\odot} \text{ yr}^{-1}$ , comparable (although at the lower end of the distribution) to the outflow rates found for starburst-driven superwinds in Ultra Luminous IR Galaxies (ULIRG), see Rupke et al. (2002). This suggests that massive, jet-driven outflows of neutral gas in radio-loud AGN can have as large an impact on the evolution of the host galaxies as the outflows associated with starbursts. This is important as starburst-driven winds are recognised to be responsible for inhibiting early star formation, enriching the ICM with metals and heating the ISM/IGM medium.

In few cases we have done a more detailed study of the characteristics of the outflow to investigate whether its properties are consistent with the assumption of the AGN feedback models. Particularly interesting is the case of IC 5063, where the mass outflow rates of cold (HI) and warm (ionised) gas have been found to be comparable,  $\sim 30 M_{\odot} \text{ yr}^{-1}$ . With a black-hole mass of  $2.8 \times 10^8 M_{\odot}$  (Nicastro, Martochia & Matt 2003), the Eddington luminosity of IC 5063 is

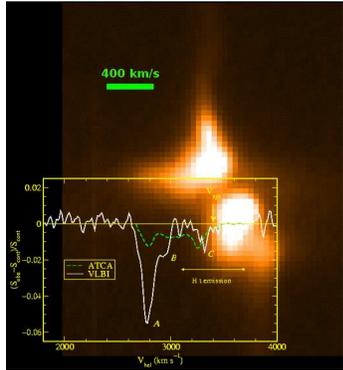


Figure 2. Comparison between the width of the HI absorption (white profile, Oosterloo et al. 2000) and that of the ionised gas (from the [O III]5007Å). The first order similarity between the amplitude of the blueshifted component covered by the two phases of the gas is clearly seen.

$3.8 \times 10^{46}$  erg s $^{-1}$ , this means that the kinetic power of the outflow represents only about few  $\times 10^{-4}$  of the available accretion power (Morganti et al. in prep). This result is similar to what found for PKS 1549-79 (Holt et al. 2006 and these proceedings). However, unlike the case of PKS 1549-79, IC 5063 accrete at low rate ( $\dot{m} \sim 0.02$ , Nicastro et al. 2003). Thus, in IC 5063 the kinetic power of the outflow appears to be a relative high fraction of the nuclear bolometric luminosity ( $\sim 8 \times 10^{-2}$ ) compared to what found in some more luminous radio galaxies. This might be relevant for the feedback process.

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