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Fast outflow of neutral hydrogen in the radio galaxy 3C 293 [1]

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ABSTRACT

We report the detection of very broad H I absorption against the central regions of the radio galaxy 3C 293. The absorption profile, obtained with the Westerbork Synthesis Radio Telescope, has a full width at zero intensity of about 1400 $\mathrm{km\,s^{-1}}$ and most of this broad absorption (~ 1000 $\mathrm{km\,s^{-1}}$) is blueshifted relative to the systemic velocity. This absorption represents a fast outflow of *neutral* gas from the central regions of this AGN. Possible causes for such an outflow are discussed. We favour the idea that the interaction between the radio jet and the rich ISM produces this outflow. Some of the implications of this scenario are considered.

Subject headings: galaxies: active - galaxies: individual: 3C 293 - ISM: jets and outflow - radio lines: galaxies

The physical and kinematical conditions of the gas surrounding an active galactic nucleus (AGN) offer key diagnostics for understanding the impact of the nuclear activity on the interstellar medium (ISM). As the gas is likely to be found in different phases, the study of all possible phases (atomic, molecular and ionized) is crucial to obtain a complete view of the processes occurring, in particular in the inner few kpc around the nucleus.

The picture of these regions provided by the ionized gas is often quite complex. For example, fast gas outflows are now detected (from optical, UV and X-ray observations) in a wide range of AGNs, from Seyfert galaxies to quasars (see e.g. Crenshaw et al. 2000, 2001; Aoki et al. 1996; Turnshek 1986 and refs. therein). Unambiguous evidence for outflows have been recently found also in radio galaxies from studies of the ionized gas (Tadhunter et al. 2001, Holt et al. 2003). These outflows can be produced by different and highly energetic phenomena, such as interaction of the radio plasma with the ISM as well as nuclear and/or starburst winds. Apart from telling us about the way the energy is released by the active nucleus, the feedback mechanisms originating by these outflows are considered to be critical in regulating the growth of the central black-hole (BH) and possibly explaining, e.g., the correlation between BH and galaxy bulge properties (see e.g. Silk & Rees 1998).

Neutral hydrogen is another important diagnostic to investigate the physical conditions and the kinematics of the gas in the central regions of AGNs. So far, observations of H I absorption in radio galaxies (but also in Seyfert galaxies) have been often interpreted as the neutral gas being mainly associated with circum-nuclear tori or kpc-scale disks (see e.g. the case of Cygnus A, Hydra A or NGC 4261, Conway & Blanco 1995, Taylor 1996, van Langevelde et al. 2000). In these cases, the neutral gas is supposed to trace relaxed/settled structures and its kinematics is found to be less extreme than that of the ionized gas. However, recent observations indicate that such an interpretation cannot always be applied and that also for the neutral gas the situation can be much more complex (Morganti 2002 and refs therein) with, for example, interaction between the radio jet and the neutral gas (see e.g. the case of the Seyfert galaxies IC 5063 and Mrk 1; Oosterloo et al. 2000, Omar et al. 2002 respectively).

Here we present the discovery of an even more extreme case. New H I data of the radio galaxy 3C 293, obtained with the broad band system now available at the Westerbork Synthesis Radio Telescope (WSRT), reveal the presence of a fast outflow of *neutral* gas in the central regions of this radio source. This is the first case found in a radio galaxy. This result shows that, despite the extremely energetic phenomena occurring near an AGN - including the powerful radio jet as in the case of 3C 293 - some of the outflowing gas remains, or

[1]Based on observations with the Westerbork Synthesis Radio Telescope (WSRT)

becomes again, neutral. This result is giving new and important insights on the physical conditions of the gaseous medium around an AGN.

1. The broad H I absorption from the WSRT observations

The WSRT observations of 3C 293 were performed at four epochs (August 2002, December 2002, January 2003 and March 2003) using the new backend that allows a broad observing band (20 MHz) with a large number of channels (1024) so that a wide velocity range is covered (~ 4000 km s^{-1}) while high velocity resolution (~ 4 km s^{-1}) can be maintained. We used different central frequencies in the different observations (1359.2 MHz in the August and December observations, 1361.4 and 1357.9 MHz for the remaining two) to eliminate systematic errors due to bandpass uncertainties.

Each observation was about one hour in duration. Over this time interval we verified that the bandpass stability of the system (using a calibrator before and after the observation of 3C 293) is better than 1 in 10^4 in each observation. The data were calibrated and reduced using the MIRIAD package. The final r.m.s. noise is 0.86 mJy beam^{-1} with a velocity resolution of 9 km s^{-1} (after Hanning smoothing). The peak of the continuum emission is ~ 3.8 Jy. The final spectrum is thermal-noise limited with a spectral dynamic range of about 2×10^{-4}.

The H I spectrum, obtained from the combination of all data, is shown in Fig. 1. In addition to the strong and relatively narrow H I absorption already known (Haschick & Baan 1985, Beswick et al. 2002), we detect a new very broad component. This broad component is also detected in each of the four observations when analysed separately.

The broad H I absorption (clearly seen in the zoom-in of Fig. 1), has a full-width at zero intensity (FWZI) of ~ 1400 km s^{-1}and, if fitted with a gaussian, FWHM~ 850 km s^{-1}. This absorption extends from ~ -1000 km s^{-1} to $+400$ km s^{-1} (i.e. from ~ 12450 km s^{-1} to ~ 13850 km s^{-1}) compared to the systemic velocity - taken from the literature as 13500 km s^{-1}.

The structure of the continuum emission of 3C 293 at 21 cm at the resolution of the WSRT is shown in Fig. 1 (from Emonts et al. in prep.). The typical size of the WSRT synthesised beam is about 10 arcsec, corresponding at ~ 9.2 kpc at the distance of 3C 293 (for $H_\circ = 71$ km s^{-1} Mpc^{-1}). Despite the short duration of our observations, we can verify that all the detected H I absorption (including the new broad component) is coming from the central region, because the fan-beam is perpendicular to the radio source structure. It is worth mentioning that the central region, unresolved with the WSRT beam, is in fact relatively complex when observed at higher spatial resolution. A two-sided jet structure and a flat-spectrum core were observed by Akujor et al. (1996). The brighter structure detected is an hot-spot-like region situated around 1.5 arcsec (1.4 kpc) from the core.

The large velocities associated with the broad H I absorption are very unlikely to be associated with gravitational motion and instead indicate a fast gas outflow in the nuclear regions. This is clearly different from the deep H I absorption that was has been previously studied in detail by, e.g., Haschick & Baan (1985) and Beswick et al. (2002). Two gas systems are believed to produce this relatively narrow part of the H I absorption. One system, at larger radii, likely represents the neutral counter-part of the large-scale ionized disk (van Breugel et al. 1984) and of the molecular gas disk (Evans et al. 1999). The second system is a more inner ring of gas (with a radius of at least 600 pc) rotating around the active nucleus (Beswick et al. 2002).

Finally, the broad H I absorption component is very shallow, with a typical optical depth of only ~ 0.15 %, assuming that it uniformly covers the central radio source (i.e. the covering factor is 1), The column density of the H I is $\sim 2 \times 10^{20}\ T_{\rm spin}/100$ K cm^{-2}. This is likely to be a lower limit to the true column density as the $T_{\rm spin}$ associated with such a fast outflow can be as large as few 1000 K (instead of 100 K which is more typical of the cold, quiescent H I in galaxy disks) and the covering factor may well be smaller than one. Thus, the true column density will likely be in excess of 10^{21} cm^{-2}.

2. The origin of the broad H I absorption

The discovery of the broad, blueshifted H I absorption indicates that fast outflows of *neutral* gas can exist near AGNs. The obvious question is, therefore, which of the mechanisms capable of producing gas outflows can also account for gas that remains, or becomes again, neutral. All the different mechanisms thought to produce fast outflows (interaction between the radio plasma and the ISM, nuclear and/or starburst winds) can be at work in the nuclear regions of a radio galaxy like 3C 293. We shall therefore consider each of them separately.

3C 293 is known to have a particularly rich ISM. A large amount of molecular gas has been detected ($\sim 1.5 \times 10^{10} M_\odot$, Evans et al. 1999) and this galaxy is also a bright far-IR source. The high concentration of molecular gas in the central few kpc and the distorted optical morphology of the galaxy has led to suggestions that 3C 293 has been involved in a recent gas-rich galaxy-galaxy interaction (Heckman et al. 1986; Evans et al. 1999). A relatively young stellar population component is also observed in optical spectra (Robinson 2001). The presence of a starburst wind is, therefore, quite conceivable. The age of the young stellar population component has been estimated between 0.4 and 2.5 Gyr. Thus, the neutral outflow would have to be a "fossil" starburst-driven wind from the strong starburst that may have occurred of the order of 1 Gyr ago. Given this condition, it is not clear whether the starburst-driven outflow would survive to the present day and whether it would be still seen against the central regions. In fact, following Heckman, Armus & Miley (1990), the size of the gas shell produced by a starburst wind of this age will be very large and not limited anymore to the nuclear region. We, therefore, consider the effect of such wind unlikely to produce the fast H I outflow that we see against the nuclear regions of 3C 293.

More promising mechanisms to explain the outflow are those related to the effects of the AGN activity. As mentioned in the introduction, fast gas outflows have been detected in a number of Seyfert galaxies. In some of these objects (in particular where no correlation between the radio structures and the peculiar velocities of the ionized gas has been found) acceleration of the gas due to radiation and/or wind pressure has been proposed. Dopita et al. (2002) have considered in detail the case of dusty narrow-line regions that are radiation pressure dominated. This mechanism may be able to explain the overall kinematics of the gas (including the fast outflow) in the case of NGC 1068. In this scenario, if the column density is high enough, the gas clouds are ionisation bounded and some neutral gas can be present in the outflow.

However, unlike NGC 1068, the gas in the centre of 3C 293 appears to have very low ionisation and has very faint emission lines (in particular [O III]5007Å, Gelderman & Whittle 1994). This could indicate that the AGN in 3C 293 is relatively weak. Based on the observation of the emission lines, this is, however, quite difficult to quantify given the strong obscuration by the dusty environment around the centre. It is nevertheless clear that the ionisation of this galaxy appears to be low.

We can alternatively use the far-IR luminosity of 3C 293. Even assuming that the far-IR emission is all due to re-radiated quasar light - rather than re-radiated starburst light - the FIR luminosity (from IRAS observations, Golombek et al. 1988) is $\log L_{60\mu m}/L_{\odot} = 10.08$. This is at the lower end of the luminosity for quasars (Neugebauer et al. 1986), therefore indicating, as the low ionisation level, that the nucleus of 3C 293 does not have a particularly powerful AGN in the centre. It seems therefore unlikely that there is enough energy in the UV radiation field from the nucleus to be able to accelerate the gas to such large velocities as observed in the H I profile.

The last, and perhaps more likely, possibility is that the outflow is the driven by the interaction between the radio plasma and the ISM. Although the WSRT observations cannot resolve the complex nuclear structure of 3C 293 (see above) and therefore exactly locate where the broad H I is occurring, we know that some interaction between the radio plasma and the ISM is taking place. Evidence was found that the broadest optical lines are seen in coincidence with the region of the most intense radio emission, which is a radio hot-spot about 1.4 kpc east of the core, as determined by VLBI observations (Akujor et al. 1996). New optical spectra (see Fig. 2, from Emonts et al. in prep.) show that in this location the optical emission lines contain a broad component that is very similar to the broad H I absorption. This suggests that also the H I absorption is coming from this region. However, this will need to be confirmed with higher resolution H I observations.

Also for this scenario, the central question is how *neutral* gas can be associated to the fast outflow. A possible model is that the radio plasma jet hits a (molecular) cloud in the ISM. As a consequence of this interaction, part of the gas is ionized and its kinematics is disturbed by the shock. 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. To understand whether this scenario could be feasible, it is worth considering the model proposed for the evolution of clouds in radio galaxy cocoons as they are overtaken by a strong shock wave (Mellema, Kurk & Röttgering 2002). This model predicts that, as the shock runs over a cloud, a compression phase starts because the cloud gets embedded in an overpressured cocoon. The shock waves start travelling *into* the cloud and the cloud fragments with the fragments moving at high velocities. They find that the cooling times for the dense fragments are very short (few times 10^2 years) compared to the lifetime of the radio source and that the excess of energy is quickly radiated away. This results in the *formation of dense, cool and fragmented structures at high velocities*. It would be interesting to explore the parameter space of such models in more detail in order to see whether, for the conditions in 3C 293, an outflow of neutral gas with the high velocities observed can be produced.

As indirect support to this hypothesis, it is worth mentioning that in the only other case of broad blueshifted H I absorption (of 700 $\mathrm{km\,s^{-1}}$ FWZI) studied in detail so far (the Seyfert galaxy IC 5063, Oosterloo et al. 2000), the H I absorption is coincident with the brighter radio lobe where also the most kinematically disturbed ionized gas is observed. This supports the idea of jet/cloud interaction as most likely mechanism in this Seyfert galaxy. A detailed high-resolution study to investigate whether or not a spatial coincidence exists between the broad component seen in ionized and neutral gas and the features seen in radio continuum is needed to further clarify whether IC 5063 and 3C 293 are indeed similar.

3. Final remarks

Broad, blueshifted H I absorption, as reported here for 3C 293, is only very rarely seen. As mentioned above, the only other object studied in some detail where broad blueshifted absorption has been found is the Seyfert galaxy IC 5063 (Oosterloo et al. 2000). This could well be due to a technical bias. In order to detect the broad and shallow H I absorption, the radio source has to be quite strong while also broad-band (i.e. 16 MHz or more) observations with very high spectral dynamic range are necessary, conditions that are not satisfied by most observations available in the literature. Indeed, most Seyfert galaxies are too weak in the radio for detecting broad, shallow H I absorption.

The detection of such a component is more likely, given their stronger radio emission, in radio galaxies and a systematic search is now in progress. We have indeed recently found two other candidate radio galaxies (4C 12.50 and 3C 305) where similarly broad and blueshifted H I absorption may be occurring.

It is intriguing that 4C 12.50 and 3C 305, as well as 3C 293, are classified as “starburst” radio galaxies, i.e. show evidence of a relatively young stellar population component. Such galaxies appear to be among the best candidates for detecting H I in general (see e.g. Morganti et al. 2001). This might be due to the richer ISM that characterises radio galaxies in this stage of their evolution, with the rich ISM possibly resulting from a recent merger. It is then perhaps not surprising that fast gas outflows are also produced in this rich ISM by the young radio source. More observations are needed to study how common neutral gas outflows are and whether they are associated with particular kinds of AGN.

Following these results, a tantalising connection can be made with the high-z radio galaxies. Outflow phenomena have been detected in many high-redshift radio galaxies. In many cases, asymmetric Lyα profiles suggest the presence of blueshifted absorbing gas (likely neutral hydrogen, Dey 1999, van Ojik et al. 1997, de Breuck et al. 1999). Additionally, complex gas kinematics is also observed in a large fraction of high-z radio galaxies (van Ojik et al. 1997). There is clear evidence for the presence of large amounts of cold gas and, in general, for the presence of a rich gaseous environment in radio galaxies at high redshift (see e.g. van Breugel 2000 for a review). Strong interactions between the radio plasma and the medium are therefore expected to be very important. Because of this, similar processes as observed in 3C 293 are likely to be even more common in these high-z systems. Understanding the physics of fast gas outflows and the conditions for which part of the outflowing gas is neutral, is thus also quite relevant for understanding high-z radio galaxies.

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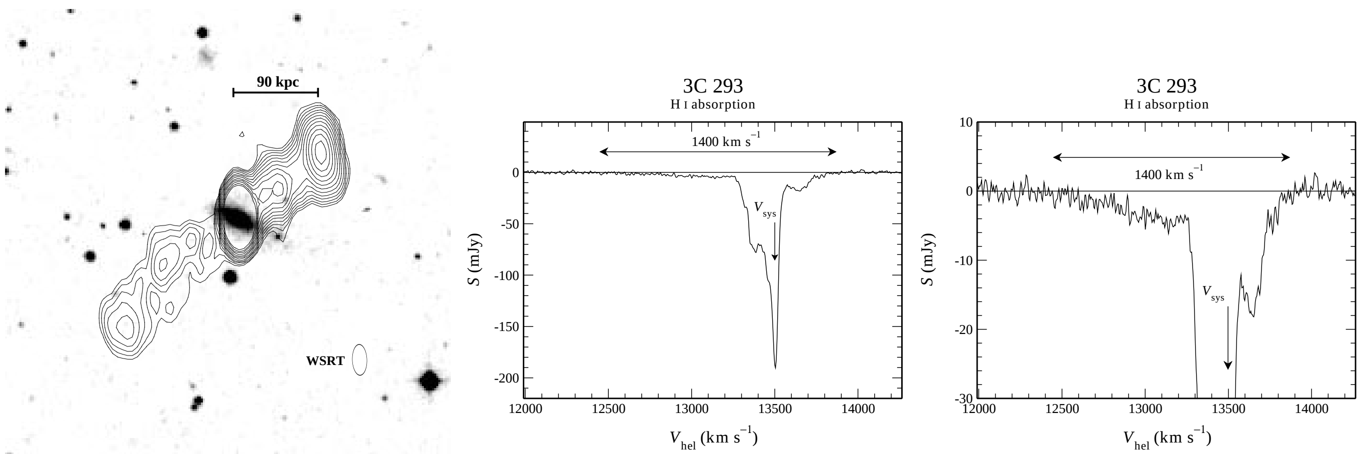

Fig. 1.— *(Left)* Continuum image of 3C 293 at the resolution of WSRT 21-cm observations (Emonts et al. in prep). *(Middle)* The H I absorption spectra with a zoom-in (*Right*) to better show the new detected broad H I absorption. The spectra are plotted in flux (mJy) against optical heliocentric velocity in $\mathrm{km\,s^{-1}}$.

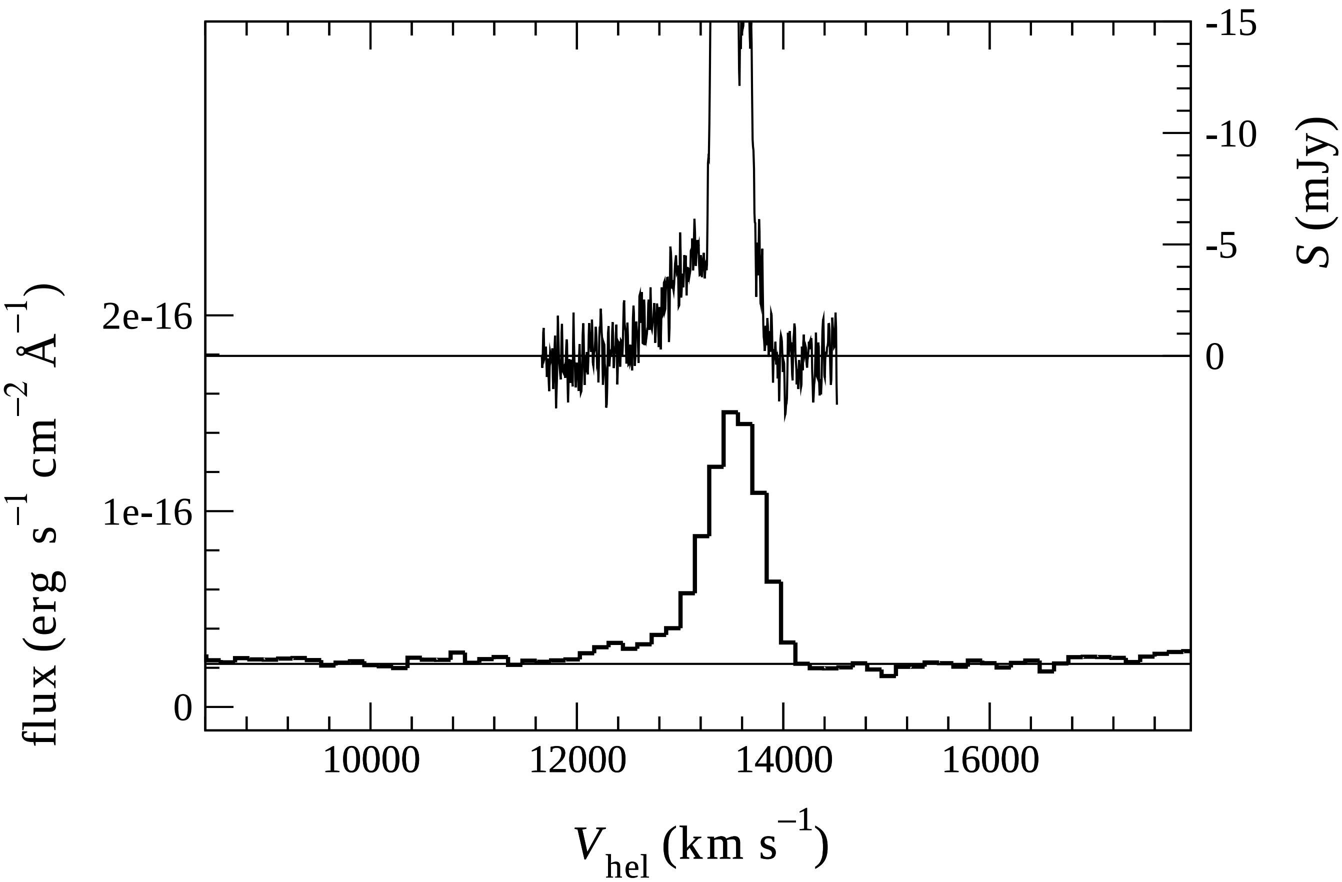

Fig. 2.— Comparison between the H I absorption (top) and the [OII]3727Å (bottom, from Emonts et al. in prep.) profiles. The similarity of the broad, blueshifted wing in the two profiles is evident.