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Evidence for jet driven outflows: the case of 3C293

E. K. Mahony[1], J. B. R. Oonk[1,2], R. Morganti[1,3], T. A. Oosterloo[1,3], B. H. C. Emonts[4] and C. N. Tadhunter[5]

[1]ASTRON, the Netherlands Institute for Radio Astronomy,
Postbus 2, 7990 AA, Dwingeloo, The Netherlands
email: mahony@astron.nl

[2]Leiden Observatory, Leiden University,
P.O. Box 9513, 2300 RA Leiden, The Netherlands

[3]Kapteyn Astronomical Institute, University of Groningen,
Postbus 800, 9700 AV Groningen, The Netherlands

[4]Centro de Astrobiología (INTA-CSIC),
Ctra de Torrejón a Ajalvir, km 4, 28850 Torrejón de Ardoz, Madrid, Spain

[5]Department of Physics & Astronomy, University of Sheffield, Sheffield S3 7RH, UK

Abstract. The tight correlations observed between galaxies and their SMBH provides compelling evidence that the evolution of the galaxy and its central black hole are strongly linked. This is generally attributed to feedback mechanisms which, according to simulations, often take the form of outflows of gas, quenching star formation in the host galaxy and halting accretion onto the central black hole. While there are a number of plausible ways that outflows could be produced, recent results have shown that in some cases radio jets could be responsible for driving fast outflows of gas. One such example is seen in the nearby radio galaxy 3C293. In this talk I will present results from JVLA radio observations where we detect fast outflows (∼1200 km/s) of neutral gas which are being driven by the radio-jet approximately 0.5 kpc from the central core, providing direct evidence for jet-ISM interaction. This is accompanied with recent IFU observations showing that ionised gas outflows are also being driven by the radio jet. Pinpointing the location of these outflows enables us to derive crucial parameters, such as the mass outflow rates and kinetic energy involved, which we can compare to predictions from galaxy evolution simulations.

Keywords. ISM: jets and outflows, galaxies: active, galaxies: individual (3C293), galaxies: jets

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1. Introduction

It is widely recognised that the growth and evolution of galaxies is strongly tied to that of the central supermassive black hole. This is generally attributed to AGN feedback, where the interplay between the central active galactic nucleus (AGN) and surrounding medium regulates the growth of the galaxy (Croton *et al.* 2006, Bower *et al.* 2006). This feedback often takes the form of large outflows of gas, quenching star formation in the host galaxy and halting accretion onto the AGN. While these outflows can be modelled in galaxy formation simulations, the observational evidence of these gas outflows is limited, particularly on scales close to the black hole.

The physical mechanisms driving these outflows are generally attributed to either star-formation driven winds or accretion disk winds. However, there is increasing evidence that in radio loud AGN the interaction between the radio jets and ISM of the host galaxy can be responsible for large outflows. Massive, fast outflows of HI and CO, possibly driven by this interaction, are being observed in a growing number of objects (see e.g. Morganti

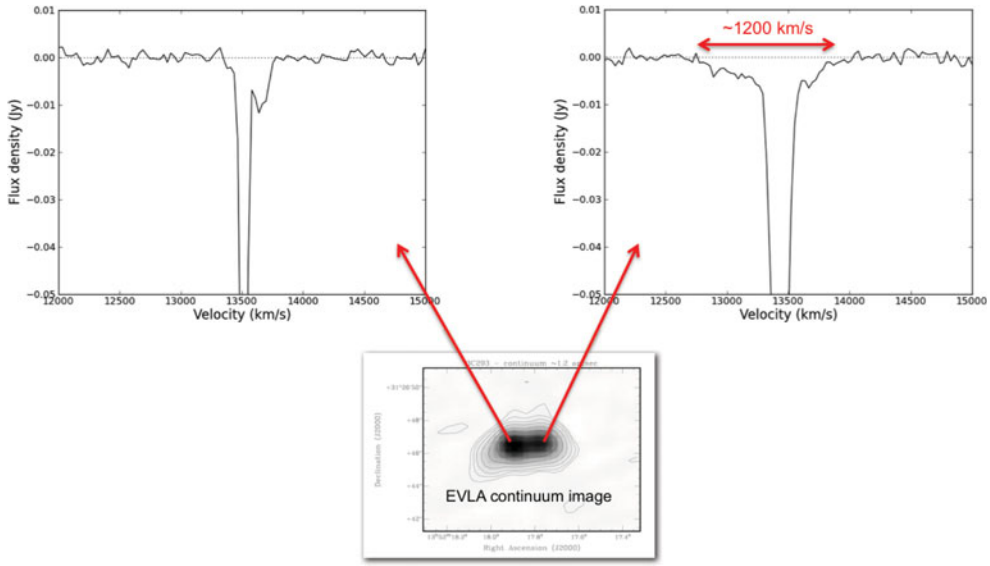

Figure 1. HI absoprtion features observed in 3C293. The bottom images shows the JVLA continuum image while the top images show the HI absoprtion profile extracted in the eastern and western radio jets respectively. The broad, shallow absorption feautre (indicative of outflowing material) is only observed in front of the western radio lobe.

et al. 2005, Dasyra & Combes 2012, Feruglio *et al.* 2010, Morganti *et al.* 2013). One such example is seen in the nearby radio galaxy 3C293.

2. Jet-driven outflows of neutral gas

Fast outflows, up to $1400\,\mathrm{km\,s^{-1}}$, were first detected in 3C293 using the Westerbork Synthesis Radio Telescope (WSRT) to observe neutral hydrogen in absorption (Morganti *et al.* 2003). However, the spatial resolution was not high enough to determine if the outflows were coming from the central AGN or from the radio jets in the central kpc of the galaxy. Recent observations using the Jansky Very Large Array (JVLA) provided higher spatial resolution data needed to localise the HI outflows on arcsec scales. This data is shown in Figure 1. When looking at the HI absorption profile in front of the eastern radio jet, a deep, narrow component of HI is detected due to the rotating disc of the galaxy. On the other hand, the HI profile along the sightline to the western radio jet shows a shallow, very broad component in addition to the narrow component associated with the HI disc. By comparing with higher resolution VLBI images we can conclude that this broad, outflowing component is located approximately 0.5 kpc from the core (Mahony *et al.* 2013).

Pinpointing the location of this outflow allows us to calculate associated parameters with better accuracy. The mass outflow rate falls within the range of $8-50\,\mathrm{M_\odot\,yr^{-1}}$ and the corresponding kinetic energy power injected back into the ISM is in the range $1.38\times10^{42}-1.00\times10^{43}\,\mathrm{erg\,s^{-1}}$ corresponding to $0.01-0.08$ per cent of the Eddington luminosity. This places it just below the 0.5 per cent required by the galaxy evolution simulations of Hopkins & Elvis (2010) to heat or drive-out the gas, thereby halting star formation in the host galaxy.

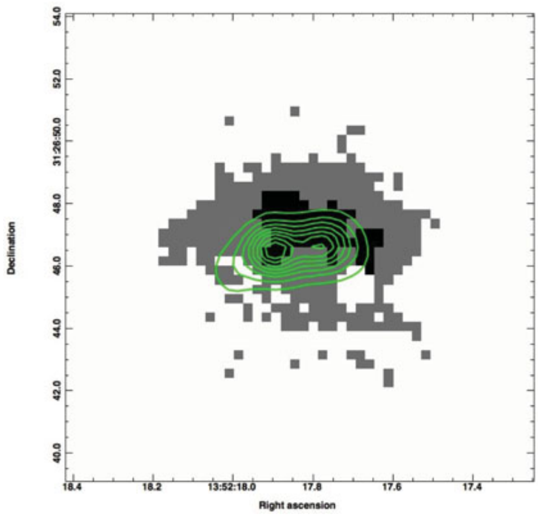

Figure 2. The number of gaussian components fitted to each line overlaid with radio contours from the JVLA observations. The black regions denote areas where 2 gaussian components provided a better fit to the data than a single gaussian.

3. Jet-driven outflows of ionised gas

Although the outflow observed in HI does not appear to be enough to fully account for the feedback required in this galaxy, it is important to note that this is only looking at the neutral gas along the line of sight to the background radio continuum source. To better understand the physics and kinematics of the jet-ism interaction in this system it is vital to also look at other phases of the gas.

3.1. *Previous observations*

Emonts *et al.* (2005) first detected ionised gas outflows in this galaxy using longslit observations on the William Herschel Telescope (WHT). Intriguingly, the most significant detection was associated with the eastern radio jet, the opposite jet to where we have since located the HI outflow. To investigate this further we have reobserved this source, this time using an IFU to better map the kinematics of the ionised gas in this system.

3.2. *New observations*

Observations were carried out using the OASIS IFU instrument on the WHT. Two different grisms were used with similar resolutions (2.13 and 2.16Å) to observe the Hα,[NII] lines and the [SII] lines. For each grism, six exposures of 900s were taken with each exposure offset by 2 arcsec in a rectangular pattern to slightly increase the 10x7 arcsec instrumental field of view. The data reduction was carried out using the OASIS data reduction pipeline except for the sky subtraction, flux calibration and mosiacing which were done in IDL. The data was then resampled to 0.3 arcsec pixels and continuum subtracted to allow for better fitting of the emission lines. In order to detect the faint, broad signatures indicative of an outflow, the data was binned using a voronoi binning algorithm to ensure there was a minimum S/N ratio per bin for the full image (Cappellari & Copin 2003).

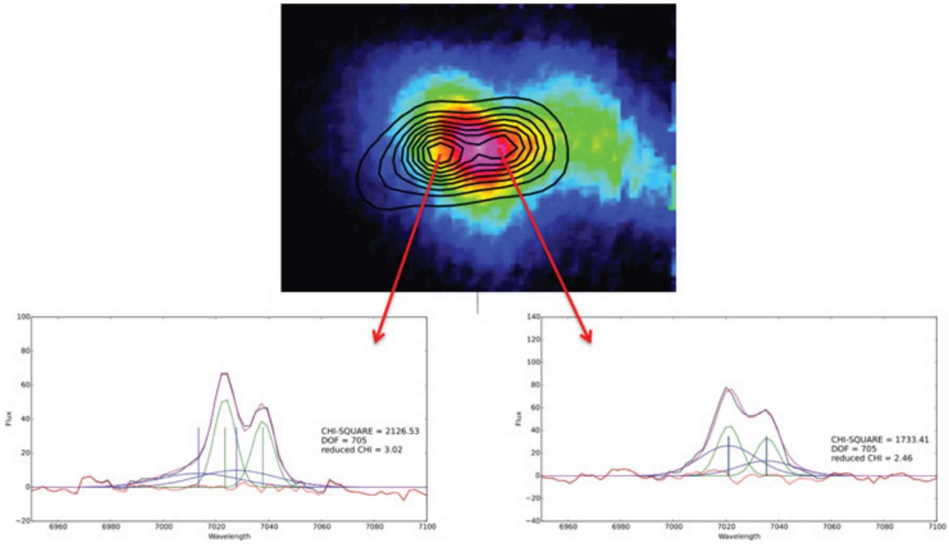

Figure 3. The optical continuum image of 3C293 obtained from the WHT observations overlaid with the JVLA radio contours. Below is shown an example spectrum extracted from the eastern and western radio lobes respectively. Each spectrum is then run through a line-fitting routine to identify the number of gaussian components needed to fit each line. In both these cases two gaussian fits are needed, a narrow component (shown in green) and a broader component (shown in blue). The vertical lines mark the central velocities of each fitted component.

The output spectrum was run through a gaussian line-fitting routine (based on the mpfit package†) to fit either 1, 2 or 3 gaussian components to each line. To constrain the line-fitting, the line widths of each gaussian component were set to be the same for all lines since each component is probing the same gas. Figure 2 shows the areas where 2 gaussian components provided a better fit to the data (shown in black) than a single gaussian component based on the reduced chi-squared. No pixels required 3 gaussian components to adequately fit the lines.

For regions where a 2-gaussian fit was needed, the second gaussian component was typically much broader than the first component fitted. As such, the two components were separated to distinguish between the gas associated with the outflow (the broad component) and the gas associated with the galaxy disk (the narrow component). Figure 3 shows an example spectrum taken from the eastern and western jet respectively. In the spectrum associated with the eastern jet, the broad component is significantly blueshifted compared to the narrow component in that region (the vertical lines shown in Figure 3 mark the central wavelength of each component). This is in agreement with the results obtained from the previous longslit observations of 3C293 (Emonts *et al.* 2005). In the western jet, the broad component associated with the outflow is close to the systemic velocity, very similar to what we see in the HI outflow. While the central velocities are similar for the ionised gas and neutral gas outflows, the line width of the ionised gas outflow (FWHM of approximately 1400 km/s) is much larger than measured for the HI (FWHM approximately 700 km/s). However, this can be explained by the fact that we detect the HI in absorption, so only detect the gas along the line of sight to the radio jet and could therefore be missing a lot of the gas either behind the jet or not along that sightline.

† I used the python package written by Mark Rivers (http://cars.uchicago.edu/software/python/mpfit.html) which was based on the IDL mpfit package (Markwardt 2009).

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Studying the gas kinematics in emission gives us a more detailed and unbiased look at the physical mechanism driving the outflow. As can be seen in Figure 2, ionised gas with disturbed kinematics (i.e. the outflowing gas) is detected all along the radio jet axis, not just at the hotspots. This provides further evidence that the radio jet is responsible for driving the outflow in 3C293. To obtain a complete picture of the kinematics and physics behind this jet-ISM iteraction, the next step would be to search for outflows of molecular gas. Unfortunately no significant outflows of molecular gas have been detected in this object to date (Labiano *et al.* 2014).

4. Conclusions

Fast, jet-driven outflows of both neutral and ionised gas have been observed in the nearby radio galaxy 3C293. Observations of the HI line in absorption using the JVLA revealed a fast outflow (FWHM ∼700 km/s) associated with the western radio jet, but previous longslit observations suggested that an extreme outflow of the ionised gas was associated with the eastern jet. New observations using the OASIS IFU instrument on the WHT revealed that ionised gas outflows are detected all along the radio jet axis, providing the missing link between the previous observations which appeared to show conflicting results. The outflowing gas associated with the eastern radio jet is blueshifted in agreement with the outflow detected from the longslit observations (Emonts *et al.* 2005), whereas the outflow associated with the western jet is closer to the systemic velocity of the galaxy, similar to what was seen in the HI data (Mahony *et al.* 2013). These observations provide clear evidence that the radio jet is capable of driving fast outflows and suggests that jet-driven outflows should be considered in future AGN feedback models.

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