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The parsec-scale structure of jet-driven H I outflows in radio galaxies

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Abstract. Radio jets can play multiple roles in the feedback loop by regulating the accretion of the gas, by enhancing gas turbulence, and by driving gas outflows. Numerical simulations are beginning to make detailed predictions about these processes. Using high resolution VLBI observations we test these predictions by studying how radio jets of different power and in different phases of evolution affect the properties and kinematics of the surrounding H I gas. Consistent with predictions, we find that young (or recently restarted) radio jets have stronger impact as shown by the presence of H I outflows. The outflowing medium is clumpy with clouds of with sizes up to a few tens of pc and mass $\sim 10^4 M_\odot$) already in the region close to the nucleus (< 100 pc), making the jet interact strongly and shock the surrounding gas. We present a case of a low-power jet where, as suggested by the simulations, the injection of energy may produce an increase in the turbulence of the medium instead of an outflow.

Keywords. ISM: jets and outflows, radio lines: galaxies, galaxies: active

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The impact of active galactic nuclei (AGN) on the surrounding medium can be due to either winds and radiation from the nuclear region, or to plasma jets. Both these mechanisms are known to play a role and, depending on the situations and on the physical conditions, one can dominate via a strong coupling with the surrounding medium (e.g. Cielo *et al.* 2018). However, quantifying the actual impact of these phenomena is still a challenging task. Radio jets play a particularly important role in the feedback process, providing the best examples of AGN-driven feedback seen in action by preventing the cooling of the X-ray gas on cluster scales. However, radio jets can also provide an effective mechanism on *galaxy scales*. Their impact manifests itself in different ways: by counterbalancing the cooling of the hot coronae present around even isolated galaxies (e.g. Croston *et al.* 2008; Ogorzalek *et al.* 2017); by driving fast outflows traced by different gas phases or by injecting turbulence in the ISM, e.g. Alatalo *et al.* (2015); Guillard *et al.* (2015). All these mechanisms are relevant and need to be quantified.

Particularly interesting are the results from recent numerical simulations (Wagner *et al.* 2012, Mukherjee *et al.* 2018a, 2018b, Cielo *et al.* 2018). These show that radio jets can couple more strongly to the ISM if that is modelled to be clumpy (Wagner *et al.* 2012). Furthermore, a connection is expected with the cycle of activity of radio galaxies: given their small size, young (and recently restarted) radio jets have the highest impact on the gas. A dependence is also expected with jet power: powerful jets can drive faster outflows while low power jets can be "trapped" for longer times and induce more turbulence in the galactic ISM (Mukherjee *et al.* 2018b). Finally, the orientation of the jet with respect to the distribution of gas in the host galaxy is also relevant for the impact of the jet.

AGN-driven and jet-driven outflows are known to be multi-phase and can be traced also by atomic neutral hydrogen. This has opened the possibility to test the impact of plasma jets using radio data and, in particular, 21-cm H I observed in absorption (see Morganti & Oosterloo 2018 for an overview). The advantage of this is that the gas can be traced down to very small scales and the location of the outflow and their properties can be studied. This can be done using (sub-)arcsec down to milli-arcsec data (i.e. down to pc scales) as shown by the global Very Long Baseline Interferometry (VLBI) data described below and obtained by arrays including telescopes from the European VLBI Network, the Very Long Baseline Array (VLBA), as well as Arecibo. The results allow us to investigate not only the impact of radio jets, but also whether the predictions from the simulations are confirmed.

1. Where and how often do we see jet-driven outflows?

Jet-driven outflows are long known from ionised gas, but more recent work has not only shown that also atomic neutral hydrogen (H I) and molecular gas can be associated with these outflows and also that they may carry a significant (possibly the largest) fraction of the outflowing gas mass. The jet-driven origin of outflows of cold gas has been confirmed in a number of cases traced by molecular gas (see e.g. Alatalo *et al.* 2011, Dasyra & Combes 2012, Combes *et al.* 2013, Morganti *et al.* 2015, García-Burillo *et al.* 2014, Oosterloo *et al.* 2017, Runnoe *et al.* 2018) and by HI, see Morganti & Oosterloo (2018) for a review. The H I outflows have typically velocities between a few hundred to $\sim$1300 km s^{-1}.

In addition to this, a relation between the occurrence of H I outflows and the evolutionary status of the radio jet has been found by observations of a relatively large sample (248 objects) presented in Geréb *et al.* (2015). They find that at least 5% of all sources (15% of H I detections) show H I outflows. These numbers represent lower limits, given that absorption measurements are sensitive only to gas (and outflows) located in front of the radio continuum. Particularly interesting is that the vast majority of the H I outflows are detected in sources with newly born (or reborn) radio jets. This supports the idea that these phases in the evolution are those where the jet has most of its impact on the surrounding medium. This is in agreement with predictions from the simulations of Wagner *et al.* (2012) and Cielo *et al.* (2018). The recurrent nature of radio sources (see e.g. Morganti 2017) would ensure that this impact is repeated during the life of the host galaxy. A similar effect was also seen in the ionised gas (see Holt *et al.* 2008). However, this phase of the gas was found to show mass outflow rates reaching at most 1 $M_\odot$ yr^{-1}, while mass outflow rates up to 50 $M_\odot$ yr^{-1} have been found for the H I outflows.

2. Do we see the interaction of the jet with a clumpy medium?

For a small number of objects we have used VLBI observations to trace the properties of the H I outflows down to pc scales. The results show that a clumpy distribution of the gas is seen in all observed objects. Figure 1 illustrates the distribution of H I absorption in the central region of the restarted radio galaxy 3C 236, Schulz *et al.* (2018). Interestingly, in this and other targets observed so far, fast outflowing clouds (many hundred km s^{-1}) are detected already in the very inner region, at distances $< 50 - 100$ pc from the core. The clouds have masses of a few $\times 10^4$ $M_\odot$, and are unresolved on VLBI scales ($<$ 40 pc). The presence of a clumpy medium (see also Oosterloo *et al.* 2017) is of key importance and confirms the prediction of the numerical simulations. A clumpy medium can make the impact of the jet much larger than previously considered: because of the clumpiness of the medium, the jet is meandering through the ISM to find the path of minimum

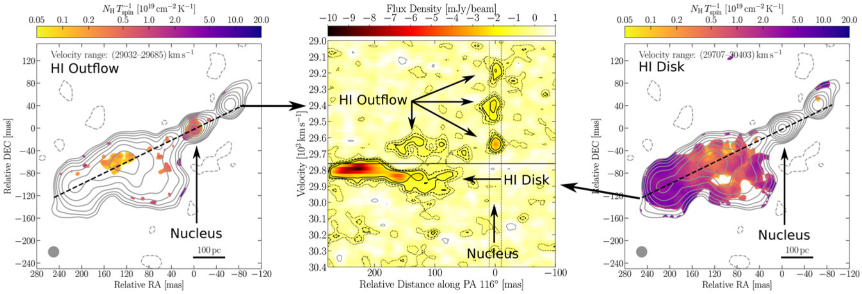

Figure 1. Radio continuum superposed on the H I absorption column density of the H I outflow (left) and of the H I disk (right) of the radio galaxy 3C236 obtained with VLBI. Position-velocity plot (centre) along the jet showing the outflowing clouds. From Schulz *et al.* (2018).

resistance and so creating an overpressured cocoon of outflowing and shocked gas, as suggested by Wagner *et al.* (2012); Mukherjee *et al.* (2018a).

Furthermore, for the smaller (and perhaps younger) sources in the sample (4C 12.50, Morganti *et al.* 2013 and 4C 52.37, Schulz *et al.* in prep) the VLBI observations not only spatially resolve the outflows, but they also recover all the H I flux observed at low resolution. This suggests that these outflows are mostly made up by relatively compact structures, easy to be detected at the very high resolution of VLBI observations. In the largest (and likely more evolved) sources, like 3C 293 (Schulz *et al.* in prep) and 3C 236 (Schulz *et al.* 2018), we also find evidence of a clumpy structure but the H I outflows in these sources are only partly recovered by VLBI. This suggests the additional presence of a diffuse component in which the clumps are embedded. This could be due to the expansion of the jet in the medium changing the structure of the outflows, the fraction of diffuse component increasing with time.

3. Do the low power jets have also an impact?

Interestingly, a growing number of cases (among which some listed above e.g. NGC1433, IC 5063, NGC1068, PG1700+518) show that, despite being classified as *radio quiet*, the power of the jet is sufficient to be the driving mechanism of their outflows. However, the simulations also show that an other effect expected from low power jets (Mukherjee *et al.* 2018b) is to increase the turbulence of the gas. Figure 2 shows the H I absorption detected against the kpc-scale jet of the low-luminosity radio source B2 0258+35. The width of the absorption (~ 400 km s^{-1}) is too large to be explained by the rotation of the large scale H I disk known to be present in this object. The most likely hypothesis is that the jet enters the disk and, being trapped there, disturbs the kinematics of the gas without being able to produce a fast outflow, but injects energy increases the turbulence of the gas (Murthy *et al.* 2019). As already suggested for the low-power radio source NGC 1266 (Alatalo *et al.* 2015), jet-induced turbulence may play a role in preventing star formation despite the large reservoir of cold gas observed in these objects.

4. Implications

The observations are showing evidence - in a growing number of sources - of interaction between the radio jets and the surrounding ISM. The properties appear to be, to first order, consistent with the predictions from some of the recent numerical simulations. This supports the idea that also on galactic scales the role of radio jets should not be neglected. However, the impact of outflows may not always be as large as required by models of galaxy evolution. A relatively small fraction of the outflowing gas may actually

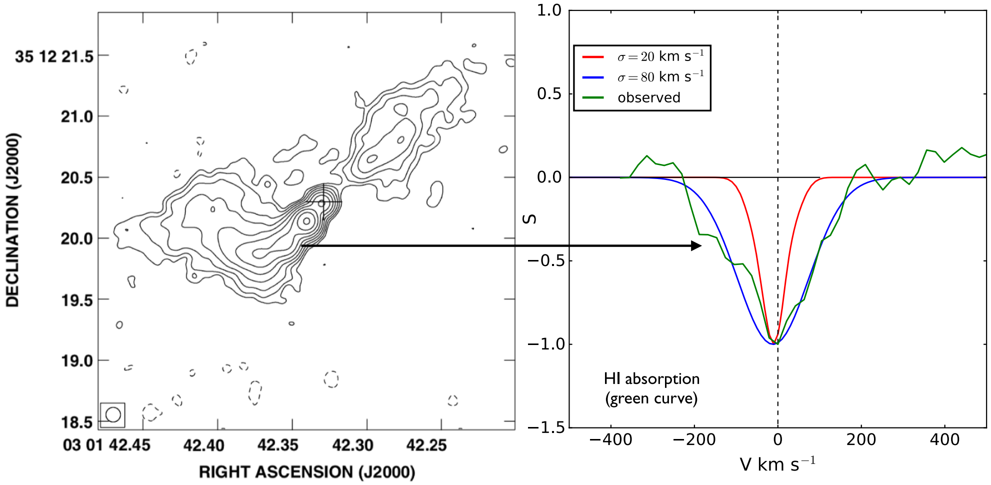

Figure 2. **Left:** Radio continuum image from Giroletti *et al.* (2005). **Right:** H I absorption profile (green) from VLA observations with superposed (red) the model from the H I disc observed in emission in this object by Struve *et al.* (2010) and in blue the model adding a component of turbulence due to the interaction of the jet with the H I in the disk (Murthy *et al.* 2019).

leave the galaxy. This is also seen in more AGN-driven outflows, i.e. those driven by winds or radiation. Thus, the likely main effect of jet-ISM interactions and their injection of energy could be on the redistributing the gas and possibly in keeping it turbulent for longer periods of time. This has been now seen in particular for (much more common) low luminosity radio jets. Thus, in addition to the search for violent processes like outflows, other more subtle effects needs to be searched for and investigated.

References

Alatalo, K., Blitz, L., Young, L. M., *et al.* 2011, *ApJ*, 735, 88
Alatalo, K., Lacy, M., Lanz, L., *et al.* 2015, *ApJ*, 798, 31
Cielo, S., Bieri, R., Volonteri, M., Wagner, A. Y., & Dubois, Y. 2018, *MNRAS*, 477, 1336
Combes, F., García-Burillo, S., Casasola, V., *et al.* 2013, *A&A*, 558, A124
Croston, J. H., Hardcastle, M. J., Kharb, P., Kraft, R. P., & Hota, A. 2008, *ApJ*, 688, 190
Dasyra, K. M., & Combes, F. 2012, *A&A*, 541, L7
García-Burillo, S., Combes, F., Usero, A., *et al.* 2014, *A&A*, 567, A125
Geréb, K., Maccagni, F. M., Morganti, R., & Oosterloo, T. A. 2015, *A&A*, 575, A44
Giroletti, M., Giovannini, G., & Taylor, G. B. 2005, *A&A*, 441, 89
Guillard, P., Boulanger, F., Lehnert, M. D., *et al.* 2015, *A&A*, 574, A32
Holt, J., Tadhunter, C. N., & Morganti, R. 2008, *MNRAS*, 387, 639
Morganti, R., Fogasy, J., Paragi, Z., Oosterloo, T., & Orienti, M. 2013, Science, 341, 1082
Morganti, R., Oosterloo, T., Oonk *et al.* 2015, *A&A*, 580, A1
Morganti, R. 2017, Nature Astronomy, 1, 596
Morganti, R. & Oosterloo, T. 2018, *A&ARev.* in press, arXiv:1807.01475
Mukherjee, D., Wagner, A. Y., Bicknell, G. V., *et al.* 2018a, *MNRAS*, 476, 80
Mukherjee, D., Bicknell, G. V., Wagner, A. Y. *et al.* 2018b, *MNRAS*, 479, 5544
Murthy, S., Morganti, R., Oosterloo, T., *et al.* 2019, *A&A*, 629, A58
Ogorzalek, A., Zhuravleva, I., Allen, S. W., *et al.* 2017, *MNRAS*, 472, 1659
Oosterloo, T., Raymond Oonk, J. B., Morganti, R., *et al.* 2017, *A&A*, 608, A38
Runnoe, J. C., Gültekin, K., & Rupke, D. S. N. 2018, *ApJ*, 852, 8
Schulz, R., Morganti, R., Nyland, K., *et al.* 2018, *A&A* in press, arXiv:1806.06653
Struve, C., Oosterloo, T., Sancisi, R., Morganti, R., & Emonts, B. H. C. 2010, *A&A*, 523, A75
Wagner A. Y., Bicknell G. V., & Umemura M. 2012, *ApJ*, 757, 136