Galaxy Evolution and Feedback across Different Environments
Proceedings IAU Symposium No. 359, 2020
T. Storchi-Bergmann, W. Forman, R. Overzier & R. Riffel, eds.
doi:10.1017/S1743921320001775

Taking snapshots of the jet-ISM interplay with ALMA

Raffaella Morganti[1,2], **Tom Oosterloo**[1,2] **and Clive N. Tadhunter**[3]

[1]ASTRON, the Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4,
7991PD Dwingeloo, The Netherlands
email: morganti@astron.nl

[2]Kapteyn Astronomical Institute, University of Groningen, Postbus 800,
9700 AV Groningen, The Netherlands
[3]Department of Physics and Astronomy, University of Sheffield, Sheffield, S7 3RH, UK

Abstract. We present an update of our ongoing project to characterise the impact of radio jets on the interstellar medium (ISM). This is done by tracing the distribution, kinematics and excitation of the molecular gas at high spatial resolution using ALMA. The radio active galactic nuclei (AGN) studied are in the interesting phase of having a recently born radio jet. In this stage, the plasma jets can have the largest impact on the ISM, as also predicted by state-of-the-art simulations. The two targets we present have quite different ages, allowing us to get snapshots of the effects of radio jets as they grow and evolve. Interestingly, both also host powerful quasar emission, making them ideal for studying the full impact of AGN. The largest mass outflow rate of molecular gas is found in a radio galaxy (PKS 1549−79) hosting a newly born radio jet still in the early phase of emerging from an obscuring cocoon of gas and dust. Although the molecular mass outflow rate is high (few hundred $M_\odot$ yr^{-1}), the outflow is limited to the inner few hundred pc region. In a second object (PKS 0023−26), the jet is larger (a few kpc) and is in a more advanced evolutionary phase. In this object, the distribution of the molecular gas is reminiscent of what is seen, on larger scales, in cool-core clusters hosting radio galaxies. Interestingly, gas deviating from quiescent kinematics (possibly indicating an outflow) is not very prominent, limited only to the very inner region, and has a low mass outflow rate. Instead, on kpc scales, the radio lobes appear associated with depressions in the distribution of the molecular gas. This suggests that the lobes have broken out from the dense nuclear region. However, the AGN does not appear to be able, at present, to stop the star formation observed in this galaxy. These results support the idea that the effects of the radio source start in the very first phases by producing outflows which, however, tend to be limited to the kpc region. After that, the effects turn into producing large-scale bubbles which could, in the long term, prevent the surrounding gas from cooling. Thus, our results provide a way to characterise the effect of radio jets in different phases of their evolution and in different environments, bridging the studies done for radio galaxies in clusters.

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

1. Introduction

The evolution of massive galaxies appears to be strongly influenced by the energy released during the active phase of their super massive black hole (SMBH). This process, known as feedback, is considered the one regulating, and quenching, their star formation (e.g. Harrison 2017). Feedback is believed to work in two main modes, both aimed at reducing the amount of cold gas and the related star formation: "quasar" mode, with gas outflows driven by the active galactic nucleus (AGN), clearing the gas from the host galaxy, and the "maintenance" mode, where the energy released by the AGN prevents the cooling of the gas on larger scales, from the hot halo or from the intergalactic medium. In the commonly assumed picture of AGN feedback, the role of radio jets is considered to be mostly connected to the latter mode (see e.g. McNamara & Nulsen 2012). This mode complements the effect of outflows/winds considered to dominate in radiatively efficient AGN. However, the picture we are getting from the growing number of detailed observations tracing multiple phases of the gas appears to be more complex and these two modes appear intertwined. An example of such complexity is the fact that radio jets can also produce gaseous outflows, thus having an impact on (sub) kpc-scales. Furthermore, their relative importance may even change during the life of the AGN. *Thus, radio AGN with jets represent ideal objects to trace the feedback while they evolve from sub-kpc to many tens of kpc scales.*

The impact of jets in producing outflows has been observed in an increasing number of both high- and low-power (including radio quiet) radio sources (Morganti 2020 and refs therein). Particularly interesting is that jet-driven outflows are more prominent when the jets are in their initial phase (see e.g. Holt *et al.* 2009; Shih *et al.* 2013; Morganti & Oosterloo 2018; Molyneux *et al.* 2019 and many others). Newly born or young radio jets can be identified by the characteristics of their radio emission (e.g. size, and peaked radio spectrum, for more details see e.g. O'Dea 1998; Orienti 2016). The impact of jets in their starting phase is also predicted by numerical simulations. The work of Wagner *et al.* (2012); Bicknell *et al.* (2018); Mukherjee *et al.* (2016, 2018a) has shown the strong coupling of the newly born jet with the surrounding clumpy interstellar medium (ISM). Furthermore, this interaction is predicted to produce a cocoon of shocked gas expanding perpendicular to the jet, thus impacting a much larger volume of the host galaxy than just the region of the jets themselves.

Finally, the *impact of jets can be dominant even when a radiatively efficient AGN is present*. The best example of this is IC 5063, a Seyfert 2 galaxy, with strong emission lines. This galaxy hosts low radio power jets ($P_{1.4\ \mathrm{GHz}} \sim 10^{23.4}$ W Hz^{-1}). Despite the low radio power, they provide one of the clearest examples of jet-induced outflows, where the radio plasma is disturbing the kinematics of *all the phases of the gas* (see Tadhunter *et al.* 2014; Morganti *et al.* 2015, for an overview). The region co-spatial with the radio emission is where the most kinematically disturbed ionised, molecular and HI gas is located (with velocities deviating up to 600 km s^{-1} from regular rotation). This jet-ISM interaction also affects the physical conditions of the gas (Oosterloo *et al.* 2017). The properties observed have been well reproduced by hydrodynamic simulations and the details of the comparison between the data and the simulation is presented in Mukherjee *et al.* (2018a).

All this strongly indicates the relevance of radio jets, particularly in the initial phases of their evolution. However, after 1-2 kpc (typically after a few Myr) the jet breaks out from the dense central core and the way it interacts with the surrounding medium changes. *Thus, should we expect that the impact will change with jet evolution?* This question is particularly important, also because there appears to be a general consensus that most observed outflows (regardless their origin) are largely limited to the central kpc region while only a small fraction of the outflowing gas is actually leaving the galaxy. Thus, gas outflows may not be enough to supply the required feedback from AGN. Here we focus on two powerful radio sources ($P \sim 10^{26}$–10^{27} W Hz^{-1}) with jets in different phases of their *initial* evolution. Interestingly, the sources also host radiativly efficient AGN. Thus, in these objects there is no shortage of energy released by their active SMBH. We use molecular gas as tracer of the impact of the AGN because it is typically found to carry most of the outflowing mass. This is part of a larger project to understand the impact of radio jet as function of their properties (i.e. power, age, environment etc.; see also Maccagni *et al.* 2018; Oosterloo *et al.* 2017 for other objects studied).

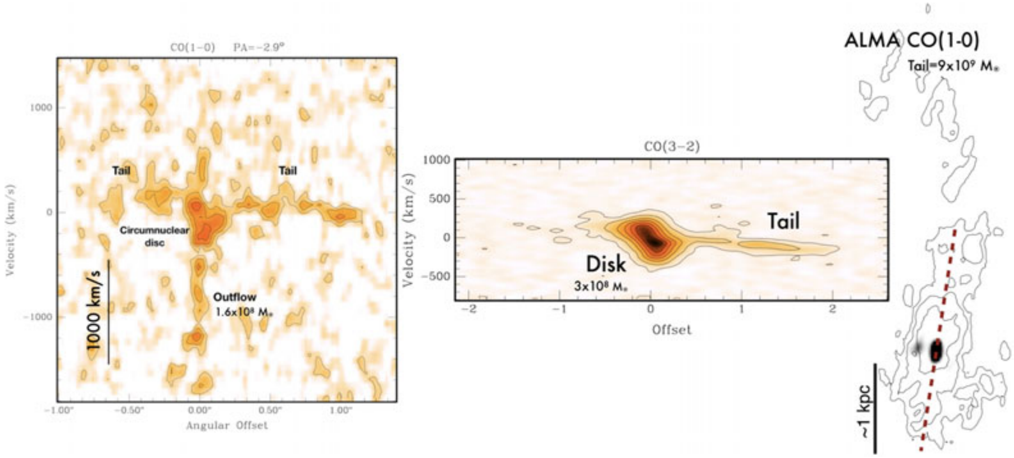

Figure 1. The distribution and kinematics of the molecular gas in the central few hundred pc of PKS 1549−79 as obtained with ALMA, see Oosterloo *et al.* (2019) for details. ALMA CO(1-0) and CO(3-2) detected in emission with spatial resolution ranging from 0.05 arcsec (∼100 pc) to 0.2 arcsec. The position-velocity plots are made along the dashed line, Morganti (2020).

2. Accretion and feedback in an obscured, young radio quasar

The first object shown here is PKS 1549−79 ($z = 0.150$), having a young radio jet (∼300 pc in size) hosted by an obscured, far-IR bright quasar and, therefore, in a particularly crucial early stage in the evolution (Holt *et al.* 2006). As expected, a fast outflow of warm ionised gas as well as a Ultra Fast Outflow in X-rays (Tombesi *et al.* 2014) are present, but the kinetic power of the warm outflow $\sim 4 \times 10^{-4}\, L_{\rm edd}$.

The ^{12}CO(1–0) and CO(3-2) ALMA high resolution observations (Oosterloo *et al.* 2019) show the presence of three gas structures, which can be seen in Fig. 1. Kiloparsec-scale tails are observed, resulting from an on-going merger which provides gas that is accreting onto the centre of PKS 1549–79. At the same time, a circum-nuclear disc has formed in the inner few hundred parsec, and a very broad ($>$2300 km s^{-1}) component associated with fast outflowing molecular gas is detected at the position of the AGN. As expected, the outflow is massive ($\sim$600 M$_\odot$ yr^{-1}) but, despite the fact that PKS 1549−79 should represent an ideal case of feedback in action, it is limited to the inner 200 pc. These results illustrate that the impact on the surrounding medium of the energy released by the AGN is not always as expected from the feedback scenario. The outflow of warm, ionised gas is slightly more extended (see Oosterloo *et al.* 2019), but modest in terms of mass outflow rate ($\sim$2 M$_\odot$ yr^{-1}; Holt *et al.* 2006, Santoro *et al.* in prep).

Both the jet and the radiation could drive the outflow. Circumstantial evidence suggests that the jet may play the prominent role. We observed a strongly bent component of the jet, characterised by a very steep radio spectrum. This suggests that this part of the jet is a remnant structure, possibly resulting from a strong interaction that has temporarily destroyed the jet. This interaction could have produced the massive outflow. This interaction is also impacting the conditions of the gas, as seen from the high ratio CO(3-2)/CO(1-0) found in the central regions. The depletion time is relatively short (10^5-10^6 yr), suggesting that the outflow will last only for a relatively short time.

3. PKS 0023−26: a few kpc-scale young radio AGN

A second object, PKS 0023−26 ($z = 0.32188$), was selected because, although still a young radio source, it is in a more evolved phase having reached already a few kpc in

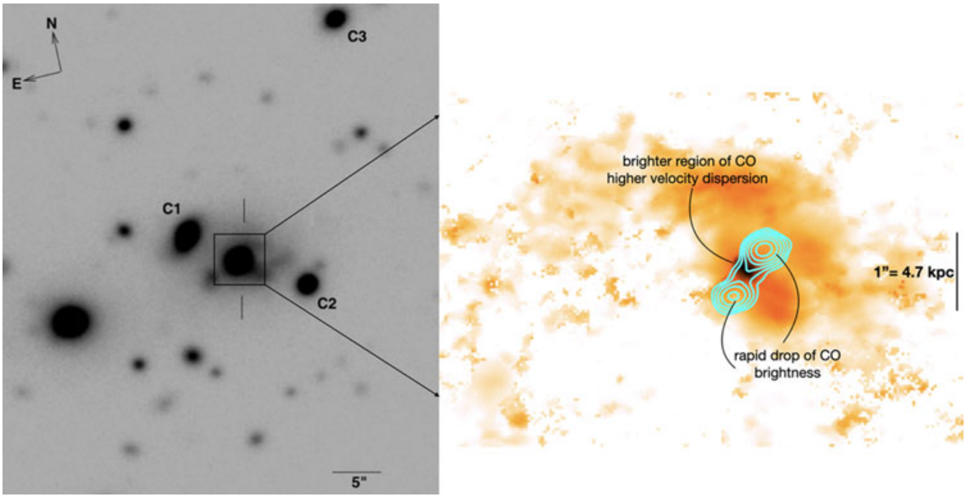

Figure 2. Left Optical image from Gemini GMOS-S. Marked as C1, C2, C3 galaxies confirmed to have redshifts similar to PKS 0023−26. More objects and tails are seen even closer (∼10 kpc) to the target galaxy, Ramos Almeida *et al.* (2013); **Right** Total intensity of the molecular gas (orange scale) with superimposed contours (cyan) of the continuum emission. The center(core) of the radio emission is coincident with the peak of the molecular gas.

size. Perhaps unusual for powerful radio galaxies, it is located in a dense environment (see Fig. 2, left; Ramos Almeida *et al.* 2013). Also interesting is the presence in the host galaxy of an extended region with a very young stellar population (∼30 Myr, Holt *et al.* 2006; Tadhunter *et al.* 2011). The corresponding star formation rate (∼30 $M_\odot$ yr^{-1}) is consistent with what is expected for main-sequence star forming galaxies of similar stellar mass as the host galaxy. The deep, high resolution (0.2 arcsec) ALMA CO(2-1) observations reveal that PKS 0023−26 is embedded in 5×10^{10} $M_\odot$ of molecular gas, distributed over about 20 kpc (see Fig. 2, right). Interestingly, the distribution is reminiscent of those seen in cool-core clusters (e.g. Russell *et al.* 2019), because it appears offset from the centre of the galaxy (and radio source). Part of the gas distributed in filaments with relatively smooth velocity gradients reaching out some of the companion galaxies. However, the large amount of molecular gas detected, and the high velocity dispersions observed, suggest that, at least part of the gas is coming from the cooling of the hot X-ray halo (tentatively detected with XMM; Mingo *et al.* 2014).

The central region is brightest in CO (Fig. 2, right), either because the molecular gas has piled up there, or because it has higher excitation due to the stronger impact of the AGN (as seen in other objects; Oosterloo *et al.* 2017, 2019). Indeed, in this object the gas with velocities deviating from the quiescent kinematics is also located in the central sub-kpc region. However, the velocities are low (not more than ∼300 km s^{-1}). If associated with an outflow, the mass outflow rate is much more modest than in PKS 1549−79. Interestingly, this appears to follow the trend found by Holt *et al.* (2008) for the ionised gas: the amplitude of the outflows decreases as the radio jets expand. Outside this central region, the brightness of the molecular gas drops rapidly in the regions of the radio lobes. A possible explanation is that the jets have already broken out from the dense, central region and are now starting to create radio plasma bubbles which, at a certain point time, will prevent the cooling of the hot ISM. Thus, the AGN (optical and radio) does not have *at present* any substantial impact on the gas on galaxy scales of tens of kpc where substantial star formation is ongoing from the large reservoir of molecular gas.

Possibly, the radio source is still too young and is in an early phase of interaction with the rich gaseous medium and *only starting* to affect it.

4. Connecting the two objects: evolution of the impact of the jets?

Based on the results on these two objects (and other cases studied in detail in the literature, see Morganti 2020 for an overview), we suggest that in the first phases (i.e. in the sub-kpc region and for ages $<10^6$yr) the radio jets are expanding in the inner dense, clumpy ISM where the coupling between the jet and the ISM is very strong. In this phase, the jets can drive fast and massive outflows. The meandering of the jet through the ISM also creates a cocoon of shocked gas expanding in the direction perpendicular to the jet (see Mukherjee *et al.* 2018a and refs therein). Although the mass outflow rate of the molecular gas can be large in very young jets (as found in PKS 1549−79), the size of the region affected can be limited to a few hundred pc. Furthermore, the speed of the outflows appears to decrease as the jet expands as seen in PKS 0023−26 (and found for the ionised gas; Holt *et al.* 2009). However, the impact appears to change as the jet evolves. When the radio jets expand further, i.e. outside the 1-2 kpc region, they break out from the dense central gas and the type of interaction changes, becoming more similar to the one observed e.g. in X-rays with the formation of cavities and jet-driven expanding bubbles in the host galaxy and in the IGM.

In the case of PKS 0023−26, the gas at kpc scales is still forming stars, unaffected by the AGN. This will likely continue until the available molecular gas is depleted by this process ($\sim 10^9$ yr) while in the meantime the effect of the growing jets will likely increase. When they reach larger scales (tens of kpc on time scales of a few $\times 10^7 - 10^8$ yr), they can become more efficient in preventing more of the hot gas in the halo from cooling and, therefore, quenching future star formation. It interesting that studies focusing on the star formation rate and AGN luminosity are reaching similar conclusions (see Harrison *et al.* 2019). In order to confirm the trends found so far and to test this scenario, we need to expand the number of radio galaxies studied, while covering a large parameter space in terms of age and radio power, as well as exploring the properties of the hot gas.

References

Bicknell, G. V., Mukherjee, D., Wagner, A. Y., *et al.* 2018, *MNRAS*, 475, 3493
Harrison, C. M. 2017, *Nature Astronomy*, 1, 0165
Harrison, C. M., Alexander, D. M., Rosario, D. J., *et al.* 2019, arXiv e-prints, arXiv:1912.01020
Holt, J., Tadhunter, C., Morganti, R., *et al.* 2006, *MNRAS*, 370, 1633
Holt, J., Tadhunter, C. N., & Morganti, R. 2008, *MNRAS*, 387, 639;
Holt, J., Tadhunter, C. N., & Morganti, R. 2009, *MNRAS*, 400, 589
Maccagni, F. M., Morganti, R., Oosterloo, T. A., *et al.* 2018, *A&A*, 614, A42
McNamara, B. R. & Nulsen, P. E. J. 2012, *New Journal of Physics*, 14, 055023
Mingo, B., Hardcastle, M. J., Croston, J. H., *et al.* 2014, *MNRAS*, 440, 269
Molyneux, S. J., Harrison, C. M., & Jarvis, M. E. 2019, *A&A*, 631, A132
Morganti, R., Oosterloo, T., Oonk, J. B. R., *et al.* 2015, *A&A*, 580, A1
Morganti, R. & Oosterloo, T. 2018, *A&ARew*, 26, 4
Morganti, R. 2020, *proceedings of IAU Symp 356*, arXiv e-prints, arXiv:2001.02675
Mukherjee, D., Bicknell, G. V., Wagner, A. Y. *et al.* 2018a, *MNRAS*, 479, 5544
Mukherjee, D., Bicknell, G. V., Sutherland, R., *et al.* 2016, *MNRAS*, 461, 967;
O'Dea, C. P. 1998, *PASP*, 110, 493
Oosterloo, T., Raymond Oonk, J. B., Morganti, R., *et al.* 2017, *A&A*, 608, A38
Oosterloo, T., Morganti, R., Tadhunter, C., *et al.* 2019, *A&A*, 632, A66
Orienti, M. 2016, *Astronomische Nachrichten*, 337, 9
Ramos Almeida, C., Bessiere, P. S., Tadhunter, C. N., *et al.* 2013, *MNRAS*, 436, 997
Russell, H. R., McNamara, B. R., Fabian, A. C., *et al.* 2019, *MNRAS*, 490, 3025

Shih, H.-Y., Stockton, A., & Kewley, L. 2013, *ApJ*, 772, 138
Tadhunter, C., Holt, J., González Delgado, R., *et al.* 2011, *MNRAS*, 412, 960
Tadhunter, C., Morganti, R., Rose, M., *et al.* 2014, *Nature*, 511, 440
Tombesi, F., Tazaki, F., Mushotzky, R. F., *et al.* 2014, *MNRAS*, 443, 2154
Wagner, A. Y., Bicknell, G. V., Umemura, M., *et al.* 2012, *ApJ,* 757, 136