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The impact of young radio jets traced by cold molecular gas

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Abstract

Ranging from a few pc to hundreds of kpc in size, radio jets have, during their evolution, an impact on their gaseous environment on a large range of scales. While their effect on larger scales is well established, it is now becoming clear that they can also strongly affect the interstellar medium (ISM) inside the host galaxy. Particularly important is the initial phase ($< 10^6$ years) of the evolution of the radio jet, when they expand into the inner few kpc of the host galaxy. Here we report on results obtained for a representative group of young radio galaxies using the cold molecular gas as a tracer of jet-ISM interactions. The sensitivity and high spatial resolution of ALMA and NOEMA are ideal to study the details of this process. In many objects, we find massive molecular outflows driven by the plasma jet, even in low-power radio sources. However, the observed outflows are limited to the circumnuclear regions and only a small fraction of the ISM is leaving the galaxy. Beyond this region, the impact of the jet seems to change. Fast outflows are replaced by a milder expansion driven by the expanding cocoon created by the jet-ISM interaction, resulting in dispersing and heating the ISM. These findings are in line with predictions from simulations of jets interacting with a clumpy medium and suggest a more complex view of the impact of AGN than presently implemented in cosmological simulations.

KEYWORDS

galaxies: active, ISM: jets and outflow, radio lines: galaxies

1 | IMPACT OF (YOUNG) RADIO JETS FROM SMALL TO LARGE SCALES

The impact on the surrounding medium of the energy released by super-massive black holes in their active phase (also known as active galactic nuclei, AGN) is an important ingredient of models of galaxy evolution. However, this effect, known as AGN feedback, has proven to be more complex than often implemented in cosmological simulations (e.g. Weinberger et al. 2017; Zinger et al. 2020). This is due to the large parameter space that determines the type and magnitude of feedback and its evolution during the life of the host galaxy. Radio jets are known to be relevant for AGN feedback. However, it is often thought that their main role is limited to preventing the cooling of gas of the large-scale inter-galactic and intra-cluster medium, the so-called *maintenance mode* (e.g. McNamara

& Nulsen 2012). Although this is some of the best evidence for AGN feedback, recent results show that the impact of jets starts at an early stage in the inner, circumnuclear regions of the host galaxy. This highlights the important role played by young radio jets (i.e. with ages $\ll 10^6$ years), which can, for example, drive fast gas outflows. Compact Steep Spectrum (CSS) and GigaHertz Peaked Spectrum (GPS) sources represent candidate young radio sources (O'Dea & Saikia 2021) and are ideal targets to study the details of this impact.

The presence of jet-driven outflows traced by warm ionized gas is known since a long time (e.g. Capetti et al. 1999; Whittle et al. 1988 and refs therein) as outflows of warm ionized gas (with velocities up to more than 2,000 km s^{-1}) are found to be common in young radio galaxies (e.g. Holt et al. 2008; Shih et al. 2013). However, the associated mass outflow rates of these outflows are modest (typically below 1 $M_\odot$ year^{-1}) and the impact—in terms of the ratio between the kinetic energy of the outflow and the bolometric or Eddington luminosity—is limited (see e.g. Holt et al. 2011 and refs therein).

However, two main aspects have recently revamped the interest in the relevance of radio jets for feedback: the discovery of young radio galaxies with massive jet-driven outflows of cold (H I and molecular) gas, which are significantly more massive than those of warm ionized gas (see Morganti & Oosterloo 2018 for a review on the HI), and the predictions from more realistic numerical simulations of the impact of jet-ISM interactions (e.g. Mukherjee et al. 2018a). Most importantly, these numerical simulations show that a large parameter space needs to be explored in order to fully quantify the impact of the jet. These results form the basis of the work presented here.

The general relevance of AGN-driven outflows of cold molecular gas is motivated by the finding that they appear to carry most of the mass of the overall outflow. Their mass outflow rate is typically found to be much higher than what is associated with warm, ionized gas (see Veilleux et al. 2020 for an overview). The presence of cold gas in AGN-driven outflows is surprising at first sight, but has been explained by the very rapid cooling that dense, shocked gas can experience (e.g. Mukherjee et al. 2018b; Richings & Faucher-Giguère 2018).

2 | THE OBSERVED SAMPLE AND THE PREDICTIONS FROM THE SIMULATIONS

Numerical simulations of jet-ISM interactions (Mukherjee et al. 2018a and refs therein) show that the impact of the jet may depend on a number of parameters, like jet power, age of the jet, and the orientation between the jet and the distribution of the ISM. Because of this, we have embarked on a project aimed to study the properties of the cold molecular gas in a representative sample of gas-rich young radio galaxies covering this parameter space. The observations are obtained with high enough spatial resolution to resolve the distribution and kinematics of the gas across the radio emission. For our project, we have used the Atacama Large Millimeter/submillimeter Array (ALMA) and, more recently, the NOrthern Extended Millimeter Array (NOEMA). Here, we present a brief summary of some of the results obtained so far.

We have observed 7 CSS and GPS sources in CO(1–0) or CO(2–1) at spatial resolutions ranging between 0.2 and 1.5 arc sec, enabling to spatially resolve the distribution of the CO along the radio continuum emission. For two more targets, the observations are in progress. Only for two objects, observations of two or more CO transitions are available. The sources were mainly selected from Holt et al. (2008) and Geréb et al. (2015) so that also information about the other component of the cold gas, H I, is available. Based on their H I properties, two more sources were included (IC 5063 and PKS 1718-64). The sample is, therefore, selected to include some of the best cases where to study the process of jet-ISM interaction. Furthermore, the objects were selected to cover a variety of properties of young radio galaxies. They range from extremely small and young sources (like PKS 1718-64: 2 pc in size and a $\sim 10^2$ year age of the radio activity; Maccagni et al. 2018) to older and larger, kpc-scale sources (like PKS 0023-26: ~4 kpc in size and $\sim 10^6$ year old; Morganti et al. 2021). Furthermore, the sample includes radio-quiet, low radio power radio sources ($<10^{24}$ W Hz^{-1}) as well as very powerful ones ($>10^{27}$ W Hz^{-1}).

To guide the interpretation of the observations, we use the state-of-the-art hydrodynamic simulations of jet-ISM interactions, of Sutherland & Bicknell (2007); Wagner et al. (2012) and Mukherjee et al. (2018a). An important result of these simulations is that the jet couples very strongly to the ISM if propagating in a clumpy medium. Furthermore, as shown in Figure 1, the simulations suggest four phases in the evolution of the jets, each providing a different type of impact on the surrounding ISM: (1) an initial "flood and channel" phase, where the expansion of the jet strongly depends on the interaction with high-pressure clumps of gas; (2) as consequence of this interaction, the formation of a spherical, energy-driven bubble phase starts; (3) a subsequent, rapid phase where the jet breaks free from the last obstructing dense clouds; and (4) a classical phase, where the jet propagates to large scales in a momentum-dominated fashion. The first phase is where we expect fast and massive outflows, while in the final phases the effect of the jet may act more in preventing the ISM/IGM gas to cool. The duration and details of

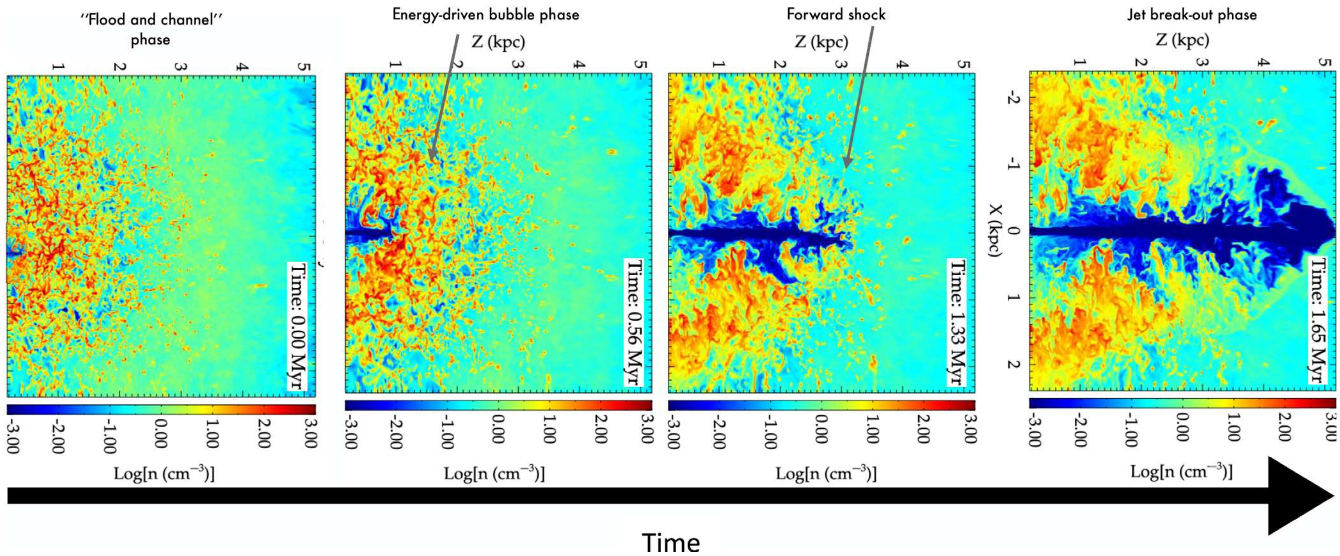

FIGURE 1 Simulations of a radio jet expanding in a clumpy medium in the inner 5 kpc of the host galaxy (images taken from Mukherjee et al. 2016). The different phases and their impact are marked following Sutherland & Bicknell (2007), see text

these phases depend on jet power. Interestingly, simulations predict that even low-power jets are able to impact the medium, as their phase of interaction with the ISM will last longer and, therefore, they will inject their energy for a longer time (see Mukherjee et al. 2018a).

3 | RESULTS SO FAR: COVERING A LARGE PARAMETER SPACE

Despite the limited sample studied so far, we already have a number of interesting insights.

- The only case where we could identify infalling clouds of molecular gas, likely connected with the fueling of the AGN, is PKS 1718-64 (Maccagni et al. 2018). Interestingly, this is the smallest (and youngest) radio source in the sample. With only 2 pc in size, the radio plasma may not have been able yet to affect the surrounding medium. The detection of infalling cloud appears to be consistent with a fueling process, as predicted by the chaotic cold accretion (e.g. Gaspari et al. 2017) and similar to the case of PKS 2322–123 in Abell 2597 (Tremblay et al. 2016).
- Molecular outflows are detected in a number of objects. In the best studied case, IC 5063 (Morganti et al. 2015; Oosterloo et al. 2017), we have detected kinematically disturbed molecular gas along the full extent of the radio source (about 1 kpc). The comparison between observations and simulations shows that the radio jets can produce the observed distribution and kinematics of the molecular gas (Mukherjee et al. 2018b).
- In the dust-obscured, young and powerful radio galaxy PKS 1549-79, we detect, using ALMA, one of the most massive molecular gas outflows ($\sim 650\, M_\odot$ year^{-1}) likely driven by the radio jet in the process of clearing its way out from the enshrouding dense gas (Oosterloo et al. 2019). However, the outflow is limited to the inner 200 pc of the galaxy, despite the presence of a powerful jet and also a powerful quasar AGN. A circumnuclear disk of $M_{H_2} = 2.6 \times 10^8\, M_\odot$ is observed and appears to co-exist with the outflow. This means that, unless the gas in the disk is replenished, on a time scale of $\sim 10^5$ years the AGN would be able to destroy the central disk of molecular gas and deplete the central region of this gas.
- Outflows are also found to be driven by low-power jets. The NOEMA CO(1–0) observations of B2 0258 + 35 ($L_{1.4\mathrm{GHz}} = 2.1 \times 10^{23}$ W Hz^{-1}; Murthy et al. 2021) show a spectacular example of this and further confirms the predictions from simulations. We detect a highly turbulent molecular circumnuclear structure, where a fast (FWHM $\sim$350 km s^{-1}) jet-driven outflow of $\sim 2.6 \times 10^6\, M_\odot$ is observed. This outflow comprises of $\sim$75% of the total gas in the nuclear region. In addition, in this case, the jet will deplete the kpc-scale molecular gas reservoir on a relatively short time scale (i.e. within 2×10^6 years).
- We find mass molecular gas outflow rates ranging from tens to a few hundred $M_\odot$ year^{-1}, but only a relatively small fraction of the gas (at most $\sim$10%) leaves the galaxy: most of the gas will rain back in a *fountain-like effect*. Thus, our work suggests that molecular outflows, even if present, cannot be the only effect

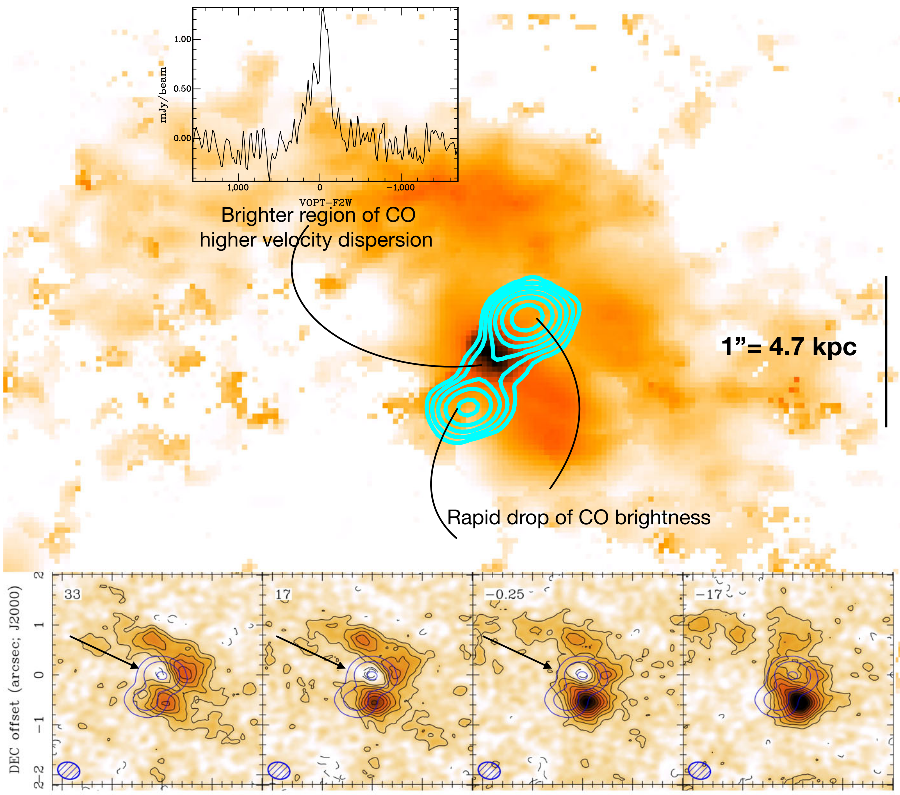

FIGURE 2 Top—distribution of the molecular gas (CO(2–1) from ALMA) of PKS 0023-26. The contours of the 3-mm continuum emission are indicated in cyan. The locations of the most relevant features are indicated. Bottom—four channel maps showing the distribution of the gas at different velocities (33, 17,–0.25, –27 km s^{-1} w.r.t. the systemic velocity). Some of the regions/velocities where the molecular gas is seen to wrap around the radio lobes are indicated for clarity

responsible for the AGN feedback required in cosmological simulations.

- Interestingly, in the most extended (~4 kpc) and powerful radio source of the sample (PKS 0023-26, which also hosts a quasar AGN), only a mild outflow is observed limited to the sub-kpc region. Instead, on kpc scales, the molecular gas is distributed predominantly around the radio lobes forming a bubble-like structure (see Figure 2 and Morganti et al. 2021). This bubble is likely driven by the expansion of the cocoon created by the jet-ISM interaction, pushing aside the preexisting molecular gas and resulting in dispersing and heating the molecular clouds. This is more similar to the "maintenance" phase, preventing the gas from cooling, known to happen on even larger scales. Thus, these ALMA observations suggest that the mode of coupling between radio jets and the ISM could change as the jet expands and that, already on galaxy scales, the impact of the AGN is not limited to outflows.
- Finally, also the physical conditions of the molecular gas are affected by the impact of the (radio) AGN. This has been seen using multiple CO transitions in the cases of IC 5063 (see Figure 3) and PKS 1549-79, see Oosterloo et al. (2017) and Oosterloo et al. (2019), respectively. The line ratios of the CO transitions indicate that the gas in the region affected by the interaction with the radio plasma has different excitation and/or optical thickness, as result of the impact from strong shocks. Instead, where the gas has quiescent kinematics, the line ratios are similar to what is observed in normal gas disks in galaxies.

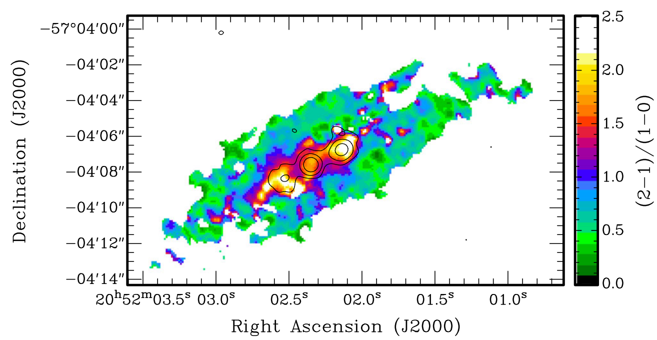

FIGURE 3 Line ratio CO(2–1)/CO(1–0) of IC 5063 with overlaid the radio continuum contours. A sharp difference is visible between the region co-spatial with the radio jet and where the gas has a quiescent kinematics (from Oosterloo et al. 2017)

4 | CONCLUSIONS AND FUTURE WORK

The results obtained, even if limited to a small number of cases, show the impact of radio jets on the surrounding molecular gas, demonstrating the relevance for feedback. Confirming predictions of the simulation for the importance of low-power radio sources is also important: these sources are relatively common in massive galaxies (Best et al. 2005) and, therefore, they can provide an important population of AGN for feedback. These results will be expanded to more objects (two more sources are in the process of being observed) to better sample how the impact changes with the properties of the jet and to improve the comparison with the predictions of the simulations.

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Raffaella Morganti is a senior astronomer at the Netherlands Institute of Radio Astronomy and affiliated to the University of Groningen as professor. She works on radio AGN and, in particular, on the gas content and properties of these objects in relation to their evolution and life-cycle. This has been the focus of her ERC-AdG RadioLife (see also http://astron.nl/~morganti).

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