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Jet-CO alignments in the environments high-z radio galaxies

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Abstract. In the outskirts of massive high-redshift radio galaxies, powerful radio-jets often interact with ambient warm Lyα-emitting gas. We present the discovery of luminous reservoirs of cold molecular gas in these environments, based on CO(1-0) observations with the Australia Telescope Compact Array. The CO-emission is aligned with the radio jets, and found tens of kpc outside the host galaxy. These molecular gas reservoirs have CO luminosities in the range of those found in submm-galaxies ($L'_{\rm CO} \sim 4{-}9 \times 10^{10}$ K km/s pc^2), but they lack any near-infrared counterpart in deep *Spitzer* imaging. These results suggest that jet-triggered feedback takes place in the circum-galactic environment of high-z radio galaxies. We prefer the interpretation that the CO-emitting gas is formed when the propagating jets enrich, shock and cool pre-existing dusty halo gas. We further argue that sensitive low-surface-brightness CO observations, using radio interferometers in very compact array-configurations, are essential to study the role of the cold molecular medium in the outskirts of massive high-z galaxies.

Keywords. galaxies: halos, active, jets, intergalactic medium, techniques: interferometric

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1. Introduction

High-z radio galaxies (HzRGs) are among the most massive and active galaxies in the Universe (e.g. Miley & De Breuck 2008). They are often embedded in giant ∼100 kpc halos of Lyα-emitting gas (T∼10^4 K; Villar-Martin *et al.* 2003). Soon after their initial discovery in the late 1980s, near-universal alignments were found between the radio synchrotron jets and the optical/UV morphology of the host galaxies (Chambers *et al.* 1987; Mc Carthy *et al.* 1987). These alignments were initially ascribed to jet-triggered star-formation, although their true nature has since remained elusive. Later, similar alignments were reported between the radio jets and the distribution of both dust and cold molecular gas (Stevens *et al.* 2003, Klamer *et al.* 2004).

We here report on recently completed CO(1-0) studies, which reveal that detectable amounts of cold molecular gas can reside in the environments of HzRGs (Emonts *et al.* 2014, 2015a,b). We confirm the trend that CO often aligns with the radio jets, as evidence for jet-induced feedback onto the gaseous medium around HzRGs,

2. Methods

We used the 30-50 GHz system of the Australia Telescope Compact Array (ATCA) to study CO(1-0) in a representative sample of 13 southern HzRGs at $z \sim 1.4 - 2.9$, with no selection-bias on infrared- or submm-luminosity (Emonts *et al.* 2014). The on-source integration time ranged from 10−25h per target. The ground-transition CO(1-0) is the most robust tracer of the overall molecular gas mass, including any widespread and sub-thermally excited component (Papadopoulos *et al.* 2001). The ATCA has very compact, hybrid array-configurations with short baselines, which makes it sensitive for detecting low-surface-brightness emission of CO(1-0).

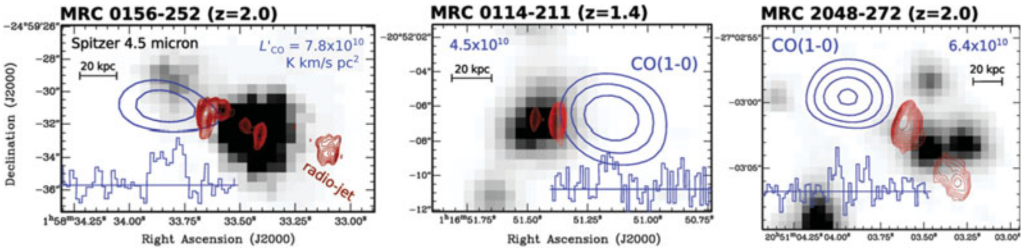


Figure 1. CO(1-0) in the environments of three HzRGs (adapted from Emonts *et al.* 2014, their Fig. 5). The CO (thick blue contours) is found beyond the radio-jet (thin red contours), at a location devoid of *Spitzer* 4.5 μm emission (greyscale). CO contours: 2.8, 3.5, 4.2, 4.9σ, with $\sigma = 0.095, 0.094, 0.080$ Jy/beam × km/s for MRC 0156-252, 0114-211, 2048-272. The 8.2 GHz radio-continuum data are from Carilli *et al.* (1997) and De Breuck *et al.* (2010), *Spitzer* data from Wylezalek *et al.* (2013); color version available online.

3. Results

We detect CO(1-0) in 5 out of 13 HzRGs (Emonts *et al.* 2014). Fig. 1 shows three cases where an unresolved CO(1-0) reservoir is found tens of kpc outside the radio galaxy. The CO(1-0) is located beyond the brightest edge or the radio source, and covers $\mathrm{FWZI_{CO}} \sim 1000-2000$ km/s. The CO luminosities, $L'_{\rm CO} \sim 4-9 \times 10^{10}$ K km/s pc^2, are comparable to those of submm galaxies, but no counterpart is visible in deep 4.6μm *Spitzer* data. This is similar to the case of TXS 0828+193 (Nesvadba *et al.* 2009). Therefore, the CO traces a cold and possibly diffuse molecular medium.

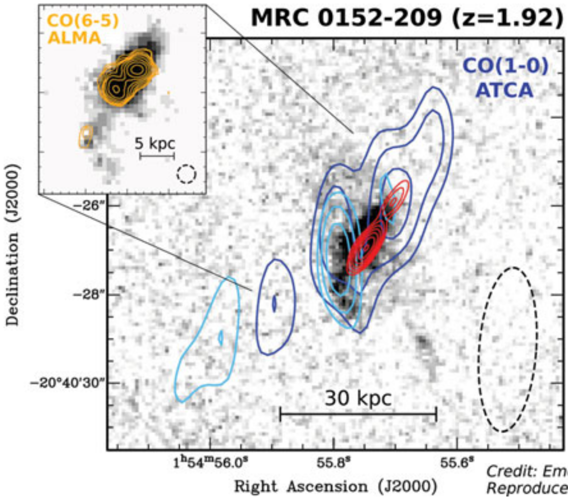
Fig. 2 shows the CO-rich environment of the Dragonfly Galaxy (MRC 0152-209) at $z = 1.92$. This is one of the most IR-luminous HzRGs (SFR ~ 3000 M$_\odot$ yr^{-1}; Drouart *et al.* 2014). ALMA revealed three compact CO(6-5) components in the central 10 kpc, classifying this is a rare triple merger (Emonts *et al.* 2015b). With ATCA we detect tidal debris in CO(1-0) across ~60 kpc (Emonts *et al.* 2015a). Also here, the ~18 kpc radio source aligns with part of the extended CO.

4. Discussion

The jet-CO alignments suggest that powerful high-z radio jets exert feedback onto the circum-galactic environment, tens of kpc outside the host galaxy. We believe that the molecular CO-emitting gas is likely formed when the propagating jets shock, compress and cool pre-existing dusty halo-gas (see discussion in Emonts *et al.* 2015a). Possibly the jets also enrich the gas by dragging metals out into the environment (Kirkpatrick *et al.* 2011). These CO(1-0) results may thus provide evidence in support of predicted key processes that drive the early evolution of massive galaxies, such as jet-triggered star formation or cooling flows. However, the exact mechanism behind the jet-CO alignments is not yet clear. An alternative explanation is that the radio jets brighten when they encounter a pre-existing reservoir of dense gas (also Stevens *et al.* 2003). We are currently analysing low-surface-brightness ALMA data to further study these cold gas reservoirs.

5. Outlook

Our results show the need to study the cold molecular medium around active galaxies to fully understand black-hole feedback in the Early Universe. Traditional mm-facilities can only target the $J \geqslant 3$ transitions of CO(J, J-1) at high-z. This led to a bias of tracing dense molecular gas in starburst/AGN regions. The advantage of targeting CO(1-0) at $\nu_{\rm obs} < 50$ GHz is shown in Fig. 2: where ALMA reveals high-J CO on kpc scales, ATCA –a 5-dish interferometer at sea level– detects extended emission from the intrinsically much



Credit: Emonts et al 2015b, A&A, 584, 99
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Figure 2. Molecular debris around the merging Dragonfly Galaxy (adapted from Emonts *et al.* 2015a,b). The thick dark (light) blue contours show the CO(1-0) in the velocity range 53−113 (113−172) km/s, while the bulk of the CO(1-0) that coincides with the central galaxy has been omitted from this plot. The radio jet is shown in thin red contours. The grey-scale image is from *HST*/NICMOS (Pentericci *et al.* 2000, 2001). The inset shows CO(6-5) contours from ALMA. Contours: CO(1-0) – 0.020, 0.026, 0.031; CO(6-5) – 0.1 to 1.7 (steps ×1.4) Jy/beam×km/s.

weaker CO(1-0) across many tens of kpc. The key to finding this weak but extended CO is to use interferometers that are optimized for detecting low-surface-brightness emission, with as many short baselines as possible. Our ATCA results show the potential for low-surface-brightness studies of the cold molecular medium when using very compact array-configurations on future instruments, like ALMA/ACA Band 1 and next-generation VLA.

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