CO(1-0) survey of high-z radio galaxies: alignment of molecular halo gas with distant radio sources

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\textbf{ABSTRACT}

We present a CO(1-0) survey for cold molecular gas in a representative sample of 13 high-

z radio galaxies (HzRGs) at 1.4 < z < 2.8, using the Australia Telescope Compact

Array. We detect CO(1-0) emission associated with five sources: MRC 0114-211, MRC 0152-209, MRC 0156-252, MRC 1138-262 and MRC 2048-272. The CO(1-0) luminosities are in the range $L'_\text{CO} \sim (5-9) \times 10^{10}$ K km s\textsuperscript{-1} pc\textsuperscript{2}. For MRC 0152-209 and MRC 1138-262 part of the CO(1-0) emission coincides with the radio galaxy, while part is spread on scales of tens of kpc and likely associated with galaxy mergers. The molecular gas mass derived for these two systems is $M_{\text{H}_2} \sim 6 \times 10^{10}$ M\textsubscript{\odot} ($M_{\text{H}_2}/L'_\text{CO} = 0.8$). For the remaining three CO-detected sources, the CO(1-0) emission is located in the halo (~50-kpc) environment. These three HzRGs are among the fainter far-IR emitters in our sample, suggesting that similar reservoirs of cold molecular halo gas may have been missed in earlier studies due to pre-selection of IR-bright sources. In all three cases the CO(1-0) is aligned along the radio axis and found beyond the brightest radio hot-spot, in a region devoid of 4.5$\mu$m emission in Spitzer imaging. The CO(1-0) profiles are broad, with velocity widths of ~ 1000 - 3600 km s\textsuperscript{-1}. We discuss several possible scenarios to explain these halo reservoirs of CO(1-0). Following these results, we complement our CO(1-0) study with detections of extended CO from the literature and find at marginal statistical significance (95\% level) that CO in HzRGs is preferentially aligned towards the radio jet axis. For the eight sources in which we do not detect CO(1-0), we set realistic upper limits of $L'_\text{CO} \sim 3 - 4 \times 10^{10}$ K km s\textsuperscript{-1} pc\textsuperscript{2}. Our survey reveals a CO(1-0) detection rate of 38\%, allowing us to compare the CO(1-0) content of HzRGs with that of other types of high-z galaxies.

\textbf{Key words:} galaxies: high-redshift – galaxies: evolution – galaxies: haloes – galaxies: active – galaxies: jets – radio lines: galaxies

\section{1 INTRODUCTION}

High-redshift radio galaxies (HzRGs, with $L_{500 \, \text{MHz}} > 10^{27}$ W \text{Hz}^{-1}) are among the most massive and best studied
galaxies in the early Universe \cite{Seymour2007,DeBreuck2010}. They have traditionally been identified by the ultra-steep spectrum of their easily detectable radio continuum, which served as a beacon for tracing the faint host galaxy environment \cite{Rottgering1994,Chambers1996}. HzRGs have been observed to be the signposts of large overdensities in the early Universe, the so-called proto-clusters that are believed to be the ancestors of local rich clusters \cite[e.g.][]{Venemans2007,Miley2008,Wylezalek2013}. The radio host galaxies are typically the massive central sources of these proto-clusters and are surrounded by giant (100 kpc-scale) ionised gas halos \cite{VillarMartin2002,2003,2006,Humphrey2007}. A significant fraction of these gaseous emission-line halos show spatially resolved absorption from extended regions of neutral gas \cite{vanOjik1997,2003,Jarvis2003,Humphrey2008a}.

HzRGs are in a very active stage of their evolution. They show clumpy optical morphologies \cite{Pentericci2001}, which indicates that continuous mergers are taking place. They often also contain evidence for massive star formation \cite[e.g.][]{Dunlop1994,Ivison1995,Ivison2000,Archibald2001,Stevens2003,Seymour2012,RoccaVolmerange2013}. Alignments have been seen between the radio synchrotron jets that emanate from the central super-massive black hole and optical/UV emission from warm gas and stellar continuum \cite[e.g.][]{McCarthy1987,Chambers1987}, as well as X-ray emission \cite[e.g.][]{Carilli2002,Smal2013} and dust re-radiated submillimetre emission \cite{Stevens2003}. The powerful radio jets can also exert significant feedback onto the surrounding interstellar medium \cite[ISM; e.g.][]{VillarMartin2003,Nesvadba2006,Humphrey2006,Ogle2012}. On average, HzRGs with smaller jets show stronger jet-ISM interaction, more intense star formation and larger reservoirs of neutral gas \cite{vanOjik1997a,Humphrey2008a}.

A crucial component in the research on high-z proto-cluster radio galaxies is the study of cold molecular gas, which is the raw ingredient for star formation \cite[and potential fuel for the AGN. An excellent review on the research of cold gas in high-z galaxies is given by Carilli & Walter (2013). Because molecular hydrogen (H\(_2\)) has strongly forbidden transitions, it can only be detected when it is shocked-heated to high (T\(\gtrsim\)100 K) temperatures. An excellent tracer for the cold component of molecular gas is carbon monoxide (CO), because it is the most abundant molecule after H\(_2\) and its excitation to the various CO(J,J-1) transitions occurs at low temperatures, through collisions with H\(_2\) \cite[even at modest densities;][]{Solomon2005}.

In the 1990’s, the first surveys for CO in HzRGs \cite[mainly using the higher J-transitions;][]{Evans1996,vanOjik1997b}. Subsequently, improvements in millimetre receivers brought interesting results on CO in individual HzRGs between z \(\sim\) 2–5.\cite{Scoville1997,2000,Alloin2000,2001,2005,DeBreuck2003a,2005,Greve2004,Klamer2005,Ivison2008,Nesvadba2009,Emonts2012,2013} see also review by \cite{Miley2008}. In some cases CO is resolved on tens of kpc scales \cite{Ivison2012}, associated with various components (e.g. merging gas-rich galaxies; \cite{DeBreuck2005,Emonts2013}, or found in giant Ly\(_\alpha\) halos that surrounds the host galaxy \cite{Nesvadba2009}. Several studies also identified alignments between the CO emission and the radio jet axis \cite{Klamer2004}. These results show that detectable amounts of cold molecular gas in HzRGs are not restricted to the central region of the radio galaxy.

Despite these interesting results, a lack of sensitivity and bandwidth coverage at existing millimetre facilities \cite[often not more than the width of the CO line, or the accuracy of the redshift][]{Rottgering1994} severely hindered systematic searches for molecular gas in HzRGs. Instead, targets were generally pre-selected on a high infra-red (IR) of submillimetre (submm) luminosity.

The introduction of broad-bandwidth receivers at most of the large millimetre observatories has opened new possibilities for accurate searches for CO at high-z. A crucial species for quantifying the cold molecular gas is the ground transition CO(1-0). While the high CO transitions trace dense and thermally excited gas in the central starburst/AGN region, only the lowest CO transitions may fully reveal widely distributed reservoirs of less dense, subthermally excited gas \cite[e.g.][]{Papadopoulos2000,2001,Carilli2010}. The ground transition CO(1-0) is least affected by the excitation conditions of the gas, hence observations of CO(1-0) provide the most robust estimates of the overall molecular gas content.\footnote{Although see \cite{Papadopoulos2012} for important caveats when using only CO(1-0) to determine the molecular gas content.} For high-z sources, observations of CO(1-0) require observing capabilities in the 20-50 GHz regime, hence accurate studies of CO(1-0) at z \(\geq\) 1.3 have become feasible with the vastly improved millimetre receivers of the Karl G. Jansky Very Large Array (JVLA) and Australia Telescope Compact Array (ATCA) \cite[e.g.][]{Aravena2010,Emonts2011}. Only a handful of observations of CO(1-0) in HzRGs currently exist, but they show evidence for large gas reservoirs \cite[in some cases spread across tens of kpc;][]{Ivison2012,Emonts2011,2013}.

In this paper, we present a survey for CO(1-0) emission in a representative sample of 13 high-z radio galaxies with the ATCA. Throughout this paper we will assume \(H_0 = 71\ \text{km\ s}^{-1}\ \text{Mpc}^{-1}\), \(\Omega_M = 0.27\) and \(\Omega_\Lambda = 0.73\).

### 1.1 Sample

We initially selected those HzRGs from the flux-limited 408 MHz Molonglo Reference Catalogue \cite{Large1981} which were defined by \cite{McCarthy1996} to have \(S_{408\text{MHz}} > 0.95\ Jy\), \(30.0 < \text{dec} < -20.0\) and \(9.20^{\text{th}} < \text{R.A.} < 14^{\text{h}}4^{\text{m}}\) or \(20^{\text{th}} < \text{R.A.} < 6h14^{\text{m}}\).\footnote{This approach primarily selects sources based on their flux density, not their ultra-steep spectrum, as in other effective searches for HzRGs \cite{Rottgering1994,Chambers1996}.
} We subsequently selected for observing those sources for which the CO(1-0) line (\(\nu_{\text{rest}} = 115.271203\ \text{GHz}\)) is observable in the ATCA 7mm band (30 – 50 GHz), corresponding to a redshift range of \(1.3 < z_{\text{CO(1-0)}} < 2.8\). In addition, in order to
keep the sample manageable (given the large amount of observing time required; Sect. 2) and to maximize the scientific output, we only included sources for which complementary optical and infra-red data from the Hubble Space Telescope (HST) and Spitzer Space Telescope are available (Seymour et al. 2007; De Breuck et al. 2010; Pentericci et al. 2001). The well-studied source MRC 0211-112 (outside the declination range sampled by McCarthy et al. 1996) was also added to our sample (van Ojik et al. 1997a; Pentericci et al. 2001; Vernet et al. 2001; Humphrey et al. 2013; De Breuck et al. 2010).

In total, our sample consists of 13 southern MRC sources (see Table 1). All 13 sources have a 3 GHz rest-frame radio luminosity of $L_{3\text{GHz}} > 10^{27.5}$ W Hz$^{-1}$ and they sample the full range in mid-IR (5 μm rest-frame) luminosities found across a large sample of HzRGs by De Breuck et al. (2010). Our sources also sample the K-band magnitude range covered by De Breuck et al. (2010) for objects with $16 < m^\text{K} < 19$, but our sample does not include sources in their lowest $m^\text{K}$ bin (19 < $m^\text{K}$ < 20). We argue that this is likely because of optical/near-IR selection biases in the existing HST/WFPC2 and HST/NICMOS studies on which we based our sample selection.

An additional source (MRC 0943-242; $z = 2.92$) was observed in CO(1-0) just beyond the nominal edge of the ATCA 7mm band ($\nu_{\text{CO}} = 29.4$ GHz), where increased noise and low-level instrumental effects prevented us from reaching the same sensitivity as for the 13 sample sources presented in this paper. MRC 0943-242 is therefore excluded from this paper. Results of MRC 0943-242, including a tentative CO(1-0) detection in the halo of this HzRG, have been described in Emonts et al. (2011b).

2 OBSERVATIONS

CO(1-0) observations were performed with the Australia Telescope Compact Array (ATCA) during 2009 - 2013 in the most compact hybrid H75, H168 and H214 array configurations (which contain both an EW and NS spur and maximum baselines of 89, 192 and 247 m respectively). The bulk of the observations were done during the night in the southern late-winter and early-spring (months of Aug, Sept, Oct). A summary of the observations is given in Table 1.

The Compact Array Broadband Backend (CABB) with 2 × 2 GHz receiver bands was used in its coarsest spectral resolution of 1 MHz per channel (Wilson et al. 2011). For an object at $z = 2$ at which the CO(1-0) emission line ($\nu_{\text{rest}} = 115.271$ GHz) is observed at $\nu_{\text{obs}} = 38.400$ GHz, this setup results in a velocity coverage of 16,000 km s$^{-1}$ per 2 GHz band with 8 km s$^{-1}$ maximum spectral resolution. During the early observing period of this project (immediately after the CABB upgrade in 2009), several corrupted correlator blocks caused a significant number of channels to drop out in the first part of each 2 GHz band. We therefore centred the bands such that the expected CO(1-0) signal would fall in the clean part of each band. During the later period this problem did not occur and we centred each band around the redshift of the expected CO(1-0) line. For redundancy (in case of technical issues, which occurred more frequently in the months after the CABB upgrade), both 2 GHz bands were centred around the same frequency, but because the signal is not independent in the two bands, only a single band was used in the final analysis of each observation. To better handle potential bandpass or systematic effects, we frequently introduced a small offset (tens to hundreds of MHz) in the central frequency of the bands between runs on a particular target.

For data calibration, we followed the strategy described in Emonts et al. (2011b). The phases (and in many cases also the bandpass) were calibrated every 5-15 minutes with a short (~2 min) scan on a nearby bright calibrator (Table 1). In case the flux of this calibrator was <1 Jy, or the calibrator was not suitable for bandpass calibration, a strong bandpass calibrator was observed at the start, middle and end of each run. Fluxes were calibrated using (in order of preference) Uranus, Mars, PKS 1934-638 or the ultra-compact HII region G309 (for the latter see Emonts et al. 2011b). While the accuracy of the relative flux calibration between runs of the same target was ≲5%, the error in absolute flux calibration was ~20%, due to a small difference in the models for the various flux calibrators. We note, however, that the latter only introduces a scaling factor that depends on the used flux calibrator for a particular source.

For the data reduction and visualisation we used the software packages MIRIAD (Sault et al. 1995) and KARMA (Gooch 1996). All of the HzRGs in our sample were detected in the 115 GHz rest-frame radio continuum at the mJy level. The continuum was separated from the line data by fitting a straight line to the line-free channels in the uv-domain. Because of the large velocity coverage per 2 GHz receiver band, the continuum subtraction could initially be done reliably using all channels, without affecting a potential weak CO signal. For those cases where CO(1-0) was detected, the continuum subtraction was repeated by excluding the channels in which the faint CO(1-0) signal was present. We note, however, that this did not significantly alter the final results. For MRC 0114-211 the radio continuum flux is ~80 mJy. This allowed us to do a self calibration on the continuum of MRC 0114-211, which solutions were copied to the corresponding line data. The velocity axis of each individual line data set was transformed into optical barycentric velocity definition with respect to the redshift of the object (as given in Table 1). While each data set was reduced and analysed individually for CO signals, as well as for spurious signals or abnormalities, a Fourier transform was eventually performed on the combined line data for each object in our sample, using robust +1 weighting (Briggs 1995). Because of the low peak-flux of our CO(1-0) detections, no cleaning was done on the line data, except for a mild clean of the strong CO(1-0) signal in MRC 0152-209 (Sect. 3). The line data were subsequently binned to the results given in Table 2 and Figs. 1 and 2. Total intensity images were made by summing the signal across the channels in which CO(1-0) was detected (without setting a noise threshold/cutoff). Values of $L_{\text{CO}(1-0)}$ from the CO(1-0) detections provided in this paper have all been derived from these total intensity images. The beam-size and rms noise level of our data is summarised in Table 3. The primary beam of our observations is 80 arcsec at $\nu_{\text{obs}} = 35$ GHz.

The continuum data for each object were combined into a map of the 115 GHz restframe emission. By comparing the location of the peak emission (and in some cases also the morphological structure) of this radio continuum with pub-
Figure 1. CO(1-0) spectra and total intensity images of the five CO-detected sample sources: MRC 0114-211, MRC 0152-209 (Emonts et al. 2011a), MRC 0156-252, MRC 1138-262 (Emonts et al. 2013) and MRC 2048-272. The channel width of the plotted spectra is shown at the bottom of each plot and was chosen to best visualize the CO(1-0) detection. For MRC 0152-209, MRC 0156-252 and MRC 1138-262 a Hanning smoothed version of the spectra is shown to best visualize the CO(1-0) emission, while for MRC 0114-211 and MRC 2048-272 no Hanning smoothing was applied to better distinguish the CO(1-0) emission from the noise characteristics across the bandpass. The 0-velocity is defined as the optical redshift of the host galaxy (see De Breuck et al. 2000, and references therein), except for MRC 0114-211, where the uncertainty in optical redshift is as large as the velocity coverage of our CO observations (see Appendix A). The red bar indicates the velocity range across which we integrated to obtain the total intensity map of each source. Contours levels are spaced $1\sigma$ apart (with $\sigma = 0.094, 0.095, 0.095, 0.046, 0.080\ Jy\ beam^{-1}\times km\ s^{-1}$ for MRC 0114-211, MRC 0152-209, MRC 0156-252, MRC 1138-262, MRC 2048-272, respectively). The diamond indicates the position of the host galaxy. [Color versions of all the Figures in this paper are available in the on-line edition.]
lished high-resolution 4.7 and 8.2 GHz data (Carilli et al. 1997; Pentericci et al. 2000b; De Breuck et al. 2010), we were able to verify that the positional accuracy of our mm data (line and continuum) is better than 1 arcsec. The presentation of the continuum data is left for a future paper.

3 RESULTS

3.1 CO detections and upper limits

We detect CO(1-0) emission associated with five of our sample sources. These are MRC 0114-211 ($z = 1.40$), MRC 0152-209 ($z = 1.92$), MRC 0156-252 ($z = 2.02$), MRC 1138-262 (also called the ‘Spiderweb Galaxy’; $z = 2.16$) and MRC 2048-272 ($z = 2.06$). The CO(1-0) emission-line profiles of these five sources are shown in Fig. 1 and their properties are summarised in Table 2. The characteristics and spatial distribution of the CO(1-0) emission in these sources will be discussed in Sect. 3.2.

The CO(1-0) emission-line luminosities of the five CO(1-0) detected sources in Fig. 1 are in the range $L_{\mathrm{CO}} = 4.5 - 9.2 \times 10^{10} \, K \, km \, s^{-1} \, pc^2$ (see Table 2). $L_{\mathrm{CO}}$ was calculated following Solomon & Vanden Bout (2005) and references therein:

$$L_{\mathrm{CO}} = 3.25 \times 10^7 \left( \frac{\int S_{\mathrm{CO}} \delta v}{Jy \, km/s} \right) \left( \frac{D_L}{Mpc} \right) \left( \frac{\nu_{\mathrm{rest}}}{GHz} \right)^{-2} \left( 1 + z \right)^{-1}, \tag{1}$$

with $\int S_{\mathrm{CO}} \delta v = I_{\mathrm{CO}}$ the integrated flux density of the CO(1-0) emission and $L_{\mathrm{CO}}$ expressed in K km s$^{-1}$ pc$^2$.

Uncertainties in $L_{\mathrm{CO}}$ are calculated following Sage (1990), assuming that they are dominated by the noise in the spectrum:

$$\Delta I_{\mathrm{CO}} = \sigma \Delta v \sqrt{\frac{FWZI}{\Delta v}} \left( \rightarrow \text{uncertainty in } L_{\mathrm{CO}} \right), \tag{2}$$

with $\sigma$ the rms (root mean square) noise, $\Delta v$ the channel width and FWZI the full width over which the CO profile was integrated. A second error term in $\Delta I_{\mathrm{CO}}$ arises from an uncertainty in determining the baseline ($\Delta I_{\mathrm{baseline}} = \sigma \Delta V_{\mathrm{CO}} \sqrt{\Delta V_C / \Delta V_b}$, with $\Delta V_{\mathrm{CO}}$ the FWZI of the CO signal, $\Delta V_C$ the channel width and $\Delta V_b$ the length of the baseline; see Sage 1990). However, because of the large CABB bandwidth ($\Delta V_{\mathrm{baseline}} >> \Delta V_{\mathrm{channel}}$), this term is expected to be negligible. Our quoted uncertainties in $L_{\mathrm{CO}}$ do not include the 20% uncertainty in absolute flux calibration (Sect. 2).

To derive realistic upper limits for the non-detections in our sample, we set boundary conditions based on the CO(1-0) characteristics of our five CO-detected sources. They show CO(1-0) components with FWZI $= 800 - 2000$ km s$^{-1}$. In addition, the widest profiles (MRC 0156-252; MRC 1138-262...
Results are given in Fig. 2 and Table 2.

### Table 1: Observing details.

| Name         | $z$  | $v_{CO(1-0)}$ (GHz) | Observing dates                                      | $t_{\text{int}}$ (h) | Calibrators |
|--------------|------|---------------------|------------------------------------------------------|-----------------------|-------------|
| MRC 0114-211 | 1.402| 47.998              | 03,09,22-AUG-11, 25,27-SEP-11, 23,24-OCT-11           | 24.8                  | 0130-171 (P+B), 1921-293 (B), Uranus (F) |
| MRC 0152-209 | 1.9212| 39.476              | 25,26-AUG-10, 28,29-SEP-10 †                         | 15.5                  | 0130-171 (P+B), Uranus (F) |
| MRC 0156-252 | 2.016| 38.220              | 05,07-AUG-10, 29-SEP-12                              | 13.5                  | 0135-247 (P+B), Uranus (F) |
| MRC 0211-122 | 2.540| 34.512              | 08,10-AUG-11, 26,27-SEP-11                           | 10.9                  | 0202-172 (P+B), 0537-141 (B), Uranus (F) |
| MRC 0324-228 | 1.898| 39.776              | 30-SEP-11, 20,21,22-OCT-11                           | 11.1                  | 0346-279 (P), 0537-141 (B), 1921-293 (B), 2223-052 (B), Uranus (F) |
| MRC 0350-279 | 1.900| 39.749              | 30-SEP-11, 20,21,22-OCT-11                           | 10.7                  | 0346-279 (P), 0537-141 (B), 1921-293 (B), 2223-052 (B), Uranus (F) |
| MRC 0406-244 | 2.440| 33.509              | 21,22-AUG-11, 15,16-SEP-11                           | 14.0                  | 0346-279 (P), 0537-141 (B), Uranus (F) |
| MRC 1017-220 | 1.768| 41.644              | 24-OCT-11, 30,31-MAR-12, 25,26,27-SEP-12             | 17.2                  | 1034-293 (P+B), Uranus (F) |
| MRC 1138-262 | 2.161| 36.467              | 18,19-AUG-11, 26,27-SEP-11                           | 22.0                  | 1124-186 (P+B), Mars (F) |
| MRC 2025-218 | 2.630| 31.755              | 12,13,14,15-AUG-10                                   | 17.4                  | 1958-179 (P+B), 2008-159 (P+B), 1934-638 (F) |
| MRC 2048-272 | 2.060| 37.670              | 21,22-AUG-11, 23-SEP-11                              | 19.8                  | 2058-297 (P), 0537-141 (B), 1921-293 (B) |
| MRC 2104-242 | 2.491| 33.020              | 25-MAR-13, 03,04,05-OCT-13                            | 19.5                  | 2223-052 (B), Uranus (F), G309 (F) |
| MRC 2224-273 | 1.678| 43.044              | 20,25,26-SEP-10, 01,02-OCT-10                         | 15.3                  | 2255-282 (P+B), Uranus (F) |

† Additional high-resolution ATCA data of MRC 0152-209 is presented in Emonts et al (in prep).

### Table 2: Observed CO(1-0) properties.

| Name         | beam (PA) | rms (mJy/bm) | ∆v (km/s) | FWZI (K km s$^{-1}$) | $I_{CO(1-0)}$ (Jy km km s$^{-1}$) | $L'_{CO(1-0)}$ (K km s$^{-1}$ pc$^2$) | $M_{H2}$ (M$_\odot$) | σ-level |
|--------------|-----------|--------------|-----------|-------------------|-----------------------------------|-----------------------------------|-----------------|---------|
| MRC 0114-211 | 8.1 × 6.0 (89) | 0.22 | 125 | 1130 | 0.43 ± 0.08 | 4.5 ± 0.9 × 10$^{10}$ | 3.6 ± 0.7 × 10$^{10}$ | 4.5σ    |
| MRC 0152-209 | 9.8 × 7.1 (90) | 0.23 | 40 | 800 | 0.37 ± 0.04 | 6.6 ± 0.8 × 10$^{10}$ | 5.3 ± 0.6 × 10$^{10}$ | 9σ      |
| MRC 0156-252 | 6.9 × 4.9 (71) | 0.17 | 154 | 2000 | 0.38 ± 0.09 | 9.2 ± 1.8 × 10$^{10}$ | 7.4 ± 1.5 × 10$^{10}$ | 5σ      |
| MRC 2025-218 | 11.1 × 8.0 (99) | 0.19 | 91 | -   | < 0.17 | < 4.6 × 10$^{10}$ | < 3.7 × 10$^{10}$ | < 3σ    |
| MRC 2048-272 | 13.6 × 10.6 (106) | 0.27 | 78 | -   | < 0.23 | < 4.2 × 10$^{10}$ | < 3.3 × 10$^{10}$ | < 3σ    |
| MRC 2104-242 | 13.7 × 10.6 (102) | 0.28 | 78 | -   | < 0.23 | < 4.3 × 10$^{10}$ | < 3.5 × 10$^{10}$ | < 3σ    |
| MRC 2224-273 | 12.4 × 8.9 (77) | 0.14 | 95 | -   | < 0.13 | < 3.7 × 10$^{10}$ | < 3.0 × 10$^{10}$ | < 3σ    |
| MRC 2058-218 | 6.7 × 4.5 (84) | 0.20 | 74 | -   | < 0.16 | < 2.6 × 10$^{10}$ | < 2.1 × 10$^{10}$ | < 3σ    |
| MRC 2224-273 | 9.7 × 6.1 (66) | 0.12 | 129 | 1680 | 0.31 ± 0.06 | 7.2 ± 1.3 × 10$^{10}$ | 5.8 ± 1.0 × 10$^{10}$ | 8σ      |
| MRC 2224-273 | 7.8 × 4.8 (71) | 0.16 | 94 | -   | < 0.15 | < 4.8 × 10$^{10}$ | < 3.8 × 10$^{10}$ | < 3σ    |

3.1.1 Significance level of the CO(1-0) detections

An important consideration in the interpretation of our results is the significance of the CO(1-0) signals that we detect. In Table 2 we show the signal-to-noise level of the integrated CO(1-0) signal. Most of the CO(1-0) detections and MRC 2048-272 appear to be double-peaked and cannot be fitted with a single Gaussian profile. This makes any assumption on the shape of the expected profile for the nondetections unjustified. We therefore derive conservative upper limits on $L'_{CO}$ for the non-detected HzRGs in our sample by assuming a 3σ signal smoothed across 1000 km s$^{-1}$ (FWZI):

$$I_{CO} < 3\sigma \Delta v \sqrt{\frac{1000}{\Delta v}} \rightarrow \text{upper limits } L_{CO},$$

Results are given in Fig 2 and Table 2.
presented in this paper are found $\lesssim 1$ synthesized beam-size from the core of the radio galaxy (Sect. 3.2) and near the redshift determined from optical emission-line observations (De Breuck et al. 2000 and references therein), resulting in a low probability that these signals are spurious (see Krips et al. 2012). For sources that showed an initial tentative CO(1-0) signal (including MRC 0114-211, MRC 0156-252 and MRC 2048-272), we continued observing them until the tentative CO(1-0) signal was either confirmed or judged spurious. The two main criteria that we used for confirming a CO(1-0) signal are: 1) indications for the CO(1-0) emission are present across the different observing runs; 2) at a channel-binning that is optimized to reveal the integrated CO(1-0) signal, the CO(1-0) emission stands out above the noise as the signal with the highest absolute value across the full primary beam and frequency coverage of the data cube. All five CO-detected sources in our sample satisfy these criteria. Appendix A provides additional details on our five CO(1-0) detections.

Krips et al. (2012) show that blind CO searches (i.e. searches for CO emission not associated with objects with known coordinates and redshifts) are likely to result in spurious CO detections at a 5σ level (see also Aravena et al. 2012). Because many of the HzRGs in our sample have no or no complete information on proto-cluster galaxies in their environment, and because our observing strategy was not optimized for a blind CO(1-0) search, this paper does not address the CO(1-0) content of the larger (hundreds of kpc) environment of these HzRGs.

### 3.2 CO characteristics

In this Section we briefly discuss the characteristics of the CO(1-0) detections across our sample. Details on the individual sources are given in Appendix A.

#### 3.2.1 ‘On-source’ CO(1-0) emission

For two of the five CO(1-0) detected sources (MRC 0152-209 and MRC 1138-262) a substantial fraction of the CO(1-0) emission coincides with the bright optical/near-IR emission associated with the radio galaxy. In both cases, however, part of the CO(1-0) emission is also spread across scales of several tens of kpc (Figs. 3 and 4). This is consistent with the idea that observations of the ground-transition CO(1-0) are sensitive to tracing wide-spread cold molecular gas (Papadopoulos et al. 2001, see also Sect. 1). Results on MRC 0152-209 and MRC 1138-262 are presented in detail in related papers (Emonts et al. 2011a, 2013, Emonts et al in prep.), and will thus only be briefly summarised here.

Figure 3 shows the CO(1-0) distribution in MRC 1138-262 (from Emonts et al. 2013). As discussed in Emonts et al. 4 Figure 3 only includes the CO(1-0) features from Emonts et al. (2013) that have recently been confirmed with additional ATCA observations (Emonts et al in prep.). Several additional 3σ features

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Figure 3. Spatial distribution of the CO(1-0) emission associated with MRC 1138-262 (see also Emonts et al. 2013). Left: CO(1-0) emission integrated over three distinct velocity ranges and overlaid onto an HST/ACS (g475 + i814) image from Miley et al. (2006). The velocity ranges for the three components are indicated in the plot (in km s\(^{-1}\)). A velocity gradient is visible in the CO(1-0) emission, which is spread across scales of 30-40 kpc (see Emonts et al. 2013 for details, including channel maps and spectra). CO(1-0) contour levels are at 3, 3.8, 4.6, 5.4, 6.2 \(\sigma\) level (with \(\sigma = 0.033\) Jy beam\(^{-1}\) \(\times\) km s\(^{-1}\) for the red/green components and 0.047 Jy beam\(^{-1}\) \(\times\) km s\(^{-1}\) for the blue component). The beam-size of the ATCA data is 9.7\(\prime\prime\) \(\times\) 6.1\(\prime\prime\) (PA = 66\(^{\circ}\)). The thin black contours show the 8.2 GHz radio continuum image from Carilli et al. (1997), while the black dotted line visualises the extrapolated radio jet axis. Right: three-color image of the CO(1-0) components from the left plot overlaid onto the HST image.

Figure 4. Spatial distribution of the CO(1-0) emission associated with MRC 0152-209 (see Emonts et al. in prep for details, including channel maps and spectra; see Emonts et al. 2011a for the original CO(1-0) detection). Left: CO(1-0) emission integrated over three distinct velocity ranges and overlaid onto an HST/WFPC2 F555W [Program 8183; PI: Miley] image (Emonts et al. in prep). The velocity ranges for the three components are indicated in the plot (in km s\(^{-1}\)). CO(1-0) contour levels are at 2.8, 3.5, 4.2, 4.9, 5.6 \(\sigma\) level (with \(\sigma = 0.0073\) Jy beam\(^{-1}\) \(\times\) km s\(^{-1}\) for the red/green components and 0.012 Jy beam\(^{-1}\) \(\times\) km s\(^{-1}\) for the blue component). Note the highly elongated beam (dashed ellipse) that we obtained by using the extended-baseline East-West array configurations of the ATCA, which resulted in a lack of uv-coverage in North-South direction by staying above the typical 30\(^{\circ}\) elevation suitable for millimetre observations (see Emonts et al. in prep for details). The radio source (not shown in this plot) has a total linear extent of only 2.2 arcsec (18 kpc; Pentericci et al. 2000a), while the black dotted line visualises the extrapolated radio jet axis. Right: three-color image of the CO(1-0) components from the left plot overlaid onto the HST image. The inset in the top-left highlights the prominent optical tidal features.
the kinematics of the CO(1-0) emission appears to follow the velocity distribution of several satellite galaxies in the same region, hence the extended part of the CO(1-0) is likely associated with (interacting/merging) satellites or the inter-galactic medium (IGM) between them.

Figure 4 shows high-resolution ATCA data of MRC 0152-209 (Emonts et al. in prep), which is a follow-up study of our original low-resolution work (Emonts et al. 2011a). MRC 0152-209 is a gas-rich major merger system at $z = 2$, with a double nucleus and prominent tidal tails in HST/NICMOS and WFPC2 imaging (Pentericci et al. 2001; Emonts et al. in prep). While the bulk of the CO(1-0) emission is co-spatial with the main body of the host galaxy, part of it seems to follow the optical tidal features. Interestingly, the small radio source appears to be aligned with the NW component of the off-nuclear CO(1-0) emission.

Galaxy mergers and interactions thus seem important to explain the CO(1-0) distribution in both MRC 0152-209 and MRC 1138-262. This is consistent with the suggestions by Ivison et al. (2012) that galaxy mergers are ubiquitous among starburst radio galaxies at high-$z$.

3.2.2 ‘Off-source’ CO(1-0) emission

For the remaining three CO-detected sources in our sample (MRC 0114-211, MRC 0156-252 and MRC 2048-272), the CO(1-0) emission is offset from the radio galaxy. As can be seen in Fig. 5 for all three sources the CO(1-0) emission is located along the radio axis, on the side of the brightest radio emission, and found beyond the outer radio hot-spot.

The alignment of the CO with the radio jet axis is within $20^\circ$ for the three sources. A fourth case may be the NW ‘off-source’ component of CO(1-0) emission in MRC 0152-209 (Sect. 3.2.1 and Fig. 4), as it shows a similar alignment with the small radio jet. These alignments resemble earlier results by Klamer et al. (2004) and Nesvadba et al. (2009).

It suggests that there is a causal connection between the propagating radio jets and the presence of large amounts of cold molecular gas in the halo environment of these sources (which we will discuss further in Sect. 4.2).

The peak of the CO(1-0) emission is located at an apparent ~10, 30 and 40 kpc distance from the radio hot-spot for MRC 0156-252, MRC 0114-211 and MRC 2048-272, respectively. However, the synthesized beam-size of our data corresponds to 60 - 70 kpc at these redshifts, and undetectable lower surface brightness radio plasma may be present beyond the hot-spot, so sensitive high resolution CO observations and deeper low-frequency radio imaging are required to further investigate how close the cold gas is located to the radio source.

While $L'_\text{CO}$ of these three off-nuclear CO-emitters is similar to what is found in submillimetre galaxies (SMGs; see Sect. 5.3, Fig. 3) it shows that no Spitzer/IRAC 4.5 $\mu$m emission is found at the location of the CO(1-0) to a level of one to two magnitudes below $L'$ (see Galametz et al. 2012; Wylezalek et al. 2013). For MRC 0114-211, however, the CO(1-0) emission is co-spatial with a very faint optical peak of the original data presented in Emonts et al. (2013) have not yet been confirmed due to poor weather conditions during the new observations, hence they are not included in Fig. 4.
(i.e. near-UV rest-frame) counterpart that is visible in an archival HST/WFPC2 image (Fig. 6). Brighter optical emission is found just outside the edge of the bright western radio jet, reminiscent of the shell of shocked emission-line gas, such as the one that Overzier et al. (2005) found around the bended radio lobe in MRC 0156-252. It is possible, however, that the error in the astrometry of the archival HST image is as much as 1.5 arcsec (see Appendix A) and that the bright optical emission is the host galaxy.

Fig. 6 shows that the CO(1-0) emission in MRC 0156-252 located just outside a large reservoir of Lyα emission, with the boundary region between the Lyα and CO(1-0) gas occurring at the edge of the radio hot-spot. The CO(1-0) emission consists of two kinematically distinct peaks that both lie ∼20 kpc distance from two satellite galaxies detected with HST/NICMOS (Pentericci et al. 2001). The innermost companion (near the blue CO peak) has blue colors that are indicative of enhanced star formation (possibly triggered by the passage of the radio jet; Pentericci et al. 2001). Very recent work by Galametz et al. (2013) suggests that the redshift at which we centred the CO(1-0) profile (z = 2.016) is more closely related to the redshift of this blue companion than of the HzRG (see Appendix A for details).

For MRC 2048-272, the two kinematically distinct CO(1-0) components from Fig. 1 peak at the same spatial location (see Appendix A for details).

We also note that the CO(1-0) emission of these three off-nuclear detections covers a wide velocity range (1100 < FWZI < 3600 km s⁻¹). The CO(1-0) profiles are broad compared to what is generally found in quasars and submillimetre galaxies (Coppin et al. 2008; Wang et al. 2010; Ivison et al. 2011; Riechers et al. 2011; Bolatto et al. 2013; Krips et al. 2012), with the exception of what is found in a few high-z merging galaxies (see Salomé et al. 2012 and references therein). Possible scenarios on the nature of the off-nuclear CO(1-0) emission in MRC 0114-211, MRC 0156-252 and MRC 2048-272 are discussed in Sect. 4.2.

3.3 Derivation of H₂ mass

Molecular gas masses (and upper limits) are estimated from $L_{\text{CO}}$ using a conversion factor $X_{\text{CO}} = M_{\text{H}_2}/L_{\text{CO}} = 0.8$ M⊙ (K km s⁻¹ pc²)⁻¹ (where M_{H₂} includes a helium fraction; e.g. Solomon & Vanden Bout 2005). This value is found for Ultra Luminous Infra-Red Galaxies ($L_{\text{IR}} > 10^{12} L_{\odot}$; Downes & Solomon 1998) and is within the range of $X_{\text{CO}} = 0.8 - 1.6$ M⊙ (K km s⁻¹ pc²)⁻¹ assumed for high-z submillimetre galaxies and star forming galaxies (Tacconi et al. 2008; Stark et al. 2008). However, we stress that $X_{\text{CO}}$ depends on important properties of the gas (such as metallicity, extinction and radiation field; Papadopoulos et al. 2008a; Glover & Mac Low 2011; Bolatto et al. 2013), and is not yet well understood (Tacconi et al. 2008; Ivison et al. 2011; see additional discussion in Sect. 4.2).

Taking the above into account, our assumed $X_{\text{CO}} = 0.8$ M⊙ (K km s⁻¹ pc²)⁻¹ results in molecular gas mass estimates in the range $M_{\text{H}_2} = 4 - 7 \times 10^{10}$ M⊙ for the CO(1-0)
detected HzRGs in our sample. Value and upper limits of $M_{\text{H}_2}$ are given in Table 2.

4 DISCUSSION

We have performed a systematic search for CO(1-0) emission of cold molecular gas in a representative sample of 13 high-z radio galaxies and have presented five CO(1-0) detections. The most intriguing result from this work is that we find three cases where bright CO(1-0) emission is found along the radio jet axis and beyond the outer radio hot-spot. This indicates that the alignments seen in HzRG between the radio jets and optical/UV (McCarthy et al. 1987; Chambers et al. 1987), X-ray (Carilli et al. 2002; Smail & Blundell 2013) and submillimetre emission (Stevens et al. 2003) now also have to take into account the component of cold molecular CO(1-0) gas.

In Sect. 4.1 we will first present a comparison between $L'_{\text{CO}(1-0)}$ and the far-IR luminosity ($L_{\text{FIR}}$) from the starburst component. We will use this information in Sect. 4.2 to interpret the alignments that we find between the radio source and cold molecular halo gas in several of our sample sources. A more statistical investigation of the radio-CO alignment, based on CO results from the literature, is given in Sect. 4.3. In Sect. 4.4 we will compare the CO(1-0) properties of HzRGs with those of other types of high-z galaxies.

4.1 Cold gas ($L'_{\text{CO}}$) vs. starburst ($L_{\text{FIR}}$)

Following the Schmidt-Kennicutt relation between star formation and gas reservoir (Schmidt 1959; Kennicutt 1998), relations between $L'_{\text{CO}}$ and the far-IR luminosity ($L_{\text{FIR}}$) are frequently observed in both low- and high-z galaxies (see Ivison et al. 2011; Villar-Martín et al. 2013, for recent examples). Figure 8 shows $L_{\text{CO}}'$ plotted against the starburst component of $L_{\text{FIR}}$ for our sample sources. Values of $L_{\text{FIR}}$-starburst (hereafter $L_{\text{FIR}}$) are from Drouart et al. (in prep) and have been derived from modeling the Spectral Energy Distribution (SED) across $8 - 1000 \mu m$ to separate the starburst from other, e.g. torus and stellar, components. Details and a list of $L_{\text{FIR}}$ values will be provided in Drouart et al. (in prep).

Given the small range of $L'_{\text{CO}}$ and $L_{\text{FIR}}$ values that our sample covers, it is not surprising that there is no clear trend visible. However, it is interesting that the sources in which we detect CO(1-0) solely offset from the central host galaxy (MRC 0114-211, MRC 0156-252 and MRC 2048-272) have a starburst FIR luminosity that falls in the lower half of the $L_{\text{FIR}}$ values of our sample sources. This suggests that earlier studies that pre-selected targets based on their high FIR luminosity may have missed similar systems where detectable amounts of molecular gas are located outside the host galaxy, but in the galaxy’s halo environment.

MRC 1138-262 and MRC 0152-209 (the two sample sources where part of the CO(1-0) emission coincides with the host galaxy) are among the stronger FIR emitters in the sample. Their high FIR luminosity implies high star formation rates (up to $\sim 1400 M_\odot \text{yr}^{-1}$; Emonts et al. 2011a; Seymour et al. 2012). As discussed in Emonts et al. 2011a; 2013, if the CO(1-0) represents a reservoir of molecular gas that is consumed by this massive star formation, the minimum gas depletion time-scale in these two HzRGs is of order 40 Myr. This is comparable to the typical life-time of a massive burst of star formation in ultra-luminous IR ($L_{\text{IR}} > 10^{12} L_\odot$) merger systems (e.g. Mihos & Hernquist 1994).

When comparing the CO(1-0) luminosity of our sample sources with other properties of the host galaxy (as observed by De Breuck et al. 2010; Pentericci et al. 2006), we find no apparent correlation between $L'_{\text{CO}}$ and $z$, $P_{\text{500 W km}^{-1}}$, spectral index $\alpha_{\text{2 GHz}}$, total linear extent of the radio source and core fraction of 20 GHz radio continuum. Three of our CO(1-0) detected sources (MRC 1138-262, MRC 0156-252 and MRC 0152-209) appear to have a relatively high stellar mass (in the range $5 - 2 \times 10^{12} M_\odot$), compared to the CO non-detections ($M_\star < 0.5 \times 10^{12} M_\odot$; De Breuck et al. 2010). With better statistics it would be worth investigating whether there is a trend between $L'_{\text{CO}(1-0)}$ and $M_\star$.

4.2 Cold halo gas: radio - CO alignment

Our survey suggests that CO reservoirs of cold molecular gas exist in the halo ($\sim 50$ kpc-scale) environment of a significant fraction of HzRGs. These cold gas reservoirs are likely part of metal-enriched quiescent Ly$\alpha$ halos that have been observed to surround HzRGs (Villar-Martín et al. 2003; 2006; Binette et al. 2006). Extended reservoirs of neutral hydrogen gas and large dusty shells have also been observed in these Ly$\alpha$ halos (van Ojik et al. 1997a; Jarvis et al. 2003; Humphrey et al. 2008a; 2013). The most intriguing result from this paper is that this CO(1-0) is preferentially aligned along the radio jet axis and found beyond the brightest part of the radio continuum. This is similar to the case of TXS 0828+193 (z = 2.6), where Nesvadba et al. 2009 found CO(3-2) emission ($L'_{\text{CO}} \sim 2 \times 10^{10} \text{ K km s}^{-1} \text{ pc}^{-2}$) beyond the tip of the SW hot-spot ($\sim 80$ kpc from the radio core). No optical or IR...
corresponding was detected at this location and the CO kinematics are in good agreement with those of CIV emission at the edge of the optical gaseous halo (Villar-Martín et al. 2002). Our results also resemble the radio – CO alignments found in $z > 3$ HzRGs by Klamr et al. (2004) as well as in the $z \sim 0.3$ quasars [H89]1821+643 (Blundell & Rawlings 2001; Aravena et al. 2011; and HE 0450-2958 (Feain et al. 2007; Papadopoulos et al. 2008a; Elbaz et al. 2009). We here address several possible explanations for this alignment.

4.2.1 Jet-induced star formation or gas cooling

Klamr et al. (2004) found that in $z > 3$ radio galaxies CO and dust emission are also preferentially aligned along the radio axis. They discuss a scenario in which the CO is formed in sites of star formation that are initially triggered by the radio jets – a mechanism that may perhaps also explain alignments found between the radio jets and UV/optical continuum (McCarthy et al. 1987; Chambers et al. 1987; Rees 1989; De Young 1989; Begelman & Ciotti 1989; Bicknell et al. 2000), or the increased star formation rates found in AGN with pronounced radio jets (Zinn et al. 2013). Klamr et al. (2004) make three predictions for the scenario of jet-induced star formation that our independent CO(1-0) results appear to confirm, namely that the CO in HzRGs is extended and aligned with observable synchrotron radio emission (see our Fig. 5), that the CO profiles from emission outside the host galaxy will be broad (see our Fig. 1) and that CO and Lyα emission will be tracing different physical regions (see our Fig. 7).

It is possible that at $z \sim 2$ (where the massive radio galaxies have already gone through several cycles of chemical enrichment) the CO is associated with jet-induced gas cooling that precedes the star formation, rather than being a product of the star formation itself. Gas cooling is feasible if the IGM is compressed and cooled through shocks induced by the radio source (e.g. Mellema et al. 2002; Sutherland et al. 2003; Fragile et al. 2004; Gaibler et al. 2012). As discussed in detail by Nesvadba et al. (2009), this may also result in cooling-flow processes similar to those observed in low-$z$ giant central cluster galaxies (despite morphological and kinematical differences in the CO distribution, which in low-$z$ cooling flows is mainly concentrated towards the central galaxy and along the sides of the cavities that are excavated by the radio lobes; e.g. Fabian 1994; Edge 2001; Salomé & Combes 2003; Salomé et al. 2006, 2011).

4.2.2 Jet-driven enrichment

An alternative scenario is that the carbon and oxygen were created during massive bursts of star formation within the host galaxy and subsequently transported into the halo environment by the radio source, forming a reservoir of metal-enriched gas beyond the edge of the radio plasma. Jet-driven outflows of ionised, neutral and molecular gas have been observed along the radio axis in both low- and high-$z$ radio galaxies (e.g. Villar-Martín et al. 2003; Morganti et al. 2003, 2005; Emonts et al. 2005; Humphrey et al. 2006; Nesvadba et al. 2008; Holt et al. 2008; Daszyr & Combes 2012; Morganti et al. 2013a,b; Mahony et al. 2013). In addition, it is believed that powerful radio-loud AGN are responsible for the formation of filamentary Extended Emission Line Regions (EELRs) in quasars (Fu & Stockton 2007a,b; 2009). Several studies suggest that the radio jets may also be responsible for transporting dust and metals far outside the host galaxy. In low-$z$ brightest clusters galaxies, Kirkpatrick et al. (2009, 2011) find that metal-enrichment takes place along the radio axis. They show that heavy elements are often found beyond the extent of the innermost X-ray cavities, which suggests that the metal-enrichment by the radio source is sustained over multiple generations of radio outbursts. At high-$z$, Ivison et al. (2012) argue that jet-induced feedback may explain a large ($\sim 500$ kpc) dusty filamentary structure that is co-aligned with the radio source 6C 1909+72 ($z = 3.5$).

Interestingly, extended emission-line halos around HzRGs and quasars have been found to display near-solar metallicities (e.g. Vernet et al. 2001; Humphrey et al. 2008a; Prochaska & Hennawi 2009). It is interesting to speculate that in this metal-rich halo environment, the potentially low gas densities and high velocity dispersion of the cold gas (as traced by the wide FWZI of our CO profiles), in combination with a potentially high-pressure environment induced by the radio plasma and the absence of a strong stellar radiation field, may conspire in favor of a lower conversion factor than our assumed $X_{\text{CO}} = 0.8$ (see Papadopoulos et al. 2008a; Glover & Mac Low 2011). This would lower the mass of molecular gas responsible for the bright CO(1-0) emission and alleviate the problem that this cold halo gas is found in regions devoid of Spitzer 4.5μm emission. Because the CO(1-0) emission in the halo is produced in a profoundly different environment than models on the $X_{\text{CO}}$ factor generally assume, a more detailed analysis of this is beyond the scope of this paper.

When considering the timescales involved, assuming that the enriched material is expelled with a typical velocity of $\sim 500$ km s$^{-1}$ (Nesvadba et al. 2008), it would take the gas $\sim 6 \times 10^7$ yr to reach a distance of 30 kpc. In agreement, the typical lifetime of extended radio sources is expected to be at least several $10^7-8$ yrs (Parma et al. 1999; Blundell & Rawlings 2000). Overzier et al. (2005) argue that the nuclear activity in MRC 2048-272 has recently ceased (given the lack of X-ray and radio continuum in the core), indicating that this system is at the end of its current radio-loud AGN cycle.

In addition, in several $\times 10^7$ yr a major starburst episode may have passed its peak activity (e.g. Mihos & Hernquist 1994), which may perhaps explain why the hosts of the off-nuclear CO(1-0) emitters are fainter in the FIR than MRC 0152-209 and MRC 1138-262, which have the bulk of CO (still) centred on the host galaxy. While for MRC 0152-209 part of the CO(1-0) appears to extend along the radio axis (Sect. 4.2.1), it is also interesting to note that for MRC 1138-262 Nesvadba et al. (2006) detect a fast, redshifted ionised gas outflow along the same direction as the extended CO(1-0) emission (see Emonts et al. 2013 for a discussion).

If jet-driven enrichment is a viable scenario for the radio - CO alignment, we can make the testable predictions that (i) the chemical enrichment of the halos around HzRGs should occur mainly along the radio jet axis, (ii) HzRGs with CO reservoirs in their halos may have passed a peak-period of major starburst activity and (iii) there should be high-
z galaxies in which the radio source has recently switched off (e.g. radio-quiet QSOs) with similar off-nuclear CO(1-0) reservoirs.

4.2.3 Jet-brightness enhancement by cold ISM

Alternatively, the CO(1-0) emission may represent tidal debris from the host or companion galaxies (similar to the tidal CO(1-0) gas we find around MRC0152-209; Fig. 7, or a filamentary structure of cold molecular gas (possibly an imprint of the large-scale Cosmic Web in the center of the proto-cluster; West et al. 1991 Springel et al. 2006 Ceverino et al. 2010). In those cases, the radio - CO alignment effect could occur because the working surface of the radio jet is brightest there where it encounters the densest medium (e.g. Barthel & Arnaud 1996). The characteristic bright radio continuum in HzRGs would then be a consequence of the fact that the synchrotron jets propagate into a high density region. This scenario was also used by Stevens et al. 2003 to explain their observed alignment between the radio source and extended submillimetre emission in and around HzRGs (and has also been invoked to explain the relatively high occurrence of bright, compact radio sources in gas-rich and starbursting radio galaxies at low-z; e.g. Tadhunter et al. 2011 Morganti et al. 2011 Emonts et al. 2012).

4.3 Radio - CO alignment: general statistics

As mentioned in Sect. 3.2 for all three HzRGs with CO(1-0) emission found solely at large distance from the host galaxy, the CO(1-0) emission is aligned to within 20° of the radio axis. For MRC0152-209, the off-nuclear the CO(1-0) emission towards the NE is also appears to be aligned with the small radio jet (Sect. 3.2.1). The chance of CO(1-0) being aligned within 20° for four out of the five CO-detected sources in our sample is < 1%. However, the beam-size of our observations is large and these CO(1-0) signals peak at only ~5σ significance, introducing substantial uncertainty in the exact location of the CO(1-0) emission. Moreover, given the low number of CO-detected sources in our sample, we cannot place reliable statistical significance on these results.

In order to investigate in a more statistical way whether there is evidence for a general alignment between CO emission and radio jets in HzRGs, we show in Table 3 and Fig. 9 a summary of all HzRGs (with $L_{500} > 10^{27} \text{ W Hz}^{-1}$) from the literature for which extended CO and radio emission have been imaged. We use a one-tailed Mann-Whitney U-test to verify the hypothesis that the CO emission in this sample is preferentially aligned towards the radio jet axis, compared to samples of equal size where the differences in position angle between the CO and radio are presented by randomly chosen numbers between 0 and 90 degrees. We find marginal statistical significance at the 95% level that such an alignment is present in the data.

These results are a largely independent confirmation of the results by Klamer et al. (2004), who derived their conclusions from a sample of high-z radio sources with a lower average radio power. We note, however, that we are still dealing with low-number statistics and that most of the studies from the literature where done with higher order CO transitions (which likely trace a different component of the gas than CO(1-0); Sect. 4.4. Larger samples observed with ALMA and the EVLA are required to verify the alignment effect for various J-transitions of CO.

4.4 The CO(1-0) content of HzRGs

We detect CO(1-0) emission (with $L'_{CO} > 4 \times 10^{10} L_\odot$) associated with 38% of our sample of southern HzRGs. In earlier studies van Ojik et al. (1997b) did not detect any CO among a sample of 14 northern HzRGs (see also Evans et al. 1996). van Ojik et al. (1997b) derived upper limits of $L'_{CO} \sim \text{ few } \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$, but mainly using the higher order J-transitions. These high-J transitions are believed to trace the denser and often thermally excited gas in the more centrally concentrated in starburst/AGN regions. Our results that the CO(1-0) emission in HzRGs is often spread across tens of kpc scales thus strengthen the idea discussed in Sect. 4.4 that studies of low- and high-J transitions may be biased towards tracing different reservoirs of molecular gas. Thus, while a direct comparison between our study and the earlier work by van Ojik et al. (1997b) and Evans et al. (1996) is difficult, it shows the need for sensitive studies of HzRGs across a wide range of molecular transitions and species.

4.4.1 Low-J transitions at high-z: a comparison

Our survey is the first survey for the ground-transition CO(1-0) in a representative sample of HzRGs. With upgrades to wide-band receivers and observing capabilities below 50 GHz at the large millimetre facilities, a growing num-
Figure 9. Left: Difference in position angle (\(\psi\)) between the CO and synchrotron radio emission in HzRG (Table 3) plotted against the distance to which the CO emission extends. The filled and open circles are the same as in Fig. 8 and represent our sample sources detected in CO(1-0). The crosses are HzRGs with extended CO(\(J,J-1\)) emission from the literature. Right: Histogram of the distribution of \(\psi\) among HzRGs with extended CO(\(J,J-1\)) emission.

Table 3. Literature study on the potential alignment of CO(\(J,J-1\)) emission with radio source axis in HzRGs. \(\psi\) is the difference in position angle between the CO and radio jet. \(D_{\text{CO}}\) and \(D_{R}\) are the maximum distance out to which the CO and radio emission are detected, \(R = D_{\text{CO}}/D_{R}\) is the ratio of these values, which thus gives an indication how far inside (\(R < 1\)) or outside (\(R > 1\)) the radio jet the CO emission is found. References: 1. De Breuck et al. (2005); 2. Carilli et al. (1994); 3. Papadopoulos et al. (2000); 4. Ivison et al. (2008); 5. Carilli et al. (1997); 6. Pentericci et al. (2001); 7. De Breuck et al. (2003b); 8. Ivison et al. (2012); 9. Pérez-Torres & De Breuck (2005); 10. Nesvadba et al. (2009); 11. this work.

| Name         | \(z\)  | CO transition | \(\text{PA}_{\text{CO}}\) (\(^\circ\)) | \(\text{PA}_{R}\) (\(^\circ\)) | \(\psi\) (\(^\circ\)) | \(D_{\text{CO}}\) (kpc) | \(D_{R}\) (kpc) | \(R (D_{\text{CO}}/D_{R})\) | Refs. |
|--------------|--------|---------------|--------------------------------------|-------------------------------|----------------------|-----------------|-----------------|-----------------------------|-------|
| 4C 41.17     | 3.792  | (4-3)         | -140                                 | -130                          | 10                   | 10.9            | 57.9            | 0.19                        | 1,2   |
| 4C 60.07     | 3.791  | (4-3)         | -70                                  | -123                          | 53                   | 43.4            | 45.6            | 0.95                        | 3,4.5 |
| 6C 1908+7220 | 3.537  | (4-3)         | -127                                 | -154                          | 27                   | 37.1            | 50.5            | 0.73                        | 6     |
| B3 1329+3927 | 3.089  | (1-0)/(4-3)   | -154                                 | -213                          | 59                   | 33.4            | 15.5            | 2.15                        | 8-9   |
| TXS 0828+193 | 2.6    | (3-2)         | -131                                 | -141                          | 10                   | 78.0            | 56.9            | 1.37                        | 2.10  |
| MRC 1138-262 | 2.161  | (1-0)         | 56                                    | 95                            | 39                   | 25.2            | 63.8            | 0.39                        | 11    |
| MRC 0156-252 | 2.016  | (1-0)         | 76                                    | 67                            | 9                    | 59.3            | 25.4            | 2.33                        | 11    |
| MRC 2048-272 | 2.060  | (1-0)         | 58                                    | 43                            | 15                   | 55.8            | 22.8            | 2.45                        | 11    |
| MRC 0152-209 | 1.921  | (1-0)         | -31                                   | -32                           | 1                    | 25.5            | 18              | 1.42                        | 11    |
| MRC 0114-211 | 1.402  | (1-0)         | -92                                   | -93                           | 1                    | 34.9            | 4.3             | 8.12                        | 11    |

The number of studies are targeting the low-order CO transitions in various samples of high-z galaxies. This allows a fair comparison of the cold molecular gas content of these various types of galaxies, without having to deal with uncertainty in the thermalisation of the gas or the possibility of missing CO emission due to the very limited velocity coverage that plagued past studies (see Sect. 1).

In Fig. 10 we compare the CO(1-0) content of our HzRGs with that of samples of other types of galaxies in the same redshift range as our sample sources \((z \sim 1.5 - 2.5)\). We only included studies performed with wideband receivers (covering \(\geq 2000\)\(\text{km s}^{-1}\)) that targeted either the CO(1-0) or CO(2-1) transition, resulting in comparison samples of submillimetre galaxies (SMGs; Ivison et al. 2011; Hainline et al. 2011; Bothwell et al. 2013), starforming galaxies (Daddi et al. 2008; Dannerbauer et al. 2009; Aravena et al. 2010; 2012) and two obscured (type-2) quasi-stellar objects (QSO2; Lacy et al. 2011). Low-order CO observations done with narrow-band receivers (e.g. Papadopoulos et al. 2001; Greve et al. 2004, 2005) or observations that targeted either systems at \(z > 2.5\) (e.g. Klamer et al. 2005; Coppin et al. 2010; Carilli et al. 2011; Wang et al. 2011; Ivison et al. 2008, 2012; Huyu et al. 2013; Riechers et al. 2013) or lensed systems (e.g. Swinbank et al. 2010; Danielson et al. 2011; Riechers et al. 2011; Johansson et al. 2012; Aravena et al. 2013; Rawle et al. 2013) are excluded from our high-z comparison in order to introduce as little bias as possible.

Figure 10 shows \(L_{\text{CO}(1-0)}^{\prime}\) plotted against the starburst far-IR luminosity \(L_{\text{FIR}}\) for the various types of high-z galaxies.\(^5\) It is immediately clear that the five CO-detected

\(^5\) It is likely that \(L_{\text{FIR}}\) in some of the SMGs and QSO2 that we present is contaminated by an AGN-contribution (unlike for the HzRG, where the AGN contribution is separated from the starburst \(L_{\text{FIR}}\) values; Sect. 4.1). However we argue that this will not likely alter the main conclusions that we derive in this Section.
HzRGs in our sample have a CO(1-0) luminosity that is comparable to what is found in the CO-brightest SMGs.

Our CO(1-0) detection rate of 38% (taking into consideration a typical 3σ detection limit of $L_{\text{CO}(1-0)} \lesssim 4 \times 10^{10}$ K km s$^{-1}$ pc$^2$) is in rough agreement with the fact that 33% of the SMGs observed in CO(1-0) or CO(2-1) have $L_{\text{CO}(1-0)} \gtrsim 4 \times 10^{10}$ K km s$^{-1}$ pc$^2$ (Fig. 10). None of the $z \sim 1.5 - 2.5$ starforming galaxies is detected in CO(1-0) at this level, which reflects in their lower $L_{\text{FIR}}$.

It is, however, interesting that when excluding the three off-nuclear CO(1-0) detections in our sample (i.e. when only taking into account CO detections at the location of the host galaxy), the CO(1-0) detection rate of HzRGs drops to less than half that of SMGs (assuming a similar sensitivity cutoff). It would be worth to verify a possible deficiency of CO(1-0) emission in HzRGs, and investigate whether this can be related to the observed shock-heating of molecular H$_2$ gas in the centres of HzRGs (Nesvadba et al. 2010; Ogle et al. 2012; Guillard et al. 2012) and the highly shock-excited (‘above thermalisation’) CO-emitting gas found in some radio galaxies (Papadopoulos et al. 2008b; Ivison et al. 2012).

Larger CO surveys of unbiased samples with EVLA and ALMA are required to further investigate how the amount and properties of the CO-emitting gas in HzRGs compares to that of other types of high-$z$ galaxies.

5 CONCLUSIONS

We have performed the first representative survey for cold molecular CO(1-0) gas in a sample of 13 high-$z$ radio galaxies ($1.4 < z < 2.8$) using the Australia Telescope Compact Array. The main results from this work are:

i). We detect CO(1-0) emission in 38% (5/13) of our sample sources. The CO(1-0) luminosities are in the range $L_{\text{CO}} = (4.5 - 9.2) \times 10^{10}$ K km s$^{-1}$ pc$^2$, which correspond to molecular gas masses of $M_{\text{H}_2} = (4 - 7) \times 10^{10}$ M$_\odot$ when assuming $M_{\text{H}_2}/L_{\text{CO}} = 0.8$. The CO(1-0) profile for four of the five detections is broad ($FWZI \sim 1100 - 3600$ km s$^{-1}$).

ii). Only for two of these sources (MRC0152-209 and MRC1138-262), part of the CO(1-0) emission is co-spatial with the radio host galaxy, although a significant fraction of the CO(1-0) is spread across tens of kpc scales and likely related to the process of galaxy merging.

iii). For the other three CO-detections (MRC0114-211, MRC0156-252 and MRC2048-272) the CO(1-0) is found in the halo of the host galaxy. These three HzRG are among the fainter FIR emitters in the sample, indicating that large amounts of molecular halo gas ($L_{\text{CO}(1-0)} = \text{several} \times 10^{10}$ K km s$^{-1}$ pc$^2$) may have been missed in previous studies that mostly pre-selected targets based on a high FIR luminosity.

iv). We find an alignment between the off-nuclear CO(1-0) emission and the radio jet axis, with the CO located outside the brightest edge of the radio source. We discuss several scenarios that may explain this, including jet-induced star formation / gas cooling, jet-driven metal-enrichment of the gaseous halo and flux boosting of jets that propagating into a dense filament of cold halo gas.

v). Following our results, we performed a literature study on extended CO(J,J − 1) emission in HzRGs and find marginal statistical significance (95% level) for the hypothesis that the CO is preferentially aligned towards the radio axis.

vi). The majority of the host galaxies of high-$z$ radio sources does not contain CO(1-0) emission down to a secure limit of $L_{\text{CO}} \lesssim 3 \times 10^{10}$ K km s$^{-1}$ pc$^2$.

We have shown that from now on, the well-known alignments between the radio jets and optical, UV, X-ray and submm emission in HzRGs (see Sect. 1) will have to be discussed taking into account the component of cold molecular gas.

We note that the CO(1-0) emission that we found in the halos of three HzRG may only reveal part of the cold molecular gas content around HzRGs, as our observations are only sensitive to tracing those sites where the CO emission is brightest. Follow-up observations with the ATCA, EVLA and ALMA are essential to confirm the general existence of large reservoirs of cold molecular halo gas and study them in more detail. Given that the CO in these halo reservoirs may be widespread and is likely not forming stars at the rates seen in high-$z$ starforming and submillimetre galaxies, we argue that it is important to target the low-$J$ transitions of CO with short-baseline array configurations, and to study samples that are unbiased in IR or submm luminosity.

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APPENDIX A: NOTES ON INDIVIDUAL OBJECTS AND THEIR CO(1-0) CONTENT

MRC0114-211 ($z = 1.40$): MRC 0114-211 has a strong ($\sim 80$ mJy) 48 GHz radio continuum flux, and was also detected in the Australia Telescope Telescope 20 GHz (AT20G) Survey (Murphy et al. 2010; Massardi et al. 2011). The radio source is a Compact Steep Spectrum object with a total linear extent of 6 kpc (De Breuck et al. 2010; Randall et al. 2011).

We detect CO(1-0) emission 4 arcsec (34 kpc) west of the radio core, along the axis of the compact radio jet (Fig. 5). An archival HST image from Program 8838 (PI: Lehner) obtained with the Wide-Field Planetary Camera 2 (WFPC2F555W) shows faint optical emission centred at the location of the CO(1-0) emission, with brighter emission found just outside the edge of the radio source (Fig. 6). However, since the archival HST data were calibrated using the Guide Star Catalogue 1 (GSC-1; Lasker et al. 1990), an astrometric error of $\sim 1.5''$ in these HST data is possible (Russell et al. 1988; 1990), which could place the bright optical emission at the location of the host galaxy.

As shown in Table 1, the observing time on MRC 0114-211 had to be longer than for the other sources in our sample to reach a similar sensitivity (because observations were done in the lower sensitivity part of the ATCA 7mm band). In total 7 independent runs of 3-5 hours on-source observing time each were devoted to this target. Low-level indications for the CO(1-0) signal are present across the individual data sets from these runs.

MRC 0114-211 is the only source in our sample with a large uncertainty in optical redshift ($z = 1.41 \pm 0.05$; McCarthy et al. 1996).

MRC 0152-209 ($z = 1.92$): MRC 0152-209 has an HST morphology reminiscent of a major merger system, with large-scale tidal tails and a double nucleus (Pentericci et al. 2001; Emonts et al. in prep.). The 18 kpc-wide radio source is aligned along the main optical emission from the host galaxy (Pentericci et al. 2000b; 2001).

The CO(1-0) detection is discussed in detail in Emonts et al. (2011a). Due to the relatively narrow FWHM $\approx 400$ km s$^{-1}$ of the CO profile, the CO(1-0) peaks at high significance and a high-resolution follow-up study to spatially map the CO emission is in progress (Emonts et al. in prep; see also Fig. 1).

MRC 0156-252 ($z = 2.02$): MRC 0156-252 contains an extended radio source (diameter 70 kpc; Carilli et al. 1997; Pentericci et al. 2001) showed that there are several companion galaxies detected with HST/NICMOS that are aligned along the radio axis, as well as a large reservoir of Ly$\alpha$ emission that stretches inside the extent of the radio source.

The CO(1-0) emission in MRC 0156-252 peaks just outside the bright hot-spot of the bent NE radio jet ($\sim 50$ kpc or 6 arcsec from the radio core) and aligns with the reservoir of Ly$\alpha$ emission. It is thus feasible that the CO(1-0) and Ly$\alpha$ emission trace the same gas reservoir, which is ionised within the extent of the radio source (possibly as a combination of photo-ionisation of the AGN and shock-excitation by the radio jet; Villar-Martín et al. 2003; Overzier et al. 2005). Just north of the hot-spot and region of Ly$\alpha$ and CO(1-0) emission, Overzier et al. (2005) found a tentative reservoir of diffuse X-ray emission. Therefore, an even more complex gas reservoir (with a wide range of temperatures) may surround the bright radio lobe structure.

Figure 7 shows that the CO(1-0) emission appears to consist of two marginally resolved components that are located less than 15-20 kpc from each of the two NE companions in the HST/NICMOS image. Recent work by Galametz et al. (2013) suggests that the redshift at which we centred our CO(1-0) profile ($z = 2.016$) is closely related to the redshift of the innermost companion ($z_{\text{He II}} = 2.0171 \pm 0.0004$), which has blue colors indicative of star formation (Pentericci et al. 2001; see also Sect. 3.2.2). According to Galametz et al. (2013), this blue companion is shifted by almost $1000$ K km s$^{-1}$ with respect to the revised redshift of the central HzRG ($z_{\text{He II}} = 2.0256 \pm 0.0002$). The 'blue' and 'red' CO(1-0) component in Fig. 7 have a luminosity of $L'_{\text{CO}} \sim 5 \times 10^{10}$ and $\sim 4 \times 10^{10}$ K km s$^{-1}$ pc$^2$, respectively.

Because MRC 0156-252 was targeted only during three observing runs, Fig. A1 shows the spectra of the three individual observing epochs (Table 1). The dashed red line is the total spectrum from Fig. 4.

MRC 1138-262 ($z = 2.16$): MRC 1138-262, also called the Spiderweb Galaxy, is one of the most massive and...
active galaxies in the Early Universe (Miley et al. 2006
Seymour et al. 2007; De Breuck et al. 2010). It is a
conglomerate of star-forming galaxies that are embedded
in a giant (> 200 kpc) Lyα halo, located in the core of
the Spiderweb proto-cluster (Pentericci et al. 1997, 2000a
2002; Carilli et al. 1998; Kurk et al. 2004; Croft et al.
2005; Kodama et al. 2007; Zirm et al. 2008; Hatch et
2009; Doherty et al. 2010; Kuiper et al. 2011). Massive
star formation (SFR ~ 1400 M⊙ yr−1) occurs on scales of
> 200 kpc (Stevens et al. 2003; Seymour et al. 2007; Ogle
et al. 2012). The central galaxy hosts the radio source
MRC 1138-262, which induces significant feedback onto the
surrounding ISM (Nesvadba et al. 2006; Ogle et al. 2012).
Our CO(1-0) results are discussed in Emonts et al.
(2013). Part of the CO(1-0) emission is associated with the
central host galaxy of the radio source, but a significant
fraction of the gas is spread across at least several tens of
kpc (Fig. 3), most likely associated with merging companion
galaxies or the IGM between them (see Emonts et al.
2013 for a discussion).

MRC 2048-272 (z = 2.06): HST/NICMOS and VLA
imaging by Pentericci et al. (2000a, 2001) revealed that the
radio source is likely hosted by a bright NIR object that is
surrounded by two NIR companions. The brighter of the
two companions is an AGN (De Breuck et al. 2010). The
fainter of the two NIR companions is located in between the
tip of the bright NE radio hot-spot and the location where
the CO(1-0) peaks. Another IR-bright source is located in between the
two companions is an AGN (De Breuck et al. 2010). The
radio source is likely hosted by a bright NIR object that is
surrounded by two NIR companions. The brighter of the
two companions is an AGN (De Breuck et al. 2010). The
fainter of the two NIR companions is located in between the
tip of the bright NE radio hot-spot and the location where
the CO(1-0) peaks. Another IR-bright source is located at ∼ 8
arcsec SE of the radio galaxy (De Breuck et al. 2010).

For MRC 2048-272 the CO(1-0) profile appears double-
peaked and centred around zLyα from Venemans et al.
(2007). While the overall CO(1-0) emission covers a very
wide velocity range (FWZI = 3570 km s−1), both peaks are
spatially unresolved and centred at the same location, about
56 kpc or 6 arcsec (i.e. one synthesized beam radius) away
from the core of the radio galaxy. For both the blue and red
peak λCO ∼ 4 × 1019 K km s−1 pc2. More sensitive observations are required to verify the exact shape of the CO profile and related total CO(1-0) intensity.

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