

A Molecular Gas Study of Low Luminosity Radio Galaxies

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Abstract

We discuss CO spectral line data of a volume-limited sample of 23 nearby ($z < 0.03$) low luminosity radio galaxies, selected from the B2 catalogue. We investigate whether the CO properties of our sample are correlated with the properties of the host galaxy, and in particular with the dust component. We find strong evidences for a physical link between the dust disks probed by HST in the galaxy cores and the molecular gas probed by the CO spectral lines, which in two cases display a double-horn shape, consistent with ordered rotation. On the other hand, from a preliminary comparison with other samples of radio sources we find no significant differences in molecular gas properties between FRI and FR II radio sources. In order to confirm the suggestion that the CO is dynamically associated with the core dust disks, the most suitable sources of our sample will be proposed for interferometric imaging at PdBI.

Key words: galaxies:active, radio lines:galaxies

1 Background

The fuelling of relativistic jets in radio-loud active galactic nuclei is still not fully understood. It is clear that energy is released in the vicinity of a supermassive black hole, but whether the mechanism is direct electromagnetic extraction of rotational kinetic energy (e.g. Blandford & Znajek 1977; Koide et al. 2002) or more closely related to the process of accretion (e.g. Blandford & Paine 1982; Hujeirat et al. 2003) remains a matter of debate. The ratio of energy flux in jets to that radiated by an accretion disk varies by orders of magnitude between different classes of AGN. Here, we are concerned with

low-luminosity (FRI) radio galaxies (Fanaroff & Riley 1974). These are known to contain very massive black holes, but show very little evidence for emission from accretion disks, their nuclear luminosities being a small fraction of that expected from accretion at the Eddington rate, $L/L_{\text{Edd}} < 10^{-4}$ (Marchesini et al. 2004). They form the parent population for nearby BL Lac objects and must therefore produce highly relativistic jets on sub-pc scales. There is direct evidence for relativistic motion on parsec scales in FRI jets (Giovannini et al. 2001) and for smooth deceleration from relativistic to sub-relativistic speeds on scales of 1 – 10 kpc (Laing et al. 1999). FRI radio sources are located in fairly normal elliptical galaxies, invariably containing hot, X-ray emitting plasma (thought to confine the jets on large scales), but little ionized, line-emitting material at $\approx 10^4$ K. It has recently become clear that they may also contain substantial amounts of cool gas and dust (e.g. de Ruiter et al. 2002; Verdoes Kleijn & de Zeeuw 2005; Lim et al. 2000; Lim et al. 2003). Dust is observed in 53% of the B2 sample of nearby radio galaxies (mostly FRI; see below) and the dust mass is correlated with radio power (de Ruiter et al. 2002). There is also a connection between the dust-lane morphology (disk/irregular) and the presence of jets, and some tendency for dust lanes and jets to be orthogonal (de Ruiter et al. 2002; Verdoes Kleijn & de Zeeuw 2005). These associations argue that accretion of cool gas may indeed power the radio jets. The next step is to understand the dynamics of the cool gas. Lim et al. (2000) detected ^{12}CO ($1 \rightarrow 0$) and ($2 \rightarrow 1$) emission from the FRI radio galaxies 3C 31 and 264 with the IRAM 30m Telescope and established that the line profiles indicate disk rotation. Interferometric observations of 3C 31 by Okuda et al. (2005) showed that the CO coincides spatially with the dust disk observed by HST (Martel et al. 1999) and is in ordered rotation. These authors suggest that the cool gas is in stable orbits.

In order to increase the number of FRI radio galaxies with CO observations and so to improve our knowledge of their molecular gas properties, we are studying a volume-limited sample of 23 nearby ($z < 0.03$) low luminosity radio galaxies, selected from the B2 catalogue (Colla et al. 1975). We notice that for 16 of such objects HST imaging is available (Capetti et al. 2000). The CO properties of this sample are compared to the 23 $z < 0.03$ 3C radio galaxies studied by Lim et al. (2003) and to the 18 $z < 0.0233$ (or $v < 7000$ km/s) UGC galaxies with radio jets, studied by Leon et al. (2003). We notice that the three samples are partially overlapping.

2 Line Observations and Measurements

We used the IRAM 30m telescope to search for emission in the ($1 \rightarrow 0$) and ($2 \rightarrow 1$) transitions of ^{12}CO in 9 B2 radio galaxies of the $z < 0.03$ volume-limited sample, described above. We used receivers A100 and B100 connected to the 1

Table 1
IRAM 30m CO line measurements

Source	$^{12}\text{CO}(1\rightarrow 0)$			$^{12}\text{CO}(2\rightarrow 1)$			$\log M_{H_2}$ M $\odot$
	$\Sigma T_a^* dv$	Δv_{FWHM}	$\frac{T_{\text{peak}}}{T_{\text{rms}}}$	$\Sigma T_a^* dv$	Δv_{FWHM}	$\frac{T_{\text{peak}}}{T_{\text{rms}}}$	
	K km/s	km/s		K km/s	km/s		
0120 + 33	< 0.35	-	-	< 0.61	-	-	< 7.7
0149 + 35	1.34	545	5.4	3.15	551	7.7	8.3
0258 + 35	0.88	382	6.6	0.21	127	2.4	8.1
0326 + 39	< 0.35	-	-	0.64	171	1.9	< 8.0
0331 + 39	1.35	807	3.6	0.90	679	3.4	8.5
1122 + 39	6.84	670	23.0	5.93	672	16.7	8.2
1217 + 29	0.58	346	3.3	< 0.87	335	3.1	6.1
1321 + 31	< 0.35	-	-	1.24	297	2.7	< 7.7
1615 + 35	< 0.35	-	-	0.52	129	4.1	< 8.2

M_{H_2} derived from CO(1 $\rightarrow$ 0) measures and assuming $H_0 = 100$ km/s/Mpc

MHz filter bank in 2×512 MHz blocks together with receivers A230 and B230 with the 4 MHz filter bank in 2×1 GHz blocks. After averaging the outputs of the two pairs of receivers we got noise levels of $T_{\text{rms}} \sim 0.5 - 1$ mK and $\sim 1 - 2$ mK respectively (1σ , $\Delta v \sim 40$ km/s). The data were reduced with the CLASS package and line fluxes were measured by numerically integrating over the channels in the line profile. Line widths were measured as full widths at 50% of the peak. A source was considered detected when both (1 $\rightarrow$ 0) and (2 $\rightarrow$ 1) emission lines have $T_{\text{peak}} > 2T_{\text{rms}}$, with at least one having $T_{\text{peak}} > 3T_{\text{rms}}$. In case of non detections, upper limits were calculated (see Evans et al. 2005). A summary of our CO line measurements is given in Table 1. Line widths of the 5 detected sources are of the order of 500 km/s, and in a few cases lines show a double-horn structure, indicating rotating CO disks. H_2 molecular masses were derived as in Lim et al. (2000).

3 Molecular gas and dust properties of the B2 $z < 0.03$ sample

In this section we want to investigate whether the CO properties of our sample are correlated with the properties of the host galaxy, and in particular with the dust component. We notice that to our measurements (see Table 1) we have added CO line measurements for other 7 galaxies, observed as part of

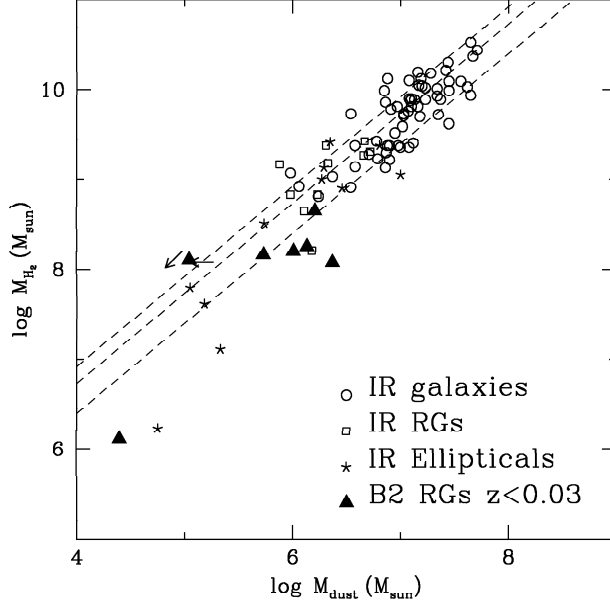


Fig. 1. Dust mass (derived from IRAS observations) vs. H_2 mass for several IR-selected samples: IRAS luminous galaxies (empty circles); IRAS radio galaxies (empty squares); IRAS ellipticals (asterisks). Filled triangles and arrows refer to IRAS $z < 0.03$ B2 radio galaxies. Dashed lines indicate the $M_{H_2}/M_{\text{dust}} = 540 \pm 290$ relation found by Sanders et al. (1991).

the UGC and 3C samples (Leon et al. 2003; Lim et al. 2003, see Sect 1). This means that our analysis can rely on 16 of the 23 galaxies (i.e. $\sim 70\%$ of the whole sample).

In Fig. 1 we show the relation between the molecular mass content, M_{H_2} , and the content in “warm” dust (derived from far-infrared 60 and 100 μm observations), M_{dust} , found for several IR-selected galaxy samples: luminous IRAS galaxies (empty circles; Sanders et al. 1991); IRAS radio galaxies (empty squares; Mazzarella et al. 1993; Evans et al. 2005); IRAS ellipticals (asterisks; Wiklind et al. 1995; Young 2002; Young 2005). Also indicated is the $M_{H_2}/M_{\text{dust}} = 540 \pm 290$ relation measured for IRAS luminous galaxies (dashed lines, Sanders et al. 1991). In our sample of 16 B2 $z < 0.03$ radio galaxies with CO line measurements, we have 9 objects detected by IRAS. Such objects are indicated in Fig. 1 by filled triangles and/or arrows (in case of upper limits). We notice that IRAS-detected sources in our sample are typically also detected in CO (only 1 CO upper limit is present in the figure¹), indicating an association between dust and molecular gas components.

Our sample can be used to probe the $M_{H_2} - M_{\text{dust}}$ relation at lower masses than typical for luminous IR galaxies and other IR-selected radio galaxies. Our low luminosity radio galaxies show a large spread in dust masses and are not well represented by the relation holding at larger masses. In particular, several galaxies show larger dust masses than expected. While this result can suggest a departure from the relation at very low mass ranges (see also IRAS ellipticals, asterisks), it can also possibly be due to the different scales probed by IRAS (the whole galaxy) and CO observations (inner 5-10 kpc at

¹ upper limits in M_{dust} are defined for objects detected by IRAS only at 60 μm .

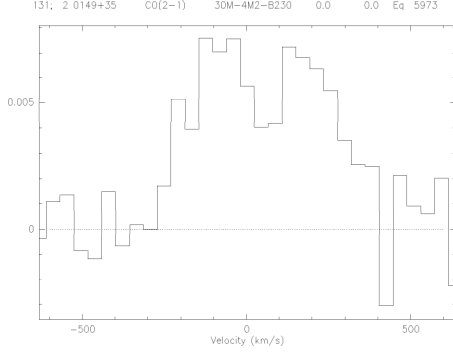


Fig. 2. *Left*: $^{12}\text{CO}(2\rightarrow1)$ spectrum obtained at IRAM 30m for the B2 radio galaxy 0149+35, showing a double-horn line. *Right*: HST image of 0149+35, showing a dusty rotating disk.

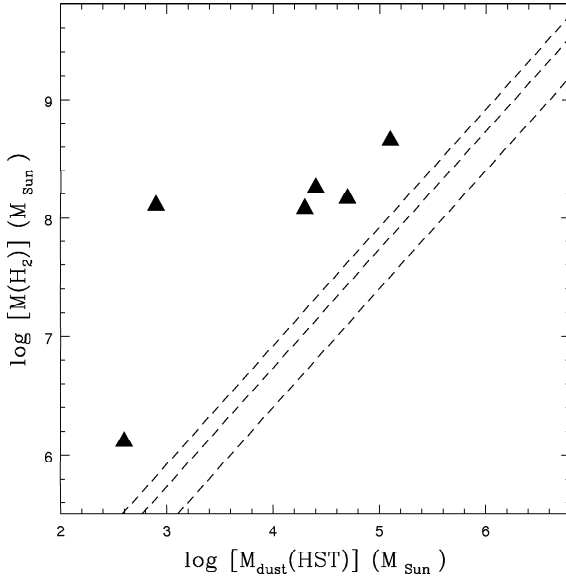


Fig. 3. Dust mass (derived from HST observations) vs. H_2 mass for the $z < 0.03$ B2 radio galaxies with HST dust and CO line detections. The $M_{H_2}/M_{\text{dust}} = 540 \pm 290$ relation found for IRAS luminous galaxies (Sanders et al. 1991) is overplotted as reference (dashed lines).

the $^{12}\text{CO}(1\rightarrow0)$ observing frequency).

More meaningful it could be from this point of view a comparison between CO and HST high resolution observations, which are approximately sensitive to the same scale (the galaxy core).

HST observations are available for 12 of the 16 galaxies with CO line measurements in our sample. We find strong evidences for a physical link between the dust component probed by HST and the molecular gas probed by CO: CO is detected only in those galaxies showing dust in HST images and double-horn CO lines are found in two galaxies, both showing HST rotating dusty disks (see example in Fig. 2). Such evidences reinforce previous indications by Lim et al. (2000) and Okuda et al. (2005).

In order to check whether any quantitative relation can be derived between molecular gas and optical dust masses in our sample, we plot in Fig. 3 M_{H_2} against the optical dust mass, as derived from HST observations ($M_{\text{dust}}(HST)$, see de Ruiter et al. 2002). Unfortunately only 5 objects have reliable CO measures (we discard upper limits) and a reliable statistical analysis must await further CO line single-dish observations. In order to probe the gas dynamics and confirm the existence of a dynamical link between CO and HST dusty disks, the most suitable B2 radio sources will also be proposed for interferometry at Plateau de Bure.

4 Comparison with other radio samples

We have finally compared the B2 $z < 0.03$ radio galaxy sample to the $z < 0.03$ 3C and the $z < 0.0233$ UGC radio samples (Lim et al. 2003; Leon et al. 2003). The aim is to check whether the molecular gas properties are different for different types of radio sources. In particular we want to confirm the findings of Evans et al. (2005), who claim that FR II galaxies are characterized by lower CO detection rates than FRI and compact radio sources.

To take into account the differences in volume, we limited the comparison to all objects with $z \leq 0.0233$. In such range we find no significant difference (see Fig. 4): molecular gas masses are very similar, approximately spanning the range $10^7 - 10^9 M_\odot$, with upper limits varying from $\sim 10^7 M_\odot$ to $\sim 10^8 M_\odot$, depending on distance. Also CO detection rates do not differ significantly in the three samples: $47 \pm 17\%$, $33 \pm 17\%$, and $75 \pm 25\%$, for the UGC, 3C and B2 samples respectively. We notice however that the three samples partially overlap and most of the FR II sources present in the 3C sample are at $z > 0.0233$. While this can explain the results of Evans et al., as a consequence of a distance bias against FR II radio galaxies, it is clear that deeper CO observations are needed to better constrain the molecular gas properties of FRI and FR II radio sources.

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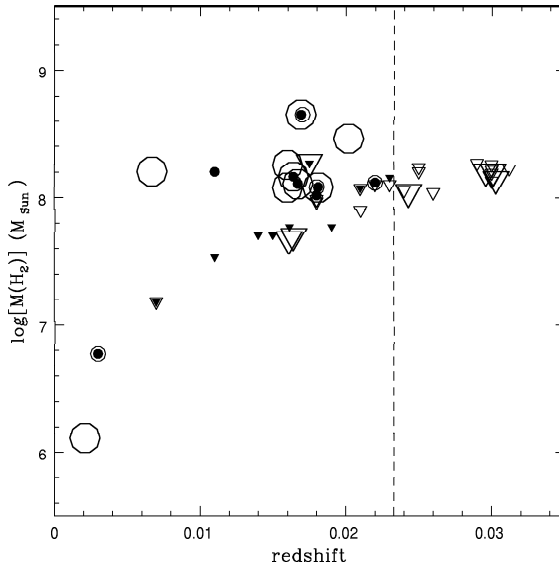


Fig. 4. H_2 mass vs redshift for the $z < 0.03$ B2 radio galaxies (large empty symbols); for $z < 0.03$ 3C radio galaxies (small empty symbols); and for $z < 0.0233$ UGC galaxies (filled symbols). Circles refer to detections and triangles to upper limits. The dashed line at $z = 0.0233$ indicates the redshift limit to which the three samples overlap.

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