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A Search for Molecular Gas in 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. Most of such objects (16/23) have HST imaging.

Our aim is to establish the distribution of molecular gas masses in low luminosity radio galaxies, in comparison with other radio source samples, confirm the suggestion that the CO is in ordered rotation, determine its relation to the dust disks observed in these objects with HST and establish targets for future interferometric imaging.

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 & Payne 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, Celotti, & Ferrarese 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

Table 1. CO line measurements

Source	$^{12}\text{CO}(1\rightarrow 0)$			$^{12}\text{CO}(2\rightarrow 1)$			$\log M_{H_2}$
	$\Sigma T_a^* dv$ K km/s	Δv_{FWHM} km/s	$\frac{T_{\text{peak}}}{T_{\text{rms}}}$	$\Sigma T_a^* dv$ K km/s	Δv_{FWHM} km/s	$\frac{T_{\text{peak}}}{T_{\text{rms}}}$	
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							

Zeeuw 2005; Lim et al. 2000, 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 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

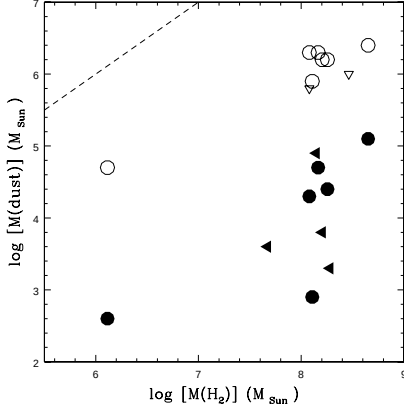


Figure 1. Dust mass vs. H_2 mass for the $z < 0.03$ B2 radio galaxies with CO line observations. Filled symbols: $M(\text{dust})$ derived from HST. Empty symbols: $M(\text{dust})$ derived from IRAS. Triangles indicate upper limits in dust mass (downwards) or H_2 mass (leftwards). The dashed line indicate the $M(\text{dust}) = M(H_2)$ locus.

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 properties of the B2 $z < 0.03$ sample

In Fig. 1 we compare the molecular mass content, M_{H_2} , to the content in dust, $M(\text{dust})$, as derived from both IRAS far-infrared (empty symbols) and HST optical (filled symbols) observations for the B2 $z < 0.03$ radio galaxies. To our measurements (see Table 1) we have added CO line measurements for other 7 galaxies which were observed as part of the UGC and 3C samples (Leon et al. 2003; Lim et al. 2003, see Sect. 1). This means that our analysis is based on 16 of the 23 galaxies (i.e. $\sim 70\%$ of the whole sample). We notice that $M_{H_2} > M_{\text{dust}}(\text{IRAS}) > M_{\text{dust}}(\text{HST})$. The fact that $M_{\text{dust}}(\text{IRAS}) > M_{\text{dust}}(\text{HST})$ probably just reflects the different scales probed in the two cases: the whole galaxy for IRAS FIR observations and the inner galaxy core for HST high resolution observations. On the other hand, the CO observations are approximately sensitive to the same scale as HST ($< 5 - 10$ kpc at the $^{12}\text{CO}(1 \rightarrow 0)$ observing frequency), and a comparison is more meaningful. Our observations show several hints for a physical link between the dust component probed by HST and the molecular gas probed by CO: CO was detected only in those galaxies showing dust in HST images and double-horn CO lines were 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). For further confirmation on the gas dynamics, the most suitable B2 radio sources will be proposed for interferometry at Plateau de Bure.

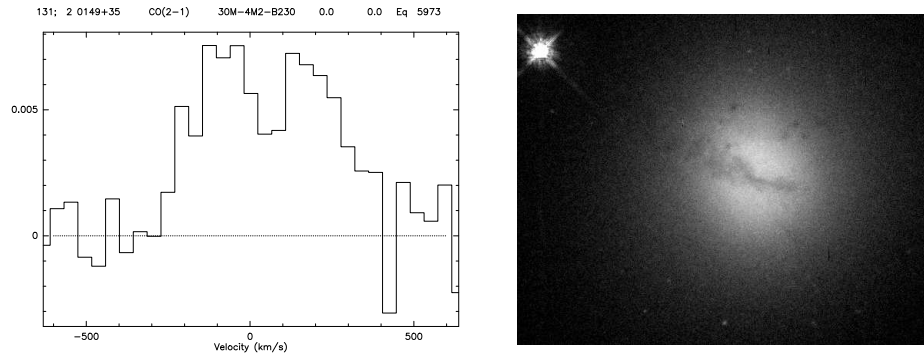


Figure 2. *Left:* $^{12}\text{CO}(2\rightarrow 1)$ spectrum obtained at IRAM 30m for the B2 radio galaxy 0149+35, showing a double-horn line. *Right:* HST image of 0149+35, showing a dusty rotating disk.

4. Comparison with other samples

We compared the B2 $z < 0.03$ radio galaxy sample to the $z < 0.03$ 3C and the $z < 0.023$ UGC radio samples (Lim et al. 2003; Leon et al. 2003). To take into account the differences in volume, we limited the comparison to all objects with $z \leq 0.023$. In such range we found no significant difference: 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 statistics is poor and larger samples are needed to better constrain the molecular gas properties of such objects.

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