MOLECULAR DISKS IN RADIO GALAXIES - THE PATHWAY TO ALMA

I. Prandoni[1] , R.A. Laing[2], H.R. de Ruiter[1], P. Parma[1]

[1]IRA-INAF, Bologna, Italy; [2]ESO, Garching, Germany

Summary

It has recently been proposed that the jets of low-luminosity radio galaxies are powered by direct accretion of the hot phase of the IGM onto the central black hole. Cold gas remains a plausible alternative fuel supply, however. The most compelling evidence that cold gas plays a role in fueling radio galaxies is that dust is detected more commonly and/or in larger quantities in (elliptical) radio galaxies compared with radio-quiet elliptical galaxies. On the other hand, only small numbers of radio galaxies have yet been detected in CO (and even fewer imaged), and whether or not all radio galaxies have enough cold gas to fuel their jets remains an open question. If so, then the dynamics of the cold gas in the nuclei of radio galaxies may provide important clues to the fuelling mechanism.

The only instrument capable of imaging the molecular component on scales relevant to the accretion process is ALMA, but very little is yet known about CO in southern radio galaxies. Our aim is to measure the CO content in a complete volume-limited sample of southern radio galaxies, in order to create a well-defined list of nearby targets to be imaged in the near future with ALMA. APEX has recently been equipped with a receiver (APEX-1) able to observe the 230 GHz waveband. This allows us to search for CO(2-1) line emission in our target galaxies.

Here we present the results of CO(2-1) APEX-1 spectroscopy taken during Science Verification for three southern low luminosity radio galaxies: NGC3557, IC 4296 and NGC1399. The experiment was successful with two targets detected, and possible indications for a double-horned CO line profile, consistent with ordered rotation. These early results are encouraging, demonstrating that APEX can efficiently detect CO in nearby radio galaxies. We therefore plan to use APEX to obtain CO spectroscopy for a wider southern volume-limited (z<0.03) sample. For more details see Prandoni et al. (2010, A&A, in press, arXiv:1009.0156).

Sample

The parent sample is selected from the Parkes 2.7-GHz survey, in the declination range $-17^o<\delta<-40^o$, as described by Ekers et al. (1989). It has a radio flux-density limit of 0.25 Jy at 2.7 GHz and an optical limit of $m_V \leq 17.0$, and consists of 191 radio galaxies. We extracted those sources with redshifts z<0.03 which are associated with elliptical galaxies. The resulting 11 objects thus form a small, but volume-limited and complete subset of the Ekers et al. (1989) sample. All eleven sources of the volume-limited sample are of the FRI type (Fanaroff & Riley 1974). The subset is quite similar to the sample of 3C and B2 radio galaxies in the Northern Hemisphere, which consists of 23 low luminosity radio sources associated with elliptical galaxies at z<0.03; 16 of these have been observed in CO with the IRAM 30m telescope (Prandoni et al. 2007).

As part of the science verification programme of the APEX-1 receiver, three of the eleven sources in our sub-sample were selected for observation in the ^{12}CO(2-1) line. They were: PKS0336-35 (NGC 1399), PKS1107-372 (NGC 3557), and PKS1333-33 (IC 4296). All three are radio sources with twin radio jets (**Figure 1, left panels**), and had been observed with the WPFC2 of the Hubble Space Telescope (Lauer et al. 2005). While no trace of dust was found in the nucleus of NGC 1399, the other two show prominent dusty disks around their respective nuclei (**Figure 1, right panels**).

A fourth sample member, PKS0320-37 (Fornax A) was imaged in ^{12}CO(1-0) and ^{12}CO(2-1) by Horellou et al. (2001); it shows a complex dust structure in HST observations (Grillmair et al. 1999). No CO imaging is available for the remaining sample members.

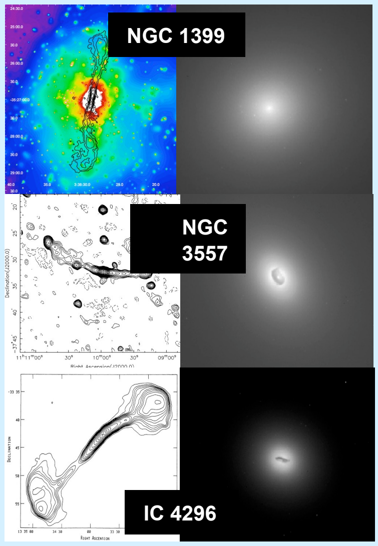

Figure 1
Left: 1.4 GHz VLA radio continuum contours. *Right:* HST images.

CO(2-1) Line Observations & Measurements

We used the APEX-1 SHeFI receiver connected to the FFTS backend to search for emission in the (2-1) transition of ^{12}CO. The APEX 230-GHz 30 arcsec FWHM beam probes the presence of molecular gas in the galaxy cores (the inner 3 - 7 kpc, depending on the redshift), allowing a direct comparison with dust structures on similar scales imaged with HST.

The observations were carried out in Summer 2008 and the data were reduced with the CLASS package. Scans severely affected by ripples and/or noisy baselines were removed and first-order baselines were subtracted. Line fluxes were measured by numerically integrating over the channels in the line profile. A source was considered detected when the ^{12}CO(2-1) emission line had $T_{a\ peak}>3\ T_{a\ rms}$, and tentatively detected when $T_{a\ peak}>2\ T_{a\ rms}$. In case of non detections, upper limits were calculated, following Evans et al. (2005). H_2 molecular masses were derived using the same relation as used by Gordon et al. (1992) and later by Lim et al. (2000), but modified for a Λ-CDM cosmology and H_0=70 km/s/Mpc. A summary of our CO line measurements is given in **Table 1**. The final baseline-subtracted and smoothed CO line spectra are shown in **Figure 2**.

NGC 3557 was easily detected at a channel resolution of Dv_{res} ~ 40 km/s, while for IC 4296 (the source at highest redshift) only an upper limit could be derived. In the case of NGC 1399 only the higher of the two peaks in the spectrum (**Figure 2, top left**) has a signal-to-noise ratio}>2 and can be considered tentatively detected. However the systemic velocity of the galaxy falls between the two peaks. By increasing the smoothing to Dv_{res}~120 km/s (**Figure 2, top right**), we can reduce the noise level to $T_{a\ rms}$ ~ 0.35 mK and get a clear >3s detection over a wider velocity range (**Table 1**). NGC 1399 does not show detectable dust features in the HST image, and the presence of CO is particularly interesting in this case.

There is some evidence for a double-horned structure in the spectrum of NGC 3557, although the statistical significance is low (**Figure 2, bottom left**). If confirmed, the presence of CO in ordered rotation would be consistent with the strong dusty disk seen in HST observations (**Figure 1**). A very marked dusty disk is present even in IC 4296 (**Figure 1**) and we suspect that a longer observation (t_{ON} >> 30 min), possibly with better weather conditions (T_{sys} < 300 K), will lead to a detection.

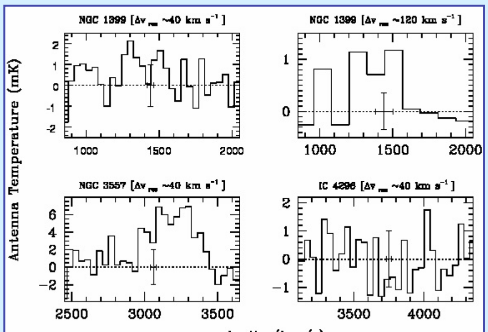

Figure 2

Source Name	Redshift	t_{ON} (min)	T_{sys} (K)	Δv_{res} (km/s)	$T_{a\ rms}$ (mK)	$\Sigma\ T_a$ dv (K km/s)	Δv_{FWHM} (km/s)	S/N	log M(H_2) (M_{Sun})
NGC 1399	0.0048	108.2	272	40	1	0.20	127	2.1	7.47
				120	0.35	0.39	365	3.3	7.75
NGC 3557	0.0102	18.4	316	40	2	1.52	348	3.5	9.02
IC 4296	0.0125	37.4	315	40	1	<0.51	…	<2	<8.70

Table 1

Columns 1-10: Source name; source redshift; on-source integration time (t_{ON}), after flagging data affected by poor baselines and/or ripples; mean system temperature during the observations (T_{sys}); channel width after smoothing (Δv_{res}); corresponding noise level in the line spectra ($T_{a\ rms}$); line integrated flux ($\Sigma\ T_a dv$); FWHM line width (Δv_{FWHM}); line signal to noise (S/N=$T_{a\ peak}$ / $T_{a\ rms}$); molecular gas mass (log M(H_2)).

Discussion and Conclusions:

The H_2 masses of the four low-luminosity southern radio galaxies observed so far (including Fornax A) are plotted against redshift in **Figure 3**, together with the 23 B2 z<0.03 radio galaxies (Prandoni et al. 2007), the brighter z<0.03 3C radio galaxies studied by Lim et al. (2003) and the z<0.0233 UGC galaxies with radio jets studied by Leon et al. (2003). We find that molecular gas masses are very similar over the full range of redshift (and, implicitly, radio power) for the combined samples, spanning the range 10^7 - 10^9 M_{Sun}, with upper limits (**triangles in Figure 3**) varying from ~10^7 to ~10^8 M_{Sun}, depending on distance. These values are consistent with the hypothesis that the jets of low-luminosity (FRI) radio galaxies can be powered by accretion of cold gas, but there is a large scatter in molecular gas mass at a given radio luminosity, as also found by McNamara et al. (2010) for brightest cluster galaxies.

Seven examples of CO detections without visible dust, including NGC 1399, are plotted in **Figure 3**. The inferred H_2 masses range from 8x10^7 to 4x10^8 M_{sun} . It is therefore not yet clear whether there is a significant difference between the H_2 masses of radio galaxies with and without dust. Nevertheless CO line detections are frequent in radio galaxies with dust, even more when the dust is in form of nuclear disks. We also find that almost one half of the objects with dusty disks detected in CO have double-horned line profiles. The double-horned CO line profiles characteristic of ordered rotation (indicated by the **crosses in Figure 3**) occur over a wide range of molecular gas masses. Since many of the other detections are still marginal, it is possible that the molecular gas in the majority of low-luminosity radio galaxies is in the form of kpc-scale nuclear disks or rings, co-spatial with the dust and in ordered rotation. ***The fact that we are finding CO in radio galaxies with no detectable dust may suggest that in (at least some) objects the bulk of the gas is in a cold (molecular) phase, supporting the idea that virtually all radio galaxies may be fuelled by cold gas.***

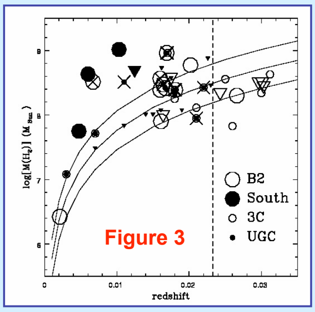

Figure 3

Solid lines indicate the M(H_2) 3σ detection limit for σ (=$T_{a\ rms}$) = 0.1, 0.2 and 0.4 mK respectively. The vertical dashed line at z=0.0233 indicates the redshift limit to which all three Northern samples overlap.