A search for molecular gas in restarting radio galaxies

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ABSTRACT

Several radio galaxies are known that show radio morphological signatures that are best interpreted as restarting of nuclear activity after a period of quiescence. The conditions surrounding the phenomenon of nuclear recurrence are not understood. In this paper we have attempted to address this question by examining the nuclear fuelling characteristics in a sample of restarting radio galaxies. We have examined the detection rate for molecular gas in a representative sample of nine restarting radio galaxies, for seven of which we present new upper limits to the molecular gas mass derived from CO line observations we made with the IRAM 30-m telescope. We derive a low CO detection rate for the relatively young restarted radio galaxies suggesting that the cessation of the nuclear activity and its subsequent restarting may be a result of instabilities in the fuelling process rather than a case of depletion of fuel followed by a recent fuel acquisition. It appears that abundant molecular gas content at the level of few $10^8$–$10^9 M_\odot$ does not necessarily accompany the nuclear restarting phenomenon. For comparison we also discuss the molecular gas properties of five normal giant radio galaxies, three of which we observed using SEST. Despite obvious signs of interactions and nuclear dust disks none of them has been found to host significant quantities of molecular gas.

Key words: Galaxies: active — radio lines: galaxies — galaxies: ISM — galaxies: nuclei

1 INTRODUCTION

One of the exciting developments in radio galaxy research in recent years has been the recognition of a restarting of nuclear activity following a quiescent period. The usual extended twin-lobe radio morphology of radio galaxies are in some cases found to be accompanied by a second pair of lobes sharing the same central radio core (Roettiger et al. 1994; Subrahmanyan, Saripalli & Hunstead 1986; Schoenmakers et al. 2000a). The ‘double-double’ structures were interpreted by these authors as radio galaxies that were experiencing a second epoch of activity. Detailed studies of some of the more striking examples of this class of radio galaxies (e.g. Lara et al. 1999; Schoenmakers et al. 2000b; Saripalli, Subrahmanyan & Udayashankar 2002; Saripalli, Subrahmanyan & Udayashankar 2003) have estimated the ages of the second activity epoch to be few times $10^6$ yr suggesting that the restarted activity is fairly recent in comparison with the ages of radio galaxies in general (Scheuer 1995; Mack et al. 1998).

The nuclear activity that manifests itself as extended twin lobe radio structures in radio galaxies is believed to be the result of gas being accreted on to a super-massive black hole located at the centre. There is evidence that gas at the centres of active galaxies forms an accretion disk via which it gets transported to the vicinity of the Schwarzschild radius of a few thousandths of a parsec. An important component of the central region of an active galaxy is a torus of dust and gas situated at much larger scales from several hundred parsec to a few kiloparsec. Observations have targeted this region for clues to the presence of a fuel reservoir powering the active galaxies (e.g. Mazzarella et al. 1993; Lim et al. 2000). The fuel searched for at millimetre wavelengths is the CO gas since next to molecular hydrogen, that has only weak emission lines, the CO molecules are the most abundant.

The causes behind the restarting of nuclear activity are far from clear. Suggestions have been speculative and have included ‘long term variability’ in central engine output (Roettiger et al. 1994) and accretion disk instabilities (e.g. Schoenmakers et al. 2000a). In this paper we explore...
this question of why radio galaxies become inactive and then restart their nuclear activity after several million years. We look at the causes from the point of view of fuel availability to the central engine. Starting from the basic premise that all AGN require fuel for their activity we enquire whether the inactivity is caused by an interruption to the fuelling process or a depletion of the fuel store that sustained the activity. Are the manifestations we see (of nested, inner double lobe structures) a result of a new accumulation of fuel after its depletion in the earlier epoch or a continuation of the old fuelling process after an interruption?

The CO observations of powerful radio galaxies made using the J(1–0) and J(2–1) line transitions have revealed interesting results – it is found that compact radio galaxies and edge darkened (FR-I) radio galaxies are more frequently detected than larger radio galaxies with edge brightened (FR-II) structures even considering their larger distances (given their sufficiently low upper limits; Evans et al. 2005 and references therein). Together with the high detection rate for the ultra-luminous infra-red galaxies (ULIRGs) the gradation in CO detection rates prompted suggestions of an evolutionary link between the ULIRGs, compact radio sources and larger radio galaxies (e.g. Mazzarella et al. 1993; Sanders et al. 1988). The underlying hypothesis was that as the radio galaxies form and evolve there is a depletion of fuel as it is processed. In this sequence the ULIRGs are at initial stages of fuel accumulation and the compact radio sources, which form after nuclear activity is triggered, are in the early phase of nuclear activity with the large FR-II being at later stages. The large FR-IIs, with their higher detection rate of molecular gas, do not fit into this picture.

The notion of consumption of fuel as the source grows has implications for the formation of the ‘double-double’ radio sources. With the restarting radio galaxies found to be relatively young, they should be more amenable to the detection of molecular gas than larger radio galaxies if the new activity resulted from a recent fuel accumulation.

We have compiled a sample of radio galaxies considered to be sources with restarted nuclear activity with the aim of exploring their fuel aspects. We expect that the CO detection rate among this class of radio galaxies is intermediate between the detection rate of compact radio sources and larger radio galaxies if they have restarted due to a recent acquisition of fuel. If however the new activity is a consequence of an interruption to the original fuelling process and subsequent resumption the sources should have low or zero detection rate just as is the case for the large FR-II radio galaxies. In this paper we present CO J(1–0) and CO J(2–1) observations of a small sample of restarting radio galaxies made using the IRAM radio telescope.

In a separate program, we observed three megaparsec-size radio galaxies with the 15-m SEST in the CO J(1–0) and CO J(2–1) line transitions. We have included these data in the present paper for comparison (a) because they are radio galaxies at the extreme end of the linear size distribution and hence among the oldest radio galaxies, (b) they form a good contrast in age with respect to the radio galaxies with restarting nuclear activity and (c) following the model proposed by Kaiser et al. (2000) they form the parent sample of most restarting sources.

In the following section we present our sample. The observations are described in Section 3. In Section 4 we give the results and this is followed with a discussion in Section 5. We adopt a flat cosmology with Hubble constant $H_0 = 71\text{ km s}^{-1}\text{ Mpc}^{-1}$ and matter density parameter $\Omega_m = 0.27$.

We have included from the literature four radio galaxies (NGC 315, 4C 29.30, 3C 293 and NGC 6251) that were observed in the CO J(1–0) and CO J(2–1) line transitions. Two are normal giant radio galaxies (NGC 315, NGC 6251) that do not show evidence for restarting of nuclear activity and two, 4C 29.30 and 3C 293 exhibit strong evidence for a recurrence in their nuclear activity (Jamrozy et al. 2006, submitted; Akujor et al. 1996). The discussion section will be based on the 9 restarting radio galaxies and 5 normal giant radio galaxies.

### 2 Sample Selection

In Table 1 we list the two samples, the 9 restarting radio galaxies and 5 normal, giant radio galaxies. Both samples are representative samples of their class of sources, neither being a complete sample. The restarting radio galaxy sample is part of a larger compilation of sources from the literature that have been recognised as having undergone a second epoch of nuclear activity. Signatures of restarted activity are most often in the form of morphological structures such as an inner pair of bounded emission peaks within the extended radio lobes. 4C 12.03 (Leahy & Perley 1991), 4C 26.35 (Owen & Ledlow 1997), 3C 219 (Bridge et al. 1986), 3C 424 (Black et al. 1992) and 3C 445 (Leahy et al. 1997) all have bounded emission peaks within their lobes. 3C 236 and 3C 293 are found to have such a pair of emission peaks well within their central compact cores (Schilizzi et al. 2001; Akujor et al. 1996). In one source, 3C 388, there is radio spectral evidence for a second activity epoch – the source is found to have radio lobes of a typical spectral index distribution embedded within two outer features of much steeper spectral index values (Roettiger et al. 1994). In selecting the seven restarting radio galaxies for our observations we were constrained by the declinations accessible to the IRAM telescope and the redshifts of the sources. With the standard setup (as used by us) the IRAM observing band allowed a

### Table 1. The sample

| Source        | RA (J2000) | Dec (J2000) | z | lin. size |
|---------------|------------|-------------|---|-----------|
| 4C 12.03      | 00:09:52.6 | +12:44:05   | 0.156 | 577       |
| 4C 29.30      | 08:40:02.4 | +29:49:03   | 0.065 | 97        |
| 3C 219        | 09:21:08.6 | +45:38:57   | 0.174 | 405       |
| 3C 236        | 10:06:01.7 | +34:54:10   | 0.101 | 4500      |
| 2C 26.35      | 11:58:20.1 | +26:21:12   | 0.112 | 514       |
| 3C 293        | 13:52:17.8 | +31:26:46   | 0.045 | 218       |
| 3C 388        | 18:44:02.4 | +43:33:30   | 0.092 | 82        |
| 3C 424        | 20:48:12.0 | +07:01:18   | 0.127 | 76        |
| 3C 445        | 22:23:49.6 | −02:06:12   | 0.056 | 596       |
| NGC 315       | 00:57:48.9 | +30:21:09   | 0.016 | 1080      |
| 0319–454      | 03:20:57.6 | −45:15:10   | 0.063 | 1789      |
| 0503–286      | 05:05:49.3 | −28:35:20   | 0.038 | 1800      |
| 0511–305      | 05:13:31.9 | −30:28:50   | 0.058 | 740       |
| NGC 6251      | 16:32:32.0 | +82:32:16   | 0.025 | 1857      |
redshift range of up to 0.42 and 0.17 for the two CO J(1–0) and J(2–1) frequencies respectively.

The sources observed with the SEST were all large sized radio galaxies with linear sizes in the megaparsec range. Three radio galaxies (0319−454, 0503−286 and 0511−305) were selected with declinations suitable for observations with SEST. The sources had redshifts that allowed CO J(1–0) and J(2–1) line transitions to be observable within the SEST receiver bandwidths.

The sources added from the literature were observed with different telescopes: NGC 315 with the IRAM 30-m telescope (Braine et al. 1997), 4C 29.30 and 3C 293 with the NRAO 12-m telescope (Evans et al. 2005) and NGC 6251 with the OSO 20-m telescope (Elfhag et al. 1996).

3 OBSERVATIONS AND DATA ANALYSIS

3.1 IRAM observations

At the IRAM 30-m telescope we used the A100/B100 receiver combination for the CO(1-0) line and the A230/B230 combination for the CO(2-1) line search. The beam-sizes were 23′′/4 and 11′′/7 (at the typical frequency of 105 GHz and 210 GHz respectively). The observations were mostly performed in wobbler secondary mode with a beam throw between on and off symmetric off-source positions of 240′′ and a switching rate of 0.5 Hz. The observation of 3C 445 and about two thirds of the 4C 12.03 scans had to be accomplished in a symmetrical position switching mode with offsets of −80′′ and +80′′ from the source position. All signals were connected to the VESPA autocorrelator with bandwidths of 640 MHz and spectral resolutions of 1.25 MHz. In addition and for redundancy, the A100 and B100 receivers were also linked to the 1-MHz filterbank with 512 MHz bandwidth for each part and a spectral resolution of 1 MHz. The observations were spread over three separate terms. The last term (June 2006) when sources 3C 236, 3C 219 and 4C 26.35 were observed was carried out in the dual beam-switching mode using a first-order polynomial baseline after dis-regarding the channels at the edge of the band. The rms noise was estimated after subtracting the continuum.

The spectra were smoothed to reach a final velocity resolution of about 22 km s\(^{-1}\) for CO(1-0) and about 14 km s\(^{-1}\) for CO(2-1), for the exact values we refer to Table 2. Throughout the article, unless explicitly stated otherwise, the brightness temperatures are expressed in the T\(_{\text{mb}}\) = (η\(f\)/η\(_{\text{mb}}\))T\(_A\) scale, where η\(f\) is the forward efficiency (Pico Veleta: 0.95 and 0.91 at 105 and 210 GHz, SEST assumed to be unity) and η\(_{\text{mb}}\) is the main beam efficiency (Pico Veleta: 0.75 and 0.57 at 105 and 210 GHz; SEST; 0.70 and 0.50 at 105 and 210 GHz).

4 RESULTS

Our results for all the sources observed are presented in Table 2. In Col. 5 we give the rms value of the observed main beam temperatures after smoothing to the velocity resolution given in Col. 6. None of the sources was detected above the 3-σ level. In order to derive upper limits to the molecular gas estimates for our sample of radio galaxies we have used the expression given by Braine et al. (2000):

\[ M_{\text{H}_2} = 2I_{\text{CO}}\sigma_{\text{mb}}\Delta V \Omega D^2 \]

where \(I_{\text{CO}} = T_{\text{mb}}\Delta V \) for detected CO emission and \(I_{\text{CO}} = \sigma_{\text{mb}}\sqrt{\Delta V \delta v} \) for upper limits.

Here \(\sigma_{\text{mb}}\) is the noise level derived from the spectra (in case of no detections, the masses were calculated for 3- \(\sigma_{\text{mb}}\) values of the main beam temperature), \(\Delta V\) the line width (for the limits assumed to be 300 km s\(^{-1}\)), \(\delta v\) the velocity resolution (in km s\(^{-1}\)) and \(m_p\) the proton mass. \(X\) represents the CO-to-H\(_2\) conversion factor (no correction has been made for the presence of helium), \(\Omega\) corresponds to the beamsize (assumed Gaussian) and \(D\) is the luminosity distance to the target.

To allow for a deviation of the X-factor for molecular clouds in our sample of galaxies from the value determined for our Galaxy we have used a range (3.7 · 10\(^{-3}\) to 2.1 · 10\(^{-3}\)m\(^{-2}\)(K km s\(^{-1}\))\(^{-1}\)). The lower value is determined for the ULIRGs (Solomon & Vanden Bout 2005) whereas the higher value is appropriate for normal galaxies (Braine et al. 2000). Following de Blok & van der Hulst (1998) we used a conversion factor for mass estimates based on the CO J(2–1) transition which is 20% higher than that based on CO J(1–0) transition.

These values have been used to calculate the molecular
gas masses in Table 3 in units of $10^9 M_\odot$. The two columns are for the two extreme values of the CO-to-H$_2$ conversion factor, as given above. As restarting radio galaxies should possess characteristics that are closer to the ULIRGs rather than normal spirals we take the lower value to be a more realistic representation of the conversion factor for our sources.

5 DISCUSSION

The work reported in this paper centres around radio galaxies that show strong evidence for a new epoch of activity at their centres. The new activity epoch manifests itself as bounded, inner emission peaks within the extended radio lobes, in most cases seen as an embedded pair. From Table 3 we see that only one out of nine restarting radio galaxies is detected in CO. The non-detections translate to 3-σ upper limits of $10^8$ – $10^9 M_\odot$ for the molecular gas mass within the host galaxies of the restarting radio galaxies.

Comparing our limits with those obtained in the comprehensive and consolidated CO observational study of radio galaxies of Evans et al. (2005), it is seen that for the lower value of the X-factor used, our limits are similar and the average upper limit to the molecular hydrogen mass we derive is lower.

What do our derived upper limits to the molecular gas content mean for the recurrence phenomenon in radio galaxies? The restarting radio galaxies all have upper limits that are lower than the molecular gas mass found in 3C 293. If they possessed gas masses at a level of or above that found in 3C 293 they would have been detected. With 3C 293, the only example of a restarting radio galaxy, setting the standard for fuel content in this class of sources, that of abundant molecular gas content, our observations have clarified that 3C 293 may be atypical and that abundant molecular gas content of the level of $10^9 M_\odot$ does not necessarily accompany the nuclear restarting phenomenon. Interestingly, 3C 236, which is a re-starting source with a sub-galactic inner double source like 3C 293, as well as having abundant dust content is not detected in CO showing that molecular gas of the amount found in 3C 293 is not a necessary condition for restarting of nuclear activity.

None of the five normal, giant radio galaxies has a detection in CO. It appears that the normal GRGs too in general do not possess molecular gas at the level of few $10^9 M_\odot$, and that they are not hosts to unusually large stores of molecular

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**Figure 1.** The CO spectra of our target sources. The CO(2-1) spectrum of 3C 219 could not be obtained since the A230/B230 receivers of the 30-m telescope could not be tuned to the required redshifted frequency. The temperature scales of the ordinates are calibrated in Kelvin on the $T_A^*$ scale.
gas in their nuclear regions. It is interesting to note that two of these large radio galaxies, 0319−454 and 0511−305, show obvious signs of interactions – suggesting presence of large quantities of dust and accompanying gas (Subrahmanyan et al. 1996; Saripalli et al. 1994; Bryant & Hunstead 2000) and the two GRGs NGC 315 and NGC 6251 are known to have nuclear dust disks.

Searches for molecular gas in radio galaxies with known strong IRAS detections (e.g. Evans et al. 2005) have shown that molecular gas is not commonly seen in these objects: less than one third are detected in CO. The detections abound in compact and FR-I radio galaxies and tend to have nuclear dust disks.

Table 2. Observing Log

| Source   | line transition | time | frequency | σ_{mb} | vel. res. | date     | telescope | τ  | T_{sys} |
|----------|-----------------|------|-----------|--------|-----------|----------|-----------|-----|----------|
| 4C 12.03 | CO(1-0)         | 158  | 99715.574 | 0.85   | 24.05     | Jul 2003 | PV        | 0.06| 121      |
|          | CO(2-1)         | 158  | 199427.327| 4.39   | 15.03     | Jul 2003 | PV        | 0.33| 410      |
| 3C 219   | CO(1-0)         | 222  | 98151.769 | 0.55   | 24.44     | Jul 2006 | PV        | 0.04| 120      |
|          |                 |      |           |        |           |          |           |     |          |
| 3C 236   | CO(1-0)         | 111  | 104906.447| 1.39   | 22.86     | Jun 2006 | PV        | 0.11| 147      |
|          | CO(2-1)         | 111  | 209808.873| 4.16   | 11.43     | Jun 2006 | PV        | 0.42| 449      |
| 4C 26.35 | CO(1-0)         | 310  | 103661.155| 0.63   | 23.14     | Jul 2006 | PV        | 0.06| 130      |
|          | CO(2-1)         | 310  | 207318.336| 1.81   | 11.57     | Jul 2006 | PV        | 0.24| 298      |
| 3C 388   | CO(1-0)         | 452  | 105656.466| 0.57   | 22.70     | Sep 2004 | PV        | 0.11| 132      |
|          | CO(2-1)         | 452  | 211308.882| 2.00   | 14.19     | Sep 2004 | PV        | 0.32| 307      |
| 3C 424   | CO(1-0)         | 281  | 102282.366| 0.84   | 23.45     | Jul 2003 | PV        | 0.09| 155      |
|          | CO(2-1)         | 280  | 204560.812| 2.27   | 14.66     | Jul 2003 | PV        | 0.36| 532      |
| 3C 445   | CO(1-0)         | 56   | 109137.667| 2.83   | 21.98     | Jul 2003 | PV        | 0.09| 189      |
|          | CO(2-1)         | 42   | 218272.151| 3.69   | 13.73     | Jul 2003 | PV        | 0.21| 264      |
| 0319−454 | CO(1-0)         | 273  | 108408.866| 0.96   | 30.60     | Dec 2001 | SEST      | 0.07| 214      |
|          | CO(2-1)         | 211  | 216813.484| 2.04   | 15.47     | Dec 2001 | SEST      | 0.15| 522      |
| 0503−286 | CO(1-0)         | 24   | 111008.456| 7.45   | 29.88     | Dec 2001 | SEST      | 0.20| 300      |
|          | CO(2-1)         | 30   | 222012.657| 14.11  | 15.10     | Dec 2001 | SEST      | 0.63| 668      |
| 0511−305 | CO(1-0)         | 46   | 108921.090| 3.66   | 30.45     | Dec 2001 | SEST      | 0.23| 325      |
|          | CO(2-1)         | 46   | 217837.866| 14.00  | 15.39     | Dec 2001 | SEST      | 1.17| 886      |

suggests that they are similar to the large FR-II's with respect to their molecular gas content: that abundant molecular gas presence eludes them just like the FR-IIs. This could be viewed as supporting disruption to the fuel flow (e.g. instabilities in the accretion disk, see Wada 2004) as a cause for the interruption to the jet production rather than a depletion of fuel. More sensitive upper limits would need to be obtained however for a more robust comparison with the upper limits achieved for FR-II radio galaxies.

How do the limits compare with the estimates of fuel required for powering radio galaxies? With an Eddington accretion rate for a typical central black hole mass of 10^8 M⊙ of 5 to 40 M⊙ yr^{-1} (for maximally spinning and non-rotating black holes, respectively), access to fuel masses of at most 5 · 10^8 to 4 · 10^9 M⊙ would be required for sustaining the activity over intrinsic ages of ~ 10^7 yr (Hopkins et al. 2006). The upper limits we derive are mostly of the order of few 10^8 M⊙. The observations suggest prevalence of sub-Eddington accretion processes among the restarted radio galaxies, a scenario that was recently suggested also for FR-I and FR-II radio galaxies based on an analysis of black hole mass estimates and nuclear luminosities (Marchesini et al. 2004).

We note that the targets in our sample of restarted radio galaxies were not selected on the basis of their IRAS flux densities unlike the sources in Evans et al. (2005); only two are comparable in strength to Evans’ sources. For three IRAS detected restarted radio galaxies in our sample, the IR luminosities are comparable to those of the radio galaxies in Evans’ sample. However, differences in selecting the sources in the two samples (with respect to their IRAS fluxes) as well as the small numbers make a direct comparison difficult. For this reason we cannot rule out a possible influence of pre-disposition to IRAS flux strengths on the molecular gas detection rates.

An interesting possibility is the existence of fuel in
Table 3. Derived H₂-masses, assuming different values for the X-factor. Column (a) gives the lower limit with $X = 3.7 \times 10^{23} \text{m}^{-3}(\text{K km s}^{-1})^{-1}$; column (b) the upper limit with $X = 2.1 \times 10^{24} \text{m}^{-3}(\text{K km s}^{-1})^{-1}$.

| Source   | line transition | $H_2$ mass $[10^9 M_{\odot}]$ | Reference |
|----------|-----------------|-------------------------------|-----------|
| (a)      |                 | (b)                           |           |
| 4C 12.03 | CO(1-0)         | < 1.12                        | < 6.35    | this work |
|          | CO(2-1)         | < 1.37                        | < 7.79    | this work |
| 4C 29.30 | CO(1-0)         | < 0.38                        | < 2.16    | 1         |
| 3C 219   | CO(1-0)         | < 0.95                        | < 5.42    | this work |
| 3C 236   | CO(1-0)         | < 0.63                        | < 3.58    | this work |
|          | CO(2-1)         | < 1.05                        | < 2.28    | this work |
| 4C 26.35 | CO(1-0)         | < 0.37                        | < 2.09    | this work |
|          | CO(2-1)         | < 0.22                        | < 1.27    | this work |
| 3C 293   | CO(1-0)         | 4.32                          | 24.56     | 1         |
| 3C 388   | CO(1-0)         | < 0.21                        | < 1.19    | this work |
|          | CO(2-1)         | < 0.17                        | < 0.98    | this work |
| 3C 424   | CO(1-0)         | < 0.66                        | < 3.74    | this work |
|          | CO(2-1)         | < 0.42                        | < 6.40    | this work |
| 3C 445   | CO(1-0)         | < 0.33                        | < 1.90    | this work |
|          | CO(2-1)         | < 0.13                        | < 0.76    | this work |
| NGC 315  | CO(1-0)         | < 0.041                       | < 0.234   | 2         |
|          | CO(2-1)         | < 0.013                       | < 0.072   | 2         |
| 0319-454 | CO(1-0)         | < 0.77                        | < 4.38    | this work |
|          | CO(2-1)         | < 0.51                        | < 2.90    | this work |
| 0503-286 | CO(1-0)         | 1.98                          | 11.22     | this work |
|          | CO(2-1)         | < 0.83                        | < 4.73    | this work |
| 0511-305 | CO(1-0)         | < 2.44                        | < 13.85   | this work |
|          | CO(2-1)         | < 2.08                        | < 11.81   | this work |
| NGC 6251 | CO(1-0)         | < 3.85                        | < 21.83   | 3         |

References: 1: Evans et al. (2005), 2: Braine et al. (1997), 3: Elfhag et al. (1996)

atomic form. This can be tested with studies of HI absorption against the compact cores of radio galaxies. Such studies have been carried out (e.g. van Gorkom et al. 1989; Morganti et al. 2001) with the result that although only about one third are detected it is once again the compact radio galaxies that predominantly constitute the detections. However the studies have targeted strong radio core objects and a deeper study is needed that includes weak cores found in larger radio galaxies. We have commenced such a study with the Australia Telescope Compact Array of a large sample of radio galaxies with a range in linear sizes. The results will be presented in a future publication.

Among the restarting radio galaxies in Table 3 only four have been included in samples of HI absorption studies. Three out of four (3C 236, 3C 293 and 4C 29.30) have been detected in HI absorption against the cores indicating presence of atomic hydrogen gas close to the centres. Interestingly, the three also have among the most compact inner sources. Saikia et al. (2006) report detection of HI absorption against the core of a restarted radio galaxy, J1247+6723, that has a compact, 14 pc inner double. While there is evidence for presence of atomic hydrogen in at least some restarting radio galaxies its role as fuel awaits a systematic HI study of a larger sample made with high resolution to resolve the radio structures.

6 SUMMARY

We have presented results of a search program for molecular gas in a sample of powerful radio galaxies that are thought to be undergoing a second epoch of nuclear activity. The search was carried out using the IRAM 30-m telescope on Pico Veleta in the CO J(1–0) and J(2–1) line transitions of the CO molecule, a known effective tracer of molecular hydrogen. The motivation for the search for molecular gas in these radio galaxies was to throw light on the possible causes of the restarting of nuclear activity after a period of quiescence. One possible scenario is depletion of a previous tranche of fuel followed by recent accumulation of fuel after a period of time and another possibility is the continuation of the original fuelling process after an interruption. We expect that the former possibility, where a recent fuel accumulation has restarted the nuclear activity in these sources would increase their detectability in CO.

We discuss the CO detection rate for a representative sample of nine restarting radio galaxies, seven of which were observed for the first time. We report relatively sensitive upper limits that suggest there is no indication of molecular gas mass larger than few $10^8 - 10^9 M_{\odot}$. Abundant molecular gas content therefore does not necessarily seem to accompany the nuclear restarting phenomenon. The restarting radio galaxies are found to be as deficient in molecular gas as the edge brightened FR-II radio galaxies suggesting that there has been no recent accumulation of molecular gas. The interruption to the jet production in these sources may have been a result of instabilities in the earlier fuel flow rather than due to a depletion of fuel. For comparison, we also discuss the molecular gas properties of five normal giant radio galaxies, three of which were observed by us using SEST. These sources are thought to form the parent sample of restarting sources. All five have only upper limits suggesting a lack of large ($\gtrsim 10^9 M_{\odot}$) molecular gas content in these largest and among the oldest of radio galaxies.

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REFERENCES

Akujor C.E., Leahy J.P., Garrington S.T., Sanghera H., Spencer R.E., Schilizzi R.T., 1996, MNRAS, 278, 1
Black A.R.S., Baum S.A., Leahy J.P., Perley R.A., Riley J.M., Scheuer P.A.G., 1992, MNRAS, 256, 186
Braine J., Henkel C., Wiklind T., 1997, A&A, 321, 765
Braine J., Herpin F., Radford S.J.E., 2000, A&A, 358, 494
Bridle A.H., Perley R.A., Henriksen R.N., 1986, AJ, 1992, 534
Bryant J.J., Hunstead R.W., 2000, ApJ, 545, 216
de Blok W.J.G., van der Hulst J.M., 1998, A&A, 336, 49
Elfhag T., Booth R.S., Hoeglund B., Johansson L.E.B., Sandquist A., 1996, A&AS, 115, 439
Evans A.S., Sanders D.B., Surace J.A., Mazzarella J.M., 1999, ApJ, 511, 730
Evans A.S., Mazzarella J.M., Surace J.A., Frayer D.T., Iwasawa K., Sanders D.B., 2005, ApJS, 159, 197
Gordon M.A., Baars J.W.M., Cocke W.J., 1992, A&A, 264, 337
Jamrozy M., Konar C., Saikia D.J., Stawarz L., Mack K.-H., Siemiginowska A., 2006, MNRAS (subm.)
Kaiser C.R., Schoenmakers A.P., Röttgering H.J.A., 2000, MNRAS, 315, 381
Lara L., Marquez I., Cotton W.D., Feretti L., Giovannini G.,Marcaide J.M., Venturi T., 1999, A&A, 348, 699
Leahy J.P., Perley R.A., 1991, AJ, 102, 537
Leahy J.P. Black A.R.S., Dennett-Thorpe J., Hardcastle M.J., Komissarov S., Perley R.A., Riley J.M., Scheuer P.A.G., 1997, MNRAS, 291, 20
Lim J., Leon S., Combes F., Dinh-V-Trung 2000, ApJ, 545, L93
Mack K.-H., Klein U., O’Dea C.P., Willis A.G., Saripalli L., 1998, A&A, 329, 431
Marchesini D., Celotti A. Ferrarese L., 2004, MNRAS, 351, 733
Mazzarella J.M., Graham J.R., Sanders D.B., Djorgovski S., 1993, ApJ, 409, 170
Morganti R., Oosterloo T.A., Tadhunter C.N., van Moorsel G., Killeen N., Eills K.A., 2001, MNRAS, 323, 331
Owen F.N., Ledlow M.J., 1997, ApJS, 108, 41
Roettiger K., Burns J.O., Clarke D.A., Christiansen W.A., 1994, ApJ, 421, 23
Saikia D.J., Gupta N., Konar C., 2006, MNRAS (in press)
Sanders D.B., Soifer B.T., Elias J.H., Madore B.F., Matthews K., Neugebauer G., Scoville N.Z., 1988, ApJ, 325, 74
Saripalli L., Subrahmanyan R., Hunstead R.W., 1994, MNRAS, 269, 37
Saripalli L., Subrahmanyan R., Udaya Shankar N., 2002, ApJ, 565, 256
Saripalli L., Subrahmanyan R., Udaya Shankar N., 2003, ApJ, 590, 181
Scheuer P.A.G., 1995, MNRAS, 277, 331
Schilizzi, R.T. et al., 2001, A&A, 368, 398
Schoenmakers A.P., de Bruyn A.G., Röttgering H.J.A., van der Laan H., Kaiser C.R., 2000a, MNRAS, 315, 395
Schoenmakers A.P., de Bruyn A.G., Röttgering H.J.A., van der Laan H., 2000b, MNRAS, 315, 371
Solomon P.M., Vanden Bout P.A., 2005, ARA&A, 43, 677
Subrahmanyan R., Saripalli L., Hunstead R.W., 1996, MNRAS, 279, 257

van Gorkom J.H., Knapp G.R., Ekers R.D., Ekers D.D., Laing R.A., Polk K.S., 1989, AJ, 97, 708
Wada K., 2004, Carnegie Observatories Astrophysics Series, Cambridge University Press, Ed., L.C.Ho, 186