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# A SEARCH FOR MOLECULAR GAS IN GHz-PEAKED SPECTRUM RADIO SOURCES

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## ABSTRACT

We present searches for molecular gas (CO, OH, CS, and NH<sub>3</sub>) in six gigahertz-peaked spectrum (GPS) radio sources. We do not detect gas in any source and place upper limits on the mass of molecular gas that are generally in the range from  $\sim 10^9$  to a few times  $10^{10} M_{\odot}$ . These limits are consistent with the following interpretations: (1) GPS sources do not require very dense gas in their hosts, and (2) the GPS sources are unlikely to be confined by dense gas and will evolve to become larger radio sources.

*Key words:* galaxies: active — galaxies: ISM — radio lines: galaxies

## 1. INTRODUCTION

The gigahertz-peaked spectrum (GPS) and compact steep-spectrum (CSS) radio sources make up significant fractions of the extragalactic bright (centimeter-wavelength–selected) radio source population ( $\sim 10\%$  and  $\sim 20\%$ , respectively) but are not well understood (e.g., O'Dea 1998). They are powerful but compact radio sources whose spectra are generally simple and convex with peaks near 1 GHz and 100 MHz, respectively. The GPS sources are entirely contained within the extent of the nuclear narrow-line region (NLR;  $\lesssim 1$  kpc), whereas the CSS sources are contained entirely within the host galaxy ( $\lesssim 15$  kpc).

GPS and CSS sources are important because (1) they probe the NLR and interstellar medium (ISM) of the host galaxy and (2) they may be the younger stages of powerful large-scale radio sources, giving us insight into radio source genesis and evolution.

There are two main hypotheses for the GPS and CSS sources. They could be the young progenitors of the large-scale powerful double sources (e.g., Carvalho 1985; Hodges & Mutel 1987; Begelman 1996; Fanti et al. 1995; Readhead et al. 1996a, 1996b; O'Dea 1998; Snellen et al. 2000; Alexander 2000). In this model they propagate relatively quickly through the ISM of the parent galaxy with advance speeds of a few percent of the speed of light. (Observed proper motions tend to be a bit higher—in the range  $0.1$ – $0.2c$ , e.g., Polatidis & Conway 2003, although the detections may be biased toward objects with the highest velocities.) In order to allow these high velocities, the ISM cannot be very dense, and the total cold gas content can be no more than about  $10^{10} M_{\odot}$ . These sources must also undergo strong luminosity evolution as they evolve, dimming by 1–2 orders of magnitude in radio flux density.

In the second hypothesis, these sources are older and propagate much more slowly through a dense ISM acquired via cannibalism (O'Dea et al. 1991; De Young 1993; Carvalho 1994,

1998). These frustrated sources interact strongly with their dense ambient medium, driving a shock that ionizes the gas and produces two effects: (1) free-free absorption, which is responsible for the turnover in the radio spectrum, and (2) optical emission lines (Bicknell et al. 1997). In this second model, there is very little luminosity evolution. Bicknell et al. predict that the host galaxies will be relatively gas-rich, with total masses of cold gas in the range  $10^{10}$ – $10^{11} M_{\odot}$ . We note that this is similar to the cold gas content of the ultraluminous infrared galaxies (ULIRGs; e.g., Sanders et al. 1991). So far molecular gas (as traced by CO) has been detected in only one GPS source (1345+125; Mirabel et al. 1989; Evans et al. 1999a) with an estimated mass of  $6 \times 10^{10} M_{\odot}$ . No CO was detected in the GPS source 1934–638 at a limit of  $5 \times 10^{10} M_{\odot}$  (O'Dea et al. 1994a).

Searches for the 21 cm line have produced a 50% detection rate in GPS and CSS sources, whereas the detection rates for large sources are only  $\sim 10\%$  (Vermeulen et al. 2003; Pihlström et al. 2003; van Gorkom et al. 1989). This indicates that clouds of atomic hydrogen are very common in the environments of GPS and CSS sources. Recent *Hubble Space Telescope* imaging and spectroscopy has shown that high surface brightness emission-line gas is aligned with the radio axis in CSS radio galaxies (De Vries et al. 1996, 1999; Axon et al. 2000; O'Dea et al. 2002).

Thus, the two models for GPS/CSS sources predict a substantial and testable difference in the cold gas content of the host galaxies, and there is some existing evidence that GPS/CSS sources contain dense gas in their host galaxies. We have undertaken two complementary searches for molecular gas in GPS sources. First, we obtained Very Large Array (VLA) observations to search for several molecular species (NH<sub>3</sub>, CS, and OH) in four GPS sources. Second, we obtained IRAM 30 m observations of three (relatively) low-redshift GPS sources to detect or set limits on the cold gas content. These three sources are the lowest redshift sources from volume-limited subsets of complete samples of

TABLE 1  
SOURCE LIST

Name (1)	Other Name (2)	ID (3)	$z$ (4)	$D_{\text{lum}}$ (Gpc) (5)	Transition (6)	Rest Frequency (GHz) (7)
0116+319 .....	4C 31.04	G	0.0598	0.26	CO 1 $\rightarrow$ 0 CO 2 $\rightarrow$ 1	115.271 230.542
0237–233 .....	OD 263	Q	2.223	17.9	CS 1 $\rightarrow$ 0	48.991
0404+768 .....	4C 76.03	G	0.59846	3.51	NH <sub>3</sub> (1,1)	23.694
0428+205 .....	OF 247	G	0.219	1.07	OH CO 1 $\rightarrow$ 0	1.667 115.271
					CO 2 $\rightarrow$ 1	230.542
0941–080 .....		G	0.2280	1.12	CO 1 $\rightarrow$ 0	115.271
					CO 2 $\rightarrow$ 1	230.542
2352+495 .....	OZ 488	G	0.23831	1.18	OH	1.667

NOTES.—Col. (1): B1950 IAU source name. Col. (2): Other name. Col. (3): ID; G=Galaxy, i.e., narrow lines only, and Q=quasar, contains broad emission lines. Col. (4): Redshift. 0404+768 and 2352+495 taken from Lawrence et al. (1996). Col. (5): The luminosity distance estimated using N. Wright’s cosmology calculator applet, assuming the current  $\Lambda$  cosmology, i.e.,  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_M = 0.27$ . Col. (6): The molecular transition observed. Col. (7): Rest frequency of transition.

GPS (Stanghellini et al. 1998) and CSS (Fanti et al. 1990) sources. One object, 0428+205, is observed in both the VLA and IRAM searches.

In this paper we present searches for molecular gas with the VLA and IRAM in six GPS sources. In principle, both emission and absorption searches are possible. Given the redshifts of the sources and the centimeter-wavelength flux densities, absorption and emission limits are most sensitive for the VLA and IRAM data, respectively. We estimate constraints on the molecular gas content and discuss the implications for models of these sources.

## 2. OBSERVATIONS AND REDUCTION

### 2.1. VLA Observations

We searched for absorption in a transition of either ammonia, CS, or OH (whichever fell in a VLA band) in four GPS sources (Table 1). We observed with the VLA (Napier et al. 1983) on 1993 January 22 in the A configuration in spectral-line mode (mode 1A), using online Hanning smoothing, 32 channels, a channel spacing of 390.625 kHz, and 12.5 MHz total bandwidth for each observation. For the 15 GHz observations of 0237–233, we obtained additional observations with the central frequency offset by  $\pm 10$  MHz to cover a total bandwidth of about 33 MHz. Observational parameters are given in Table 2. Bandpass calibration was performed using observations of the

closest of either 3C 84 or 3C 454.3. Flux density calibration was carried out using observations of 3C 48. The data were reduced in AIPS following standard procedures.

A few very noisy channels at both ends of the spectra were deleted. Since the sources are compact and unresolved at the VLA resolution, we used the task POSSM to average the data for all the antennas to obtain the integrated spectrum. We subtracted a least-squares linear fit to the continuum.

### 2.2. IRAM Observations

We used the IRAM 30 m millimeter-wave telescope, located on Pico Veleta, Spain, to search for CO emission in the GPS sources 0116+319, 0428+205, and 0941–080. The observations took place over 1998 July 11–13 during daylight hours. Receivers were tuned to the redshifted CO 1 $\rightarrow$ 0 transition (115 GHz rest frequency), and, for 0116+319 only, separate receivers were tuned simultaneously to the CO 2 $\rightarrow$ 1 transition (230 GHz rest frequency). The beam sizes at these transitions are 21'' and 11'', respectively. The telescope pointing and focus were calibrated against scans of Jupiter, Mars, and the BL Lac object 0235+164. To stabilize the spectral baselines and perform initial sky subtraction, the targets were observed with a wobbling secondary. The secondary throw angles ranged from 60'' to 150'', and the wobble frequency was 0.25 Hz.

Each transition was observed in two backends, an autocorrelator with 1.25 MHz channel separation over a 600 MHz

TABLE 2  
VLA OBSERVATION PARAMETERS

Name (1)	Integration Time (minutes) (2)	Central Frequency (GHz) (3)	Velocity Resolution (km s <sup>-1</sup> ) (4)	Velocity Coverage (km s <sup>-1</sup> ) (5)
0237–233 .....	39	15.2004	7.7	246
0237–233 .....	20	15.2104	7.7	246
0237–233 .....	24	15.2204	7.7	246
0237–233 total .....	83	15.2104	7.7	650
0404+768 .....	43	14.82296	7.9	253
0428+205 .....	44	1.36781	85.5	2740
2352+495 .....	37	1.34790	86.7	2780

NOTES.—Col. (1): Source name. Col. (2): Integration time in minutes. Col. (3): Central frequency in gigahertz. Col. (4): Velocity spacing of a 390 kHz channel. Col. (5): Total velocity coverage in km s<sup>-1</sup>.

TABLE 3  
IRAM OBSERVATION PARAMETERS

Source	Backend	Transition	Integration Time (minutes)	$T_A^*$ rms (mK)	rms (mJy)	Channel Width (km s <sup>-1</sup> )
0116+319 .....	1 MHz filter bank	CO 1→0	309	2.0	12.6	2.9
		CO 2→1	309	5.5	52.8	1.5
	Autocorrelator	CO 1→0	309	3.4	21.4	3.7
		CO 2→1	309	4.0	57.6	1.8
0428+205 .....	1 MHz filter bank	CO 1→0	720	1.6	9.6	3.9
	Autocorrelator	CO 1→0	720	1.5	9.0	4.8
0941-080 .....	1 MHz filter bank	CO 1→0	610	2.2	13.2	3.9
	Autocorrelator	CO 1→0	610	2.0	12.0	4.9

bandwidth and a filter bank with 1 MHz channel separation over a 512 MHz bandwidth. Spectral baselines were subtracted using low-order polynomial fits to the raw spectra. The baseline-subtracted spectra for each source were then averaged using statistical ( $1/\text{rms}^2$ ) weighting. The averaged spectra were finally converted to millijanskys from  $T_A^*$  using nominal sensitivity curves provided by IRAM. The basic properties of the reduced spectra are listed in Table 3.

### 3. RESULTS

#### 3.1. VLA Results

We did not detect any significant absorption in these sources. VLA results are given in Table 4. We obtain upper limits to the absorption optical depth of typically a few percent with a total range of 1%–10%.

The column density for OH 1667 MHz absorption is given by

$$N(\text{OH}) \simeq 2.2 \times 10^{14} T_{\text{ex}} \tau \Delta V \text{ cm}^{-2}, \quad (1)$$

where  $T_{\text{ex}}$  is the excitation temperature,  $\tau$  is the optical depth, and  $\Delta V$  is the FWHM of the line in km s<sup>-1</sup>. (For 0428+205 and 2352+495, we adopt the values  $\Delta V = 297$  and 82 km s<sup>-1</sup>, respectively, matching the widths of the broadest H I absorption features found by Vermeulen et al. 2003.) Following O'Dea & Baum (1987), we adopt a fiducial excitation temperature  $T_{\text{ex}} = 10$  K (e.g., Dickey et al. 1981; Turner 1985). We convert from OH to H<sub>2</sub> column density assuming a relative abundance ratio of  $10^{-7}$  (e.g., Guélin 1985; Irvine et al. 1985). The mass of molecular gas is given by  $M(\text{mol}) = 1.36\pi R^2 2m_{\text{H}} N(\text{H}_2)$ , where  $2m_{\text{H}}$  is the mass of a hydrogen molecule,  $R$  is the radius of the region considered (assuming for simplicity a plane-parallel

geometry), and the factor of 1.36 includes the contribution of He to the total molecular mass at solar abundance (e.g., Sanders et al. 1991).

We applied a similar approach to evaluate the detection limits on the CS and NH<sub>3</sub> absorption. The column density of CS can be estimated by

$$N(\text{CS}) \simeq 3.6 \times 10^{12} [1 - \exp(-2.35/T_{\text{ex}})] \tau \Delta V \text{ cm}^{-2} \quad (2)$$

(e.g., Turner et al. 1973; Gardner & Whiteoak 1978). The relative abundance ratio CS/H<sub>2</sub> in dense Galactic cloud cores is  $\sim 10^{-9}$  (e.g., Snell et al. 1982). As for OH, we also adopt  $T_{\text{ex}} = 10$  K.

Only 0237–233 was searched for CS absorption (or emission). The relatively narrow velocity coverage of the CS observations limits the detection of absorption lines to line widths  $\Delta V$  less than or equal to half of a single bandpass. For the purposes of evaluating molecular mass limits, we therefore adopted  $\Delta V = 0.5$  times the velocity range spanned by an individual bandpass, or  $\sim 120$  km s<sup>-1</sup>. In principle, a large amount of molecular gas could “hide” in a larger line-of-sight velocity dispersion, but the range of velocities that absorption selects is restricted by the compact and narrow background continuum source. The velocity widths of absorption lines detected in active spiral and elliptical galaxies tend to be  $\leq 150$  km s<sup>-1</sup> (e.g., Vermeulen et al. 2003; Gallimore et al. 1999; van Gorkom et al. 1989; Dickey 1986; Kazès & Dickey 1985), although very broad absorption lines have been detected (albeit rarely) in systems with larger background radio sources (e.g., PKS 2322–123, FWHM  $\sim 735$  km s<sup>-1</sup>; O'Dea et al. 1994b; Taylor et al. 1999). Therefore it seems unlikely that large molecular columns are suppressed by line-of-sight velocity dispersions (greatly exceeding 150 km s<sup>-1</sup>) in this particular compact radio source.

Assuming LTE, the column density of NH<sub>3</sub> is given by

$$N(\text{NH}_3) \simeq 2.8 \times 10^{13} T_{\text{ex}} f_{11}^{-1} \tau_{11} \Delta V \text{ cm}^{-2} \quad (3)$$

(e.g., Batrla et al. 1984; Herrnstein 2003), where  $\tau_{11}$  refers to the peak optical depth of the  $(J, K) = (1, 1)$  rotation inversion transition and  $f_{11}$  is the fraction of NH<sub>3</sub> molecules in the  $(1, 1)$  state. Typical excitation temperatures in Galactic cloud cores are  $T_{\text{ex}} \simeq 40$  K (e.g., Morris et al. 1973; Barrett et al. 1977; Ho et al. 1977), at which  $f_{11} \simeq 0.3$  (Herrnstein 2003). We adopt the relative abundance ratio NH<sub>3</sub>/H<sub>2</sub> =  $10^{-8}$  (e.g., Morris et al. 1973; Turner 1995). Only 0404+768 was searched for NH<sub>3</sub> absorption (or emission), and for the purposes of evaluating the molecular mass limit, we assume  $\Delta V = 107$  km s<sup>-1</sup>, based on the broadest H I absorption line detected in this source (Vermeulen et al. 2003).

TABLE 4  
VLA RESULTS

Name (1)	Flux Density (Jy) (2)	rms Noise (mJy) (3)	Optical Depth (4)
0237–233 .....	1.46	2.3	0.0047
0237–233 .....	1.46	5.0	0.0103
0237–233 .....	1.46	3.4	0.0069
0404+768 .....	1.45	2.7	0.0056
0428+205 .....	3.84	1.5	0.0012
2352+495 .....	2.71	2.2	0.0024

NOTES.—Col. (1): Source name. Col. (2): Flux density in janskys. Col. (3): Channel-to-channel rms noise in millijanskys. For 0237–233, the noise is given for each of the three observations in order of increasing central frequency. Col. (4):  $3\sigma$  upper limit on the optical depth of the line.

TABLE 5  
CONSTRAINTS ON MOLECULAR GAS

Name (1)	Transition (2)	$M(\text{H}_2)$ ( $M_\odot$ ) (3)
0116+319 .....	CO 1 $\rightarrow$ 0	$5.9 \times 10^8$
0237-233 .....	CS 1 $\rightarrow$ 0	$5.9 \times 10^8$
0404+768 .....	NH <sub>3</sub> (1, 1)	$1.2 \times 10^{11}$
0428+205 .....	OH 1667 MHz	$5 \times 10^9$
	CO 1 $\rightarrow$ 0	$1.3 \times 10^{10}$
0941-080 .....	CO 1 $\rightarrow$ 0	$2.0 \times 10^{10}$
2352+495 .....	OH 1667 MHz	$2.8 \times 10^9$

NOTES.—Col. (1): B1950 IAU source name. Col. (2): The observed transition. Col. (3): The estimated upper limit to the molecular gas mass. For the limits on absorption, we assume a size of  $R = 3$  kpc.

### 3.2. IRAM Results

The results of the IRAM observations are summarized in Table 5. We do not detect CO in any of the three GPS sources searched. We obtain an upper limit to the integrated flux density of the CO line  $W_{\text{CO}}$  and convert this to an upper limit on the molecular gas content using the relation given by Sanders et al. (1991)

$$M(\text{H}_2) = 1.18 \times 10^4 W_{\text{CO } 1 \rightarrow 0} D_{\text{lum}}^2 M_\odot \quad (4)$$

where  $W_{\text{CO}}$  is in units of jansky kilometers per second and the luminosity distance  $D_{\text{lum}}$  is in units of megaparsecs. The conversion to molecular hydrogen is subject to systematic uncertainties that have been thoroughly discussed elsewhere (e.g., Bloemen et al. 1986; Scoville & Sanders 1987; Young & Scoville 1991; Sanders et al. 1991; Maloney & Black 1988; Sage & Isbell 1991). The limits derived from the CO 2 $\rightarrow$ 1 measurements assume CO 2 $\rightarrow$ 1/CO 1 $\rightarrow$ 0 = 0.6 (Lazareff et al. 1989).

### 4. IMPLICATIONS OF THE LACK OF DENSE MOLECULAR GAS

We did not detect molecular gas in any of the six GPS sources we searched. The estimated upper limits to the masses of molecular gas in the range from a few times  $10^8$  to a few times  $10^{10} M_\odot$  (Table 5), with the weakest limit of  $\lesssim 10^{11} M_\odot$  based on the non-detection of NH<sub>3</sub> absorption toward 0404+768. These are less than the amounts detected via CO in the most gas-rich systems, such as ULIRGs (e.g., Sanders et al. 1991). However, most of these GPS sources could still possess gas masses consistent with the lower end of the range observed in luminous infrared galaxies.

The detection of 21 cm H I absorption toward roughly half of the known GPS sources, but the absence of molecular line absorption, suggests two possibilities: either (1) the circumnuclear gas is predominantly atomic, or (2) atomic gas is easier to detect than molecular gas. For absorption experiments against a very bright continuum source, only the line optical depth determines the absorption signal strength. Assuming LTE and large densities, we can compare the column densities detectable by the two methods.

For the atomic hydrogen 21 cm line, we can estimate the column density by

$$N_{\text{H}} = 2 \times 10^{20} \text{ cm}^{-2} \left( \frac{\tau}{0.1} \right) \left( \frac{\Delta V}{10 \text{ km s}^{-1}} \right) \left( \frac{T}{100 \text{ K}} \right),$$

where  $N_{\text{H}}$  is the neutral atomic hydrogen column density,  $\tau$  is the optical depth,  $\Delta V$  is the linewidth, and  $T$  is the gas temperature.

For the CO 1 $\rightarrow$ 0 molecular line, the column density is

$$N_{\text{H}_2} = 5 \times 10^{21} \text{ cm}^{-2} \left( \frac{\tau}{0.1} \right) \left( \frac{\Delta V}{10 \text{ km s}^{-1}} \right) \left( \frac{T}{100 \text{ K}} \right).$$

Here, we assume that the CO/H<sub>2</sub> abundance ratio is  $10^{-5}$ . Results for the other molecules in our survey will give similar results. Thus, these estimates show that absorption atomic hydrogen is indeed easier to detect than molecular line absorption.

The few powerful *extended* radio galaxies that have been detected in molecular gas tend to have gas masses in the range  $10^9$ – $10^{10} M_\odot$  (e.g., Israel et al. 1991; Mazzarella et al. 1993; O’Dea et al. 1994b; Evans et al. 1999b; Lim et al. 2000; Das et al. 2005). This suggests that the GPS and larger radio galaxies may have similar molecular gas content.

These results suggest the following implications for GPS sources.

1. GPS sources do not require extremely dense environments.
2. The lack of very large masses of dense gas is consistent with the hypothesis that the majority of GPS sources are generally not frustrated and will likely expand to become CSS sources. This is consistent with the proper motions of  $\sim 0.1$ – $0.2c$  observed in about 10 GPS sources so far (e.g., Owsianik & Conway 1998; Owsianik et al. 1998; Tschager et al. 2000; see compilation by Polatidis & Conway 2003). However, these results do not *require* that all GPS sources evolve to become large classical sources, although evolution is favored by the existing data (e.g., O’Dea 1998). Alternate models are still possible for part of the GPS source population; e.g., some GPS sources may be intrinsically short-lived (Readhead 1995).

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