THE SEARCH FOR COLD MOLECULAR GAS IN THE OUTER GALAXY

E.J. DE GEUS AND J.A. PHILLIPS
Caltech MS 105-24, Pasadena, CA 91125, USA

1. Introduction

It is well known that the rotation curves of many galaxies remain flat well outside their optical disks. This leads to the conclusion that the visible mass in galaxies is only a small fraction of the total (see *e.g.* Faber & Gallagher 1979). Although we are certain that "dark matter" exists, its composition and distribution are still unknown.

In a recent paper Pfenniger *et al.* (1994) argued strongly for the possibility that dark matter could well be in the form of cold, predominantly molecular gas in a flat distribution. To have escaped previous detection in the outer parts of our Galaxy, the gas would need to have a low temperature and thus a low emissivity. Because most substantial heating sources of gas are associated with the presence of massive stars (UV radiation and cosmic rays) this requirement may be satisfied in the Galactic plane outside the optical disk.

Support for the existence of molecular gas at large Galactic radii was obtained recently through a detection of 11 CO clouds beyond the optical disk of the Galaxy (Digel *et al.* 1994). CO(1-0), CO(2-1) and ^{13}CO (1-0) observations of the two most remote of these objects, at 22 and 28 kpc from the Galactic center, revealed kinetic temperatures similar to those of molecular gas locally and in the inner Galaxy, rather than the low temperatures proposed by Pfenniger *et al.* (1994). Subsequent Hα observations towards the cloud at 28 kpc from the center revealed the presence of ionized gas and an associated B 0.5 I star (de Geus *et al.* 1993). These observations allow us to speculate that a cold component of molecular gas might indeed exist in the outer parts of our Galaxy, which only becomes easily detectable in emission when stars form and provide a source of heating for the gas.

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Because the emissivity of the cold molecular gas is low, the best way to look for it is in absorption against a background continuum source. Absorption experiments at mm wavelengths have been successfully carried out toward the inner regions of the Galaxy (Marscher *et al.* 1991; Lucas & Liszt 1994) and, recently, Lequeux, Allen & Guilloteau (1993, hereafter LAG) detected CO absorption toward two quasars probing lines of sight through the outer Galaxy. They detected gas at Galactic radii between 8.8 and 11.5 kpc.

If we take the LAG results at face value, cold molecular gas in the outer Galaxy must be abundant. They detected absorption lines toward every quasar they observed (4 absorption lines were detected along only two lines of sight), and they argued that the gas they saw was cold, with temperatures as low as 3.5 K. To test these conclusions we have undertaken to observe as many lines of sight as possible toward mm-bright quasars to probe the outer parts of the Galactic disk. We formulated our source list as follows: We searched the NASA Extragalactic Database and the OVRO millimeter array flux history tables for extragalactic radio sources with $S(3\mathrm{mm}) \geq 1$ Jy, at low galactic latitudes in the longitude range $55° \leq l \leq 125°$. The warp in the outer parts of the Galaxy increases the useful range of Galactic latitudes to as much as $b \approx 10°$, depending on the longitude. We used the Leiden-Green bank HI maps (Burton 1985) to determine whether the line of sight to a quasar passed through the Galactic disk. Our search yielded the 6 objects listed in Table 1.

We observed each object in our sample with the Owens Valley millimeter interferometer to search for CO and HCO^+ absorption lines. The results are given in §2. We will show in this paper that the gas found in absorption is not necessarily cold, and furthermore, that the number of absorption features is significantly smaller than estimated by LAG.

2. Observations and Results

We made our observations using the Owens Valley millimeter interferometer between Oct 93 and July 94. Most of our data were collected with a five element array, but some of the HCO^+ observations of 2013+370 in July 1994 were obtained with six antennas. Table 1 summarizes the observations.

We searched for absorption at two frequencies: 115.27 GHz, which corresponds to the CO(0-1) transition, and 89.189 GHz, which is the HCO^+(0-1) transition. Although the abundance of HCO^+ is lower than that of CO in Galactic molecular clouds ($[\mathrm{CO}]/[\mathrm{HCO}^+] \sim 10^3$), it offers three advantages over CO: (1) the quasar fluxes are $\approx 20\%$ higher at 89 GHz, (2) HCO^+ has a larger dipole moment and thus a larger optical depth per molecule, and (3) the system temperature at 89 GHz is typically 3 times lower than

TABLE 1. Observations

Source	ℓ	b	Line	rms Jy	Δv km s^{-1}	v_{LSR} km s^{-1}	R_G kpc
1923+210	150°.38	−1°.60	CO	0.30	0.33	−102 → −18	10 → 20
2005+403	76°.82	+4°.30	CO	0.25	0.65	−152 → −36	10 → 28
			HCO^+	0.10	0.42	−144 → −36	10 → 28
2013+370	74°.87	+1°.22	CO	0.33	0.16	−65 → −45	10.7 → 12.3
			CO	0.25	0.33	−120 → −10	9 → 20
			HCO^+	0.07	0.21	−68 → −42	10.5 → 12.5
			HCO^+	0.10	0.42	−137 → −35	10 → 25
			HCO^+	0.13	0.11	−7 → +19	$\sim$ 8.5
3C418	88°.81	+6°.04	CO	0.40	0.32	−122 → −38	10 → 19
			HCO^+	0.06	0.42	−134 → −26	10 → 22
NRAO150	150°.38	−1°.60	CO	0.25	0.33	−122 → −38	$\geq$ 13
Cyg A 1	76°.19	+5°.77	HCO^+	0.25	0.42	−139 → −41	10 → 24
Cyg A 2	76°.19	+5°.74	HCO^+	0.25	0.42	−139 → −41	10 → 24

at 115 GHz because of a strong telluric oxygen line near 115 GHz. Figure 1 illustrates the advantage of searching for HCO^+ absorption. The HCO^+ spectrum (bottom panel) clearly shows a line close to −60 km s^{-1}, which is lost in the noise in the CO (1-0) spectrum; for the same integration time the HCO^+ spectrum has much higher signal-to-noise.

We detected absorption in only 2 objects, 3C418 and 2013+370 (Figures 1 and 2). The velocities of the lines we detected correspond to galactocentric radii between 8 and 12 kpc, formally placing them in the outer Galaxy (de Geus & Phillips 1994). We did not detect any gas in the "far outer galaxy", such as the cloud found at 28 kpc from the galactic center (Digel *et al.* 1994).

3. Discussion

The object 2013+370 was observed by us and by LAG. Their 30-m single-dish spectrum showed absorption at 4 different velocities (and thus 4 different Galactic radii). A Plateau de Bûre interferometer spectrum was also presented as confirmation of the single dish spectrum.

The OVRO mm-interferometer CO and HCO^+ spectra we are reporting here had a comparable or significantly lower rms noise level than the single dish and the interferometer spectra presented by LAG, and Figure 2 shows that we can confirm only two of the four lines they reported (one line

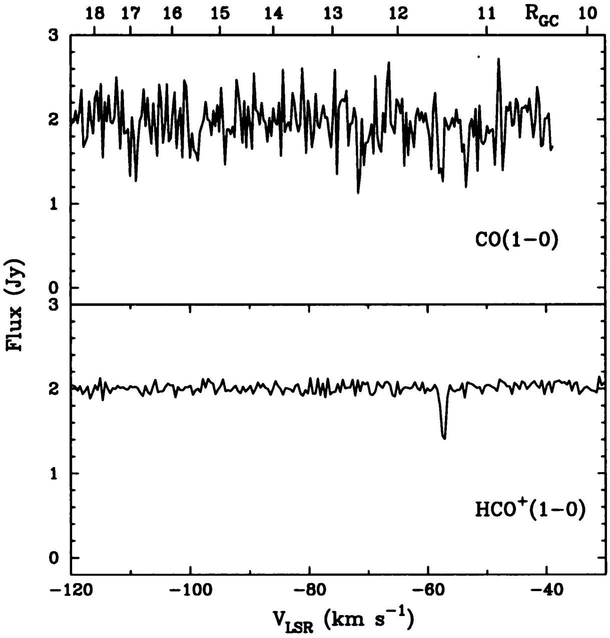

Figure 1. OVRO spectra of the low-galactic latitude quasar 3C418. The top panel shows an 8 hour track on the CO(1–0) line at 115 GHz, and the bottom panel the same integration time on the HCO$^+$(1–0) line.A line at a Galactic radius of 11.5 kpc is clearly detected in HCO$^+$ but it is hidden in the noise in the CO spectrum.

at +6 km s^{-1} and a closely-spaced pair near −56 km s^{-1}). The two lines that we observed close to −56 km s^{-1} have significantly different velocities and optical depths from the lines in the LAG single dish spectrum. Upon close inspection we find that LAG's interferometer spectrum is also in disagreement with their single dish spectrum, (despite their statement to the contrary) and that their interferometer spectrum (within the noise) agrees with ours. We conclude that the LAG single dish absorption spectrum is probably corrupted by inaccurate subtraction of extended CO emission.

We would like to point out that, although we have detected molecular gas in absorption along two lines of sight with the interferometer, this does not imply that the absorbing gas is necessarily cold. The standard equation of radiative transfer is:

$$T_b = T_o e^{-\tau_\nu} + T_k(1 - e^{-\tau_\nu}), \tag{1}$$

from which we see that absorption below the continuum level (T_0) may occur if the kinetic temperature of the foreground gas (T_k), which has optical depth τ_ν, is lower than the background source temperature. Hence the general conclusion that absorption implies cold gas. However, an interferometer, which has a zero response to extended emission and therefore

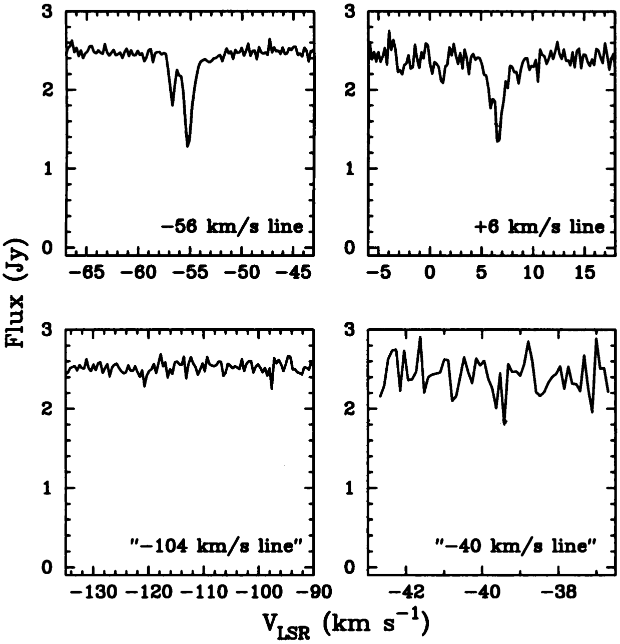

Figure 2. OVRO HCO^+ spectra of the low-galactic latitude quasar 2013+370. The four panels show the 4 different velocities at which Lequeux, Allen & Guilloteau (1993) reported the detection of absorption. We can only confirm two of those lines: the top panels show our detections of the lines at +6 $km\,s^{-1}$ and the composite line at –56 $km\,s^{-1}$. The lines at –104 $km\,s^{-1}$ and –40 $km\,s^{-1}$ are not confirmed at higher resolution and better rms noise level than the data by LAG either at HCO^+ (bottom panels) or CO (not shown).

acts as a spatial filter, cancels the emission part of the radiative transfer equation, leaving:

$$T_b = T_o e^{-\tau_\nu}. \tag{2}$$

Ideally this equation also holds for the single dish experiment by LAG, who used the average of 4 neighboring spectra to cancel the emission from the spectrum taken toward the quasar (whether the cancelation is accurate is another issue). The foreground gas temperature does not appear in equation (2). Therefore, when using either of these techniques, the conclusion that gas is cold simply because it is seen in absorption is false.

LAG argued that gas found in emission toward 0727-115 was cold, with $T_k \approx 3.5$ K. For this conclusion they had to assume that the filling factor of CO emission in the 23″ IRAM beam was unity. However, they also noted that there were significant emission gradients in the vicinity of 0727-115. This fact indicates that the filling factor is less than unity and that the gas temperature is higher than 3.5 K. For a discussion of kinetic temperatures of gas in the outer Galaxy see also Wilson & Mauersberger (1994).

4. Conclusions

Our observations do not confirm the conclusion by LAG that a significant component of cold molecular gas resides in the outer Galaxy. However, neither do the observations exclude an abundant cold molecular component. If such a component does exist the only way to detect it is in absorption against a background source, but the small number of background sources in the 3-mm wave band severely limits the detection probability. The probability (P_n) of detecting the molecular component using a limited number (n) of (pencil-beam) lines of sight depends directly on the volume filling factor (f_V) of the gas:

$$P_n = 1 - (1 - (f_V)^{2/3})^n. \tag{3}$$

If the cold molecular gas density is $\sim$ 300 cm^{-3}, then $f_V \sim 10^{-3}$. The probability of detecting a cold cloud with six lines of sight is only $P_6 \approx 6\%$. Thus, the null results so far do not rule out the possibility of cold gas in the far outer galaxy.

Since the molecular gas is expected to have a low volume filling factor, it is essential that we sample a larger number of lines of sight. Because the number of strong quasars increases dramatically toward lower frequencies, and because the new Q-band opportunity at the VLA has made the CS(0-1) transition accessible to observation, we have obtained observing time at the VLA to search for this molecular line in absorption in the outer Galaxy. With the improved sampling possible at 49 GHz we are hopeful that statistically meaningful surveys for cold gas in the outer Galaxy are now within reach.

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DISCUSSION

R. Allen: Your suggestion that we could not have computed reliable excitation temperatures assumes that we observed only one line in absorption. In fact, the values of excitation temperature which I gave in my paper require, and were derived from, a combination of both emission and absorption observations, in some cases even for both the 2-1 and the 1-0 transition. I would be happy to discuss the algebra involved with you during the coffee break.

de Geus: Our comment about the temperature derivation was based on the information given in Lequeux, Allen & Guilloteau (1994). There, only the temperature along the line of sight to 0727-115 is discussed, and for this object no mention is made of data other than CO (1-0) absorption and emission. Lequeux et al. (1994) then state that *because* the CO absorption line is saturated, the corresponding emission gives the excitation temperature, provided that the beam filling factor is unity. Besides arguing that the uncertainty in the beam filling factor is important and will always make the temperature estimate a lower limit, we mostly take issue with the statement that the CO line is saturated. In our data 0727-115 has revealed NO CO(1-0) absorption ($\tau < 0.65$), which implies that there is no basis for the assumption that the corresponding emission gives the excitation temperature.