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Research Paper

Formaldehyde in the Far Outer Galaxy: Constraining the Outer Boundary of the Galactic Habitable Zone

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ABSTRACT

We present results from an initial survey of the 2_{12}–1_{11} transition of formaldehyde (H_2CO) at 140.8 GHz in giant molecular clouds in the far outer Galaxy ($R_G \geq 16$ kpc). Formaldehyde is a key prebiotic molecule that likely plays an important role in the development of amino acids. Determining the outermost extent of the H_2CO distribution can constrain the outer limit of the Galactic Habitable Zone, the region where conditions for the formation of life are thought to be most favorable. We surveyed 69 molecular clouds in the outer Galaxy, ranging from 12 to 23.5 kpc in galactocentric radius. Formaldehyde emission at 140.8 GHz was detected in 65% of the clouds. The H_2CO spectral line was detected in 26 of the clouds with $R_G > 16$ kpc (detection rate of 59%), including 6 clouds with $R_G > 20$ kpc (detection rate of 55%). Formaldehyde is readily found in the far outer Galaxy—even beyond the edge of the old stellar disk. Determining the relatively widespread distribution of H_2CO in the far outer Galaxy is a first step in establishing how favorable an environment this vast region of the Galaxy may be toward the formation of life. Key Words: Extraterrestrial life—Habitable zone—Interstellar molecules—Spectroscopy. Astrobiology 8, 59–73.

1. INTRODUCTION

To determine which regions of the Galaxy are most favorable for the formation of life, the galactic distribution of biologically important molecules must be established. Because all stars and their protoplanetary disks form from molecular clouds (*e.g.*, Smith, 2004), the presence of prebiotic molecules in the parent molecular clouds can seed newly formed planetary systems with the compounds necessary for the production of amino acids and other biologically important molecules. This concept is closely tied to the idea of a Galactic Habitable Zone (GHZ), an annular region that lies in the plane of the galactic disk and possesses the necessary conditions for facilitating the formation of life.

The concept of a GHZ was introduced by Marochnik and Mukhin (1986) and Balázs (1986, 1988). However, their discussion was limited to identifying the region of the Galaxy deemed suitable for the formation of *intelligent* life. Stars between spiral arms within a narrow (0.5 kpc) annulus that is centered at the Galaxy's corotation radius [taken to be 10.1 kpc by Balázs (1986) with the Sun assumed to be 10 kpc from the Galactic

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Center] would tend to remain there and not undergo a passage through the arms—a necessary condition, according to the authors, for establishing a long-lived civilization. Later, Gonzalez *et al*. (2001) defined the GHZ in broader terms: "the region in the Milky Way where an Earth-like planet can retain liquid water on its surface and provide a long-term habitat for animal-like aerobic life." No longer focusing exclusively on intelligent life, these authors examined where in the Galaxy the metallicity, supernova frequency, and stellar lifetimes conspired to produce a favorable environment for the formation of life. They also determined the GHZ—at the current time—to be a narrow annulus at approximately the Sun's galactocentric distance ($R_G \approx 8.5$ kpc, but see below). Finally, Lineweaver *et al.* (2004) modeled the above astrophysical parameters and included considerations on the timescale for the development of life. They concluded that the GHZ is 7–9 kpc from the Galactic Center and widening with time.

All of the above authors place the Sun squarely in the middle of the GHZ—pre-Copernican echoes notwithstanding. While we do not intend to dispute, in this paper, the pros and cons of the above approaches, we do propose that an important additional consideration in establishing the location of the GHZ is the presence (in abundant quantity) of key prebiotic molecules. This is especially relevant if we broaden the definition of the GHZ to encompass all the regions of the Galaxy that can give rise at least to lower lifeforms.

Planetary systems that form from molecular clouds rich in prebiotic molecules will have an advantage in producing the building blocks of life (see Section 2). Local star-forming molecular clouds, both giant molecular clouds (GMCs) and dark clouds, within the 7–9 kpc annulus contain complex molecules (*e.g.*, Turner, 1988) so that, by our criterion, this region is certainly a valid GHZ; but to what distance from the Galactic Center is the abundance of key prebiotic molecules significant? Is there an "outer edge" to the Galaxy where the abundances of important organic precursor molecules such as formaldehyde (H_2CO) and hydrogen cyanide (HCN) decrease markedly in comparison to the inner Galaxy?

To determine the outermost limits of the GHZ, we have begun a program to map the distribution and abundance of H_2CO in the *outer* Galaxy (defined in Section 3). In this paper, we describe the initial results of this program. The specific reasons for choosing H_2CO, and the role this molecule plays in the formation of amino acids and other biogenically important molecules, are discussed in Section 2. We briefly describe the molecular environment of the outer Galaxy in Section 3. The setup for the H_2CO observations is described in Section 4 along with the search criteria, and our results are presented in Section 5. A discussion of the results concludes the paper in Section 6.

2. THE ROLE OF FORMALDEHYDE IN THE FORMATION OF LIFE

In his early experiments with regard to the chemical origin of life, Miller (1953, 1955) demonstrated that reactions in a mixture of CH_4, NH_3, H_2O, and H_2 gases subjected to electrical discharge can produce amino acids, aldehydes, and various other organic compounds. Specifically, the amino acid glycine can be formed from a reaction of H_2CO with NH_3 and HCN (Oro *et al.,* 1959; Miller, 1992). Because all of these molecules can be found readily in galactic molecular clouds, it is conceivable that the complex chemistry in the denser regions of these clouds may produce amino acids in sufficient quantities for spectroscopic detection. Glycine itself has been searched for and tentatively identified in GMCs in the inner Galaxy (Kuan *et al.,* 2003), but the detection is still controversial (Snyder *et al.,* 2005).

In addition to its instrumental role in the formation of some amino acids, H_2CO molecules can polymerize via the formose reaction to form sugars, including ribose (Butlerow, 1861). Weber (2000) postulated that the reactions that form sugars may have occurred, and may even have been facilitated, in an early Earth environment devoid of molecular oxygen. While the stability of ribose synthesis from H_2CO under prebiotic conditions has been questioned, a recent study by Ricardo *et al.* (2004) demonstrated the stability of pentose sugar synthesis from H_2CO in the presence of borate minerals.

Where did early Earth's H_2CO come from? The formation of organic molecules, including formaldehyde and amino acids, under early Earth conditions has been extensively investigated (Miller, 1957; Hubbard *et al.,* 1971; Hatanaka and Egami, 1977; Bar-Nun and Hartman, 1978; Chittenden and Schwartz, 1981; Miller and Schlesinger, 1984; Chadha and Choughuley, 1984; Hennet *et al.*, 1992). Pinto *et al.* (1980) and Canuto *et al.* (1983) proposed that photochemical oxidation of CH_4 and subsequent precipitation into oceans could have provided a carbon source for biomolecular reactions that led to the formation of H_2CO, and Kasting (1993) developed atmospheric models of early Earth in an effort to address the conditions under which H_2CO could have formed.

In contrast to the above, there is evidence that the early terrestrial atmosphere may have been more neutral than reducing (Kasting and Catling, 2003). If this were the case, then the formation of sufficient quantities of key prebiotic molecules, such as HCN or H_2CO, may have been more difficult than the mechanisms described above suggest. There is, however, the possibility that H_2CO and other prebiotic molecules can be directly introduced onto a planetary surface via impacting comets and asteroids (*e.g.*, Chyba *et al.*, 1990). It is this particular scenario that would benefit most from a normal to high abundance of H_2CO in the parent molecular cloud, since the comets and asteroids that would form directly from the protoplanetary disk would, in turn, directly reflect the cloud's chemical composition.

With regard to the hydrocarbons that have been identified in the interstellar medium (see, *e.g.*, http://www.cv.nrao.edu/~awootten/allmols.html), H_2CO is one of the most important prebiotic molecules. Formaldehyde can form directly on a terrestrial planet from pre-existing molecules, or it can be introduced via impacting comets or asteroids. It is likely that both mechanisms play a role. In the case of H_2CO accreting from impacting comets or asteroids, a high, or at least normal, abundance of H_2CO in the parent molecular cloud would result in a favorable situation for seeding terrestrial planets with the molecule. Thus, we began our program for determining how favorable the outer Galaxy is to the formation of life by surveying the GMC population in that region for the presence of H_2CO. Below, we discuss the molecular environment of the outer Galaxy and previous galactic surveys of H_2CO.

3. MOLECULAR CLOUDS IN THE OUTER GALAXY

Formaldehyde was the first polyatomic organic molecule identified in the interstellar medium (Snyder *et al.*, 1969), and it is more easily detected throughout the Galaxy than molecules such as NH_3 or HCN (Zuckerman *et al.*, 1970). It is likely that H_2CO shares the same general distribution as CO (Few, 1979), which is the second most abundant molecule after H_2 and the best ground-based tracer of molecular gas in the interstellar medium. The distribution of CO surface density shows a strong concentration at the Galactic Center and a sharp decrease to about 2 kpc, followed by a marked increase peaking at the so-called "Molecular Ring" at about 4–6 kpc. At larger R_G there is a gradual drop-off in concentration to about 18–20 kpc (Scoville and Sanders, 1987; Wouterloot *et al.*, 1990). The molecular component of the Galaxy is contained in clouds with a large range of sizes and masses, from small, parsec-scale globules with a mass of a few solar masses to GMCs that comprise several tens of parsecs and contain up to 10^6 solar masses of gas and dust. The molecular cloud mass distribution is such that most of the molecular gas mass in the Galaxy is contained in GMCs. Beyond $R_G \approx 10$ kpc, the molecular clouds tend to be smaller, less massive, and more isolated compared to molecular clouds in the inner Galaxy (Brand and Wouterloot, 1995).

The outer Galaxy begins immediately beyond the Solar Circle, defined as the circular orbit whose radius is that of the distance of the Sun from the Galactic Center, commonly denoted as R_o. In 1985, the International Astronomical Union recommended that a value of 8.5 kpc be adopted for R_o (Kerr and Lynden-Bell, 1986), though more recent work (*e.g.*, Vallée, 2005, and references therein) points to $R_o \approx 7.9$ kpc as a more accurate value. In this paper, we will retain $R_o = 8.5$ kpc. Various surveys of the molecular material in the outer Galaxy have been carried out (*e.g.*, Wouterloot and Brand, 1989; Digel *et al.*, 1994; Heyer *et al.*, 1998), from which it has been established that the molecular disk of the Galaxy extends to more than 20 kpc from the Galactic Center.

In the far outer Galaxy ($R_G \geq 16$ kpc), the nature of the galactic molecular environment is significantly different from that of the Galaxy inside the Solar Circle. Specifically, the HI and H_2 gas surface and volume densities are much smaller than in the inner Galaxy, and their scale heights are larger. Also, the stellar density is much smaller, there is less star formation, and the interstellar radiation field is much weaker. Further, there are fewer supernova remnants in the far outer Galaxy, so there are fewer and, possibly, weaker triggers for star formation, and abundances of helium and heavier elements are lower.

The far infrared emissivity of the dust in the interstellar medium of the far outer Galaxy is smaller, and the pressure of the intercloud medium is much smaller (Brand and Wouterloot, 1996). Although these factors might be expected to negatively influence the cloud- and star-formation activity in the far outer Galaxy, hundreds of molecular clouds are found there (Brand and Wouterloot, 1995; Snell *et al.,* 2002; Brunt *et al.,* 2003), as well as substantial star formation (Wouterloot *et al.,* 1988; Kobayashi and Tokunaga, 2000; Santos *et al.,* 2000; Brand and Wouterloot, 2007). Thus it is likely that hundreds, if not thousands, of planetary systems should be present even at these large distances from the Galactic Center.

The above studies of the outer Galaxy have been based almost exclusively on studies of the rotational transitions of CO and its isotopologues. The CO(1–0) transition has a characteristic or critical density of 3×10^3 cm^{-3}, which is ideal for study of the large-scale distribution of molecular gas in interstellar clouds, whereas the 140.8 GHz line (the lowest commonly-observable rotational transition of ortho-H_2CO) has a value of 1.3×10^6 cm^{-3} (Wooten *et al*., 1980). Moreover, H_2CO is less abundant than CO and consequently H_2CO observations are almost always limited to small samples of selected molecular clouds and star-forming regions. Exceptions include the study in the inner Galaxy by Zylka *et al.* (1992), who observed H_2CO near the Galactic Center (between longitudes 0.5° and 4°) at 4.83 and 14.5 GHz, while Few (1979) observed 38 lines of sight along the galactic plane between longitudes 8° and 60° in the 4.83 GHz transition of H_2CO.* Despite the relatively few points and poor sampling, Few (1979) was able to show that the H_2CO in the inner Galaxy generally follows the CO distribution. However, his data extend only to a maximum R_G of 10 kpc (scaled to R_o = 8.5 kpc).

As part of her H_2CO survey of a subset of dark clouds from the Lynds (1962) catalogue, Dieter (1973) detected H_2CO absorption at 4.83 GHz in 73 clouds with $90° \leq \ell \leq 270°$. Nearly all of these objects were in the galactic plane. At higher galactic latitudes, several small, local molecular clouds were observed in H_2CO by Heithausen *et al.* (1987) and Turner (1993), and several authors (*e.g.*, Liszt and Lucas, 1995, and references therein) have observed galactic H_2CO in absorption against extra-galactic radio continuum sources. Most recently, a blind survey for H_2CO absorption at 4.83 GHz was carried out by Rodriguez *et al.* (2006), with detections in about 10% of 143 lines of sight toward the galactic anticenter in the range $-1° \leq \ell \leq +1°$. Although kinematic distances to objects in the direction of the anticenter are very uncertain (see Section 5), the molecular clouds responsible for the absorption are thought to be located in the nearby Perseus spiral arm.

All these outer Galaxy H_2CO detections are either from small molecular clouds that are situated a few hundred pc from the Sun or from larger clouds in the nearby Perseus spiral arm (<2 kpc from the Sun). Prior to the results of the survey described in this paper, there was no systematic search for H_2CO in the GMCs of the far outer Galaxy.

4. SAMPLE SELECTION AND OBSERVATIONS

To study the extent of H_2CO in the outer Galaxy, we selected a total of 70 objects from 3 sources, as follows:

(1) The Wouterloot and Brand (1989) catalogue of IRAS† sources beyond R_o. These are IRAS sources, primarily in the second and third galactic quadrants, with infrared colors typical of star-forming regions, toward which, in most cases, CO emission has been detected.
(2) The Digel, de Geus, and Thaddeus (1994) compilation of 11 molecular clouds in the "extreme outer Galaxy" (ranging from $18 < R_G < 28$ kpc; however, see below). These molecular clouds were found by searching for CO emission in regions of relatively high HI column density, and are likely to be located in the outermost spiral arm.
(3) The Bronfman, Nyman, and May (1996) catalogue of CS(2–1) emission toward IRAS point

*The 4.83 and 14.5 GHz spectral lines of H_2CO (1_{11}–1_{10} and 2_{12}–2_{11} transitions, respectively) are subject to anomalous excitation in many molecular clouds, because for molecular cloud densities less than 10^6 cm^{-3}, the lines appear in absorption against the cosmic microwave background radiation. The excess population in the lower levels of the pertinent J = 1, 2 states requires a refrigeration mechanism, which was first suggested by Townes and Cheung (1969).

†Infrared Astronomical Satellite (see Low *et al.,* 1984).

sources in the galactic plane. This latter survey differs from the Wouterloot and Brand (1989) survey in that the CS(2-1) line traces denser molecular gas than the CO(1–0) line, and the Bronfman *et al.* catalogue includes full coverage of the first galactic quadrant.

From these 3 sources, we selected candidates on the basis of distance from the Galactic Center (the farther the object, the more preferable it was), CO(1–0) signal strength, and galactic latitude and sidereal time considerations. Of the 70 GMCs that we observed, 59 are from the Wouterloot and Brand (1989) catalogue, 5 are from Digel *et al.* (1994), and 6 are from Bronfman *et al.* (1996).

The 70 selected GMCs from the 3 sources described above cover a range in R_G between 8.5 and 23.5 kpc, and a total of 75 lines of sight were observed. Sixty-nine of the clouds are at $R_G \geq 12$ kpc, with only the cloud WB89-002 at $R_G \approx 8.6$ kpc being relatively close to the Sun. The positions of all the observed lines of sight are listed in Table 1, and histograms of the galactocentric distribution of all clouds and detections are shown in Fig. 1. Some clouds were observed at another position besides the one from the Wouterloot and Brand (1989) catalogue (designated by an "a" at the end of the source name). The "a" positions were chosen by looking for the most intense dust emission from the cloud in question by way of the Schlegel *et al.* (1998) dust maps. In Table 1, we list kinematic distances for the clouds even though these distance determinations may be subject to large uncertainties (see Section 5). Toward each object, we observed the 2_{12}–1_{11} transition of ortho-H_2CO at 140.8 GHz with the Arizona Radio Observatory 12 m millimeter-wave telescope on Kitt Peak, Arizona, during May and November of 2005.‡

The 2_{12}–1_{11} transition of H_2CO was chosen despite its fairly high critical density (see above), because at the 12 m telescope, the angular resolution at this frequency is 44″. For a cloud at a distance of 10 kpc, this corresponds to a linear size of 2 pc. The 1_{11}–1_{10} transition at 4.83 GHz is sensitive to lower density gas because of its anomalous excitation (*e.g.*, Evans, 1975), but a comparable angular resolution to the 12 m is available only at the Arecibo 305 m telescope, which has limited sky coverage. Most of the lines of sight in our sample likely traverse high-density gas regions so that the relatively high critical density of the 140.8 GHz transition should not present a significant handicap. However, it is plausible that some of the nondetections in our survey might be detectable via 4.83 GHz observations.

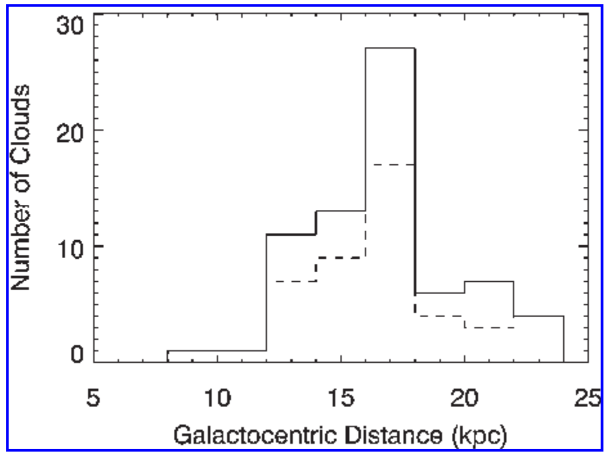

FIG. 1. Histogram of the galactocentric distribution of the observed clouds. The distance is derived from the clouds' kinematics and is in units of kpc from the Galactic Center. The total number of observed clouds (70) is represented by the dark line and detections (46) by the dashed line.

To maximize velocity coverage, all the observations were made in position-switched mode with the off position chosen to be 1° east or west of the source in azimuth. The 100 kHz and 250 kHz filter banks were chosen to provide velocity coverages of 27 and 68 km s^{-1}, respectively, and velocity resolutions of 0.21 and 0.53 km s^{-1}. Because many of the lines of sight had CO emission at 2 or even 3 different velocities (see Wouterloot and Brand, 1989), we centered the filter banks at the Local Standard of Rest (LSR) velocity of the molecular cloud with the greatest R_G.

At the 12 m telescope, the H_2CO line antenna temperature (T_A* see Kutner and Ulich, 1981) is corrected for the spillover and scattering efficiency of the antenna, so that the resulting quantity is T_R*, the radiation temperature uncorrected for the antenna-source coupling efficiency, η_c. For the 12 m telescope at 140.8 GHz, η_c is approximately 0.7 (Apponi *et al.*, 2006). Another correction factor is the beam dilution that we assume to be equal to 1 (see Section 6).

Typical rms noise values per channel in the 250 kHz filter banks ranged from 10 to 30 mK. The

‡The 12-meter millimeter-wave, radiotelescope is operated by the Arizona Radio Observatory, Steward Observatory, University of Arizona.

TABLE 1. H_2CO (2_{12}–1_{11}) OBSERVATIONS OF OUTER GALAXY MOLECULAR CLOUDS

Source	l (degrees)	b (degrees)	R_G (kpc)	T_R^* (K)	ΔV (km s^{-1})	V_{LSR} (km s^{-1})	rms (K)
WB89-002	85.409	3.741	8.6	0.114	1.54	−2.75	0.025
WB89-006	86.274	3.210	14.9	0.163	2.71	−91.38	0.019
WB89-013	88.211	3.275	15.3	—	—	—	0.028
WB89-013a	87.610	3.490	15.3	—	—	—	0.029
WB89-014	88.990	3.451	15.5	0.081	2.00	−96.03	0.013
WB89-031	88.057	−0.019	14.6	0.099	1.21	−89.40	0.011
WB89-035	89.942	1.445	13.4	0.175	2.16	−77.68	0.010
WB89-040	90.676	1.781	12.1	0.145	1.90	−62.65	0.020
WB89-040a	91.110	1.560	12.1	—	—	—	0.020
WB89-059	92.898	1.934	14.3	—	—	—	0.025
WB89-060	95.054	3.972	14.0	0.362	2.78	−84.29	0.025
WB89-066	95.588	3.897	13.9	—	—	—	0.008
WB89-076	95.248	2.405	15.7	0.243	2.04	−97.17	0.026
WB89-080	95.444	2.182	13.1	0.191	2.50	−74.24	0.018
WB89-083	96.077	2.563	15.3	0.172	1.46	−93.77	0.015
WB89-098	98.507	3.311	14.8	—	—	—	0.013
WB89-145	102.634	3.758	14.8	—	—	—	0.009
WB89-152	104.008	4.200	14.8	0.087	2.05	−88.13	0.012
WB89-283	114.267	2.021	16.5	0.210	1.30	−94.49	0.026
WB89-288	114.332	0.789	17.5	0.113	1.31	−100.87	0.026
WB89-315	117.981	1.655	17.1	0.023	3.77	−95.09	0.012
WB89-361	122.604	1.641	18.2	—	—	—	0.033
WB89-361a	122.790	2.530	18.2	—	—	—	0.033
WB89-365	123.078	1.360	17.2	—	—	—	0.033
WB89-379	124.555	2.525	17.3	0.204	2.21	−89.32	0.011
WB89-380	124.643	2.539	17.0	0.457	3.46	−86.67	0.018
WB89-391	125.805	3.047	16.9	0.277	2.32	−86.06	0.016
WB89-398	128.106	1.935	17.4	—	—	—	0.018
WB89-399	128.776	2.012	16.8	0.354	1.68	−82.19	0.028
WB89-434	135.988	0.674	17.9	—	—	—	0.012
WB89-437	135.278	2.798	16.2	0.456	2.81	−71.72	0.014
WB89-438	136.348	0.822	16.9	—	—	—	0.012
WB89-440	135.626	2.765	16.4	0.055	2.21	−72.20	0.014
WB89-453	133.396	8.882	20.2	—	—	—	0.028
WB89-501	145.197	2.988	16.4	0.246	2.55	−58.44	0.028
WB89-523	149.041	1.289	19.0	—	—	—	0.013
WB89-529	149.591	0.900	17.8	0.107	1.73	−60.08	0.014
WB89-540	151.228	1.023	19.7	—	—	—	0.017
WB89-572	156.895	0.210	20.4	0.074	1.07	−48.03	0.028
WB89-621	168.063	0.820	22.6	0.629	2.58	−25.38	0.023
WB89-625	168.678	1.090	17.8	0.116	1.82	−25.98	0.018
WB89-629	170.822	0.003	16.4	0.054	2.72	−16.83	0.014
WB89-636	166.260	3.554	19.0	0.173	1.38	−24.37	0.016
WB89-640	167.060	3.464	18.4	0.382	2.37	−25.42	0.012
WB89-656	171.262	2.540	12.5	0.108	1.64	−10.53	0.012
WB89-658	171.143	2.755	21.8	—	—	—	0.011
WB89-670	173.014	2.377	23.5	0.317	1.71	−17.57	0.013
WB89-705	174.734	3.725	21.4	0.226	1.03	−12.10	0.012
WB89-730	184.002	1.833	23.5	0.109	5.87	10.10	0.018
WB89-745	182.033	4.394	21.0	—	—	—	0.012
WB89-789	195.822	−0.568	20.3	0.174	1.82	34.33	0.028
WB89-793	195.819	−0.213	18.1	0.369	2.02	30.48	0.016
WB89-794	195.650	−0.105	17.8	0.133	3.59	30.06	0.020
WB89-847	209.080	−1.949	16.5	0.196	1.62	49.98	0.013
WB89-898	217.604	−2.618	16.4	0.244	2.77	63.41	0.013
WB89-904	211.040	1.186	17.0	0.091	2.15	55.16	0.013
WB89-910	212.187	1.309	15.9	0.237	1.98	51.07	0.014
WB89-1000	234.715	−0.915	15.1	—	—	—	0.012
WB89-1012	239.334	−2.740	15.4	0.128	2.02	83.33	0.015
WB89-1023	238.773	−1.810	16.4	—	—	—	0.023

(continued)

TABLE 1. H_2CO (2_{12}–1_{11}) OBSERVATIONS OF OUTER GALAXY MOLECULAR CLOUDS (CONT'D.)

Source	*l* (degrees)	*b* (degrees)	R_G (kpc)	T_R^* (K)	ΔV (km s^{-1})	V_{LSR} (km s^{-1})	*rms* (K)
WB89-1074	250.006	−3.343	16.5	—	—	—	0.039
WB89-1103	255.547	−2.518	17.5	—	—	—	0.031
DDT01	131.38	1.79	22.0	—	—	—	0.029
DDT01a	131.14	1.39	22.0	—	—	—	0.028
DDT02	137.75	−0.98	17.0	—	—	—	0.025
DDT04	145.05	−0.10	19.0	—	—	—	0.011
DDT04a	145.40	−0.10	20.0	—	—	—	0.016
DDT05	145.30	−0.25	18.0	—	—	—	0.015
DDT07	148.90	0.90	18.0	—	—	—	0.028
19423+2541	61.719	0.864	13.6	0.385	3.93	−72.62	0.014
19383+2711	62.575	2.387	13.2	0.215	5.69	−66.85	0.010
19489+3030	66.609	2.060	13.0	0.132	2.10	−68.91	0.013
19571+3113	68.146	0.921	12.2	0.043	8.70	−62.48	0.011
20243+3853	77.605	0.556	12.9	0.356	2.95	−73.06	0.013
20321+4112	80.351	0.724	12.2	0.062	6.87	−65.64	0.009

stronger H_2CO lines were integrated for shorter periods of time because we primarily emphasized, in this initial phase of the project, the detection and identification of those molecular clouds in the outer Galaxy that are good subjects for multitransition H_2CO studies.

The 140.8 GHz spectrum for cloud WB89-670, our most distant detection at $R_G \approx 23.5$ kpc, is shown in Fig. 2a. Spectra for five other detections are shown in Figs. 2b–2f. All the observed positions are listed in Table 1, where the first column gives the name of the cloud; columns 2, 3, and 4 list the galactic longitude and latitude of the object and its R_G; columns 5, 6, and 7 list the uncorrected radiation temperature, line width (Full Width at Half Maximum, FWHM), and velocity with respect to the LSR of the line emission (for those lines of sight with detections). Finally, the last column gives the rms noise level for each observation.

5. RESULTS

In almost all cases where the CO emission had more than one component [all from the Wouterloot and Brand (1989) catalogue], the components at lower velocity, which thus originated in less distant clouds, were not detected in the 140.8 GHz H_2CO line, though they are easily detected in the CO (1–0) line. This is because we chose to observe lines of sight primarily from the Wouterloot and Brand (1989) catalogue where the most distant component had the strongest CO emission. This most likely implies that the CO emission in the distant component arises from a dense molecular core that is likely to have a significant H_2CO column density (though it is also possible that some portion of the CO line intensity arises from local heating). Any intervening molecular clouds are probably sampled through their more extended, lower density envelopes, and so are less likely to yield an H_2CO detection at 140.8 GHz.

We searched for the 140.8 GHz line in 75 lines of sight in 70 outer Galaxy molecular clouds and detected 46 clouds, which is a detection rate of 66%. Excluding cloud WB89-002, 45 out of 69 clouds were detected (65% detection rate). For those clouds with $R_G > 16$ kpc, H_2CO emission was detected in 26 out of 44 clouds (59% detection rate), which is nearly the same detection rate as for the entire ensemble. Even for objects with $R_G > 20$ kpc, at the very edge of the molecular disk of the Galaxy, the 140.8 GHz emission line was detected in 6 of 11 clouds (55% detection rate).

None of the 4 clouds from the Digel *et al.* (1994) catalogue were detected. Although these objects have kinematic distances that are larger than the typical cloud from the Wouterloot and Brand (1989) catalogue, uncertainties in the kinematic distances can be significant. For instance, Cloud 2 from the Digel *et al.* (1994) catalogue is listed at an R_G of 28 kpc, which makes it nominally the most distant galactic molecular cloud known. However, Smartt *et al.* (1996) identified the star exciting the HII region associated with the cloud and revised its R_G to a more modest 15–19 kpc. Formaldehyde had already been detected in this object by Lubowich *et al.* (2001) (13 mK at 140.8

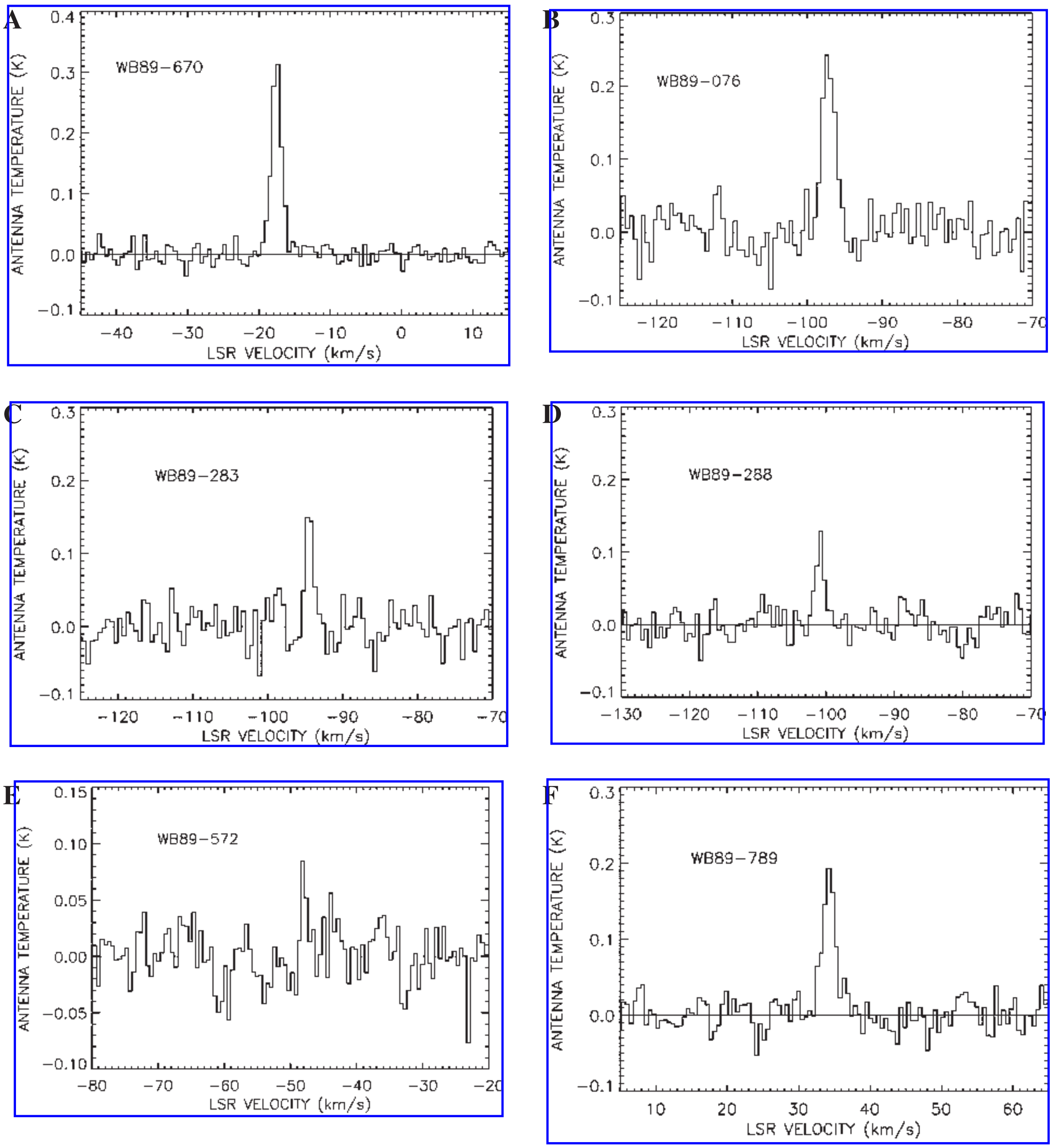

FIG. 2. (A) H_2CO spectrum at 140.8 GHz (2_{12}–1_{11} transition) for the giant molecular cloud WB89-670. This cloud is at a galactocentric distance of 23.5 kpc (however, see caveat in Section 5) and is at a distance of 15 kpc from the Sun. The beam size of 44″ at this frequency corresponds to a linear size of 3.2 pc. (**B**) H_2CO spectrum at 140.8 GHz for WB89-076. The cloud is at R_G ~15.7 kpc. (**C**) H_2CO spectrum at 140.8 GHz for WB89-283. The cloud is at R_G ~16.5 kpc. (**D**) H_2CO spectrum at 140.8 GHz for WB89-288. The cloud is at R_G ~17.5 kpc. (**E**) H_2CO spectrum at 140.8 GHz for WB89-572. The cloud is at R_G ~20.4 kpc. This spectrum is our lowest signal-to-noise detection and has a best-fit Gaussian velocity centroid at −48.03 km s^{-1} (see Table 1). The velocity of the CO(1–0) emission from this cloud as tabulated by Wouterloot and Brand (1989) is −47.86 km s^{-1}. (**F**) H_2CO spectrum at 140.8 GHz for WB89-789. The cloud is at R_G ~20.3 kpc.

GHz), and though we did not detect any emission from 2 lines of sight in the cloud, our rms level of 25 mK is consistent with not detecting emission from this object. It is almost certain that significantly lower rms values would reveal H_2CO emission in many of our nondetections. However, our survey trades sensitivity for sampling a relatively large number of clouds.

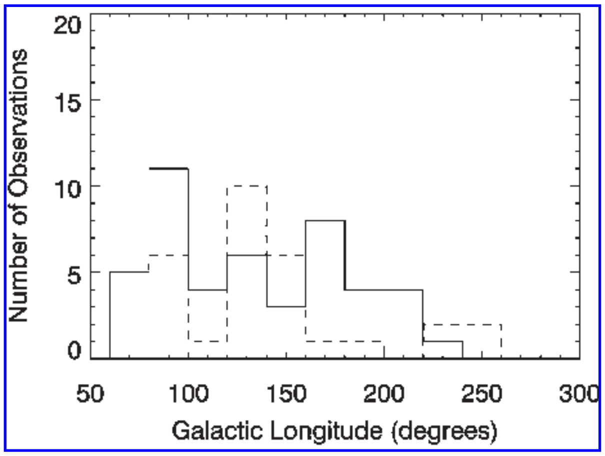

FIG. 3. Histogram of the H_2CO 140.8 GHz detections (solid line) and nondetections (dashed line) in terms of galactic longitude. Objects with $165° < \ell < 195°$ have highly uncertain distance estimates.

The distance, R_G, for each of the objects in Table 1 is the kinematic distance which is given by

$$R_G = \Theta R_o\,[\{v_{LSR}/(\sin \ell \cos b)\} + \Theta_o]^{-1}\ \text{kpc}, \quad (1)$$

where ℓ and b are the galactic longitude and latitude of the source; R_o is taken to be 8.5 kpc; Θ_o (the circular rotation velocity at the position of the Sun) is 220 km s^{-1}; and Θ is the circular rotation velocity of the object in question derived from the galactic rotation curve. A simple analytic expression for $\Theta(R)$ is given by

$$\Theta(R) = \Theta_o[1.0077\ \{R/R_o\}^{0.0394} + 0.00712]\ \text{km s}^{-1} \quad (2)$$

(Brand and Blitz, 1993). For objects with galactic longitudes, $165° < \ell < 195°$, the LSR velocity is not very sensitive to distance, and cloud random motions have a large influence on the kinematic distance determination. For instance, the cloud WB89-730 has $\ell = 184.0°$, $b = 1.83°$, and $v_{LSR} =$ 9.48 km s^{-1} (Wouterloot and Brand, 1989); the 2 formulas above yield a kinematic distance of 23.5 kpc from the Galactic Center. If the LSR velocity of the cloud is changed by ± 5 km s^{-1} [the cloud-to-cloud velocity dispersion for GMCs in the outer Galaxy (Brand and Blitz, 1993)], the kinematic distance ranges from 12.4 kpc to more than 170 kpc. Thus, the error in the kinematic distance can be very large in this longitude interval, and the derived distances to objects are very uncertain. The distribution of our detections and nondetections in terms of galactic longitude is shown in Fig. 3.

The spiral arms of the Galaxy are not well defined outside the Solar Circle. The Perseus arm has long been identified as a feature in the outer Galaxy (Morgan *et al.*, 1952), but its distance from the Sun has recently undergone a substantial revision (Xu *et al.*, 2006). Vallée (2005) compiled data on the spiral arms of the Galaxy and produced an updated model of their locations. In Fig. 4, we have plotted our detections and nondetections on a galactocentric polar plot with the Perseus and Cygnus (or Outer) spiral arms superposed. Figure 5 shows the same data plotted on a Sun-centered polar plot where the axes now correspond to 0°, 90°, 180°, and 270° of galactic longitude. With the exception of two (detected) objects (WB89-002 and WB89-656), all the GMCs that were observed are at least 8 kpc from the Sun.

In the second quadrant of Fig. 4, most of the molecular clouds with $115° < \ell < 180°$ seem to be associated with the Cygnus arm. A half-dozen objects in the direction of the galactic anticenter seem to be at significantly large R_G (>20 kpc). However, as described above, objects with $165° < \ell < 195°$ have very uncertain distances that could significantly alter their position on the plot. In the third quadrant of the plot in Fig. 4, the objects that correspond to $\ell > 230°$ seem to be associated

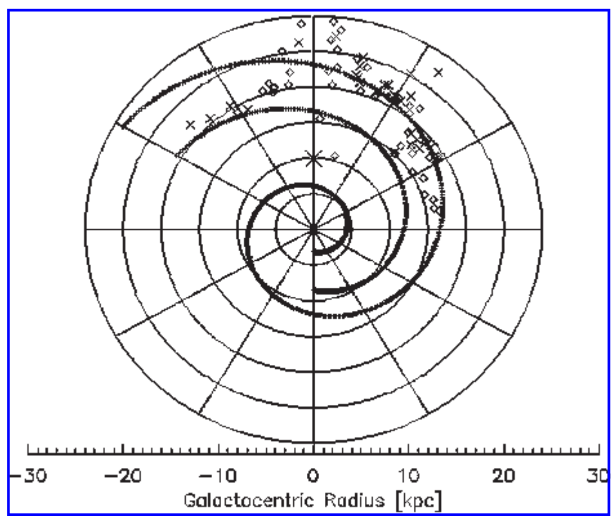

FIG. 4. Galactocentric distribution of the H_2CO observations of GMCs in the outer Galaxy. Concentric circles are spaced 4 kpc apart. The diamonds represent detections of the 140.8 GHz line, the small x's represent nondetections, and the large x represents the position of the Sun. The heavy black lines delineate the approximate positions of the Perseus spiral arm (inner line) and the Cygnus or Outer spiral arm (outer line) based on the model of Vallée (2005). Galactic longitudes of 0°, 90°, 180°, 270° are at 6, 3, 12, and 9 o'clock as centered on the large x, respectively.

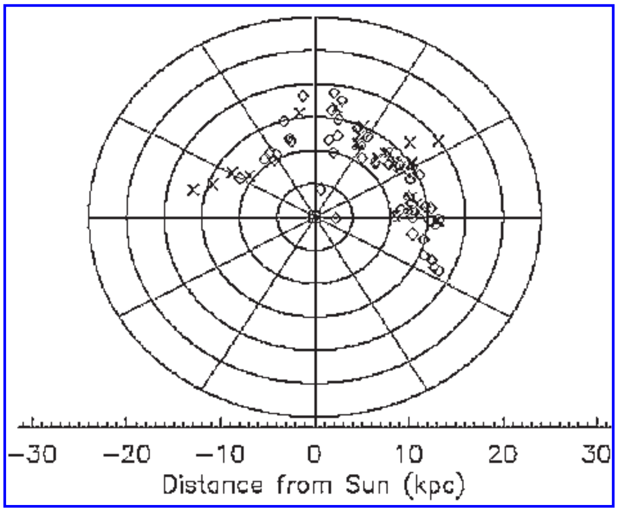

FIG. 5. Distribution of H_2CO observations of molecular clouds in the outer Galaxy with respect to the Sun (center of the polar plot). Diamonds represent detections and x's nondetections. The concentric circles are 4 kpc apart.

primarily with the Perseus arm, while those closer to the anticenter seem to be between the Perseus and Cygnus arms—though uncertainties in their kinematic distances could equally well locate them in either arm. Despite these caveats, the majority of the detected GMCs with $\ell < 180°$ are likely located in the Cygnus arm.

6. DISCUSSION

Our initial study of H_2CO in the far outer Galaxy, the first such systematic survey, reveals that the molecule is readily observable even in molecular clouds with $R_G > 20$ kpc. With two exceptions, all of the 70 GMCs that were searched for H_2CO emission are more than 8 kpc from the Sun, with some as distant as 16 kpc. At that distance, the angular resolution of the 12 m telescope at 140.8 GHz corresponds to a linear resolution of ~3 pc. Because H_2CO is distributed less extensively in molecular clouds than CO (*e.g.*, Magnani *et al.*, 1996), H_2CO-emitting regions less than a pc in size could be significantly beam diluted, especially in light of the discussion in Section 5, which indicates that H_2CO 140.8 GHz emission is difficult to detect from the lower-density envelopes of molecular clouds. To determine whether beam dilution is present in our sample, we plotted the velocity-integrated H_2CO radiation temperature as a function of distance from the Sun (Fig. 6). The results resemble a scatter plot. Thus we can deduce—assuming for now that the abundance and excitation temperature remain similar as the distance from the Sun changes from 8 to 16 kpc—that the H_2CO data presented in Table 1 are not significantly beam diluted and the emission arises from dense molecular regions at least a few pc in size.

Comparing the H_2CO results from outer Galaxy GMCs with those from inner Galaxy GMCs is difficult because most H_2CO galactic surveys were made with transitions other than the 2_{12}–1_{11} line (see Section 3). Usually, the 140.8 GHz line is used as part of multi-transition studies of individual GMCs (*e.g.*, Mundy *et al.*, 1987). An exception is the survey of 11 GMCs in the inner Galaxy and Galactic Center by Wilson and Jaffe (1981). Not surprisingly, their average T_R^* for 14 lines of sight in 11 clouds is 1.4 K compared to 0.2 K for the outer Galaxy GMCs in Table 1; Brand and Wouterloot (1995) established that the GMCs in the far outer Galaxy are less dense than their inner-Galaxy counterparts. Moreover, the sample of Wilson and Jaffe (1981) includes GMCs that are among the largest in the Galaxy and is not really representative of the 2_{12}–1_{11} emission from a "typical" inner-Galaxy GMC. Thus, although the H_2CO 140.8 GHz line strength in Table 1 is weaker than that from the GMCs observed by Wilson and Jaffe (1981) inside the Solar Circle, it is so by less than a factor of 10, which

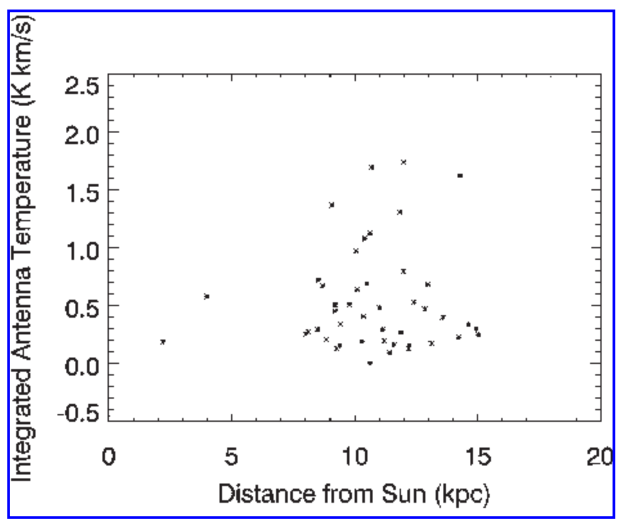

FIG. 6. Velocity-integrated H_2CO 140.8 GHz radiation temperature as a function of distance from the sun. The scatter in the plot indicates that beam dilution is not systematically decreasing the strength of the H_2CO line for the more distant clouds.

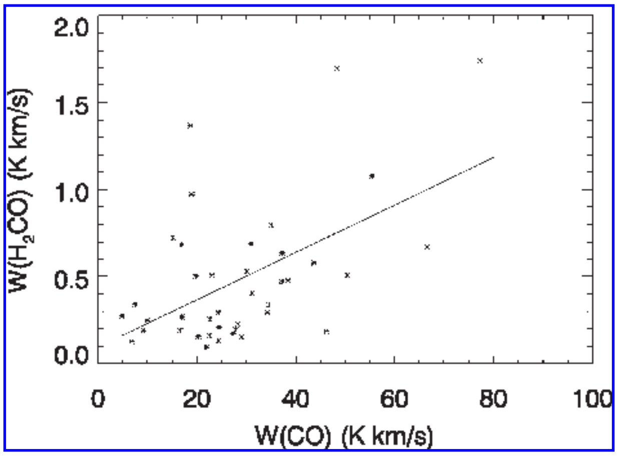

FIG. 7. Velocity-integrated H_2CO 140.8 GHz radiation temperature [W(H_2CO)] versus velocity-integrated CO (1–0) radiation temperature [W(CO)] for those detections in Table 2 from the Wouterloot and Brand (1989) catalogue. The line is the least-squares-fit to the data points with slope 0.014 and y-intercept 0.095. The correlation coefficient is 0.53.

is similar in behavior to the CO line strength in outer versus inner Galaxy GMCs.

The detection of H_2CO at the edge of the molecular disk of the Galaxy is a significant new result, but it does not directly address whether the abundance of the molecule relative to H_2 has decreased significantly at the edge of the molecular disk with respect to the Solar Circle or the inner Galaxy. Galactic chemical evolution models (*e.g.*, Maciel and Quireza, 1999) predict that atomic abundances in the far outer Galaxy should markedly decrease. By observing HII regions, Rudolph *et al.* (2006) found that the nitrogen abundance decreases by a factor of 10 from the Solar Circle to $R_G = 20$ kpc, while the oxygen and sulfur abundances decrease by slightly less than an order of magnitude. Thus, molecular species in clouds in the far outer Galaxy may have significantly lower abundances than clouds at, or interior to, the Solar Circle.

Determining whether the abundance of H_2CO with respect to H_2 in far outer Galaxy clouds is less than that inside the Solar Circle [where the H_2CO abundance ranges over $5–8 \times 10^{-9}$ for moderate-density GMCs (Mundy *et al.*, 1987)] is an important goal of our program, which, unfortunately, cannot be reliably addressed by a single-transition study. We can try to draw some general conclusions about this issue from our data, but the only way to determine with certainty the abundance of H_2CO in the clouds in our sample is to observe several transitions of H_2CO and use models for the radiative transfer through a given cloud.

Figure 7 shows a plot of the velocity-integrated H_2CO radiation temperature of the 140.8 GHz transition [defined as W(H_2CO)] versus the velocity-integrated CO(1–0) radiation temperature [W(CO)] obtained from Wouterloot and Brand (1989). The scatter in the values for the various clouds could indicate abundance, density, or excitation variations from cloud to cloud. However, a least-squares-fit to the 40 data points with accompanying CO data depicted in Fig. 7 yields a linear correlation of the form

$$W(H_2CO) = 0.014W(CO) + 0.095 \text{ K km s}^{-1} \quad (3)$$

The correlation coefficient is 0.53, which, for 40 data points, indicates a probability of less than 0.1% that this relationship arises from an uncorrelated parent population. Interpreting the implications of this correlation is not so clear. It could imply that the physical conditions (*i.e.*, density, ambient radiation fields, kinetic temperatures) in most of the sampled lines of sight are similar, so that the excitation characteristics of each transition are similar. This might, in turn, imply that the H_2CO abundance with respect to CO is fairly constant. On the other hand, such correlations could be the result of observational bias, given that there were several dozen lines of sight for which we did not detect H_2CO, though they have CO(1–0) emission.

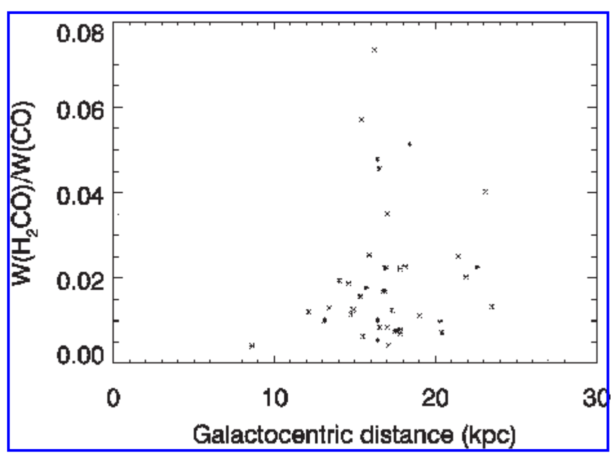

FIG. 8. The ratio [W(H_2CO)/W(CO)] as a function of R_G. The linear relation based on a least-squares-fit to the data points has a correlation coefficient of 0.13, indicating that the points are most likely not correlated.

TABLE 2. H_2CO ABUNDANCE WITH RESPECT TO H_2 AS ESTIMATED FROM CO

Source	$N_i(H_2CO)$[a] $T_{ex} = 10$ K	$N_i(H_2CO)$[a] $T_{ex} = 20$ K	$N(H_2) \times 10^{21}$ cm^{-2}	*Abundance*[b] $\times 10^{-10}$
WB89-002	2.2	1.6	7.8	1.2–1.7
WB89-006	5.6	4.0	6.3	3.8–5.4
WB89-014	2.0	1.5	4.6	2.0–2.6
WB89-031	1.5	1.1	1.2	5.5–7.6
WB89-035	4.8	3.4	5.2	4.0–5.6
WB89-040	3.5	2.5	4.1	3.7–5.2
WB89-060	12.7	9.2	9.3	6.0–8.3
WB89-076	6.2	4.5	5.0	5.4–7.5
WB89-080	6.0	4.3	8.5	3.0–4.3
WB89-083	3.2	2.3	2.8	5.0–6.9
WB89-152	2.2	1.6	2.8	3.5–4.8
WB89-283	3.4	2.5	5.8	2.6–3.5
WB89-288	1.9	1.4	3.4	2.5–3.4
WB89-315	1.1	0.78	3.7	1.3–1.8
WB89-379	5.7	4.1	6.5	3.8–5.3
WB89-380	19.9	14.4	11.4	7.6–10.6
WB89-391	8.1	5.8	5.2	6.7–9.4
WB89-399	7.5	5.4	6.3	5.2–7.2
WB89-437	16.1	11.6	14.2	4.9–6.9
WB89-440	1.5	1.1	4.1	1.6–2.2
WB89-501	7.9	5.7	11.2	3.1–4.3
WB89-529	2.3	1.7	4.7	2.2–3.0
WB89-572	1.9	1.4	3.8	2.2–3.0
WB89-621	20.4	14.8	13.0	6.9–9.5
WB89-625	2.7	1.9	4.8	2.4–3.4
WB89-629	1.8	1.3	4.9	1.6–2.2
WB89-636	3.0	2.2	3.8	3.5–4.8
WB89-640	11.4	8.2	3.2	15.5–21.6
WB89-656	2.2	1.6	3.7	2.6–3.6
WB89-670	6.8	4.9	7.3	4.1–5.6
WB89-705	2.9	2.1	1.7	7.5–10.3
WB89-730	8.0	5.8	2.8	12.5–17.3
WB89-789	4.0	2.9	5.8	3.0–4.2
WB89-793	9.4	6.8	5.9	7.0–9.6
WB89-794	6.0	4.3	3.9	6.7–9.3
WB89-847	4.0	2.9	1.2	14.6–20.2
WB89-898	8.5	6.2	2.5	15.0–20.6
WB89-904	2.5	1.8	4.1	2.74–3.7
WB89-910	5.9	4.3	3.3	7.9–10.8
WB89-1012	3.3	2.4	0.81	17.9–24.6

[a]Column density of ortho-H_2CO in J = 2 level. Values are in units of 10^{11} cm^{-2}.
[b]N(ortho-H_2CO) = $N_{J=2}$(ortho-H_2CO)/0.2 and ortho-H_2CO/para-H_2CO = 1.33 (see Section 6).

In light of the correlation described above, we have plotted in Fig. 8 the ratio of W(H_2CO)/W(CO) for the 40 lines of sight with detected emission in both species as a function of R_G. In this case, the data are more scattered in the plot, and the least-squares fit yielded a relation with a correlation coefficient of only 0.13. For 40 data points, there is more than a 40% chance that the linear relationship from the least-squares-fit arises from an uncorrelated parent population; thus there is likely no linear correlation of the ratio with R_G.

With our 140.8 GHz observations and the CO data provided in WB89, we were able to determine the abundance of H_2CO with respect to H_2 using several simplifying assumptions. Of course, such assumptions (which involve opacity, excitation temperature, partition function, and the CO-H_2 conversion factor) can lead to large errors in the abundance determination. Nevertheless, we proceeded with the calculation by assuming that the line is optically thin, and we calculated the column density for the J = 2 ortho-level for 2 excitation temperatures, 10 and

20 K. The results for those lines of sight with detected H_2CO emission and corresponding CO data are shown in Table 2. Assuming that the standard CO-H_2 conversion factor valid at the Solar Circle [1.8×10^{20} cm^{-2} (K km s^{-1})$^{-1}$ (Dame *et al.*, 2001)] is valid for the far outer Galaxy, we converted the velocity-integrated CO antenna temperature tabulated by WB89 to N(H_2). To get the total N(H_2CO) value, we assumed that only the 5 lowest rotational levels were populated and the ortho/para ratio was 1.33 (see, *e.g.*, Liszt and Lucas, 2006). The derived abundances range from 1.2×10^{-10} to 2.5×10^{-9} and are tabulated in column 5 of Table 2. The average values of the abundance for T_{ex} = 10 K and 20 K are 5.4×10^{-10} and 7.5×10^{-10}, respectively. If these values are reliable, they indicate that there is about an order of magnitude decrease in the H_2CO abundance compared to that of moderate density GMCs inside the Solar Circle. The molecule is still relatively plentiful though not as abundant as in the inner Galaxy. Moreover, the decrease in abundance would be consistent with that in metallicity described above. As tempting as this conclusion may be, it was obtained by making several assumptions; a much more reliable course would be to determine the H_2CO abundance by conducting multi-transition studies and comparing the ratio of several line intensities to the results from Large Velocity Gradient codes (*e.g.*, Mangum and Wooten, 1993). We plan to make the necessary observations and calculations to follow this strategy in the immediate future.

Our observations of H_2CO 140.8 GHz emission in nearly 6 dozen GMCs with $R_G > 12$ kpc have established that this molecule is still relatively plentiful and readily detected in the outer Galaxy. Twenty-six detections arise from clouds located in the far outer Galaxy, and most of these detections with $\ell < 180°$ are likely to be in the Cygnus spiral arm, which is the outermost arm known. The preliminary work described in this paper indicates that the GHZ—at least as far as the presence of the key prebiotic molecule, formaldehyde, is concerned—may extend to the edge of the molecular disk. If this conjecture is supported by studies of other prebiotic molecules and determinations of their abundances, then the galactic volume capable of supporting at least low-level life forms is dramatically greater than was previously thought.

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ABBREVIATIONS

GHZ, Galactic Habitable Zone; GMC, giant molecular cloud; IRAS, Infrared Astronomical Satellite; LSR, Local Standard of Rest; R_G, galactocentric distance.

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