

## CYCLOPROPENONE ( $c\text{-H}_2\text{C}_3\text{O}$ ): A NEW INTERSTELLAR RING MOLECULE

J. M. HOLLIS,<sup>1</sup> ANTHONY J. REMIJAN,<sup>1,2</sup> P. R. JEWELL,<sup>3</sup> AND F. J. LOVAS<sup>4</sup>

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### ABSTRACT

The three-carbon keto ring cyclopropenone ( $c\text{-H}_2\text{C}_3\text{O}$ ) has been detected largely in absorption with the 100 m Green Bank Telescope (GBT) toward the star-forming region Sagittarius B2(N) by means of a number of rotational transitions between energy levels that have energies less than 10 K. Previous negative results from searches for interstellar  $c\text{-H}_2\text{C}_3\text{O}$  by other investigators attempting to detect rotational transitions that have energy levels  $\sim 10$  K or greater indicate no significant hot core component. Thus, we conclude that only the low-energy levels of  $c\text{-H}_2\text{C}_3\text{O}$  are populated because the molecule state temperature is low, suggesting that  $c\text{-H}_2\text{C}_3\text{O}$  resides in a star-forming core halo region that has a widespread arcminute spatial scale. Toward Sagittarius B2(N), the GBT was also used to observe the previously reported, spatially ubiquitous, three-carbon ring cyclopropenylidene ( $c\text{-C}_3\text{H}_2$ ), which has a divalent carbon that makes it highly reactive in the laboratory. The presence of both  $c\text{-C}_3\text{H}_2$  and  $c\text{-H}_2\text{C}_3\text{O}$  toward Sagittarius B2(N) suggests that gas-phase oxygen addition may account for the synthesis of  $c\text{-H}_2\text{C}_3\text{O}$  from  $c\text{-C}_3\text{H}_2$ . We also searched for but did not detect the three-carbon sugar glyceraldehyde ( $\text{CH}_2\text{OHCHOHCHO}$ ).

*Subject headings:* ISM: abundances — ISM: clouds — ISM: individual (Sagittarius B2(N)) — ISM: molecules — radio lines: ISM

### 1. INTRODUCTION

The Sagittarius B2 star-forming region contains hot compact molecular cores of arcsecond dimensions, molecular maser emitting regions, ultracompact continuum sources that are surrounded by larger scale continuum features and molecular material extended on the order of arcminutes. Moreover, small-scale and large-scale shock phenomena characterize the complex (e.g., Chengalur & Kanekar 2003). In particular, the hot compact molecular core known as the Large Molecule Heimat (LMH), which is centered on the K2 ultracompact continuum source, has for the last decade been a primary target to be searched for the presence of large interstellar molecules such as methyl formate ( $\text{CH}_3\text{OCHO}$ ; Miao et al. 1995), acetic acid ( $\text{CH}_3\text{COOH}$ ; Remijan et al. 2002; Mehringer et al. 1997), acetone ( $\text{CH}_3\text{COCH}_3$ ; Snyder et al. 2002), and ethyl cyanide ( $\text{CH}_3\text{CH}_2\text{CN}$ ; Hollis et al. 2003).

Within the last 5 yr, a number of large interstellar molecules have been found toward the LMH that have spatial scales of arcminutes that far exceed the confines of the LMH  $\sim 5''$  diameter. These spatially extended molecules in the direction of the LMH include glycolaldehyde ( $\text{CH}_2\text{OHCHO}$ ; Hollis et al. 2001, 2004a), acetaldehyde ( $\text{CH}_3\text{CHO}$ ; Chengalur & Kanekar 2003), propenal ( $\text{CH}_2\text{CHCHO}$ ; Hollis et al. 2004b), propanal ( $\text{CH}_3\text{CH}_2\text{CHO}$ ; Hollis et al. 2004b), and ethylene glycol ( $\text{HOCH}_2\text{CH}_2\text{OH}$ ; Hollis 2005). Interferometry maps of acetaldehyde and glycolaldehyde exist (Chengalur & Kanekar 2003; Hollis et al. 2001), but the other large molecules in this category are inferred to be spatially extended because only transitions between low-energy levels have been detected, and these transitions would be inconsistent with compact hot molecular core regions. In particular, glycolaldehyde,

propenal, and propanal observations toward the LMH are dominated by two simple absorption features at local standard of rest (LSR) velocities of +64 and +82  $\text{km s}^{-1}$ , which are associated with star-forming cores that may have been triggered by collision between two molecular clouds with these systemic velocities, as suggested by Mehringer & Menten (1997). Glycolaldehyde, propenal, and propanal observations of their lowest energy levels transitions (i.e., levels  $< 2.7$  K cosmic background temperature), which correspond to low frequencies and therefore larger telescope beamwidths, are seen in emission at the intermediate LSR velocity of +73  $\text{km s}^{-1}$ , which is indicative of an extended cloud surrounding the two star-forming cores.

Since we had observed that transitions between low-energy levels of the two-carbon sugar glycolaldehyde were strong (Hollis et al. 2004a) toward Sgr B2(N-LMH) compared to millimeter wave transitions (Hollis et al. 2000) and that glycolaldehyde must be spatially widespread (Hollis et al. 2001, 2004a), we conducted a search for the three-carbon sugar glyceraldehyde ( $\text{CH}_2\text{OHCHOHCHO}$ ) at K band (18–26 GHz) with the GBT with beam sizes that ranged from  $\sim 29''$  to  $38''$  but could not detect this molecule (Hollis et al. 2004b). The rationale for our glyceraldehyde search was that glycolaldehyde is the parent molecule in a number of sugar synthesis processes that lead to more complex aldehyde sugars (e.g., Walker 1975; Flanagan et al. 1992; Larralde et al. 1995). In the present work, we were motivated to search again for glyceraldehyde at even lower frequencies at L band (1.15–1.73 GHz) and S band (1.73–2.60 GHz), where the larger telescope beam sizes may couple better to the expected extended emission, since this three-carbon sugar is probably as extended as the parent glycolaldehyde molecule but may have a different distribution and abundance. While we did not detect glyceraldehyde toward Sgr B2(N-LMH), we did detect and identify cyclopropenone ( $c\text{-H}_2\text{C}_3\text{O}$ ), the first keto ring molecule to be found in an interstellar cloud. The earliest search for interstellar  $c\text{-H}_2\text{C}_3\text{O}$  was conducted by Lovas et al. (1976) toward Orion A and Sgr B2 using the NRAO 36 ft radio telescope at Kitt Peak. The motivation to search for  $c\text{-H}_2\text{C}_3\text{O}$  at that time was the recent detections of dimethyl ether toward Orion A

<sup>1</sup> NASA Goddard Space Flight Center, Computational and Information Sciences and Technology Office, Code 606, Greenbelt, MD 20771.

<sup>2</sup> National Research Council Resident Research Associate.

<sup>3</sup> National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-2475.

<sup>4</sup> Optical Technology Division, National Institute of Standards and Technology, Gaithersburg, MD 20899.

TABLE 1  
OBSERVATIONAL PARAMETERS

Band (1)	Receiver (GHz) (2)	Number of IFs (3)	Number of Polarizations (4)	IF Bandwidth (MHz) (5)	Resolution (kHz) (6)	Pointing Source (7)	Date (8)
L.....	1.15–1.73	4	2	50	6.1	1712–281	2005 Sep 9
S.....	1.73–2.6	4	2	50	6.1	1712–281	2005 Sep 8
X.....	8–10	4	2	200	24.4	1700–261	2005 Sep 6, 18, 19
Ku.....	12–15.4	4	2	200	24.4	1700–261	2005 Sep 7, 14, 22
K.....	18–22.4	4	2	200	24.4	1733–130	2004 Feb 25
Q.....	40–48	4	2	800	390.7	1733–130	2005 Mar–Apr

and trans-ethanol toward Sgr B2. In the Lovas et al. survey, an  $c\text{-H}_2\text{C}_3\text{O}$  upper limit of  $\sim 10^{12} \text{ cm}^{-1}$  for Sgr B2 was obtained assuming a rotational temperature of 50 K. More recently, Dickens et al. (2001) searched for  $c\text{-H}_2\text{C}_3\text{O}$  in a wide range of interstellar environments ranging from dark clouds to high-mass star-forming regions. However, no transition of  $c\text{-H}_2\text{C}_3\text{O}$  was detected. In the present work, we report the detection and potential synthesis pathways of interstellar cyclopropenone and the latest search for glyceraldehyde.

## 2. OBSERVATIONS AND RESULTS

Spectral line searches were conducted with the NRAO<sup>5</sup> 100 m GBT in accordance with Table 1, which lists the receiver band, receiver tuning range, number of intermediate frequencies (IFs) employed, number of polarizations per IF, bandwidth per IF, spectrometer channel spacing, pointing source used, and observational date in columns (1)–(8). Table 2 lists the rotational transitions of the molecules sought. The transition quantum numbers, the transition type, the calculated transition rest frequency, the energy of the lower level ( $E_l$ ), the transition line strength (S), telescope beamwidth ( $\theta_B$ ), and telescope beam efficiency ( $\eta_B$ ) are listed in columns (1)–(7). Antenna temperatures are on the  $T_A^*$  scale (Ulich & Haas 1976) with estimated 20% uncertainties. GBT half-power beamwidths can be approximated by  $\theta_B = 740/\nu(\text{GHz})$  arcseconds. The Sgr B2(N-LMH) J2000 pointing position employed was  $\alpha = 17^{\text{h}}47^{\text{m}}19^{\text{s}}.8$ ,  $\delta = -28^{\circ}22'17''$ , and an LSR source velocity of  $+64 \text{ km s}^{-1}$  was assumed. Data were taken in the OFF-ON position-switching mode, with the OFF position  $60'$  east in azimuth with respect to the ON-source position. The OFF position is far removed from the Sgr B2N molecular complex (see Fig. 1 of Chengalur & Kanekar 2003) and is not known to be a source of molecular emission or absorption. A single scan consisted of 2 minutes in the OFF-source position followed by 2 minutes in the ON-source position. Automatically updated dynamic pointing and focusing corrections were employed based on real-time temperature measurements of the structure input to a thermal model of the GBT; zero points were adjusted typically every 2 hr or less using the pointing source listed in Table 1. The two polarization outputs from the spectrometer were averaged in the final data reduction process to improve the signal-to-noise ratio (S/N).

The spectral line parameters presented in columns (3)–(5) of Table 2 were either calculated in the present work or derived from the literature sources cited in the footnotes of Table 2. For propynal, the spectral line data were determined from a fit to the laboratory measurements of Benson et al. (1969), Costain & Morton (1959), Takami & Shimoda (1976), and Winnewisser

(1973). For cyclopropenone, the spectral line data were calculated from a fit to the laboratory frequencies reported by Benson et al. (1973) and Guillemin et al. (1990). For cyclopropene, the spectral line data were calculated from a fit to the laboratory measurements of Benson & Flygare (1969), Stigliani et al. (1975), Bogey et al. (1986), and Vrtilek et al. (1987). Dipole moment components for all species are also listed in the footnotes to Table 2.

Observations of  $c\text{-C}_3\text{H}_2$ ,  $c\text{-H}_2\text{C}_3\text{O}$ , cyclopropene ( $c\text{-C}_3\text{H}_4$ ), acetaldehyde, propynal ( $\text{HC}_2\text{CHO}$ ), and glyceraldehyde are summarized in Table 2, in which columns (8), (9), and (10) give Gaussian fitted intensities at LSR velocities of  $+64$ ,  $+73$ , and  $+82 \text{ km s}^{-1}$ , respectively; in the case in which no line was detected, a  $1 \sigma$  noise limit is given. Our rationale for observing the species in Table 2 follows. The molecule  $c\text{-C}_3\text{H}_2$  shown in Figure 1 is spatially widespread and abundant in interstellar clouds and is likely the parent molecule of the two species for which we were searching:  $c\text{-H}_2\text{C}_3\text{O}$  shown in Figure 2 and  $c\text{-C}_3\text{H}_4$ , which were unsuccessfully searched for previously by Dickens et al. (2001) and Thaddeus et al. (1985), respectively. After initially finding the first low-energy transition of  $c\text{-H}_2\text{C}_3\text{O}$ , we also included two low-energy transitions of acetaldehyde shown in Figure 3 in our program with the large GBT beams at S and X bands to sample a known interstellar molecule that is spatially widespread and has been spatially mapped with an interferometer (Chengalur & Kanekar 2003) toward Sgr B2(N-LMH). Moreover, we included the interstellar molecule  $\text{HC}_2\text{CHO}$  shown in Figure 3 because it is an isomer of  $c\text{-H}_2\text{C}_3\text{O}$  and therefore may likely be chemically related and spatially coincident. Finally, we searched for glyceraldehyde for evidence that complex sugar synthesis occurs in interstellar clouds.

## 3. DISCUSSION

Cyclopropenone ( $c\text{-H}_2\text{C}_3\text{O}$ ) is a molecule of exceptional stability that derives from electronic properties related to the cyclopropenyl cation ( $c\text{-C}_3\text{H}_3^+$ ), which is the simplest aromatic ring (Breslow 1972; Breslow et al. 1977). The observational evidence for interstellar  $c\text{-H}_2\text{C}_3\text{O}$  toward Sgr B2(N-LMH) consists of the six transitions shown in Figure 2 in which line-to-continuum ratios of all spectral features indicate apparent optical depths much less than 1. These spectra are similar to those of propanal toward the same source in which the  $J = 1\text{--}0$  transition is dominated by emission at an LSR velocity of  $+73 \text{ km s}^{-1}$ , while other transitions between higher energy levels tend toward absorption at  $+64$  and  $+82 \text{ km s}^{-1}$  (Hollis et al. 2004b); these absorption components represent the systemic LSR velocities of the two star-forming cores (Mehringer & Menten 1997). This suggests a very low temperature regime for  $c\text{-H}_2\text{C}_3\text{O}$  in which the lowest energy levels are populated and, in particular, the  $J = 1\text{--}0$  transition is observed with a larger telescope beam that

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TABLE 2  
SUMMARY OF SPECTRAL LINE OBSERVATIONS TOWARD Sgr B2(N-LMH)

TRANSITION $J'_{K-K+} - J''_{K-K+}$ (1)	TYPE (2)	FREQUENCY <sup>a</sup> (MHz) (3)	$E_l$ (cm <sup>-1</sup> ) (4)	S (5)	$\theta_B$ (arcsec) (6)	$\eta_B$ (7)	$\Delta T_A^*$ (mK) <sup>b</sup>		
							+64 (8)	+73 (9)	+82 (10)
Acetaldehyde (CH <sub>3</sub> CHO) <sup>c</sup>									
1 <sub>10</sub> -1 <sub>11</sub> E.....	a	1849.634(7)	2.24	0.495	400	0.91	187(3)	...	...
1 <sub>11</sub> -2 <sub>02</sub> A.....	b	8243.462(3)	1.93	0.516	90	0.89	-91(1)	...	-58(1)
Propynal (HC <sub>2</sub> CHO) <sup>d</sup>									
4 <sub>14</sub> -5 <sub>05</sub> .....	b	15146.048(15)	4.67	2.054	49	0.84	-15(1)	...	-9(1)
Cyclopropenylidene (c-C <sub>3</sub> H <sub>2</sub> ) <sup>e</sup>									
1 <sub>10</sub> -1 <sub>01</sub> .....	b	18343.144(1)	1.63	1.500	40	0.81	-6313(21)	...	-3412(23)
Cyclopropenone (c-H <sub>2</sub> C <sub>3</sub> O) <sup>f</sup>									
7 <sub>25</sub> -7 <sub>26</sub> .....	a	8373.738(13)	16.47	1.001	88	0.89	...	<2.3	...
3 <sub>12</sub> -3 <sub>13</sub> .....	a	9263.455(6)	3.50	0.584	80	0.88	-29(1)	...	-7(1)
1 <sub>01</sub> -0 <sub>00</sub> .....	a	14105.724(2)	0.00	1.000	52	0.85	-7(1)	3(1)	...
4 <sub>13</sub> -4 <sub>14</sub> .....	a	15427.933(10)	5.28	0.452	48	0.83	-10(1)	...	-4(2)
3 <sub>03</sub> -2 <sub>02</sub> .....	a	42031.941(6)	1.41	2.994	18	0.48	-35(2)	...	-14(2)
3 <sub>22</sub> -2 <sub>21</sub> .....	a	42316.189(6)	4.75	1.667	17	0.48	-18(4)	...	13(4)
7 <sub>16</sub> -7 <sub>17</sub> .....	a	42808.096(26)	13.23	0.279	17	0.47	...	<3.4	...
3 <sub>12</sub> -2 <sub>11</sub> .....	a	44587.398(6)	2.32	2.666	17	0.45	-60(3)	...	-22(3)
Cyclopropene (c-C <sub>3</sub> H <sub>4</sub> ) <sup>g</sup>									
1 <sub>10</sub> -1 <sub>11</sub> .....	a	8029.987(1)	1.46	1.500	92	0.89	...	<2.3	...
3 <sub>21</sub> -3 <sub>22</sub> .....	a	15089.598(1)	8.76	1.889	49	0.84	...	<2.8	...
Glyceraldehyde (CH <sub>2</sub> OHCHOHCHO) <sup>h</sup>									
4 <sub>14</sub> -4 <sub>04</sub> .....	c	1404.034(1)	1.71	5.691	527	0.91	...	<16.2	...
3 <sub>13</sub> -3 <sub>03</sub> .....	c	1880.564(1)	1.03	4.048	393	0.91	...	<13.2	...
1 <sub>11</sub> -1 <sub>01</sub> .....	c	2677.920(1)	0.17	1.500	276	0.91	...	<0.8	...
2 <sub>21</sub> -2 <sub>11</sub> .....	c	8033.679(1)	0.63	0.833	92	0.89	...	<2.3	...
1 <sub>10</sub> -0 <sub>00</sub> .....	c	8257.621(1)	0.00	1.000	90	0.89	...	<2.7	...
2 <sub>20</sub> -2 <sub>12</sub> .....	c	9231.865(1)	0.60	0.672	80	0.88	...	<1.9	...
3 <sub>21</sub> -3 <sub>13</sub> .....	c	9987.736(1)	1.10	0.977	74	0.88	...	<2.6	...

<sup>a</sup> Uncertainties in parentheses refer to the least significant digit and are 2  $\sigma$  values (Taylor & Kuyatt 1994).

<sup>b</sup> Uncertainties and limits are 1  $\sigma$  values.

<sup>c</sup> Acetaldehyde: frequency from Kleiner et al. (1996);  $\mu_a = 2.5160(43)$  D and  $\mu_b = 1.0700(65)$  D (Bossert et al. 1978).

<sup>d</sup> Propynal: frequencies from present work;  $\mu_a = 2.359(18)$  D and  $\mu_b = 1.468(22)$  D (Brown & Godfrey 1984).

<sup>e</sup> Cyclopropenylidene: frequency and  $\mu_b = 3.27(1)$  D (Lovas et al. 1992).

<sup>f</sup> Cyclopropenone: frequencies from present work;  $\mu_a = 4.39(6)$  D (Benson et al. 1973).

<sup>g</sup> Cyclopropene: frequencies from present work;  $\mu_a = 0.455(10)$  D (Kasai et al. 1959).

<sup>h</sup> Glyceraldehyde:  $\mu_a = 0.459(3)$  D and  $\mu_b = 0.36(4)$  D and  $\mu_c = 2.068(8)$  D (Lovas et al. 2003); frequencies calculated from measurements in Lovas et al. (2003).

better samples an extended +73 km s<sup>-1</sup> cloud that surrounds the two star-forming cores, giving rise to the case in which emission dominates absorption.

Figure 4 is an energy level diagram of the six transitions in Figure 2 showing that the transitions are between some of the lowest possible energy levels of the para and ortho forms of c-H<sub>2</sub>C<sub>3</sub>O. The conversion from one form to the other is strictly forbidden via radiative or collisional processes. For a molecule exhibiting para and ortho forms, the abundance ratio of ortho to para forms is assumed to be the ratio of the spin statistical weights (i.e., 3 : 1) for formation temperatures larger than the energy difference between the ground-state zero-point energies of the two forms (Kahane et al. 1984). This is likely a good approximation in particular for c-H<sub>2</sub>C<sub>3</sub>O, since the zero-point energy difference is less than the 2.7 K cosmic background temperature. For exam-

ple, the ground-state energy differences for molecular hydrogen and formaldehyde are 170 and 15 K, respectively. Using the  $J = 1-0$  emission transition of c-H<sub>2</sub>C<sub>3</sub>O, we obtain beam-averaged total column densities of  $\sim 8 \times 10^{12}$  to  $\sim 1 \times 10^{13}$  cm<sup>-2</sup> for state temperatures of 4 and 8 K (Hollis et al. 2004a). In these calculations, we employed equation (1) of Hollis et al. (2004a), assumed that the ortho to para abundance ratio of 3 : 1 applies, and used values of rotational partition function for the para form,  $Q_p$ , of 17.2 and 48.8 for state temperatures of 4 and 8 K.

It is likely that c-C<sub>3</sub>H<sub>2</sub> is the parent molecule of c-H<sub>2</sub>C<sub>3</sub>O, since c-C<sub>3</sub>H<sub>2</sub> is a ubiquitous interstellar molecule in the gas phase (Matthews & Irvine 1985) and has an unbonded pair of electrons that makes it highly reactive in the laboratory (Thaddeus et al. 1985). In the interstellar environment, c-C<sub>3</sub>H<sub>2</sub> may not be as reactive as the linear form l-C<sub>3</sub>H<sub>2</sub> (e.g., Maluendes et al. 1993), but

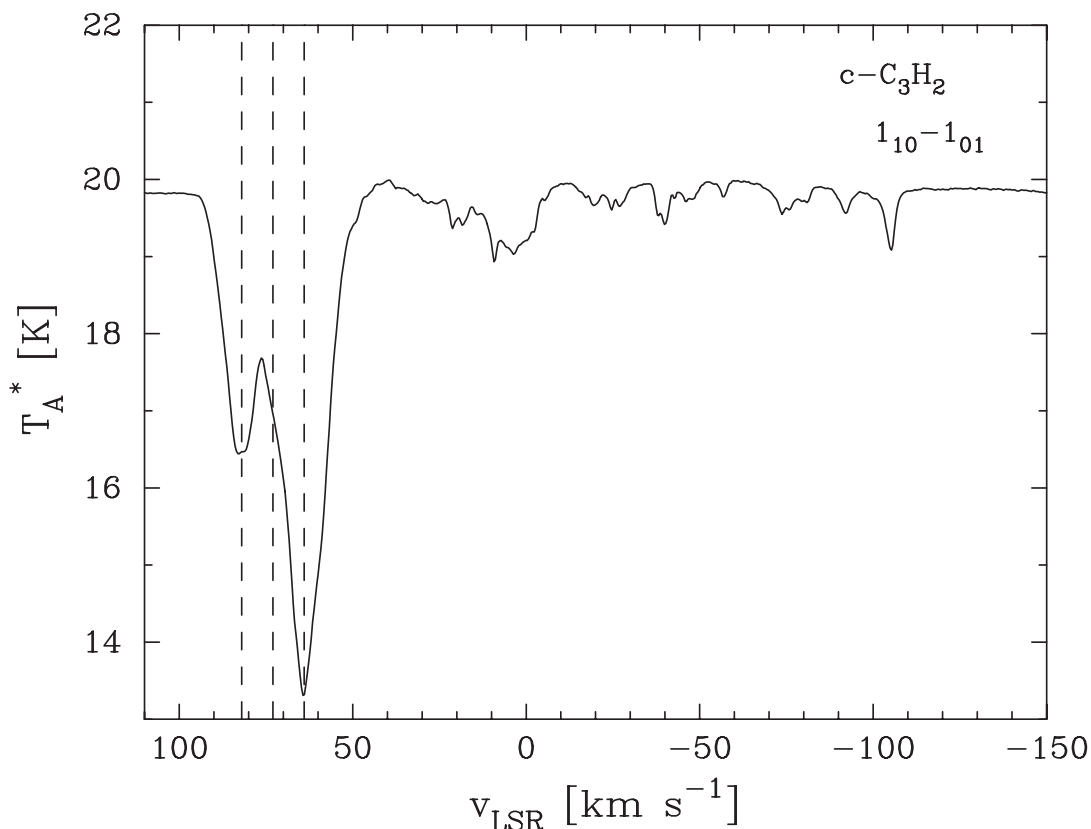
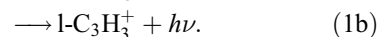
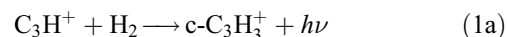


FIG. 1.—*Top*: Cyclopropenylidene ( $c\text{-C}_3\text{H}_2$ ) spectrum toward Sgr B2(N-LMH) at 24.4 kHz channel spacing. The continuum level of the source is shown as a component of the temperature scale. The spectrum was processed with a median filter to remove instrumental slopes in the bandpass. The abscissa is the radial velocity with respect to the LSR calculated for the rest frequency of the transition (see Table 1) at an assumed source velocity of  $+64\text{ km s}^{-1}$ . Dashed lines show LSR velocities at  $+64$ ,  $+73$ , and  $+82\text{ km s}^{-1}$ . There are  $c\text{-C}_3\text{H}_2$  absorption features at lower LSR velocities due to spiral arm clouds along the line of sight. *Bottom*: Schematic diagram showing oxygen addition of  $c\text{-C}_3\text{H}_2$  to form  $c\text{-H}_2\text{C}_3\text{O}$ . This reaction may have a barrier (see text). The molecular structures of both  $c\text{-C}_3\text{H}_2$  and  $c\text{-H}_2\text{C}_3\text{O}$  are also schematically represented.

the cyclic form is estimated to be more abundant by a factor of  $>50\text{--}150$  toward Sgr B2 (see Chernicharo et al. 1999 and references therein), and we believe that the divalent carbon may tend to add with an oxygen atom to produce  $c\text{-H}_2\text{C}_3\text{O}$  as shown in Figure 1. We also searched for cyclopropene ( $c\text{-C}_3\text{H}_4$ ), since it, too, could be easily produced from the parent molecule  $c\text{-C}_3\text{H}_2$  for the same reason but by successive hydrogen addition. In all probability,  $c\text{-C}_3\text{H}_4$  is as abundant as  $c\text{-H}_2\text{C}_3\text{O}$  but eludes detection (see Table 2), since the dipole moments of these two daughter

species differ by a factor of 10 and line intensity scales as the dipole moment squared.

The major source of the parent molecule  $c\text{-C}_3\text{H}_2$  and its linear isomer  $l\text{-C}_3\text{H}_2$  is believed to be the set of gas-phase, ion-molecule reactions (Herbst et al. 1984; Adams & Smith 1987),



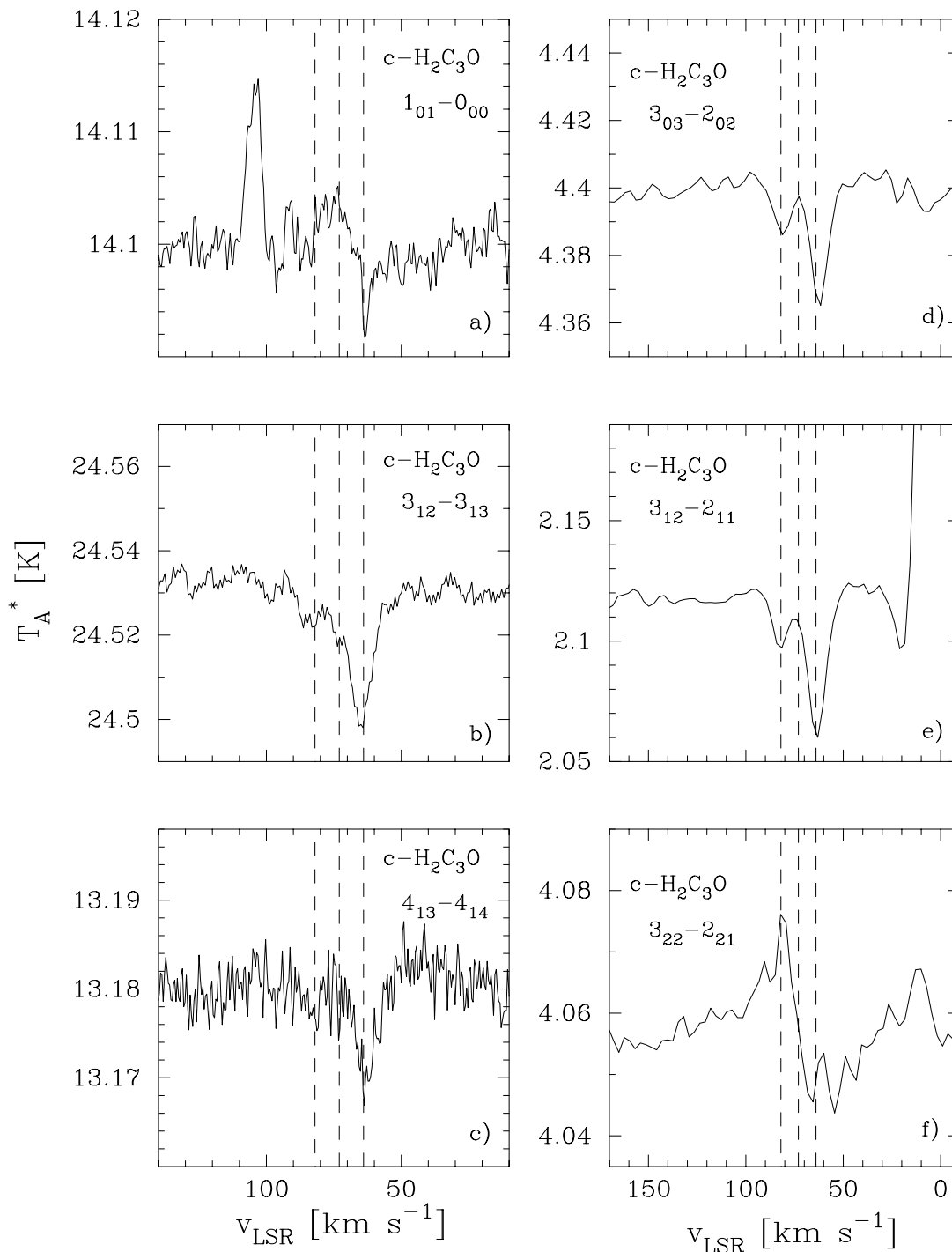
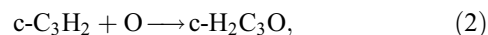


FIG. 2.—Cyclopropenone ( $c\text{-H}_2\text{C}_3\text{O}$ ) spectra toward Sgr B2(N-LMH). Channel spacing is 24.4 kHz in (a)–(c) and 390.7 kHz in (d)–(f). Fig. 1 caption applies.

Maluendes et al. (1993) have performed ab initio calculations that show the linear isomer is formed directly without an activation barrier from the reactants and that isomerization between the linear and cyclic isomers results in equal abundances of the two ions as the relaxation proceeds. Then these cyclic and linear ions can exothermically recombine with an electron to produce cyclic and linear forms of both  $\text{C}_3\text{H}_2$  and  $\text{C}_3\text{H}$ , and all four of these neutral forms have been identified as interstellar molecules. A key assumption is that recombination with an electron does not disturb the carbon skeletal structure of the parent ions. Furthermore, Maluendes et al. (1993) explained the much larger observed abundance of  $c\text{-C}_3\text{H}_2$  relative to  $l\text{-C}_3\text{H}_2$  in in-

terstellar clouds as due to differences in depletion rates. Owing to the facts that high stability of  $c\text{-C}_3\text{H}_2$  would preserve its skeletal structure in simple reactions and that  $c\text{-C}_3\text{H}_2$  is the more abundant interstellar form, the  $c\text{-H}_2\text{C}_3\text{O}$  that we observe toward Sgr B2(N-LMH) may be produced by the gas-phase oxygen addition reaction,



where the divalent carbon accounts for the reactivity of  $c\text{-C}_3\text{H}_2$  as shown in Figure 1. However, equation (2) may have a barrier

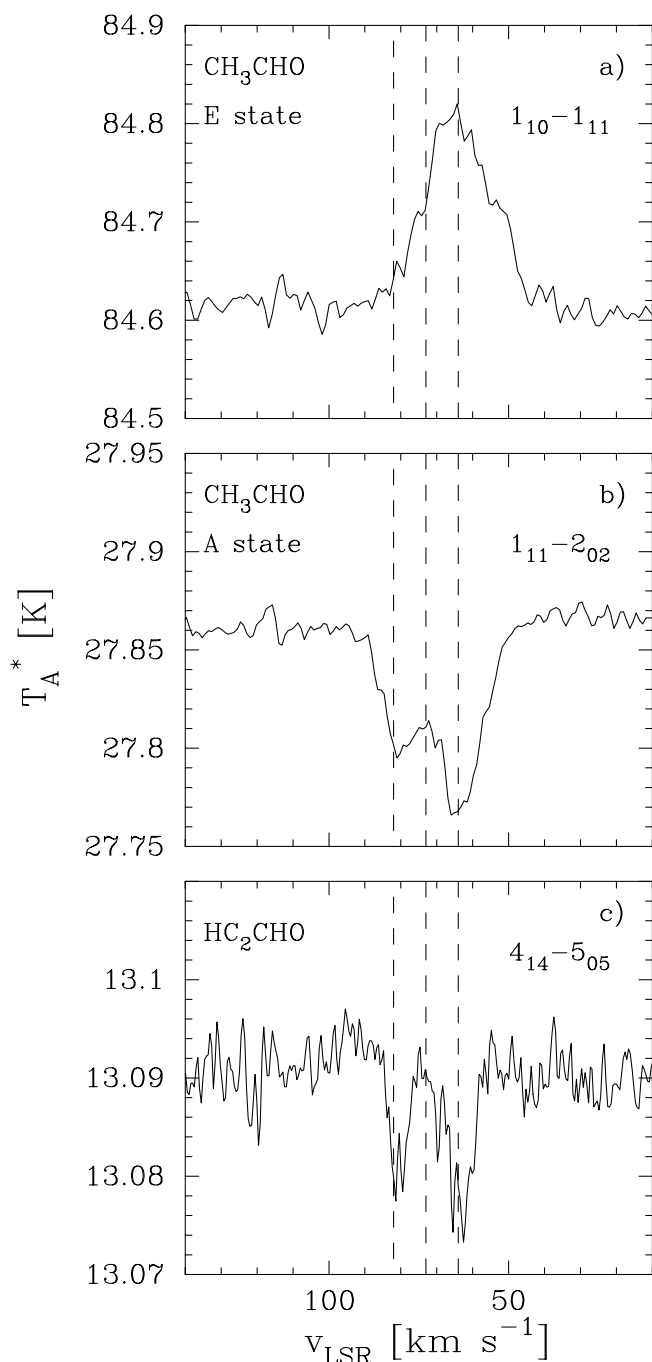


FIG. 3.—Acetaldehyde ( $\text{CH}_3\text{CHO}$ ) and propynal ( $\text{HC}_2\text{CHO}$ ) spectra toward Sgr B2(N-LMH). Channel spacing is 6.1 kHz for (a) and 24.4 kHz for (b) and (c). Fig. 1 caption applies.

because it does not conserve electronic spin, since atomic oxygen lies in a triplet state (E. Herbst 2005, private communication). If a barrier does exist, it may be that the reaction is powered by shocks for which the Sgr B2 region is well known (Chengalur & Kanekar 2003 and references therein). If shocks are essential for powering equation (2), it is interesting to note that Pineau des Forêts et al. (1987) argued that only the cyclic form  $c\text{-C}_3\text{H}_2$  would be produced from shocks, and Chernicharo et al. (1999) did not detect  $l\text{-C}_3\text{H}_2$  toward Sgr B2. On the other hand, Herbst suggests that the reaction

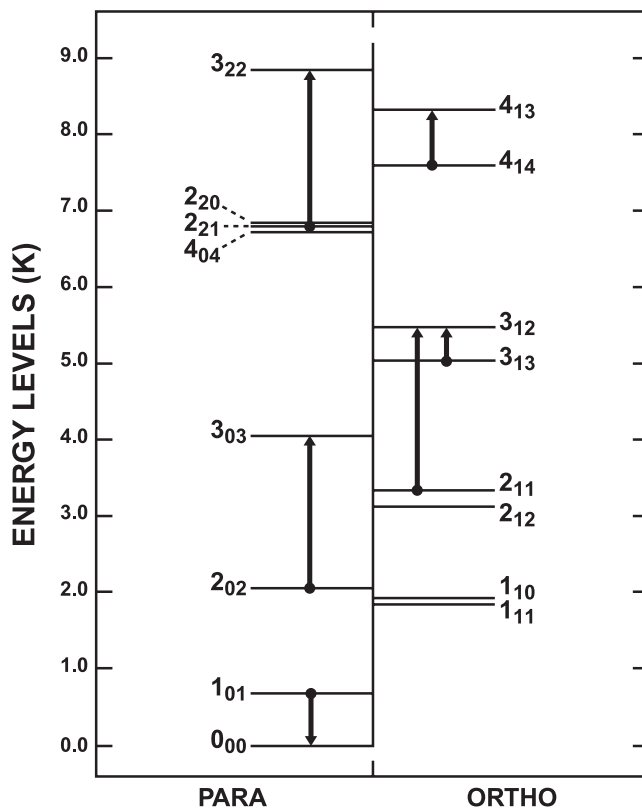
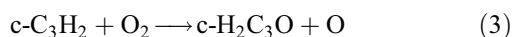
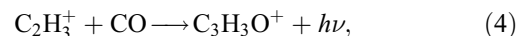


FIG. 4.—Energy level diagram for para- and orthocyclopropenone ( $c\text{-H}_2\text{C}_3\text{O}$ ). These are all the  $c\text{-H}_2\text{C}_3\text{O}$  transitions detected in this work and represent the lowest energy levels for both forms of the molecule.

may be important, since both molecular and atomic oxygen have triplet ground states (i.e., electronic spin is conserved), and the reaction is expected to have a small barrier if exothermic. If  $c\text{-C}_3\text{H}_2$  is not the parent molecule of  $c\text{-H}_2\text{C}_3\text{O}$  (as seems unlikely), an ion-molecule reaction (Adams et al. 1989),



may result in isomers of propynal (e.g.,  $l\text{-H}_2\text{C}_3\text{O}$  and  $c\text{-H}_2\text{C}_3\text{O}$ ) when the product ion  $\text{C}_3\text{H}_3\text{O}^+$  recombines with an electron. However, an investigation of the  $\text{C}_3\text{H}_3\text{O}^+$  structure that results from equation (4) would need to be done to determine if a cyclic product ion is formed that could result in  $c\text{-H}_2\text{C}_3\text{O}$  (E. Herbst 2005, private communication).

As mentioned previously, molecules of  $c\text{-H}_2\text{C}_3\text{O}$  reside in an extended cold halo region toward Sgr B2(N-LMH) and  $c\text{-H}_2\text{C}_3\text{O}$  energy level populations appear to be controlled by the cosmic background radiation field. Thus, we were unable to detect low-frequency transitions between high-energy levels (see Table 2) and, more importantly, Dickens et al. (2001) were unable to detect high-frequency transitions between levels with energies  $>10$  K toward the same source. We believe that the halo region containing both  $c\text{-C}_3\text{H}_2$  and  $c\text{-H}_2\text{C}_3\text{O}$  is probably a few degrees colder than classical cold dust clouds that have typical state temperatures of  $\sim 10$  K. Moreover, the abundance of both species must be very large indeed for equation (2) to produce easily detectable quantities of  $c\text{-H}_2\text{C}_3\text{O}$  in the gas phase. Since abundances are more reliably determined for a molecule seen in emission rather than absorption, we estimate the beam-averaged column density of  $c\text{-H}_2\text{C}_3\text{O}$  based on the  $J = 1\text{-}0$  transition centered at an LSR velocity of  $+73 \text{ km s}^{-1}$ . While this

c-H<sub>2</sub>C<sub>3</sub>O emission line has a S/N  $\sim 3$  from a Gaussian fit (see Table 2), the emission relative to the adjacent noise is clearly  $>5$  and compares favorably to the  $J = 1-0$  of propanal (Hollis et al. 2004b), which is also seen in emission centered at  $+73 \text{ km s}^{-1}$ . Thus, for c-H<sub>2</sub>C<sub>3</sub>O, we obtain  $\sim 1 \times 10^{13} \text{ cm}^{-2}$ , which may be a lower limit due to the potential for competition between emission and absorption in a star-forming region as complex as the one toward Sgr B2(N-LMH). For a molecular hydrogen column density of  $1.6 \times 10^{23} \text{ cm}^{-2}$  (derived from Martin et al. 2004 data), the c-H<sub>2</sub>C<sub>3</sub>O fractional abundance,  $X(\text{c-H}_2\text{C}_3\text{O})$ , is  $\sim 6 \times 10^{-11}$ .

Next we consider our difficulty in detecting glyceraldehyde. The interstellar molecule discoveries of formaldehyde (Snyder et al. 1969) and glycolaldehyde (Hollis et al. 2000)—a molecule that can be constructed from the constituent atoms of two formaldehyde molecules—suggest that formaldehyde polymerization may occur in space. One potentially efficient polymerization route has been shown by Flanagan et al. (1992) in a laboratory study in which condensation of atomic carbon with water at 77 K generated a mixture of aldehyde sugars, including both two-carbon glycolaldehyde and three-carbon glyceraldehyde. The formation mechanism depends on the existence of trans hydroxy methylene (t-HCOH), an isomer of formaldehyde, that is highly reactive because of a divalent carbon and, as such, is an intermediate reactant that combines with formaldehyde itself to form glycolaldehyde. In turn, t-HCOH could similarly combine with glycolaldehyde to form glyceraldehyde. Since we did not detect glyceraldehyde (see Table 2 limits) at L, S, and

X bands and previously at K band (Hollis et al. 2004b), this suggests a less efficient formation route may produce it (e.g., two successive oxygen additions to propanal on interstellar grains) if, in fact, interstellar glyceraldehyde exists.

In summary, the three-carbon keto ring c-H<sub>2</sub>C<sub>3</sub>O has been detected largely in absorption with the GBT in the star-forming region toward Sgr B2(N-LMH). Only transitions among the lowest energy levels were found, indicating that the energy level populations are controlled by the cosmic background radiation field. Since the molecule state temperature is low, this fact suggests that c-H<sub>2</sub>C<sub>3</sub>O resides in a star-forming core halo region that has a widespread arcminute spatial scale. Toward the same source, we also observed the previously reported, spatially ubiquitous, three-carbon ring c-C<sub>3</sub>H<sub>2</sub>, which has a divalent carbon that makes it highly reactive in the laboratory. The presence of both c-C<sub>3</sub>H<sub>2</sub> and c-H<sub>2</sub>C<sub>3</sub>O toward Sgr B2(N-LMH) suggests that gas-phase oxygen addition may account for the synthesis of c-H<sub>2</sub>C<sub>3</sub>O from c-C<sub>3</sub>H<sub>2</sub>. We also searched for but did not detect the three-carbon sugar glyceraldehyde.

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