GREEN BANK TELESCOPE OBSERVATIONS OF INTERSTELLAR GLYCOLALDEHYDE: LOW TEMPERATURE SUGAR

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ABSTRACT

Interstellar glycolaldehyde (CH_2OHCHO) has been detected with the 100-m Green Bank Telescope (GBT) toward the star-forming region Sagittarius B2(N) by means of the 1_{10}-1_{01}, 2_{11}-2_{02}, 3_{12}-3_{03}, and 4_{13}-4_{04} rotational transitions at 13.48, 15.18, 17.98, and 22.14 GHz, respectively. An analysis of these four high signal-to-noise rotational transitions yields a glycolaldehyde state temperature of $\sim$8 K. Previously reported emission line detections of glycolaldehyde with the NRAO 12-m telescope at mm-wavelengths (71 GHz to 103 GHz) are characterized by a state temperature of $\sim$50 K. By comparison the GBT detections are surprisingly strong and seen in emission at 13.48 GHz, emission and absorption at 15.18 GHz, and absorption at 17.98 GHz and 22.14 GHz. We attribute the strong absorption observed by the GBT at the higher frequencies to the correspondingly smaller GBT beams coupling better to the continuum source(s) in Sagittarius B2(N). A possible model for the two-temperature regions of glycolaldehyde is discussed.

Subject headings: ISM: abundances - ISM: clouds - ISM: individual (Sagittarius B2(N-LMH)) - ISM: molecules - radio lines: ISM

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1. INTRODUCTION

Interstellar glycolaldehyde (CH_2OHCHO), the simplest possible aldehyde sugar, remains the only sugar yet detected in space. The initial report of interstellar glycolaldehyde was based on the emission spectra of six rotational transitions in the mm-wave range observed with the NRAO[5] 12-m telescope (Hollis, Lovas, & Jewell 2000) while pointed at the hot molecular core SgrB2(N-LMH). Since our original spectral detections contained no spatial mapping information, we attempted to image the emission from the strongest transition (8_{08}-7_{17}) at 82.4 GHz with the Berkeley-Illinois-Maryland Association (BIMA) Array. We expected to find the spatial distribution of glycolaldehyde to be largely confined within the $\sim 5''$ diameter of the hot molecular core known as the Large Molecule Heimat (LMH) that contains other large molecules. In particular, we anticipated that glycolaldehyde would have a similar distribution to its isomer methyl formate (CH_3OCHO), but the BIMA observations indicated that the spatial scale of glycolaldehyde must be $\geq 60''$ (Hollis et al. 2001). Subsequently, we also detected four transitions of ethylene glycol ($HOCH_2CH_2OH$), which is the reduced sugar alcohol of glycolaldehyde, with the NRAO 12 m telescope and estimated that a state temperature of ~ 50 K for both molecules was appropriate for the ambient cloud surrounding the LMH (Hollis et al. 2002). Recently, Crovisier et al. (2004) confirmed eleven ethylene glycol emission lines in the archival data of Comet Hale-Bopp but found no glycolaldehyde.

Attempting to extend our research on interstellar sugars, we conducted a search for the three-carbon sugar glyceraldehyde ($CH_2OHCHOHCHO$) with the 100-m Green Bank Telescope (GBT) toward SgrB2(N) and contemporaneously observed glycolaldehyde for comparison because it is likely the two-carbon precursor to glyceraldehyde. We opted for the K-band range where spectral line confusion for interstellar molecules is much less than at mm-wavelengths. We did not detect glyceraldehyde (Hollis et al. 2004), but the intensities of glycolaldehyde lines were surprisingly strong in both emission and absorption. We had expected that glycolaldehyde energy levels at K-band would not be well populated owing to an expected state temperature of ~ 50 K based on mm-wavelength results. This finding motivated us to determine the excitation and abundance of glycolaldehyde toward SgrB2(N) by observing a number of low energy level transitions with the GBT from Ku- to K-band.

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2. OBSERVATIONS AND RESULTS

Observations of glycolaldehyde were made in 2004 Feb 29 - Mar 29 with the NRAO 100-m Robert C. Byrd GBT. Table 1 lists the rotational transitions sought. The transition quantum numbers, the calculated rest frequencies, transition line strengths (S), the lower level energies (E_l), half-power beamwidths (θ_B), and beam efficiencies (η_B) are listed in the first six columns. The Ku-band receiver and K-band receiver set used have frequency ranges covering 12 GHz - 15.4 GHz and 18 GHz - 22.5 GHz, respectively. The GBT spectrometer was configured in its 8 intermediate frequency (IF), 200 MHz, 3-level mode which provides observing four 200 MHz frequency bands at a time in two polarizations through the use of offset oscillators in the IF. This mode affords 24.4 kHz channel separation. Antenna temperatures are on the T_A^* scale (Ulich & Haas 1976) with estimated 20% uncertainties. The SgrB2(N-LMH) J2000 pointing position employed was $\alpha= 17^h47^m19^s.8$, $\delta = -28°22'17''$ and an LSR source velocity of +64 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. A single scan consisted of two minutes in the OFF source position followed by two minutes in the ON source position. Automatically updated dynamic pointing and focusing corrections were employed based on realtime temperature measurements of the structure input to a thermal model of the GBT; zero points were adjusted typically every two hours or less using the calibrators 1626-298 and/or 1733-130. The two polarization outputs from the spectrometer were averaged in the final data reduction process to improve the signal-to-noise ratio.

Table 1 summarizes our glycolaldehyde detection results toward SgrB2(N) in terms of gaussian fitting to the intensities, widths, and LSR velocities that appear in columns (7), (8), and (9), respectively. For absorption features, the average source continuum level appears in column (10). The continuum level of an individual scan was observed to vary with a standard deviation of ~0.4 K with respect to the average due to fluctuations in atmospheric and receiver system stability. Absorption features have line to continuum ratios, formed from cols. (7) and (10), that indicate apparent optical depths are much less than 1. For emission features, column (10) contains the 2.7 K cosmic background temperature which is employed in equation (1) below. Spectra corresponding to Table 1 data are shown in Figure 1.

It is now well established that aldehydes are widespread on the order of arcminutes toward SgrB2(N) (see Hollis et al. 2001; Chengalur & Kanekar 2003; and Hollis et al. 2004). Thus, for our analysis we assume that the spatial distribution of glycolaldehyde is homogeneous, extended, and larger than all half-power beamwidths listed in Table 1. Note that the 1_{10}-1_{01}, 2_{11}-2_{02}, 3_{12}-3_{03}, and 4_{13}-4_{04} transitions correspond to beamwidths of 53", 47",

40" and 33", respectively. As compared to emission, the effects of absorption strengthen as beamwidths decrease (see Figure 1 and Table 1). We interpret this as evidence that the smaller beam is coupling better to the SgrB2(N) continuum source(s), which thereby minimizes the response to the more extended gas in emission. To obtain an estimate of the temperature of the glycolaldehyde observed by the GBT we make three key assumptions: (1) the distribution function over all molecular energy levels can be characterized by a single state temperature (T_S), (2) the continuum source(s) dominate the $\theta_B \sim 33''$ beam of the $4_{13}\text{-}4_{04}$ transition seen entirely in absorption, and (3) the $\theta_B \sim 53''$ beam of the $1_{10}\text{-}1_{01}$ transition seen entirely in emission is dominated by the gas that is much more extended than the SgrB2(N) continuum source(s).

We computed glycolaldehyde total column densities (N_T) from the following expressions for emission (e.g. Hollis et al. 2000) and absorption (e.g. Lucas & Liszt 1993) which employ cgs units (cf. Table 1 parameters):

Emission:

$$N_T = \frac{Q e^{E_u/kT_S}}{(\frac{8\pi^3}{3k})\nu S\mu^2} \frac{\left\{ \frac{1}{2}\sqrt{\frac{\pi}{\ln 2}}\frac{\Delta T_A^* \Delta V}{\eta_B} \right\}}{\left\{ 1 - \frac{(e^{h\nu/kT_S}-1)}{(e^{h\nu/kT_{bg}}-1)} \right\}} \qquad (1)$$

Absorption:

$$N_T = \frac{Q \left\{ \frac{1}{2}\sqrt{\frac{\pi}{\ln 2}}\frac{\Delta T_A^* \Delta V}{\eta_B} \right\}}{(\frac{8\pi^3}{3h}) \left\{ T_S - \frac{T_c}{\eta_B} \right\} S\mu^2 \left\{ e^{-E_l/kT_S} - e^{-E_u/kT_S} \right\}} \qquad (2)$$

In both equations, the lines are assumed to be gaussian; η_B is the telescope beam efficiency (col. [6]); ΔT_A^* is the fitted peak line temperature (col. [7]); ΔV is the fitted FWHM line width (col. [8]); $Q = 6.9T_S^{1.5}$ is the partition function (see Gordy & Cook 1984, p. 58, for a more detailed formulation); S is the transition line strength (col. [3]); the electric dipole moment is $\mu = 2.33$ D (Marstokk & Møllendal 1973); and E_u is the upper rotational energy level which can be derived from cols. (2) and (4) in Table 1. In equation (1), ν is the transition frequency (col. [2]) and $T_{bg} \sim 2.7$ K is the cosmic background temperature (col. [10]). In equation (2), T_c is the measured source continuum temperature (col. [10]), and E_l is the lower rotational energy level (col. [4]).

We found that $T_S \sim 8$ K yields the same $N_T \sim 3.5 \times 10^{14}$ cm^{-2} for both the single emission component of the $1_{10}\text{-}1_{01}$ transition and sum of the two absorption components of the $4_{13}\text{-}4_{04}$ transition under the assumption that the beam filling factor for each of these

transitions is unity. The total column density of each glycolaldehyde transition component appears in col. (11) of Table 1. The total column density for each transition would be the sum of the individual components for the transition and should represent the cloud-averaged column density. Column density values for the sum of the components of the 2_{11}-2_{02} and 3_{12}-3_{03} transitions are 1.5×10^{14} cm^{-2} and 2.8×10^{14} cm^{-2}, respectively. These values are slightly lower than those obtained for the 1_{10}-1_{01} and 4_{13}-4_{04} transitions, owing likely to beam dilution of the continuum source(s) associated with absorption components in the 2_{11}-2_{02} and 3_{12}-3_{03} transitions.

3. DISCUSSION

The strongest line of glycolaldehyde previously reported was the 8_{08}-7_{17} transition at 82.5 GHz with a peak intensity of $T_R^* = 45(6)$ mK as observed by the NRAO 12-m telescope. Moreover, a rotational diagram of all the mm-wave transitions detected by Hollis et al. (2000) indicate $T_S \sim 50$ K (Hollis et al. 2002). Using the 8_{08}-7_{17} transition under the assumption of local thermodynamic equilibrium, the predicted peak emission intensity of the 1_{10}-1_{01} transition at 13.48 GHz as observed by the GBT would be $T_R^* = 2.5$ mK for a T_S value of 50 K. As shown in Table 1, the GBT obtained a peak emission intensity $T_A^* = 30(1)$ mK for the 1_{10}-1_{01} which exceeds by an order of magnitude the mm-wave intensity prediction, given that T_R^* temperature values are $\geq$ to T_A^* temperature values (see equation [15] of Kutner & Ulich 1981) and that glycolaldehyde is so extended (Hollis et al. 2001) that beam filling factor modifications are of no consequence. Thus, there is no doubt that the GBT glycolaldehyde emission and absorption observations are sampling a much colder ($T_S \sim 8$ K as shown in §2) gas than the glycolaldehyde emission environment ($T_S \sim 50$ K) sampled by the NRAO 12-m telescope. This suggests that the ambient molecular medium toward SgrB2(N) has a significant temperature gradient on a large spatial scale. Such conditions are consistent with the presence of large-scale shocks toward SgrB2 (see Chengalur & Kanekar 2003 and references therein) which probably account for the widespread distribution of a number of aldehydes in that region as most notably demonstrated by the Giant Metrewave Radio Telescope (GMRT) spatial image of the 1_{10}-1_{11} transition of acetaldehyde (CH$_3$CHO) in emission (see Fig. 1 of Chengalur & Kanekar 2003).

The LSR velocities and linewidths of glycolaldehyde emission lines at mm-wavelengths and K-band also suggest different environments. For example, the mm-wave observations, whose transitions are all observed in emission, are characterized by an LSR velocity of $\sim +71$ km s^{-1} (Hollis et al. 2002) and a linewidth ≥ 25 km s^{-1} (see Hollis et al. 2000). In contrast, the 1_{10}-1_{01}, which is the only Table 1 transition seen solely in emission, indicates an LSR

velocity of $\sim +75$ km s^{-1} and linewidth of ~ 22 km s^{-1}. These linewidth, LSR velocity, and aforementioned temperature differences suggest that the gas sampled at mm-wavelengths may be shock-heated or located in the vicinity of a continuum source and is expanding into the more extended cold gas that produced K-band emission and absorption. The column densities of the two glycolaldehyde regions are comparable: the mm-wave transitions at $T_S \sim 50$ K yield $N_T \sim 2.7(5) \times 10^{14}$ cm^{-2} (cf. Hollis et al. 2000) and the GBT transitions at $T_S \sim 8$ K yield $N_T \sim 3.5(3) \times 10^{14}$ cm^{-2} (see Table 1).

The spatial distributions of the low energy transition of acetaldehyde imaged by the GMRT (see Fig. 1 of Chengalur & Kanekar 2003) and the low energy transitions of gly-colaldehyde observed by the GBT are probably very similar since Table 1 glycolaldehyde absorption components have the same LSR velocity characteristics (extrema at $+64$ km s^{-1} and $+82$ km s^{-1}) as the emission components of acetaldehyde (see Fig. 2 of Chengalur & Kanekar 2003). Moreover, GMRT velocity channel images of acetaldehyde at these LSR velocities show that the two clouds responsible for glycolaldehyde absorption lie along the same line of sight (J. N. Chengalur 2004, private communication). Recently, Hollis et al. (2003) used the Very Large Array to obtain an ethyl cyanide (CH$_3$CH$_2$CN) image of source "h" which lies $\sim 5''$ north of the SgrB2(N-LMH); source "h" is compact ($1.''5 \times 1.''4$) in ethyl cyanide emission and has an LSR velocity centered near $+72$ km s^{-1} which is charateristic of a few large molecules observed at mm-wavelengths such as glycolaldehyde and ethylene glycol (Hollis, Lovas, & Jewell 2000; Hollis et al. 2002) and vinyl alcohol (CH$_2$CHOH; Turner & Apponi 2001).

A possible model for the the two-temperature regions of glycolaldehyde is that compact source "h", which contains a weak concentration of glycolaldehyde (see Hollis et al. 2001), is surrounded by a warm ($T_S \sim 50$ K) extended glycolaldehyde envelope which is in turn surrounded by a cold ($T_S \sim 8$ K) glycolaldehyde halo. The warm glycolaldehyde envelope is characterized by a narrow range of LSR velocities from $+71$ km s^{-1} to $+75$ km s^{-1} (see Table 1 and Hollis et al. 2002) and may be shock-heated and/or located in proximity to a continuum source. The cold glycolaldehyde halo region contains two clouds which are characterized by LSR velocities of $+64$ km s^{-1} and $+82$ km s^{-1}. These two clouds must lie in front of a distant continuum source to account for glycolaldehyde absorption. Since as noted previously the $+64$ km s^{-1} and $+82$ km s^{-1} gas appears to lie along the same line of sight, the two clouds may well represent opposite sides of the halo because the warm glycolaldehyde envelope located within the halo has an intermediate LSR velocity of approximately $\sim +71$ km s^{-1} (Hollis et al. 2002) similar to the $\sim +72$ km s^{-1} of compact source "h" (Hollis et al. 2003). Interferometry will be required to determine the details of such a model.

In summary, we have detected unexpectedly strong lines of interstellar glycolaldehyde

toward the star-forming region SgrB2(N) by using the GBT to observe four low-energy rotational transitions at low frequencies (13 GHz to 22 GHz). The lowest frequency transition, which corresponds to the largest telescope beam, is seen entirely in emission while the transition observed with the largest frequency is seen entirely in absorption which we attribute to better coupling between the smaller telescope beam and the continuum source(s) present. Our analysis of these transitions indicates a glycolaldehyde state temperature of $\sim$8 K. We compare these results with previous results in the mm-wave region and conclude that the molecular source "h", which is in close proximity to SgrB2(N-LMH), contains a weak concentration of glycolaldehyde (Hollis et al. 2001), and is surrounded by a warm T_S $\sim$50 K extended glycolaldehyde envelope (indicated by mm-wave observations) which is in turn surrounded by a cold T_S $\sim$8 K glycolaldehyde halo.

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Table 1. Summary of Glycolaldehyde Observations Toward SgrB2(N)

Transition J'_{K-K+}-J''_{K-K+} (1)	Frequency (MHz) (2)[a]	S (3)	E_l (cm^{-1}) (4)	θ_B (") (5)	η_B (6)	ΔT^*_A (mK) (7)[b]	ΔV (km s^{-1}) (8)[b]	V_{LSR} (km s^{-1}) (9)[b]	T_{bg} or T_c (K) (10)[c]	$N_T(\times 10^{-14})$ (cm^{-2}) (11)[d]
1_{10}-1_{01}	13476.990(13)	1.5000	0.383	53	0.825	30.3(10)	21.9(9)	75.4(4)	2.7	3.42(25)
2_{11}-2_{02}	15176.457(14)	2.3430	1.146	47	0.805	15.7(13)	9.9(14)	74.7(5)	2.7	0.54(12)
						-41.5(16)	8.0(4)	62.3(2)	11.55	0.96(9)
3_{12}-3_{03}	17980.834(19)	2.9594	2.277	40	0.786	-33.6(40)	8.5(12)	80.4(5)	12.75	0.54(13)
						-105.5(34)	11.1(5)	63.1(2)	12.75	2.21(17)
4_{13}-4_{04}	22142.668(28)	3.3001	3.765	33	0.750	-42.5(13)	8.6(3)	81.1(1)	10.45	0.97(6)
						-80.3(12)	11.8(2)	63.5(1)	10.45	2.50(8)

[a]Uncertainties in parentheses refer to the least significant digit and are 2 σ values (Taylor & Kuyatt 1994).

[b]Gaussian fit values with 1 σ uncertainties.

[c]Line emission assumed to emanate largely from gas seen against the ~2.7 K cosmic background (see equation[1]).

[d]T_S=8 K for all calculations and uncertainties are 1 σ.

Fig. 1.— Glycolaldehyde (CH_2OHCHO) spectra toward SgrB2(N-LMH) at 24.4 kHz channel spacing. Transition quantum numbers are shown in each panel. Each spectrum was processed with a median filter to remove instrumental slopes in the bandpass (G. Langston 2004, in preparation). The abscissa is the radial velocity with respect to the LSR calculated for the rest frequency of the transition shown (see Table 1) at an assumed source velocity of +64 km s^{-1}. Dashed lines show LSR velocities at 64, 73 and 82 km s^{-1}. The continuum level of the source is shown as a component of the temperature scale.
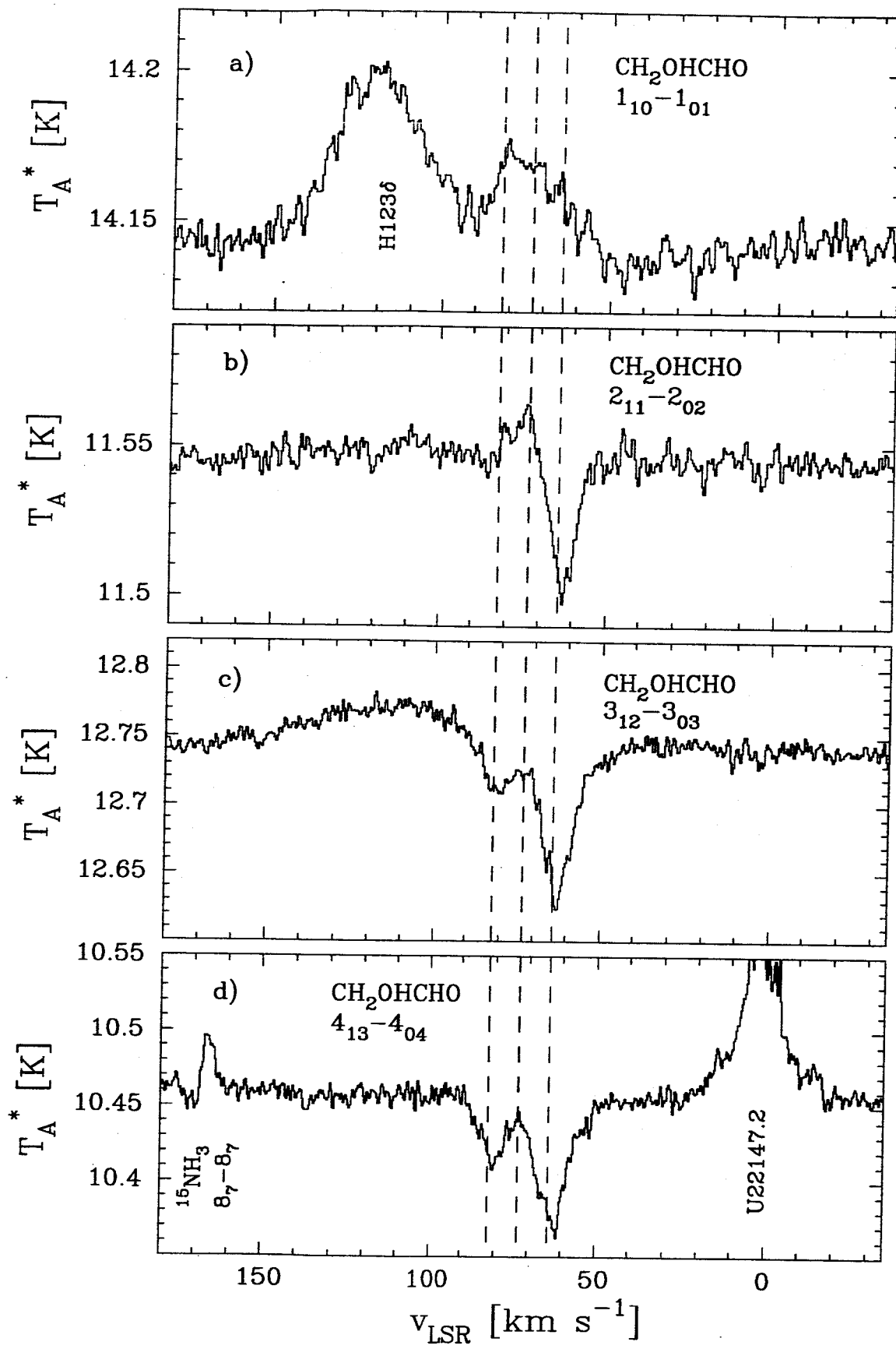
Figure 1.