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H_2CS IN OUTFLOWS OF THE MASSIVE STAR-FORMING CORE DR21(OH)

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ABSTRACT

For the first time, using the Submillimeter Array, H_2CS emission was observed to show a typical bipolar outflow morphology toward DR21(OH). The emission consisted of a strong concentration toward a hot molecular core (MM1a) and a symmetrically extended feature aligned roughly in the north–south direction. H_2CS is one of the hot core species, and its extended emission is expected to result from the interaction between the outflow of MM1a and the dense ambient gas. We derive H_2CS column densities of $\sim 3 \times 10^{15}$ cm^{-2} and $\sim 1 \times 10^{15}$ cm^{-2} toward MM1a and the centers of the extended emission, respectively. Its fractional abundance, $f(H_2CS) \sim 10^{-9}$ relative to the total H_2 abundance, is comparable to those in other star-forming regions, suggesting that H_2CS may be present in a region closer to the center than previously thought. Our results suggest that the observed H_2CS emission arises via direct evaporation or sputtering of the solid H_2CS on the grain surface, and H_2CS may be one of the major sulfur-bearing species residing in the ice grain mantles in a solid form, at least in the case of DR21(OH).

Key words: ISM: abundances – ISM: clouds – ISM: individual objects (DR21(OH)) – ISM: molecules – stars: formation

Online-only material: color figures

1. INTRODUCTION

Interstellar sulfur has been observed to be largely depleted in the gas phase of cold clouds, but its particular form on dust grain mantles is a long-standing and unresolved issue (e.g., Caselli et al. 1994; Wakelam et al. 2004). Solid state H_2S has been previously suggested to be a main reservoir of sulfur, but it is not found in grain mantles ($\lesssim 10^{-7}$ relative to H_2; Gibb et al. 2000; van der Tak et al. 2003). OCS is the only sulfur-bearing species clearly detected on the grain surface, but it also has very low fractional abundances, $\sim 10^{-7}$ relative to hydrogen nuclei (Palumbo et al. 1997; Wakelam et al. 2004). Here, we suggest that thioformaldehyde (H_2CS) may be an important sulfur-bearing species residing in the grain mantles, at least within the massive star-forming region, DR21(OH). As a slightly asymmetric rotor, H_2CS has been observed toward several interstellar sources (e.g., Minh et al. 1991), including DR21(OH) (Wootten & Mangum 2009); however, it has been studied much less than its oxygen-substituted analog, formaldehyde (H_2CO). In chemical models for hot core environments, including the cores in DR21(OH), H_2CS is considered to form in the reaction initiated between atomic sulfur and methyl radical (CH_3), and has a timescale of about 10^5 years (Charnley 1997). Alternatively, Palumbo et al. (1997) suggested that H_2CS is a probable grain mantle species with an abundance comparable to that of OCS. Bachiller & Pérez Gutiérrez (1997) found an abundance increase (by a factor of 50–100) of sulfur-bearing species, including H_2CS, in the bipolar outflow of the class 0 protostar L1157, and suggested a shock enhancement. In the massive star-forming region Cep A East, Codella et al. (2006) also reported an abundance enhancement of H_2CS. It coexists with OCS, HDO, and CH_3OH in the turbulent interface region between the molecular outflow and the ambient gas, and may be attributed to the particular condition at the interface.

At a distance about 2–3 kpc (Schneider et al. 2006; Motte et al. 2007), DR21(OH) is one of the prominent massive star-forming cores in the Cygnus X North region. It is associated with masers of OH (Norris et al. 1982; Argon et al. 2000), H_2O (Genzel & Downes 1977), and CH_3OH (Batrla & Menten 1988; Plambeck & Menten 1990; Kogan & Slysh 1998; Kurtz et al. 2004; Araya et al. 2009; Fish et al. 2011), indicative of ongoing star formation activities. This source consists of several dense clumps (mass $\sim 10^3\ M_\odot$ and $n_{H_2} \sim 10^6$ cm^{-3}) separated by 30″–50″ (Mangum et al. 1991). Woody et al. (1989) identified two bright compact cores at 1.4 mm, MM1 and MM2 separated by about 8″ from each other in the northeast–southwest direction, with MM1 showing a much stronger continuum emission than MM2 (Woody et al. 1989; Liechti & Walmsley 1997; Lai et al. 2003). Subsequent interferometric observations have further resolved MM1 into two subcores, MM1a and MM1b (∼SMA7 and SMA5/6, respectively; L. A. Zapata et al. 2011, in preparation), possibly constituting a protobinary system (Figure 1; Y. C. Minh et al. 2011, in preparation).

In this Letter, we report observational results on the H_2CS lines observed at ∼340 GHz using the Submillimeter Array (SMA). Our observations are summarized in Section 2. Results and discussions are presented in Section 3 for the emission features and in Section 4 for chemical implications. The conclusions are summarized in Section 5.

2. OBSERVATION

Observations were performed using the Submillimeter Array[4] (SMA; Ho et al. 2004) on 2006 August 21 in the 347 GHz band. Six antennas (half-power beam width of the primary beam ∼34″) were used in the compact configuration, and projected baselines ranged from about 9 m to 70 m (11–80 kλ). The phase center of the observation was $(\alpha, \delta)_{J2000}$ = ($20^h38^m36\overset{s}{.}4$, $+42°37'28\overset{''}{.}0$). The spectral resolution was

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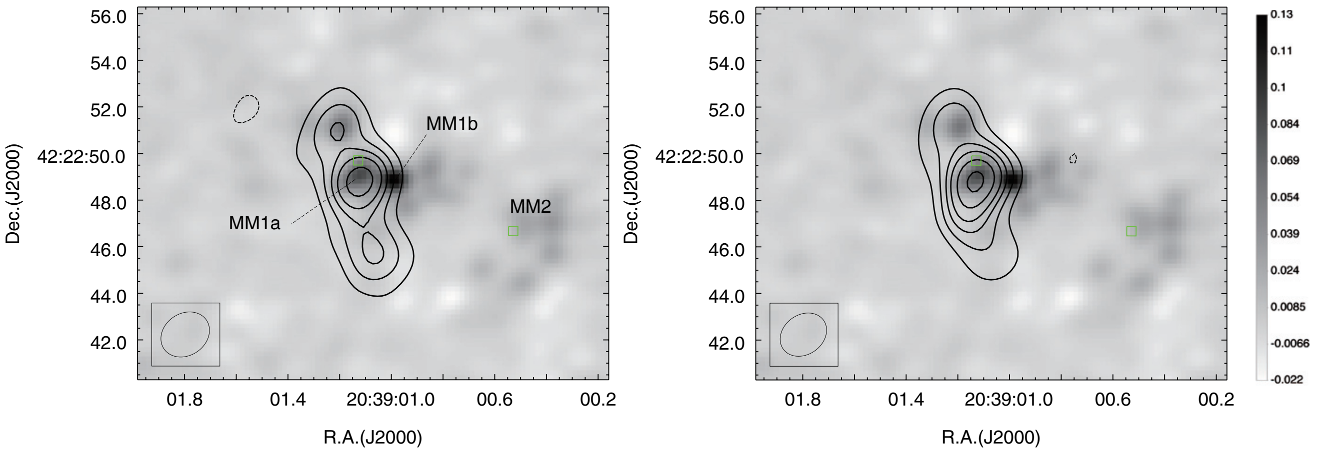

Figure 1. Integrated intensity maps of the observed H_2CS lines, overlaid on the 220 GHz continuum map having a spatial resolution of ∼1″ (gray scales are inserted in units of mJy beam^{-1}; adapted from Y. C. Minh et al. 2011, in preparation). The left panel is the $10_{1,10}$–$9_{1,9}$ transition and the right panel is the $10_{1,9}$–$9_{1,8}$ transition. Contour levels are −2, 2, 4, 6, 8, 11, and 15 Jy beam^{-1} km s^{-1} for both panels. The green boxes are millimeter continuum sources from Mangum et al. (1991). The ellipses at the bottom left are the synthesized beam sizes at the observed H_2CS frequencies.

(A color version of this figure is available in the online journal.)

0.81 MHz (0.70 km s^{-1} at 347 GHz). The data inspection, bandpass, and flux calibration were conducted with the IDL superset MIR adapted for the SMA (Scoville et al. 1993). Temporal gains were solved with respect to MWC349. The passband was calibrated using Uranus and Callisto, and the flux was calibrated with Uranus. The synthesized beams are 2.″2 × 1.″8 (P.A. = −34°) and 2.″1 × 1.″7 (P.A. = −36°) with uniform weighting for the $10_{1,10}$–$9_{1,9}$ and $10_{1,9}$–$9_{1,8}$ lines of H_2CS, respectively. Imaging and analysis were conducted with the MIRIAD package (Sault et al. 1995).

Figure 1 shows the integrated intensity maps of the observed H_2CS transitions overlaid on the 220 GHz continuum map, which was made at about 1″ spatial resolution with SMA (adapted from Y. C. Minh et al. 2011, in preparation). The star-forming core MM1 appears to consist of several subcores (see also L. A. Zapata et al. 2011, in preparation), and we labeled the two brightest subcores MM1a and MM1b (Figure 1). These two cores share similar physical conditions including mass (∼0.5 $M_\odot$), size (∼1″), density (n_{H_2} = 2–4 × 10^7 cm^{-3}), and temperature (∼200 K) (Y. C. Minh et al. 2011, in preparation).

3. THE H_2CS EMISSION IN OUTFLOWS

As shown in Figure 1, H_2CS emissions were observed to be strongly concentrated toward MM1a, one of the brightest subcores of MM1. In particular, an extended emission showing typical bipolar outflow morphology was found roughly aligned in the north–south direction from MM1a in which blueshifted and redshifted components were separated spatially and kinematically (Figure 2). The integrated intensity peaks for the blueshifted and redshifted components are referred to as positions N and S, respectively (see Table 1). Another continuum peak was found toward the N position, which may have resulted from either a separate clump in the line of sight or heated dust from the interaction with outflows from MM1a. We did not find other molecular line emissions from hot core species toward the N position; thus, we do not consider another component to be the source of H_2CS emissions at this position.

A position–velocity diagram along a presumed outflow axis and sample spectra taken at selected positions are shown in Figure 3. The fairly symmetric emissions show a flow velocity of about 0.8 km s^{-1} arcsec^{-1} that increases with

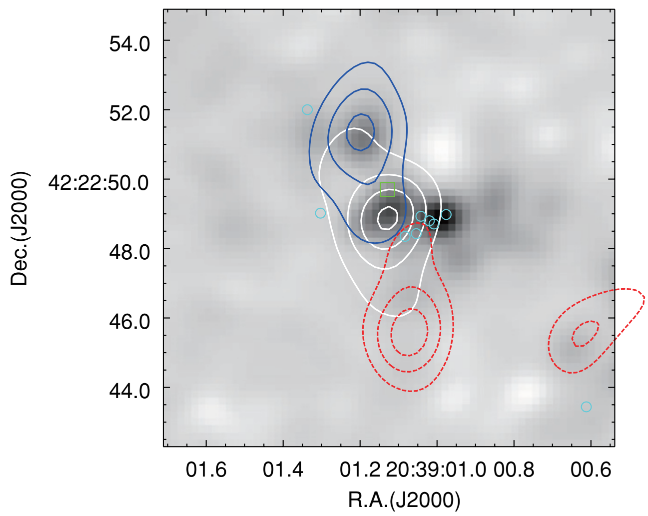

Figure 2. Integrated intensity maps for the separate velocity ranges: (blue) v = −10.0 to −5.55 km s^{-1}, (white) −5.5 to −2.0 km s^{-1}, and (red, dashed) −2.0 to 3.0 km s^{-1}. Contour levels of the blueshifted and redshifted components increase by 1 Jy beam^{-1} km s^{-1} from 1.5 Jy beam^{-1} km s^{-1}. The white contours increase by 3 Jy beam^{-1} km s^{-1} from 3 Jy beam^{-1} km s^{-1}. The green box is the MM1 of Mangum et al. (1991), and circles are radio continuum sources identified by Araya et al. (2009).

(A color version of this figure is available in the online journal.)

position along the outflow axis and resembles the monotonically increasing maximum radial velocity in typical protostellar outflows (Arce et al. 2007). The observed morphology indicates that, first, H_2CS is one of the hot core species, as its emission is highly concentrated toward MM1a. MM1a is characterized by emissions of various hot core species and is probably in a very early phase of massive star formation (Kurtz et al. 2004). This hot core nature of MM1a will be described in a forthcoming paper (Y. C. Minh et al. 2011, in preparation). Second, the extended H_2CS emission, which has an apparent symmetric distribution centered at MM1a, may have resulted from the interaction between the outflow associated with MM1a and the ambient dense gas.

Although molecular outflows, often with bipolar morphology, are common in the early stages of star formation (e.g., Fukui

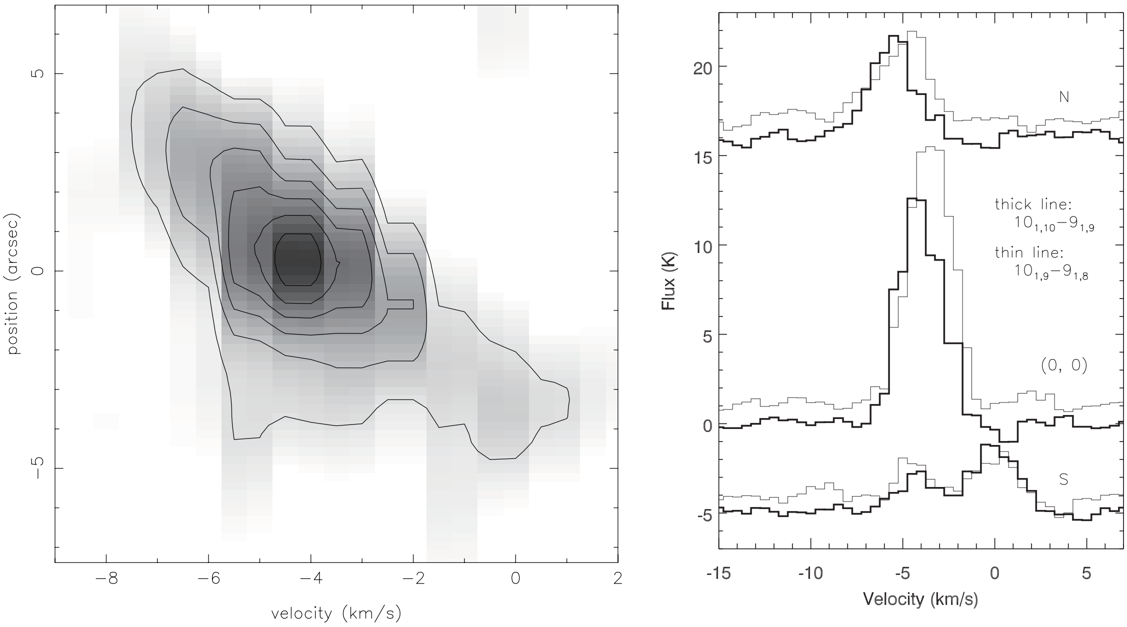

Figure 3. Left: position–velocity map of the H_2CS $10_{1,10}$–$9_{1,9}$ line along a position angle of 23° (counterclockwise from the top) toward the position, $(\alpha, \delta)_{J2000}$ = ($20^h39^m01\overset{s}{.}1$, 42°22′49″). Right: sample spectra taken along the p–v cut. Positions are included as the note to Table 1.

Table 1
Observed H_2CS Line Parameters

Transition	Frequency[a] (GHz)	Pos.[b]	Peak[c] (K)	v_{peak}[c] (km s^{-1})	Δv_{FWHM}[c] (km s^{-1})	Flux (K km s^{-1})	rms (K)
$10_{1,10}$–$9_{1,9}$	338.0832	(0, 0)	12.6	−4.1	2.8	36.1	0.26
		N	5.5	−5.6	2.9	16.6	
		S[d]	1.8/3.6	−4.4/ − 0.1	1.8/2.9	17.8	
$10_{1,9}$–$9_{1,8}$	348.5342	(0, 0)	15.2	−3.5	2.7	44.6	0.35
		N	4.5	−4.9	3.1	15.6	
		S[d]	2.1/2.3	−4.5/0.0	1.9/2.4	9.3	

Notes.
[a] From Lovas et al. (2009).
[b] The (0, 0) position is $(\alpha, \delta)_{J2000}$ = ($20^h39^m01\overset{s}{.}1$, 42°22′49″). The N and S positions are the peak emission position of the blueshifted and redshifted components in Figure 2, which are offsets (+0″.9, +2″.6) and (−0″.6, −3″.3), respectively, from the (0, 0) position.
[c] Gaussian fit values of the spectrum at the peak position.
[d] Fit with two Gaussians.

et al. 1989), the H_2CS emission has not yet been reported in a bipolar shape. If H_2CS exists as a solid at the grain surface, the effect of shocks in the outflow will enhance the H_2CS abundance in the ambient interacting region. This was observed in Cep A East (Codella et al. 2006), probably via sputtering of the species in the ice grain mantles. Some transitions of methanol (CH_3OH) and CS have also shown a similar outflow morphology toward MM1 (Y. C. Minh et al. 2011, in preparation). Methanol has been found to be abundant in the icy grain mantles, and its enhanced abundance in massive star-forming regions has been attributed without doubt to a direct release from icy grain mantles (e.g., van Dishoeck 2004). Bachiller et al. (1995) showed the first evidence for methanol evaporation from dust grains in outflows of L1157. This leads us to believe that methanol and H_2CS may share a similar enhancement mechanism. On the other hand, the enhanced CS may either be attributed to a similar mechanism as H_2CS, or to the destruction of CS-containing species (including H_2CS) in the gas phase, as a local phenomenon near star-forming cores.

By assuming optically thin emission and local thermodynamic equilibrium, we derived a beam-averaged column density of H_2CS as $(3.3 \pm 1.1) \times 10^{15}$ cm^{-2} toward MM1a, assuming a gas temperature range of 100–300 K. Meanwhile, a beam-averaged column density of $(1.4 \pm 0.4) \times 10^{15}$ cm^{-2} is obtained toward the N and S positions assuming a gas temperature range of 30–80 K for the outflows. These assumed gas temperature values are derived from observations of various molecular lines that will be described in a forthcoming paper (Y. C. Minh et al. 2011, in preparation). From the rotation diagrams of the observed methanol lines, for example, we derive $T_{rot} \sim 200$–260 K toward the MM1 cores and ∼40–60 K toward outflows. The fractional abundances of H_2CS relative to molecular hydrogen, $f(H_2CS)$, are about 4×10^{-9} and 2×10^{-9} for MM1a and the outflow region, respectively, after adopting the total H_2 column density of 8×10^{23} cm^{-2} estimated from the 220 GHz continuum emission (Y. C. Minh et al. 2011, in preparation). We derived similar H_2 column densities toward both regions from the observed continuum intensities and applied dust temperatures. At present we are unable to distinguish between H_2 in the shocked gas and in the ambient cloud in the same line of sight. Therefore, the $f(H_2CS)$ in the outflow of DR21(OH) must be *largely* underestimated. In the class 0 protostar L1157, Bachiller et al. (1995) found that the H_2CS abundance was enhanced by a factor of 60–80 in the outflow compared to the central core of the source. Our fractional abundances are comparable to those derived from several massive star-forming regions by van der Tak et al. (2003). Instead of forming H_2CS in the outer envelope at a later stage as suggested by van der Tak et al. (2003), we propose an alternative route to the production of gas-phase H_2CS in the shocked regions, via sputtering or direct evaporation of the solid H_2CS in the ice mantles.

4. CHEMICAL IMPLICATIONS

Although the two subcores, MM1a and MM1b, seem to share similar physical conditions as mentioned in Section 2, MM1b has very low ($\leqslant 1/10$) H_2CS abundance compared to MM1a, and is associated with many radio emission features that indicate shocked ionization in its immediate vicinity. We believe that MM1b may be at a slightly later stage of star formation than MM1a, which has resulted in the appreciable chemical variation between these two subcores. MM1b is about 50% brighter in the 220 GHz continuum than MM1a (Y. C. Minh et al. 2011, in preparation), and is also associated with OH masers and is probably a driving source for H_2O masers (Argon et al. 2000; Genzel & Downes 1977). On the other hand, various saturated species, which indicate the existence of hot cores, have preferentially peaked toward MM1a (Y. C. Minh et al. 2011, in preparation). The very low abundance of H_2CS in MM1b compared to that in MM1a may have resulted from the destruction of H_2CS in the gas phase of the later stage.

The H_2CS emission is observed to be largely concentrated at MM1a, with an extended morphology roughly along the north–south direction. There are two possible explanations for the H_2CS abundance in this source: one is H_2CS formation in the gas phase using sulfur (as either atomic or a simple S-bearing species) evaporated from dust grains, and another is the direct evaporation of H_2CS from grain mantles. Chemical models suggest that the formation of H_2CS through the first route will take on the order of 10^5 years after the release of the sulfur species from the grains (Charnley 1997; Langer et al. 2000); however, we believe that sources like MM1 of DR21(OH) do not have sufficient time to synthesize H_2CS in the gas phase in this way. Codella et al. (2006) suggest the formation of H_2CS in the turbulent interface between the ambient and the outflow, as a means of explaining the double-peaked emission features of H_2CS (together with OCS, CH_3OH, and HDO) observed toward Cep A East. They assumed very high abundances of solid OCS as the main reservoir of sulfur on grains, an entrainment of sufficient material on the interface on the timescale of $\lesssim$50 yr, and the proper radiation field strength. As we mentioned in the previous section, we also believe that the extended emission feature of H_2CS observed toward MM1 of DR21(OH) resulted from the interaction between the ambient and the outflow. Although it is necessary to fully investigate the OCS in MM1 of DR21(OH), we consider that the H_2CS in the extended feature may have resulted from the direct evaporation and/or sputtering of H_2CS from icy grain mantles. In addition, H_2CS is a hot core species in MM1 of DR21(OH), as its emission shows, which may suggest a similar mechanism in the hot core and in the interacting turbulent region. This differs from the Cep A East, where H_2CS is certainly not a hot core species (Codella et al. 2006).

Here we suggest that H_2CS could be one of the sulfur-bearing solid species of the ice grain mantles, at least in the MM1 core of DR21(OH). The abundance of solid H_2CS on the grain surface may depend on the chemical environment—if the hydrogenation is more efficient than the oxidization on the grain surface, the accreted S or CS may produce solid H_2S or H_2CS as major sulfur-bearing species; however, if the oxidization is more efficient, SO_2 or OCS may form instead (Tielens & Hagen 1982; Palumbo et al. 1997). Then, the abundance of the solid H_2CS in the grain mantles results from the competing efficiency between hydrogenation and oxidization on the grain surface, depending on the chemical environment.

5. CONCLUSIONS

H_2CS transitions at 340 GHz were observed using the SMA toward DR21(OH). The emission has a typical bipolar outflow morphology, consisting of a strong concentration toward MM1a (one of the subcores associated with MM1) and a symmetrically extended feature roughly in the north–south direction. This is the first identification of the bipolar outflow-like emission of H_2CS, which is also confirmed by a position–velocity map. We derived H_2CS column densities of $\sim 3 \times 10^{15}$ cm^{-1} and $\sim 1 \times 10^{15}$ cm^{-1} toward MM1a and the centers of the extended emission, respectively. Its fractional abundance, $f(H_2CS) \sim 10^{-9}$ relative to the total H_2 abundance, is comparable to those of other star-forming regions (van der Tak et al. 2003). Various hot molecular species have been found to peak toward MM1a (Y. C. Minh et al. 2011, in preparation), and H_2CS appears to be one of them. The extended H_2CS emission may result from the interaction between the outflow from MM1a and the dense ambient gas. Our results suggest that the observed H_2CS emission arises via direct evaporation and/or sputtering of the solid H_2CS on the grain surface. This leads us to conclude that H_2CS may be one of the major sulfur-bearing species residing in the ice grain mantles in a solid form, at least in the case of DR21(OH).

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