Sulfur-bearing molecules observed in the massive star-forming regions, DR21(OH) and G33.92+0.11

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Abstract. Recent high sensitive and high angular resolution observations are providing unprecedented amount of chemical data, especially, on the massive star-forming regions. It will greatly extend our understandings on the complicated star formation process, if we can digest those huge amount of information. We discuss here on the properties of the sulfur-bearing species observed with high angular resolutions toward two massive star-forming regions, DR21(OH) and G33.92+0.11. H$_2$S may not exist as a solid form in the grain mantles, but OCS is believed to be one of major solid sulfur species, as suggested before. In addition, the bipolar-like outflow of the H$_2$CS emission observed in DR21(OH) may suggest that H$_2$CS is also one of solid sulfur species on the grain mantles. Depending on the chemical environment, the competition between hydrogenation and oxidization on the grain surface may lead to formation of specific solid forms to dominate, which could be either H$_2$CS or OCS. SO and SO$_2$ are often observed to be associated with ionized gas, such as the UC HII regions. These species seem to be formed in the high temperature turbulent gas in a later stage of star formation after the hot core phase. Fractional abundances of these sulfur-bearing species appear to be consistent to a certain extent in several star-forming regions. The physical and chemical evolution of massive star formation seems to pass through very similar stages in most star-forming regions. Consequently, it may indicate that there exists a consistent and coherent pattern of processes experienced by the massive star formation, in spite of the large variations in small scale locational differences.

1. Introduction

Massive stars are forming in the dense molecular cores of GMCs. They used to form in clusters with a relatively short evolutionary time scale and include much more energetic activities compared to the low mass star formations [28, 39]. Massive star-forming regions often show the tremendous complexity associated with dust continuum emission, hot cores, outflows, various masers, complicated neutral and ionized gas components, etc. These regions show extremely rich chemistry associated with hot cores, shocks, and high temperature gas in addition to general dense gas phase chemistry. Since these sources are embedded deeply in the dense molecular cloud cores, the chemical signatures associated with the sources are one of the most useful and important probes to investigate the nature of the star-forming cores.

Complicated molecular emission features have been observed toward the dense cores in an early evolutionary stage of massive star formation [19, 21]. Among the observed species, sulfur-bearing species have been known to be chemical clocks in the early phase of the star formation evolution. It is mainly because that the interstellar sulfur has been observed to be largely depleted (by about a factor of 1000) in the quiet dense gas and to appear again in the gas phase
associated with star-forming activities [6, 12]. Some of the sulfur-bearing species observed in
the gas phase may have evaporated directly from the grain mantles, but some of them must
have been formed later in the gas phase from the evaporated species. The particular form of
solid state sulfur in the grain mantles is still a controversial issue, and the gas phase evolution
of sulfur-bearing species is also not clear [5, 12, 27, 34, 35]
Recent high sensitivity and high angular resolution observations open a new era of interstellar
chemistry. Here we discuss on the chemical properties of several sulfur-bearing species observed
in the massive star-forming regions DR21(OH) and G33.92+0.11 with SMA (Submillimeter
Array) and ALMA (Atacama Large Millimeter and submillimeter Array), respectively.

2. Emission fragmentation

2.1. DR21(OH)

DR21(OH) is a well known massive star-forming region located at a distance of 1.4 kpc in the
Cygus X North region [23, 29, 30]. This source consists of several dense clumps (∼10^3 M_⊙
and n(H_2) ∼ 10^6 cm^-3) [18], which harbor young stellar objects of very early stages. Figure 1
shows two bright compact continuum cores, MM1 and MM2, separated by ∼ 8″ from each other
[37]. This source is associated with various masers, such as OH [2, 24], H_2O [10], and CH_3OH
[1, 4, 9, 13, 14, 26], indicating ongoing star formation activities. It also shows complicated
molecular emission, which are strongly concentrated toward MM1, especially to the subcores
MM1a and b, separated by ∼ 1.6″. Depending on the peak position, the molecular emission
distributions can be grouped into two: one group of emission lines peaks toward MM1a, and a
second group peaks toward MM1b [21].

![Figure 1. Continuum emission distribution of DR21(OH) at 230 GHz (contours) and
340 GHz (false color) observed with SMA [21]. Contours of the 230 GHz emission show
the 20% levels of the peak intensity (0.13 Jy beam^-1). The beams are shown in the lower
left as ellipses (grey for 340 GHz and black for 230 GHz). The asterisk is the H_2O maser
position [10] and the crosses are methanol masers [1]. The MM2 position [37] is shown
as a box (magenta). Triangles (purple) are the SMA sources [38].]
Table 1. Physical parameters of subcores MM1a and b [21]

| Subcore | Size(HPW)(P.A.) | $M_{\text{core}}$ (M$_\odot$) | $N_{\text{H}_2}$ (cm$^{-2}$) | $n_{\text{H}_2}$ (cm$^{-3}$) |
|---------|----------------|-----------------|----------------|----------------|
| MM1a    | 1.6\times1.1 (−50°) | 0.23                                | 1.3\times10$^{23}$ | 4 \times 10$^6$ |
| MM1b    | 1.9\times1.4 (−80°) | 0.43                                | 1.1\times10$^{23}$ | 2 \times 10$^6$ |

The first group includes highly saturated molecules, such as CH$_3$OH, HCOOCH$_3$ and CH$_3$OCH$_3$, which suggests that MM1a is the site for hot cores. These saturated species are thought either to be evaporated from the grain mantles or to be formed in the hot core gas phase from the evaporated species. In contrast, the second group contains sulfur-bearing species such as SO and SO$_2$, which are thought to trace high temperature gas associated with UC HII regions [19, 21]. No close correlations between the emission peaks from these sulfur-bearing species and identified hot cores have been found [19, 21, 22]. These species are considered not to be evaporating directly from the grain mantles in hot cores, but to be formed in the dense gas phase from the evaporated sulfur or sulfur-bearing species.

One thing to note further is the discovery of the H$_2$CS bipolar-like outflow feature associated with MM1a of DR21(OH) (Figure 3) [20]. H$_2$CS can be formed in the gas phase [6], and its abundance has been reported to be increased in outflows associated with star formation [3, 7]. But it is also suggested as a grain mantle species with an abundance comparable to that of OCS [25]. The outflow feature of H$_2$CS emission in DR21(OH) indicates that H$_2$CS is either formed in the turbulent gas phase after the release of the sulfur species from the grains or evaporated directly from the grain mantles by the interaction with the outflow. Considering the formation of...
Figure 3. Integrated intensity map of the H$_2$CS $10_{1,10} - 9_{1,9}$ transition observed toward DR21(OH) [20] for the separate velocity ranges: (blue) $v_{lsr} = -10.0 \sim -5.5$ km s$^{-1}$, (white) $-5.5 \sim -2.0$ km s$^{-1}$, and (red, dashed) $-2.0 \sim 3.0$ 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 and circles are radio continuum sources [1, 18]. Sample spectra of the H$_2$CS $10_{1,10} - 9_{1,9}$ and $10_{1,9} - 9_{1,8}$ transitions taken at the emission peaks of the blue- and redshifted lobes and the center [20]. Flux of the spectra was transformed to the temperature unit.

...time scale in the gas phase of $\sim 10^5$ years [6, 15], the observed H$_2$CS is highly likely to evaporate directly from the grain mantles [20].

Although there have been several suggestions on the sulfur on dust grains [35], the major form of solid sulfur is a long standing problem. H$_2$S has previously been suggested as a main reservoir of sulfur in grain mantles, but it was not found in the observations toward continuum sources on the grain mantles [11, 34]. OCS is the only sulfur-bearing species clearly detected on the grain surface, but it also has a very low fractional abundances $\sim 10^{-7}$ relative to hydrogen [25, 35]. H$_2$CS could be one of the sulfur-bearing solid species of the ice grain mantles, depending on the chemical environment of efficient hydrogenation.

2.2. G33.92+0.11

G33.92+0.11 is a massive star-forming region classified as a UC HII region at a distance of 7.1 kpc [8]. OB star-clusters are forming in this GMC and the total mass is about $10^5$ M$_\odot$ in the central $\sim 5$ pc [16]. Figure 4(Left) shows the overall density distribution of the cloud A of G33.92+0.11 [17, 22]. This region contains all representative features related to massive star formation, such as, hot cores, outflows, UC HII regions, etc., in addition to probable on-going accretion from the ambient gas [17]. In this region, two central clumps A1 and A2 are most prominent with masses of $100 - 300$ M$_\odot$ [16, 36]. Near the A1 clump, there exists a bright UC HII region, where newly formed YSOs are embedded. Next generation stars are observed to be forming in nearby dense cores. The star formation activity seems to be enhanced by the interaction with accreting gas. The high angular resolution observations ($\sim 0.6'' - 0.8''$) made with ALMA reveal very complicated chemical gradients over the observed region.
Figure 4. Integrated intensity map of the $^{13}$CS $5-4$ transition (colored scale; left) observed toward G33.92+0.11 [22]. The outline contour in black is for the 0.15 Jy beam$^{-1}$ km s$^{-1}$ intensity. The magenta contour lines are for the H30α line with scale of 0.5, 1, 1.5, etc. Jy beam$^{-1}$ km s$^{-1}$. The labels, A1 to A13, are the positions of the dust continuum peaks [17]. Integrated intensity map (colored image) of the SO$_2$ $^{14}_{3,11} - ^{14}_{2,12} 1\nu_2$ transition (right). Its intensity scale is shown in the upper side of the panel. Contours in white is for the scale of $0.04 \times [1, 2, 3, 4]$ Jy beam$^{-1}$ km s$^{-1}$. Beam is shown in the bottom left corner. The contour in black is the outline of the $^{13}$CS $5-4$ emission in the left panel.

Figure 4 shows the integrated intensity map of the SO$_2$ $^{14}_{3,11} - ^{14}_{2,12} 1\nu_2$ transition. The energy of the upper level of this vibrational transition is about 250 K from the ground state. This high energy transition shows a very similar distribution with the H30α line of the UC HII region. This emission has also been detected toward the dust emission peak A5 with an intensity greater than 5σ of the observational uncertainty, where multiple SiO outflows have been detected [22]. The SO$_2$ emission is often observed together with UC HII regions in massive star-forming regions [19, 21]. This species seems to be formed in the high temperature gas phase from the atomic sulfur or sulfur-bearing species evaporated from the grain mantles.

Figure 5 shows the integrated intensity maps of the OCS and H$_2$S transitions observed toward G33.92+0.11. The OCS emission shows clumpy features around the dust continuum peaks of A1, A2, and A5, and also in the northern part of the A1 clump. These dust continuum peaks are the positions of hot cores associated with YSOs. The emission distribution of OCS is very similar to that of CH$_3$OH [22], which is an unambiguous first molecule evaporating in the dust mantles by heating from YSOs. As was reported previously, OCS, like CH$_3$OH, may have evaporated directly from the mantles.

On the other hand, H$_2$S shows a strong and extended emission in the A2 clump, but relatively weak at the A1 and A5 peak positions (Figure 5). Especially, the A5 peak is the position where new stars are forming and hot core features are prominent. In this position, the SiO emission also shows multiple outflows which must be driven by the embedded YSOs. H$_2$S shows a very similar emission distribution with $^{13}$CS, but not with CH$_3$OH or OCS. This fact strongly suggests that H$_2$S is not a species evaporating directly from the mantles. The H$_2$S emission also shows an enhancement along the southern boundary of the A2 clump, which is probably resulted from...
Figure 5. Integrated intensity maps of the OCS 19 – 18 (left) and H$_2$S 2$_{0,0}$ – 2$_{1,1}$ (right) transitions. The intensity scales are shown in the upper side of the panels. The white contour lines are for the scale of 0.05×[1, 2, 3] and 0.2×[2, 3, 4, …] Jy beam$^{-1}$ km s$^{-1}$ for OCS and H$_2$S, respectively. Beams are shown in the bottom left corners. The boundary contour in black is the outline of the $^{13}$CS 5 – 4 emission as included in Figure 4.

the interaction with the accreting gas to this source [17]. H$_2$S is thought to be formed in the warm and turbulent gas phase by using the evaporated sulfur or sulfur-bearing species from the grain mantles.

3. Summary on the chemical implications

Massive star-forming regions are observed to be extremely complicated in molecular emissions. There clearly exist small scale chemical differences within a cloud or a clump, which are probably resulted from the different evolutionary stages of massive star formation of the order of $10^4$ years [21]. Recent high sensitive and high angular resolution observations are providing unprecedented amount of chemical data on the massive star-forming regions. If we can digest those huge amount of information properly, the complicated star formation process will certainly be better understood. Here we discuss on some observational results for the sulfur-bearing species observed toward two massive star-forming regions, DR21(OH) and G33.92+0.11 with SMA and ALMA, respectively.

Interstellar sulfur is largely depleted in the quiet and dense gas phase to the dust grains, and appears again in the gas phase in association with star formation activities. There exist some controversial issues on the sulfur species, such as the forms of solid state sulfur on the grain mantles or the evolution of the gas phase sulfur species before accretion. We confirm that H$_2$S is not a major solid sulfur species in the grain mantles. Instead, it seems to be forming in the dense turbulent gas phase from the evaporated sulfur-bearing species. On the other hand, OCS is believed to evaporate directly from the grain mantles, as evidenced by a good locational correlation with CH$_3$OH. OCS seems to be one of major forms of solid sulfur in the grain mantles, as suggested before. In addition, the bipolar-like outflow of the H$_2$CS emission observed in DR21(OH) suggests that H$_2$CS might be another solid sulfur-bearing species on the grain mantles. Depending on the chemical environment, the competition between hydrogenation
and oxidization on the grain surface may result the formation of solid H$_2$CS or OCS on the grain surface [20, 25, 33].

The evaporated atomic sulfur and sulfur-bearing species from the dust grains will soon be transformed to other forms in the warm and dense gas phase. SO and SO$_2$ are the molecules frequently found in association with star formation activities, which show, in general, a good correlation with ionized gas, such as the UC HII regions. These species seem to be formed in the high temperature turbulent gas in a later stage of star formation after the hot core phase.

Figure 6 shows the abundance comparisons of some sulfur-bearing species in selected sources. Overall fractional abundances of H$_2$S relative to H$_2$ appear to be fairly consistent except toward OMC Hot Core, which is a nearby star-forming region consisted of various different emission sources. For SO and SO$_2$, MM1a is a little bit younger than MM1b in both sources DR21(OH) and W75N. MM1a contains hot cores and MM1b contains UC HII regions, which may result the relative abundances of SO and SO$_2$ enhanced in MM1b compared to MM1a. Giving consideration to the uncertainties involved in deriving the column densities, especially of total H$_2$ abundances, the fractional abundances of these sulfur-bearing species are observed to be relatively consistent in these sources. Although the high angular resolution observations show complicated locational variations even in a clump within a source, these sources may be experiencing very similar chemical and consequently physical evolutionary stages on the whole. From the careful investigation on the chemical evolution associated with the source structure, we may find a consistent and coherent evolutionary pattern of the massive star formation process in general.

References

[1] Araya E D, Kurtz S, Hofner P and Linz H 2009 Astrophys. J. 698 1321
[2] Argon A L, Reid M J and Menten K M 2000 Astrophys. J. Suppl. Ser. 129 159
[3] Bachiller R and Pérez Gutiérrez M 1997 Astrophys. J. 487 L93
[4] Batrla W and Menten K M 1988 Astrophys. J. 329 L117
[5] Caselli P, Hasegawa T I and Herbst E 1994 Astrophys. J. 421 206
[6] Charnley S B 1997 Astrophys. J. 481 396
[7] Codella C, Viti S, Williams D A and Bachiller R 2006 Astrophys. J. 644 L41
[8] Fish V L, Reid M J, Wilner D J and Churchwell E 2003 Astrophys. J. 587 701
[9] Fish V L, Muenchbrad T C, Pratap P, Sjouwerman L O, Strelchnski V, Pihlström Y M and Bourke T L 2011 Astrophys. J. 729 14
[10] Genzel R and Downes D 1977 *Astron. Astrophys. Suppl. Series* **30** 145
[11] Gibb E L *et al* 2000 *Astrophys. J.* **536** 347
[12] Hatchell J, Thompson M A, Millar T J and Macdonald G H 1998 *Astron. Astrophys.* **338** 713
[13] Kogan L and Slysh V 1998 *Astrophys. J.* **497** 800
[14] Kurtz S, Hofner P and Álvarez C V 2004 *Astrophys. J. Suppl. Series* **155** 149
[15] Langer W D, van Dishoeck E F, Bergin E A, Blake G A, Tielens A G G M, Velusamy T and Whittet D C B 2000 *Protostars and Planets IV* 29
[16] Liu H B, Jiménez-Serra I, Ho P T P, Chen H-R, Zhang Q and Li Z-Y 2012 *Astrophys. J.* **756** 10
[17] Liu H B, Galván-Madrid R, Jiménez-Serra I, Román-Zúñiga C, Zhang Q, Li Z and Chen H-R 2015 *Astrophys. J.* **804** 37
[18] Mangum J C, Wootten A and Mundy L G 1991 *Astrophys. J.* **378** 576
[19] Minh Y C, Su Y-N, Chen H-R, Liu S-Y, Yan C-H and Kim S-J 2010 *Astrophys. J.* **723** 1231
[20] Minh Y C, Liu S-Y, Chen H-R and Su Y-N 2011 *Astrophys. J.* **737** L25
[21] Minh Y C, Chen H-R, Su Y-N and Liu S-Y 2012 *J. Korean Astron. Soc.* **45** 157
[22] Minh Y C, Liu H B and Galván-Madrid R 2016 *submitted*
[23] Motte F, Bontemps S, Schilke P, Schneider N, Menten K M and Broguière D 2007 *Astron. Astrophys.* **476** 1243
[24] Norris R P, Booth R S, Diamond P J and Porter N D 1982 *Mon. Not. R. Astron. Soc.* **201** 191
[25] Palumbo M E, Geballe T R and Tielens A G G M 1997 *Astrophys. J.* **479** 839
[26] Plambeck R L and Menten K M 1990 *Astrophys. J.* **364** 555
[27] Pineau des Forêts G, Roneff E, Schilke P and Flower D R 1993 *Mon. Not. R. Astron. Soc.* **262** 915
[28] Reipurth B and Yan C-H 2008 *Handbook of Star Forming Regions: Volume I, The Northern Sky* ed Reipurth B (San Francisco, CA: ASP) 4 869
[29] Rygl K L J, Brunthaler A, Sanna A, Menten K M, Reid M J, van Langevelde H J, Honma M, Torstensson K J E and Fujisawa K 2012 *Astron. Astrophys.* **539** 79
[30] Schneider N, Bontemps S, Simon R, Jakob H, Motte F, Miller M, Kramer C and Stutzki J 2006 *Astron. Astrophys.* **458** 855
[31] Sutton E C, Jaminet P A, Danchi W C and Blake G A 1991 *Astrophys. J. Suppl. Series* **77** 255
[32] Sutton E C, Peng R, Danchi W C, Jaminet P A, Sandell G and Russell A P G 1995 *Astrophys. J. Suppl. Series* **97** 455
[33] Tielens A G G M and Hagen W 1982 *Astron. Astrophys.* **114** 245
[34] van der Tak F F S, Boonman A M S, Braakman R and van Dishoeck E F 2003 *Astron. Astrophys.* **412** 133
[35] Wakelam V, Caselli P, Ceccarelli C, Herbst E and Castets A 2004 *Astron. Astrophys.* **422** 159
[36] Watt S and Mundy L G 1999 *Astrophys. J. Suppl. Ser.* **125** 143
[37] Woody D P, Scott S L, Scoville N Z, Mundy L G, Sargent A I, Padin S, Tinney C G and Wilson C D 1989 *Astrophys. J.* **337** L41
[38] Zapata L A, Loinard L, Su Y-N, Rodríguez L F, Menten K M, Patel N and Galván-Madrid R 2012 *Astrophys. J.* **744** 86
[39] Zinnecker H and Yorke H W 2007 *Annu. Rev. Astron. Astrophys.* **45** 481