Mapping observations of complex organic molecules around Sagittarius B2 with the ARO 12 m telescope

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ABSTRACT

We have performed high-sensitivity mapping observations of several complex organic molecules around Sagittarius B2 with the ARO 12 m telescope at 3 mm wavelength. Based on their spatial distribution, molecules can be classified as either ‘extended’, those detected not only in Sgr B2(N) and Sgr B2(M), or ‘compact’, those only detected toward or near Sgr B2(N) and Sgr B2(M). The ‘extended’ molecules include glycolaldehyde (CH_2OHCHO), methyl formate (CH_3OCHO), formic acid (t-HCOOH), ethanol ($\text{C}_2\text{H}_5\text{OH}$) and methyl amine (CH_3NH_2), while the ‘compact’ molecules include dimethyl ether (CH_3OCH_3), ethyl cyanide ($\text{C}_2\text{H}_5\text{CN}$), and amino acetonitrile ($\text{H}_2\text{NCH}_2\text{CN}$). These ‘compact’ molecules are likely produced under strong UV radiation, while the ‘extended’ molecules are likely formed at low temperatures, via gas-phase or grain-surface reactions. The spatial distribution of ‘warm’ CH_2OHCHO at 89 GHz differs from the spatial distribution of ‘cold’ CH_2OHCHO observed at 13 GHz. We found evidence for an overabundance of CH_2OHCHO compared to that expected from the gas-phase model, which indicates that grain-surface reactions are necessary to explain the origin of CH_2OHCHO in Sagittarius B2. Grain-surface reactions are also needed to explain the correlation between the abundances of ‘cold’ CH_2OHCHO and $\text{C}_2\text{H}_5\text{OH}$. These results demonstrate the importance of grain-surface chemistry in the production of complex organic molecules.

Key words: ISM: abundances – ISM: clouds – ISM: individual (Sagittarius B2) – ISM: molecules – radio lines: ISM.

1 INTRODUCTION

Complex organic molecules (COMs) are regarded as being related to the origin of life on Earth (Herbst & van Dishoeck 2009). Thus,

understanding the properties and formation mechanism of prebiotic molecules is key for the study of astrobiology. It has been found that prebiotic molecules are very abundant in the Galactic centre giant molecular cloud Sagittarius B2 (Sgr B2) (Menten 2011). Sgr B2 contains two main sites of star formation, Sgr B2(N) and Sgr B2(M), which have been the best hunting ground for prebiotic molecules in the interstellar medium (ISM) since the early 1970s (Belloche

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et al. 2013). Many COMs are first detected toward Sgr B2(N), such as glycolaldehyde CH_2OHCHO (Hollis, Lovas & Jewell 2000), ethylene glycol $\text{HOCH}_2\text{CH}_2\text{OH}$ (Hollis, Lovas & Jewell 2002), amino acetonitrile $\text{H}_2\text{NCH}_2\text{CN}$ (Belloche et al. 2008) and so on. Some COMs, such as glycolaldehyde and ethylene glycol, were found to be widespread in the Galactic centre (Hollis et al. 2001; Requena-Torres et al. 2006, 2008; Li et al. 2017).

Theoretical and experimental studies (Garrod, Weaver & Herbst 2008; Öberg et al. 2009; Woods et al. 2013; Fedoseev et al. 2015; Chuang et al. 2016; Meinert et al. 2016; Skouteris et al. 2018) show that COMs may be formed on cosmic dust by radicals that are produced on dust grain surfaces by UV or cosmic ray induced photons. The COMs are then desorbed into the gas phase due to thermal and/or non-thermal processes (Garrod & Herbst 2006). However, these complex ice compositions cannot be directly observed with telescopes in the infrared; thus, most constraints come from millimetre observations of desorbed ice chemistry products. On the other hand, recent quantum chemical computations show that a combination of radicals trapped in amorphous water ice does not necessarily lead to the formation of COMs (Enrique-Romero et al. 2016). Recently, a new scheme for the gas-phase synthesis of glycolaldehyde, a species with prebiotic potential, has been proposed. The predicted abundance of glycolaldehyde agrees well with that measured in solar-type hot corinos and shock sites (Skouteris et al. 2018). Thus, how these species are synthesized is a mystery.

Previous mapping observations mainly concentrated on Sgr B2(N) with interferometers like ATCA and ALMA at small spatial scales (≤ 1 arcmin) (Corby et al. 2015; Belloche et al. 2016, 2019; Sánchez-Monge et al. 2017; Bonfand et al. 2019; Xue et al. 2019), and only a handful of large-scale spectral line mapping observations toward Sgr B2 have been performed (Chengalur & Kanekar 2003; Jones et al. 2008, 2011). The large-scale spatial distribution of COMs like $\text{C}_2\text{H}_5\text{CN}$, HCOOH is still unclear mainly because of their weak emission (Halfen, Woolf & Ziurys 2017). Single-dish telescopes have the ability to probe the structure of weak lines from the extended gas of the Sgr B2 complex on spatial scales much larger than 1 arcmin. In this paper we present high-sensitivity grid-imaging results of several COMs around Sgr B2 with the Arizona Radio Observatory (ARO) 12 m telescope. In Section 2, we describe the observations and data reduction. In Section 3, we present the mapping results and spatial distributions of column densities, rotational temperatures, and estimated abundances for the observed COMs. In Section 4, we discuss molecular formation pathways and compare our results with protostars and then summarize our conclusions in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

We performed point-by-point mapping observations of COMs at a 3 mm wavelength around Sgr B2 in 2017 April and May with the Arizona Radio Observatory 12 m telescope at Kitt Peak, Arizona. The 85–116 GHz sideband separating ALMA band-3 receiver was used. The beam size is 70 arcsec at 90 GHz. The two IF modes of the Millimeter Autocorrelator (MAC) were employed as backends. The MAC has 4096 channels with 195 kHz sampling interval, corresponding to 0.65 km s^{-1} at 90 GHz. Though the velocity resolution is not high enough for the study of molecular emission from hot cores, it is sufficient for single-dish observations of Sgr B2. The FWHM linewidth is up to $\sim 20 \text{ km s}^{-1}$ (Rivilla et al. 2018, 2019) due to the extended envelope and several unresolved cores with different velocities and linewidths within the beam. The temperature

scale was determined by the chopper wheel method, and is related to the main-beam brightness temperature with a main-beam efficiency of 0.88. The system temperature ranges from 90–150 K. The integration time for each position ranges from 50–90 min.

Observations were made in position-switching mode, and an offset of +30 arcmin in azimuth was used. The data processing was conducted using the GILDAS software package,¹ including CLASS and GREG. Linear baseline subtractions were used for most of the spectra. For each transition, the spectra of subscans, including two polarizations, were averaged to reduce rms noise levels. Gaussian fitting is used to derive the physical properties of molecule lines, including peak intensity, V_{LSR} , FWHM linewidth, and integrated intensity.

3 RESULTS OF OBSERVATIONS

We detected emission lines from t-HCOOH , $\text{C}_2\text{H}_5\text{CN}$, CH_3OCH_3 , CH_3OCHO , $\text{H}_2\text{NCH}_2\text{N}$, CH_2OHCHO , CH_3NH_2 , and $\text{C}_2\text{H}_5\text{OH}$ toward many positions at a rms level of $\sim 3 \text{ mK}$. Fig. 1 presents spectra observed toward several positions with the ARO 12 m telescope. As is shown in Fig. 1, some molecule lines are only detected toward Sgr B2(N) and Sgr B2(M). Table 1 presents detected transitions and their spectroscopic properties in Sgr B2(N). The molecular spectroscopic parameters are taken from the current public databases: the CDMS catalogue² (Müller et al. 2005), the JPL catalogue³ (Pickett et al. 1998) and the Spectral Line Atlas of Interstellar Molecules (SLAIM) database, which are available in the SPLATALOGUE spectroscopy database.⁴ Note that the strong $\text{C}_2\text{H}_5\text{CN}$ emission near to t-HCOOH 4(0,4)–3(0,3) (89.579 17 GHz) makes it difficult to determine the baseline and intensity of t-HCOOH . Only t-HCOOH emission toward Sgr B2(N) was affected since the $\text{C}_2\text{H}_5\text{CN}$ emission was very weak toward other positions.

The many hazards of searching for new molecules have been pointed out by Snyder et al. (2005). These authors proposed some of the criteria needed for secure molecular identification, including accurate rest frequencies and consistency among the acquired data set. Halfen et al. (2006) extended the criteria in Snyder et al. (2005) and applied them to the ARO 12 m observations. They suggest that, for an accurate identification, there must be strong evidence for emission at all favourable physically connected transitions over a sufficiently large wavelength range. There cannot be ‘missing’ favourable lines. Based on these criteria, CH_2OHCHO 9(1,8)–8(2,7) (89.868 639 GHz), the glycolaldehyde transition used in this work, was found to be strong and relatively clean. Xue et al. (2019) proposed a quantitative method to identify weak and mostly uncontaminated transitions. They used the P factor, which is the product of the observed and simulated line profiles, to characterize the frequency agreement. They used the D factor, which is the ratio between the difference of the integrated intensities of the compared spectra and the maximum of the two subtracted from 1, to measure the difference of the line intensities. For CH_2OHCHO 9(1,8)–8(2,7) at 89.868 639 GHz, the P factor is 94 per cent, while the D factor is 16.8 per cent. For CH_3OCHO 7(2,5)–6(2,4) E at 90.145 GHz, the P factor is 99.8 per cent, while the D factor is 25.4 per cent (see the appendix in Xue et al. 2019). Based on the P factors, both of these transitions are assigned to be unblended

¹<http://www.iram.fr/IRAMFR/GILDAS>

²<https://www.astro.uni-koeln.de/cdms/catalog>

³<https://spec.jpl.nasa.gov>

⁴<https://www.splatalogue.net>

Figure 1. Spectra obtained toward Sgr B2(N), Sgr B2(M) and (540, -300) away from Sgr B2(N) with the ARO 12 m telescope in the main-beam temperature scale. The line names are shown. The ‘extended’ molecular line profiles are coloured red, while the ‘compact’ molecular line profiles are coloured blue in the spectra of Sgr B2(N).

transition candidates. The low D factors are likely to be caused by the high excitation temperature (190 K) adopted by Xue et al. (2019). Transitions of other molecules have been identified by Belloche et al. (2013). Velocity-integrated images of strong and relatively clean transitions, including CH₂OHCHO 9(1,8)–8(2,7), CH₃OCHO 7(2,5)–6(2,4)E, t-HCOOH 4(0,4)–3(0,3), C₂H₅OH 4(1,4)–3(0,3) and CH₃NH₂ 1(1,0)–1(0,1), CH₃OCH₃ 2(2,1)–2(1,2)EE, C₂H₅CN 10(4,7)–9(4,6) and H₂NCH₂CN 10(0,10)–9(3,6), are presented in Figs 2 and 3. The positions of Sgr B2(N) and Sgr B2(M) are indicated with crosses. The peak integrated intensities on the T_{mb} scale are given in the caption. We can see from Figs 2 and 3 that

some molecular line emissions concentrate on Sgr B2(N) and Sgr B2(M), and some molecular line emissions extend to the eastern part of Sgr B2. Based on their spatial distributions, molecules can be classified as either ‘extended’, those detected not only in Sgr B2(N) and Sgr B2(M), or ‘compact’, those only detected toward or near to Sgr B2(N) and Sgr B2(M).

The excitation analysis of glycolaldehyde emissions at millimetre and centimetre wavelengths in Sgr B2(N) indicates that a single temperature component was unable to reproduce all the observed spectra (Hollis et al. 2004). Thus, two temperature components were invoked: a ‘warm’ extended glycolaldehyde envelope surrounded

Table 1. Identified transitions and their observed parameters in Sgr B2(N).

Species	Transitions	Rest freq. (GHz)	E_u (K)	μ^2S (D ²)	T_{mb} (mK)	V_{LSR} (km s ⁻¹)	ΔV (km s ⁻¹)	$\int T_{mb} dv$ (mK km s ⁻¹)
t-HCOOH*	4(0,4)–3(0,3)	89.579 17(1e-6)	10.76	8.077	~100	~64	~20	~2000
C ₂ H ₅ CN, $v = 0$	10(9,1)–9(9,0)	89.584 987(5e-5)	109.32	28.16	blended	–	–	–
C ₂ H ₅ CN, $v = 0$	10(9,2)–9(9,1)	89.584 987(5e-5)	109.32	28.16	blended	–	–	–
C ₂ H ₅ CN, $v = 0^*$	10(4,7)–9(4,6)	89.590 028(3e-6)	41.44	124.52	160(45)	63.0(.6)	22.0(1.4)	3520(610)
C ₂ H ₅ CN, $v = 0$	10(4,6)–9(4,5)	89.591 013(3e-6)	41.44	124.52	160(45)	63.0(.6)	22.0(1.4)	3520(610)
C ₂ H ₅ CN, $v = 0$	10(3,8)–9(3,7)	89.628 485(3e-6)	33.66	134.89	200(10)	65.0(1.4)	21.9(4.0)	4666(654)
C ₂ H ₅ CN, $v_{20} = 1$	10(8,3)–9(8,2)	89.643 412(2e-6)	630.76	52.43	blended	–	–	–
C ₂ H ₅ CN, $v_{20} = 1$	10(4,7)–9(4,6)	89.661 002(5e-5)	577.94	122.32	30(3)	67.2(.4)	7.0(1.2)	211(57)
C ₂ H ₅ CN, $v = 0$	10(3,7)–9(3,6)	89.684 710(3e-6)	33.66	134.88	134(3)	60.9(2.6)	26.8(2.6)	3821(236)
CH ₃ OCH ₃ , $v = 0$	2(2,1)–2(1,2)AE	89.697 737(1e-6)	8.36	8.475	91(8)	66.5(2.6)	18.4(2.6)	1783(158)
CH ₃ OCH ₃ , $v = 0^*$	2(2,1)–2(1,2)EE	89.699 809(1e-6)	8.36	22.31	50(8)	64.2(2.6)	15.1(2.6)	797(158)
CH ₃ OCH ₃ , $v = 0$	2(2,1)–2(1,2)AA	89.702 829(2e-6)	8.36	14.131	46(8)	65.2(.3)	23.0(2.6)	1131(158)
CH ₃ OCHO, $v_l = 1$	8(0, 8)–7(0, 7) A	89.731 695(1e-5)	207.83	41.664	29(6)	64.2(.3)	7.4(.7)	228(19)
C ₂ H ₅ CN, $v_{20} = 1$	10(3,7)–9(3,6)	89.754 402(5e-5)	570.24	132.51	43(5)	65.9(.4)	34.3(1.2)	1579(46)
H ₂ NCH ₂ CN*	10(0,10)–9(3,6)	89.770 285(7e-6)	19.50	66.296	25(3)	63.7(0.7)	14.5(1.6)	377(40)
t-HCOOH	4(2,3)–3(2,2)	89.861 484(2e-6)	23.51	5.93	50(3)	66.9(.2)	18.5(.6)	987(26)
CH ₂ OHCHO*	9(1,8)–8(2,7)	89.868 639(6e-6)	26.43	20.565	17(3)	61.5(2.6)	18.6(2.6)	338(41)
t-HCOOH	4(3,2)–3(3,1)	89.948 21(2e-6)	35.09	3.536	blended	–	–	–
CH ₃ NH ₂ *	1(1)A1–1(0)A2	89.956 068(2e-5)	6.45	1.5 ^a	31(3)	67.8(1.3)	30.3(2.8)	982(87)
CH ₃ CH ₂ C ¹³ N	10(2,8)–9(2,7)	89.992 750(1.2e-6)	28.10	139.763	blended	–	–	–
g-C ₂ H ₅ OH	13(1,12)–13(1,13),g+	90.0077(5e-5)	135.11	13.99	28(3)	64.0(.5)	6.2(1.2)	188(53)
¹³ CH ₂ CHCN	10(1,10)–9(1,9)	90.032 588(1.2e-6)	25.92	432.232	blended	–	–	–
CH ₃ ¹³ CH ₂ CN, $v = 0$	10(2,8)–9(2,7)	90.079 288(1.3e-6)	28.00	139.77	24(3)	66.3(6)	17.7(1.3)	457(29)
C ₂ H ₅ OH*	4(1,4)–3(0,3)	90.117 61(2.8e-6)	9.36	5.21	266(9)	68.5(.1)	22.4(.2)	6330(37)
CH ₃ OCHO*	7(2,5)–6(2,4) E	90.145 634(2.4e-5)	19.68	34.275	86(7)	65.7(.1)	16.7(.4)	1523(28)
CH ₃ OCHO	7(2,5)–6(2,4) A	90.156 473(1e-5)	19.67	34.289	80(7)	66.3(.4)	13.7(.9)	1166(65)

Note.*: Lines used for mapping. Col. (1): chemical formula; Col. (2): transition quantum numbers; Col. (3): rest frequency; Col. (4): upper-state energy level (K); Col. (5): dipole-weighted transition dipole matrix elements; Col. (6): peak temperature; Col. (7): centroid velocity; Col. (8): FWHM linewidth; Col. (9): integrated intensity. ^a: μ^2S is taken from Motiyenko et al. (2014) for CH₃NH₂.

by a ‘cold’ glycolaldehyde halo (Hollis et al. 2004). The 89 GHz transitions with a higher upper-level energy (26.43 K) are regarded as coming from the ‘warm’ phase, while transitions with a lower upper-level energy (1.2 K) are regarded as coming from the ‘cold’ phase. The ‘cold’ glycolaldehyde was found to be widespread around the Sgr B2 complex (Li et al. 2017). Fig. 2(a) shows a contour map of the velocity-integrated intensities of the ‘warm’ glycolaldehyde emission obtained with the ARO 12 m telescope overlaid on the ‘cold’ glycolaldehyde emission acquired with the Shanghai Tianma 65 m telescope in greyscale (Li et al. 2017). The half-power beamwidths were ~70 arcsec and ~77 arcsec for the ARO 12 m observations and 65 m observations, respectively. The ‘cold’ glycolaldehyde is distributed across 800 arcsec (~33 pc in diameter), which is substantially more extended than the ‘warm’ glycolaldehyde. The ‘warm’ glycolaldehyde emission shows several peaks, including the north cloud, the peak near Sgr B2(M), and the ridge west of Sgr B2(N). A weak ‘warm’ glycolaldehyde emission at 89 GHz was also detected toward the eastern component of the Sgr B2 complex.

According to BIMA observations (Hollis et al. 2001), glycolaldehyde is greatly extended in comparison to the ethyl cyanide and dimethyl ether, which are largely confined to the Large Molecule Heimat source (LMH) (Snyder, Kuan & Miao 1994; Miao et al. 1995), so these molecules were classified as either ‘extended’ or ‘compact’ here based on the half-power radius of the spatial distributions in Figs 2 and 3. Fig. 4 shows variation of the normalized integrated intensity of observed transitions with the distance to Sgr B2(N) for sampling points with $\Delta RA = 0$. The normalized intensity is obtained by dividing the integrated intensity by the maximum

integrated intensity of molecule. We change the declination and take a measurement at constant RA ($\Delta RA = 0$). FWHM, the full width at half maximum, is always used to evaluate the linewidth of spectral lines. Thus we selected 50 percent as a metric to evaluate the distribution of molecules. We can see from Fig. 4 that the normalized intensity of CH₃OCH₃, C₂H₅CN and H₂NCH₂CN quickly decrease below 50 per cent for sampling points away from Sgr B2(N). The half-power radii of these molecules are smaller than the sampling interval (1 arcmin). Thus these three molecules are classified as ‘compact’ molecules. H₂NCH₂CN was only detected in Sgr B2(N) in our observations; thus it is also classified as a ‘compact’ molecule. On the other hand, the normalized intensities of CH₂OHCHO, CH₃OCHO, t-HCOOH, C₂H₅OH and CH₃NH₂ vary slowly with the distance to Sgr B2(N); thus these molecules are classified as ‘extended’ molecules. In order to investigate whether only the strongest lines are extended, the ‘extended’ line profiles were coloured red, while the ‘compact’ line profiles were coloured blue in the spectra of Sgr B2(N) (Fig. 1, upper panel). As is shown in the upper panel of Fig. 1, the strongest emissions come from C₂H₅CN, C₂H₅OH, t-HCOOH and CH₃OCH₃. Among them, the C₂H₅CN and CH₃OCH₃ emissions are confined to Sgr B2(N) and Sgr B2(M). Thus it is sure that not all the strongest lines are the most extended. It is noted that CH₂OHCHO peaks away from Sgr B2(N), which seems to differ from most COMs presented in this paper. The line blending makes it difficult to obtain the intensity of CH₂OHCHO accurately. We have mapped CH₂OHCHO around Sgr B2 with the IRAM 30 m telescope with better spatial and spectral resolution to further investigate this issue. The preliminary result is consistent with the ARO 12 m result presented here. A detailed

Figure 2. (a) Velocity-integrated intensity map of ‘warm’ glycolaldehyde CH_2OHCHO 9(1,8)–8(2,7) (contours) overlaid on a velocity-integrated intensity map of ‘cold’ glycolaldehyde CH_2OHCHO 1(1,0)–1(0,1) observed at 13 GHz (Li et al. 2017) in greyscale. The contours are from 3σ increasing in steps of 3σ , which corresponds to 0.21 K km s^{-1} . The 70 arcsec FWHM ARO beam at 90 GHz is shown by a cyan circle, while the 77 arcsec FWHM TMRT beam at 13 GHz is shown by a black circle. (b) Velocity-integrated intensity map of CH_3OCHO 7(2,5)–6(2,4)E (contours) overlaid on a velocity-integrated intensity map of ‘cold’ glycolaldehyde CH_2OHCHO 1(1,0)–1(0,1) observed at 13 GHz (Li et al. 2017) in greyscale. The contours are from 5σ increasing in steps of 5σ , which corresponds to 0.35 K km s^{-1} . The 70 arcsec FWHM ARO beam at 90 GHz is shown by a cyan circle, while the 77 arcsec FWHM TMRT beam at 13 GHz is shown by a black circle. (c) Velocity-integrated intensity map of t-HCOOH 4(0,4)–3(0,3). The contours are from 5σ increasing in steps of 5σ , which corresponds to 0.35 K km s^{-1} . (d) Velocity-integrated intensity map of $\text{C}_2\text{H}_5\text{OH}$ 4(1,4)–3(0,3). The red contours started from and have steps of 1 K km s^{-1} . (e) Velocity-integrated intensity map of CH_3NH_2 1(1,0)–1(0,1). The contours are from 3σ increasing in steps of 3σ , which corresponds to 0.21 K km s^{-1} . The black contours represent 50 per cent of the map peaks, while dots stand for the sampling points in each sub-plot. The 70 arcsec FWHM ARO beam at 90 GHz is shown by a cyan circle in each sub-plot.

chemical model is needed to explain the spatial distribution of glycolaldehyde in this region.

3.1 ‘Extended’ molecules

3.1.1 Glycolaldehyde CH_2OHCHO

CH_2OHCHO , which is a sugar-related molecule, can react with propenal to form ribose – a central constituent of RNA (Sharma

et al. 2016). CH_2OHCHO was first detected in Sgr B2(N) based on the emission spectra in the millimetre-wave range observed with the NRAO 12 m telescope (Hollis et al. 2000). The CH_2OHCHO 8(0,8)–7(1,7) emission at 89 GHz was regarded as coming from ‘warm’ glycolaldehyde, while the 13 GHz emission was regarded as coming from ‘cold’ glycolaldehyde (Hollis et al. 2004). The distribution of ‘warm’ glycolaldehyde is extended and seems to be composed of several emission cores (see Fig. 2). Sensitive interferometric observations are needed to resolve and study these

Figure 3. (a) Velocity-integrated intensity map of CH_3OCH_3 2(2,1)–2(1,2)EE observed with the ARO 12 m telescope. The contours are from 10σ increasing in steps of 10σ , which corresponds to 0.7 K km s^{-1} . (b) Velocity-integrated intensity map of $\text{C}_2\text{H}_5\text{CN}$ 10(4,7)–9(4,6) observed with the ARO 12 m telescope. The contours are from 20σ increasing in steps of 20σ , which corresponds to 1.4 K km s^{-1} . (c) Velocity-integrated intensity map of $\text{H}_2\text{NCH}_2\text{CN}$ 10(0,10)–9(3,6) observed with the ARO 12 m telescope. The contours are from 5σ increasing in steps of σ , which corresponds to 0.04 K km s^{-1} . The black contours represent 50 per cent of the map peaks. Dots stand for the sampling points. The 70 arcsec FWHM ARO beam at 90 GHz is shown by a cyan circle in each sub-plot.

cores in detail. The ‘cold’ glycolaldehyde has been found to be widespread around the Sgr B2 complex (Li et al. 2017). The different spatial distribution of ‘warm’ and ‘cold’ glycolaldehyde seems to be caused by different excitation conditions, including the temperature and density of molecular gas.

3.1.2 Methyl formate CH_3OCHO

ARO observations indicate that the spatial distribution of methyl formate emission significantly differs from both the ‘warm’ and the ‘cold’ glycolaldehyde. It seems to peak toward Sgr B2(N) and Sgr B2(M), and decrease toward the surroundings. Weak emission was seen at the eastern part of the Sgr B2 complex.

3.1.3 Formic acid $t\text{-HCOOH}$

$t\text{-HCOOH}$ is a key organic molecule as the carboxyl group ($\text{C}(=\text{O})\text{OH}$) is one of the main functional groups of amino acids (the structural units of proteins). This species is involved in a chemical route leading to glycine, the simplest amino acid (Redondo, Largo & Barrientos 2015). ARO observations indicate that the spatial distribution of $t\text{-HCOOH}$ extends to the eastern component and peaks at Sgr B2(N).

3.1.4 Ethanol $\text{C}_2\text{H}_5\text{OH}$

$\text{C}_2\text{H}_5\text{OH}$ was first detected toward Sgr B2 (Zuckerman et al. 1975). This molecular was found to be present only in the dense ($\geq 10^6$

cm^{-3}) and hot ($\geq 100 \text{ K}$) cores associated with newly formed massive stars (Martín-Pintado et al. 2001; Bisschop et al. 2007; Qin et al. 2010; Widicus Weaver et al. 2017). Martín-Pintado et al. (2001) found that $\text{C}_2\text{H}_5\text{OH}$ emission in Sgr B2 is widespread. They proposed that $\text{C}_2\text{H}_5\text{OH}$ formed in grains and was released to the gas phase by shocks in the last $\sim 10^5 \text{ yr}$. The results presented here provide further evidence for the presence of extended ethanol around Sgr B2. The $\text{C}_2\text{H}_5\text{OH}$ emission peaks at the north of Sgr B2(N).

3.1.5 Methylamine CH_3NH_2

CH_3NH_2 was first detected in Sgr B2(OH) (Kaifu et al. 1974). It was also detected in the southern region of Sgr B2 (Halfen, Ilyushin & Ziurys 2013). CH_3NH_2 is thought to be a potential interstellar precursor to the amino acid glycine, $\text{NH}_2\text{CH}_2\text{COOH}$. The reaction of CH_3NH_2 with CO_2 in water ice has been shown to yield $\text{NH}_2\text{CH}_2\text{COOH}$ after UV irradiation (Bossa et al. 2009; Lee et al. 2009). Our observations indicate that CH_3NH_2 emission peaks at Sgr B2(N), and extends to the eastern part of Sgr B2 complex, which is in agreement with previous results.

3.2 ‘Compact’ molecules

3.2.1 Dimethyl ether CH_3OCH_3

The CH_3OCH_3 emission is detected toward Sgr B2(N) and a few points near to Sgr B2(N). Though CH_3OCH_3 is an isomer of $\text{C}_2\text{H}_5\text{OH}$, the distributions of these two molecules are strikingly different, implying that they have different chemical routes, which

Figure 4. Variation of the normalized intensity of observed transitions versus the distance to Sgr B2(N) for sampling points with $\Delta RA = 0$. The normalized intensity is obtained by dividing the integrated intensity by the maximum integrated intensity of the molecule. We change declination and take a measurement at constant RA ($\Delta RA = 0$).

is consistent with observations in W51 (Rong et al. 2016). As C_2H_5OH is thought to be produced by grain-surface reactions, CH_3OCH_3 is likely to form via gas-phase chemistry. The spatial distribution of CH_3OCH_3 also differs from that of CH_3OCHO , which seems to be different from observations in massive star-forming regions in the Galactic disc. A striking similarity was found in the spatial distribution, temperature and column densities of these two molecules in star-forming regions in the Galactic disc (Brouillet et al. 2013; Jaber et al. 2014; Rong et al. 2016). CH_3OCH_3 has been proposed as a precursor molecule to CH_3OCHO (Balucani, Ceccarelli & Taquet 2015). The obvious difference in spatial distribution of CH_3OCH_3 and CH_3OCHO observed in Sgr B2 suggests that the formation mechanism of these two molecules might differ in the Galactic centre and Galactic disc sources.

3.2.2 Ethyl cyanide C_2H_5CN

Previous observations of C_2H_5CN in Sgr B2 have shown that this molecule is confined to a small region, and is likely to be located in the hot dense core of the star-forming region (Miao & Snyder 1997). Our mapping results show that C_2H_5CN was only detected toward Sgr B2(N) and at four points near to Sgr B2(N), which agree with previous studies.

3.2.3 Amino acetonitrile H_2NCH_2CN

H_2NCH_2CN was first detected in Sgr B2(N) (Belloche et al. 2008). The source size was estimated to be about 2 arcmin FWHM. No evidence for colder more extended emission was found. Amino acetonitrile may well be a direct precursor of glycine. In our observations, H_2NCH_2CN was only detected toward Sgr B2(N).

3.3 Column densities

According to IRAM 30 m observations of COMs (Requena-Torres et al. 2006), T_{rot} derived from C_2H_5OH is 72.6 K for Sgr B2(N), and 55.4 K for Sgr B2(M). T_{rot} derived from C_2H_5OH ranges from 9–14 K for other Galactic centre clouds; T_{rot} derived from CH_3OCHO ranges from 8–16 K for other Galactic centre clouds. Assuming an excitation temperature of 50 K for Sgr B2(N) and Sgr B2(M), and 14 K for other positions, we calculate the total column densities of ‘warm’ CH_2OHCHO , CH_3OCHO , C_2H_5OH and $t-HCOOH$ for the i, j th grid in the position–position space N_{ij} with the expression reported by Hollis et al. (2004):

$$N_{ij} = \frac{3kQe^{E_u/kT_S}}{8\pi^3\nu S\mu^2} \times \frac{\frac{1}{2}\sqrt{\frac{\pi}{\ln 2}}\frac{\Delta T_A^* \Delta V}{\eta_B}}{1 - \frac{e^{h\nu/kT_S} - 1}{e^{h\nu/kT_{bg}} - 1}}, \quad (1)$$

in which k is the Boltzmann constant in erg K^{-1} , $\frac{\Delta T_A^* \Delta V}{\eta_B}$ is the observed line integrated intensity in K km s^{-1} , ν is the frequency of the transition in Hz, and $S\mu^2$ is the product of the total torsion–rotational line strength and the square of the electric dipole moment. T_S and T_{bg} ($= 2.73 \text{ K}$) are the excitation temperature and background brightness temperature, respectively. E_u/k is the upper-level energy in K. The partition function, Q , was estimated by fitting the partition function at different temperatures given in CDMS (Müller et al. 2005). The values of E_u/k and $S\mu^2$ are also taken from CDMS.

Because of the effects of beam dilution, we did not calculate the column densities of ‘compact’ molecules like C_2H_5CN and

CH_3OCH_3 . In the discussion below, we focus only on oxygen-bearing molecules showing extended emission, including ‘warm’ CH_2OHCHO , CH_3OCHO , C_2H_5OH and $t-HCOOH$.

We made use of the H_2 column density obtained with BGPS 1.1 mm data (Bally et al. 2010) for abundance estimation of molecules. For each position, we searched for the nearest clump identified with BGPS data, and obtained the corresponding hydrogen column density. The H_2 column densities range from 1.1×10^{23} – $1.0 \times 10^{25} \text{ cm}^{-2}$ in our observing region, and peaks toward Sgr B2(N) and Sgr B2(M).

4 DISCUSSIONS

A comparison between the abundances of ethanol and ‘warm’ glycolaldehyde relative to that of $N(H_2)$ for each position is shown in Fig. 5. We found that $X(CH_2OHCHO - \text{warm}) = 0.2X(C_2H_5OH)$, with a correlation coefficient of 0.96. This result agrees well with the relation found for star-forming regions in the Galactic disc: L1157-b1 (Lefloch et al. 2017), IRAS 16293-2422 (Jørgensen et al. 2016), IRAS 2A and IRAS 4A (Taquet et al. 2015) (see Fig. 3). The strong correlation between ethanol and ‘warm’ glycolaldehyde suggests that the ‘warm’ glycolaldehyde may be chemically related to ethanol. Recently, theoretical studies have shown that a new gas-phase scheme of reactions, involving ethanol as a parent molecule, can lead to the formation of glycolaldehyde and formic acid (Skouteris et al. 2018). This model can well explain the abundance correlation between ‘warm’ glycolaldehyde and ethanol. This model is further supported by the strong correlation between the abundances of ethanol and formic acid relative to that of $N(H_2)$ (Fig. 5), with a correlation coefficient of 0.92. The correlation between the abundances relative to H_2 of ethanol, ‘warm’ glycolaldehyde and formic acid suggests that ‘warm’ glycolaldehyde and formic acid are chemically related to ethanol and are possibly produced by ethanol via gas-phase reactions (Skouteris et al. 2018). However, we could not exclude the possibility that these molecules are co-spatial in the same gas and trace a warm gas phase. Interferometric observations of a large sample of interstellar sources could help to investigate whether ethanol, formic acid and ‘warm’ glycolaldehyde are co-spatial and constrain their formation pathways (Xue et al. 2019).

Fig. 5 shows a comparison between the abundances relative to H_2 of ethanol and ‘cold’ glycolaldehyde for each position. The abundance of ‘cold’ glycolaldehyde was observed at the 13 GHz (Li et al. 2017) range from 10^{-11} – 10^{-9} , which is similar to the value for ethanol. We found that $X_{CH_2OHCHO - \text{cold}} = 0.94X_{C_2H_5OH}$, with a correlation coefficient of 0.98. Theoretical studies show that gas-phase chemistry cannot produce the observed abundance of ethanol, even under the most favourable conditions (Charnley et al. 1995). Infrared observations also indicate that interstellar ethanol can be formed by grain-surface reactions significantly more efficiently than by gas-phase chemistry (Sandford et al. 1991); thus, ethanol is thought to be a good tracer of dust chemistry. The good correlation (~ 1) between the abundances of ethanol and ‘cold’ glycolaldehyde indicate that the ‘cold’ glycolaldehyde should also be produced by grain-surface reactions. Similar to ethanol, the desorption mechanism for the ‘cold’ glycolaldehyde should be the large-scale shocks in the Galactic centre region (Martín-Pintado et al. 2001).

Laboratory studies show that glycolaldehyde always forms on icy grains at low temperatures, regardless of UV-photon absorption (i.e. energetic processes), and methyl formate cannot form efficiently in the absence of energetic processes (Chuang et al. 2017).

Figure 5. (a) ‘Warm’ glycolaldehyde abundance as a function of ethanol abundance for different positions in Sgr B2. The relation $X(\text{CH}_2\text{OHCHO} - \text{warm}) = 0.2X(\text{C}_2\text{H}_5\text{OH})$ is marked by the black dashed line. (b) Formic acid abundance as a function of ethanol abundance for different positions in Sgr B2. The relation $X_{\text{t-HCOOH}} = 0.06X_{\text{C}_2\text{H}_5\text{OH}}$ is marked by the black dashed line. (c) ‘Cold’ glycolaldehyde abundance as a function of ethanol abundance for different positions in Sgr B2. The relation $X_{\text{CH}_2\text{OHCHO-cold}} = 0.94X_{\text{C}_2\text{H}_5\text{OH}}$ is marked by the black dashed line.

Overabundant methyl formate would mean additional UV photons to low-temperature surface chemistry. In contrast, under-abundant methyl formate would mean that only the low-temperature process is important in the production of complex organic molecules. This view agrees well with the results presented here, in which methyl formate emission is concentrated on Sgr B2(N) and Sgr B2(M), where massive star-forming activity takes place and UV photons are abundant. In contrast, ‘cold’ glycolaldehyde emission is very widespread and extends to the eastern part of the Sgr B2 complex, where no star-forming activity has been found and the UV radiation should be substantially weaker. Thus, the methyl formate and ‘cold’ glycolaldehyde near to Sgr B2(N) and Sgr B2(M) likely form on icy grains under UV radiation, while ‘cold’ glycolaldehyde in regions away from the H II region likely form on icy grains at low temperature.

5 SUMMARY

We have carried out large-scale mapping observations of a series of COMs toward Sgr B2 with the ARO 12 m telescope.

We obtained large-scale spatial distributions of COMs, including CH_2OHCHO , CH_3OCHO , t-HCOOH , $\text{C}_2\text{H}_5\text{OH}$ and CH_3NH_2 , CH_3OCH_3 , $\text{C}_2\text{H}_5\text{CN}$, in Sgr B2. The main results of this work include:

- (1) The spatial distribution of complex organic molecules can be classified as either ‘extended’ or ‘compact’. The ‘extended’ molecules include CH_2OHCHO , CH_3OCHO , t-HCOOH , $\text{C}_2\text{H}_5\text{OH}$ and CH_3NH_2 , while the ‘compact’ molecules include CH_3OCH_3 , $\text{C}_2\text{H}_5\text{CN}$, and $\text{H}_2\text{NCH}_2\text{CN}$.
- (2) The spatial distribution of CH_3OCHO obviously differs from CH_3OCH_3 , which has been observed to have similar spatial distribution and column densities to those in star-forming regions of the Galactic disc. These results suggest that the formation mechanisms of these two molecules in the Galactic centre may differ from those in star-forming regions of the Galactic disc.
- (3) These ‘compact’ molecules are likely to be produced under strong UV radiation, while ‘extended’ molecules are likely to be formed at low temperatures, via gas-phase or grain-surface reactions.

(4) We found evidence for an overabundance of CH_2OHCHO compared to that expected from the gas-phase model, which indicates that grain-surface reactions are necessary to explain the origin of CH_2OHCHO in Sagittarius B2.

Our measurements demonstrate the necessity of grain-surface chemistry for the production of COMs, such as glycolaldehyde in Sgr B2. The results open up an exciting opportunity to study COMs in the circumnuclear disc of starburst galaxies with interferometers including ALMA, the Next Generation Very Large Array (ngVLA) and SKA. Future high-sensitivity interferometric observations possess the potential to probe COM emissions to investigate whether Central Molecular Zone clouds could serve as a template for the nuclei of starburst galaxies in the nearby and distant universe (Kauffman et al. 2017).

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