Kinematics and chemistry of the hot core in G20.08–0.14N

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ABSTRACT

We present Submillimeter Array (SMA) observations of the the massive star-forming region G20.08–0.14N at 335 and 345 GHz. With the SMA data, 41 molecular transitions were detected related to 11 molecular species and their isotopologues, including SO2, SO, C34S, NS, C17O, SiO, CH3OH, HC3N, H13CO+, HCOOCH3 and NH2CHO. In G20.08–0.14N, 10 transition lines out of the 41 detected belong to SO2, which dominates the appearance of the submillimetre-wave spectrum. To obtain the spatial kinematic distribution of molecules in G20.08–0.14N, we chose the strongest and unblended lines for the channel maps. The channel maps of C34S and SiO, together with their position–velocity diagrams, show that there are two accretion flows in G20.08–0.14N. Additionally, SiO emission shows a collimated outflow in the north-east–south-west direction. The direction of the outflow is revealed for the first time. The rotational temperature and column density of CH3OH are 105 K and 3.1 \times 10^{17} \text{cm}^{-2}, respectively. Our results confirm that a hot core is associated with G20.08–0.14N. The hot core is heated by a protostar radiation at its centre, not by external excitation from shocks. Images of the spatial distribution of different species have shown that the different molecules are located at different positions of the hot core. By comparing the spatial distributions and abundances of molecules, we discuss possible chemical processes for producing the complex sulphur-bearing, nitrogen-bearing and oxygen-bearing molecules in G20.08–0.14N.

Key words: ISM: individual objects: G20.08–0.14N – ISM: kinematics and dynamics – ISM: molecules – stars: formation.

1 INTRODUCTION

Massive stars are formed in dense molecular clouds. Massive star formation also has a significant effect on the chemistry of the surrounding molecular clouds (van Dishoeck & Blake 1998). Hot cores are the formation sites of massive stars. These hot cores are defined as compact (\lesssim 0.1 \text{pc}, n \gtrsim 10^7 \text{cm}^{-3}), relatively high temperature (T_k \gtrsim 100 \text{K}) cloud cores (Kurtz et al. 2000), thought to last about 10^5 \text{yr} (van Dishoeck & Blake 1998). When a hot core is formed, the central massive protostar can produce ionizing radiation and the associated outflow can produce shocks; hence hot cores represent the most chemically rich phase of the massive star formation often associated with Ultra-Compact (UC) H ii regions (Cesaroni, Walmsley & Churchwell 1992; Hatchell et al. 1998; Garay & Lizano 1999; Churchwell 2002). The high abundances of organic molecules in hot cores are consequently attributed to grain-surface chemistry and mantle evaporation processes (van Dishoeck & Blake 1998; Liu, Mehringer & Snyder 2001). Because of the compact and dense nature of hot cores, single-dish observations with large beam sizes are not sufficient to explore dense cores and detailed kinematics. Interferometer observations at submillimetre wavelengths can filter out the extended diffuse components, so that the detailed dynamical processes and chemical conditions of hot cores can be revealed. A number of line observations at submillimetre/millimetre wavelengths were previously used to explore the molecular composition of hot cores (Beuther et al. 2005; Goddi et al. 2009; Qin et al. 2010) but more sources need to be added to the inventory of studied hot cores before their chemical evolution can be understood.

G20.08–0.14N is a massive star-forming region. It is at a distance of approximately 12.3 kpc (Fish et al. 2003; Anderson & Bania 2009), corresponding to a bolometric luminosity of about 6.6 \times 10^5 L_\odot (Galván-Madrid et al. 2009). Previous radio continuum observations at centimetre wavelengths suggest that G20.08–0.14N has three UC and Hyper-Compact (HC) H ii regions (Wood & Churchwell 1989). In addition, single-dish observations of molecular lines show the signatures of infall, accretion and outflow (Klaassen & Wilson 2007, 2008). Moreover, H2O (Hofner & Churchwell 1996), OH (Ho et al. 1983), CH3OH (Walsh et al. 1998) and NH3 (Galván-Madrid et al. 2009) masers in G20.08–0.14N were revealed in some observations. These signatures indicate active massive star formation in this region. The observed CH3CN transitions

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indicate that a hot molecular core is associated with G20.08–0.14N (Galván-Madrí et al. 2009). Thus, G20.08–0.14N provides us with an opportunity to study the physical and chemical conditions of massive star-forming processes.

We have carried out multiline observations towards the massive star-forming region G20.08–0.14N with the Submillimeter Array (SMA). Various molecular lines are used to investigate the physical and chemical processes of G20.08–0.14N. In Section 2, we summarize the observations and data reduction. In Section 3, we give general results. In Section 4, we present data analysis for deriving the rotation temperatures, column densities and abundances of various species relative to $H_2$ and the implications for chemistry. In Section 5, we summarize our main conclusions.

2 OBSERVATIONS AND DATA REDUCTION

Observations towards G20.08–0.14N were carried out with the SMA on 2009 May 20, at 335 (lower sideband) and 345 GHz (upper sideband). The data are from the SMA archive. The two sidebands of the SMA covered frequency ranges of 335.6–337.6 and 345.6–347.6 GHz, respectively. The total observing time is 9.38 h. The phase-track centre was RA (J2000.0) = 18°28'10.50 and Dec. (J2000.0) = −11°28'47.8'. The typical system temperature was 186 K. The spectral resolution is 0.812 MHz, corresponding to a velocity resolution of 0.7 km s$^{-1}$. The bright quasar 3C 273 was used for bandpass calibration, while absolute flux-density scales were determined from observations of Callisto (15 Jy). QSO 1733−130 and QSO 1751+096 were observed for antenna gain corrections. Calibration and imaging were performed in MIRIAD. The continuum image was constructed from the line-free channels. Spectral cubes were constructed using the continuum-subtracted spectral channels. Self-calibration was performed on the continuum data. The gain solutions from the continuum were applied to the line data. The synthesized beam size of the continuum was approximately 2.02 × 1.15 arcsec$^2$ with a PA = 72°.2

3 RESULTS

3.1 Continuum emission at 0.9 mm

Fig. 1 shows the 0.9-mm continuum map of G20.08–0.14N obtained through the SMA observations. Galván-Madrí et al. (2009) resolved the G20.08–0.14N system into three components with the Very Large Array (VLA) at 1.3 cm. Each component represents an H ii region marked in our Fig. 1 (Wood & Churchwell 1989). In particular, H ii region A is the brightest and closest to the peaks at 1.3 and 0.9 mm. By using a two-dimensional Gaussian fit for the continuum emission, we obtained that the total flux density is 2.72 ± 0.03 Jy, the deconvolved source size is 1.83 × 1.22 arcsec$^2$ (PA = 72°) and the peak position is RA (J2000) = 18°28'10.307 (ΔRA = ± 0.01 arcsec), Dec. (J2000) = −11°28'47.846 (ΔDec. = ± 0.01 arcsec) with an intensity of 1.33 ± 0.02 Jy beam$^{-1}$. The peak position of the 0.9-mm continuum emission is coincident with H ii region A within the uncertainty. An H$_2$O maser has been detected in G20.08–0.14N (Hofner & Churchwell 1996). In Fig. 1, the H$_2$O maser is shown by the black filled triangle. The maser is associated with 0.9-mm continuum emission but offset from its peak position.

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1 http://www.cfa.harvard.edu/rttdc/data/search.html.

2 http://www.splatalogue.net

Figure 1. Continuum map towards G20.08–0.14N at 0.9 mm. The contours are at −4, 4, 8, 12, 20, 28, 36, 44 and 49σ. The rms noise level is 0.03 Jy beam$^{-1}$ (1σ). The synthesized beam (2.0 × 1.2 arcsec$^2$) with PA = 72° is shown in the lower right corner. "∗" indicates the position of three H ii regions (Wood & Churchwell 1989; Galván-Madrí et al. 2009). The H$_2$O maser is shown by a filled triangle (blue in the online article). The velocity component of the upper contours (blue in the online article) is from 32.5–36.0 km s$^{-1}$, while the velocity component of the lower contours (red in the online article) is from 47.0–51.7 km s$^{-1}$, where the levels represent 20, 40, 60, 80 and 100 per cent of the peak values.

3.2 Molecular line emission

Molecular lines were identified using the following spectral-line catalogues: (1) Cologne Database for Molecular Spectroscopy (CDMS: Müller et al. 2005), (2) Molecular Spectroscopy data base of the Jet Propulsion Laboratory (JPL, Pickett et al. 1998) and (3) SPLATOGUE line catalogues (Remijan 2007).

The obtained SMA 4-GHz spectrum is shown in Fig. 2 and a full list of identified lines is presented in Table 1. We detected a total of 41 transitions, which includes 35 transitions from 11 species and their isotopologues and six unidentified transitions marked with ‘U’. The identified species contain simple linear molecules as well as complex oxygen-bearing, nitrogen-bearing and sulphur-bearing molecules. Many of the strongest lines in the spectrum are from diatomic molecules of the most abundant elements. The $^{12}$CO $J = 3–2$ line at 345.938 GHz is the strongest line in our passband, but its spectral profile displays absorption features as well. Because the CO absorption features are at the same velocities as the H ii absorption features of Fish et al. (2003), Galván-Madrí et al. (2009) explained that these features may be caused by foreground gas that is not associated with G20.08–0.14N but rather with intervening Galactic spiral arms. In addition, sulphur-bearing molecules such as SO$_2$ and C$^{34}$S also display strong emission lines. The line parameters are presented in Table 1. The first column is the name of the molecular species. The second and third columns list the transition and rest frequency of the molecules. The fourth column lists the upper-level energy of each transition and the fifth column is the product of the line strength and the square of the relevant dipole moment. The sixth, seventh and eighth columns list the central line velocity, peak

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http://www.cfa.harvard.edu/rttdc/data/search.html.

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intensity and full width at half-maximum (FWHM) derived from Gaussian fitting to the line profiles, respectively. The 1σ integrated-intensity noise level of each transition is given in the ninth column.

To obtain the spatial kinematic distribution of molecules in G20.08–0.14N, we chose the strongest and unblended lines for the channel maps if multiple lines for one species were detected. Here we only show the channel maps of C$_{34}$S and SiO in Figs 3–4. The contours are for velocity channels with interval 1 km s$^{-1}$, which begin at 4σ. In Figs 3–4, we present the full velocity range of each molecular emission. The three H ii regions are shown with ‘∗’ symbols. Since H ii region A is coincident with the peak position of the 0.9-mm continuum (within the uncertainty), the symbol for H ii region A can also represent the peak position of the 0.9-mm continuum. The systemic velocity ($V_{sys}$) for G20.08–0.14N is about 42 km s$^{-1}$ (Plume, Jaffe & Evans 1992; Galván-Madrid et al. 2009).

From Figs 3–4, we can see that both molecules show a velocity gradient across the 0.9-mm continuum along the north-east–south-west direction. To determine further the peak movement of the 0.9-mm continuum, we plotted a dashed line across the H ii region A of the four panels in Figs 3–4. Also, the peak position of the continuum above the dashed line is redshifted, while the blueshifted emission is under the dashed line, further confirming that there is a velocity gradient in G20.08–0.14N. According to the channel maps for each species, we produced the integrated intensity map of each species (Fig. 5). In Fig. 5, the emission peaks of CH$_3$OH and HCOOCH$_3$ are associated with the continuum peak. The emission peaks of $^{13}$CH$_3$OH and NH$_2$CHO are located to the north-east of the continuum peak, while the emission peaks of HC$_3$N, C$^{17}$O, C$^{34}$S, NS and SiO are located to the south-west of the continuum peak. Three sulphur-bearing molecules (SO$_2$, $^{34}$SO$_2$ and SO) are situated to the north-west of the continuum peak. Additionally, the emission of H$^{13}$CO$^+$ shows two molecular cores around H ii region A.

The different spatial distribution of molecular gas from different species is reminiscent of the chemical differentiation observed in other hot cores like Orion KL. Most of the nitrogen-bearing molecules peak in the Orion hot core, while most of the oxygen-bearing molecules are found towards the compact ridge (Blake et al. 1987; Beuther et al. 2005; Qin et al. 2010), similarly to what is observed in G19.61–0.23 by Qin et al. (2010). At 7 mm, however, a complex oxygen-bearing molecule (acetone) has been detected towards the Orion hot core, while two nitrogen-bearing molecules (cyanopolyynes) are found in the quiescent cold gas of the Orion extended ridge (Goddi et al. 2009), similarly to what is observed in G20.08–0.14N. Further higher sensitivity and resolution observations, especially from the Atacama Large Millimeter/submillimeter Array (ALMA), are needed to confirm the peak offsets in G20.08–0.14N.

### 3.3 Column densities and abundances

In our observations we detected multiple transitions (>3) from SO$_2$, CH$_3$OH and HC$_3$N but, owing to spectral blending of lines from SO$_2$ and HC$_3$N, we used only CH$_3$OH to calculate the rotation temperature and the column density through a rotation temperature diagram (RTD). Eight transitions of CH$_3$OH have been detected in G20.08–0.14N, containing five-ground state and three vibrationally
excited lines. With the assumptions of local thermodynamic equilibrium (LTE), lines being optically thin and gas emission filling the beam, the rotation temperature and beam-averaged column density can be determined by (Goldsmith & Langer 1999; Liu et al. 2002; Qin et al. 2010)

\[ \ln \left( \frac{N_a}{g_a} \right) = \ln \left( \frac{N \nu}{Q_{rot}} \right) - \frac{E_a}{T_{rot}} \]  

where \( N_a \) is the column density of the upper energy level, \( g_a \) is the degeneracy factor in the upper energy level, \( N \nu / Q_{rot} \) is the total beam-averaged column density, \( Q_{rot} \) is the rotational partition function, \( E_a \) is the upper level energy in K and \( T_{rot} \) is the rotation temperature. By plotting the data points from eight transitions of CH\(_3\)OH according to equation (1) and applying least-squares fitting for a straight line, a RTD is shown in Fig. 6. The RTD can be corrected by multiplying the optical depth correction factor \( \tau \).

\[ \tau = \frac{8\pi \mu^2 S \nu N_a}{3k \Delta \nu I_{rot} g_a} \]  

where \( S \) is the line strength, \( \mu \) is the dipole moment, \( \nu \) (GHz) is the rest frequency, \( k \) is the Boltzmann constant and \( \Delta \nu \) is the FWHM line width. From the optical-depth-corrected data, we derived a rotational temperature of 105 ± 29 K and a beam-averaged column density of \((3.1 ± 2.1) \times 10^{17} \) cm\(^{-2}\) for the G20.08–0.14N region.

Following Qin et al. (2010, their equation 5), the beam-averaged column density of molecules with fewer than three transitions detected could be expressed by

\[ N_f(\text{cm}^{-2}) = 2.04 \times 10^{20} \frac{I(T_{rot})}{I(0)} I_0 \frac{\int I d\nu}{\theta_0 b_0 \nu^3 S \mu^2} \]  

for linear molecules \((T_{rot} = E_b)\) and

\[ N_f(\text{cm}^{-2}) = 2.04 \times 10^{20} \frac{I(T_{rot})}{I(0)} I_0 \frac{\int I d\nu}{\theta_0 b_0 \nu^3 S \mu^2} \]  

for symmetric and asymmetric top molecules \((T_{rot} = 2/3E_b)\), where \( I(T_{rot}) \) and \( I_0 \) are the specific intensities of the spectrum at \( T_{rot} \) and of the background continuum. \( \int I d\nu \) is the integrated intensity of the specific transition in Jy beam\(^{-1}\) and \( \theta_0 \) and \( b_0 \) are the FWHM beam size in arcsec\(^2\).
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Figure 3. Sample images from $^{34}$S and SiO in different velocity channels. In each panel, the synthesized beam is shown in the lower right corner. The "∗" (red in the online article) and filled triangle indicate the position of the three H II regions and H$_2$O maser, respectively. Central velocities are indicated in each image. Contour levels are all $-4, 4, 8, 12, 20, 28, 36, 44 \sigma \ldots$ The oblique dashed line is used to determine the peak positional movement of the core. $^{34}$S, 1σ noise level is 0.1 Jy beam$^{-1}$.

In addition, the fractional abundance of a certain molecule relative to H$_2$ depends on the column densities of that molecule and the H$_2$ molecule, defined by $f_{\text{H}_2} = N_{\text{H}_2}/N_{\text{H}_2}$, where $N_{\text{H}_2}$ is the beam-averaged column density. The optically thin submillimetre dust continuum emission has been proven to be an effective way to determine the H$_2$ column density (Pierce et al. 2000; Gordon 1995). Assuming an average grain radius of 0.1 $\mu$m and a grain density of 3 g cm$^{-3}$ and a gas-to-dust ratio of 100 (Lis, Carlstrom & Keene 1991), the beam-averaged column density is given by the formula (Lis et al. 1991)

$$N_{\text{H}_2}(\text{cm}^{-2}) = 8.1 \times 10^{17} \frac{\text{S}(\nu)}{Q(\nu) \Omega} \left(\frac{\nu}{\text{GHz}}\right)^{-3},$$

where $T$ is the mean dust temperature (K), $Q(\nu)$ is the grain emissivity at frequency $\nu$, $S(\nu)$ is the peak intensity of the continuum and $\Omega$ is the beam solid angle. Assuming radiation equilibrium, Galván-Madrid et al. (2009) set the dust temperature to 230 K for G20.08–0.14N. We adopt $Q(\nu)$ of $4 \times 10^{-5}$ at 340 GHz (Lis et al. 1991) and a dust temperature of 230 K for the calculation of the beam-averaged column density. The intensity of the continuum peak is $1.33 \pm 0.02$ Jy beam$^{-1}$. The derived beam-averaged column density of H$_2$ is $(8 \pm 0.1) \times 10^{23}$ cm$^2$, which is reasonably consistent with those ($\sim 10^{23}$ cm$^2$) in NH$_3$ (Galván-Madrid et al. 2009), $(3 \times 10^{23}$ cm$^2$) in the hot core of G327.3+0.6 (Gibb et al. 2000) and $(8.4 \times 10^{23}$ cm$^2$) in the hot core of G19.61+0.23 (Qin et al. 2010). Therefore, the derived density of H$_2$ is reliable. The fractional abundances of the various species relative to H$_2$ are estimated from the beam-averaged column densities as shown in the fourth column of Table 2.
4 DISCUSSION

4.1 Kinematics

Recently, through numerical simulation, Vázquez-Semadeni et al. (2009) suggested that the formation of massive stars is coincident with large-scale collapse, while low-mass and intermediate-mass stars are associated with isolated accretion flows. Previous observations with the SMA in hot-core molecules (CH$_3$CN, OCS and SO$_2$) and the VLA in NH$_3$ show that G20.08–0.14N is surrounded by smaller scale and large-scale accretion flows (Galván-Madrid et al. 2009). The smaller scale accretion flow is across H II region A, which may be resupplied by the large-scale accretion flow. The channel maps of SiO and C$^{34}$S in Figs 3–4 exhibit a velocity gradient along the south-west–north-east, suggesting that this is an inflow or rotation motion around H II region A of G20.08–0.14N.

To explore whether there are two accretion flows in G20.08–0.14N, we made position–velocity (PV) diagrams (Fig. 7) of SiO and C$^{34}$S lines across H II region A with cuts at PA = 45° and 135°. Since SiO is more easily affected by the excitation conditions, the PV diagrams of SiO present a complex pattern containing several velocity components. To analyse each component in detail, we divide the whole component into six regions. Each has been designated alphabetically: regions D–I. From Fig. 7(a) and (b), we find two velocity components in regions D and I that are not seen in the perpendicular direction PA = 135°. The velocity component of region D is from 32.5–36.0 km s$^{-1}$, while the velocity component of region I is from 47.0–51.7 km s$^{-1}$. By comparing this with previous observations of CH$_3$CN, OCS, SO$_2$ and NH$_3$ (Galván-Madrid et al. 2009), we find that the two velocity components of SiO detected in regions D and I do not belong to the velocity ranges of the accretion flows of Galván-Madrid et al. (2009). Since SiO is considered as a good tracer of outflow (e.g. Schilke et al. 1997b; Gueth & Guilloteau 1999; Cesaroni et al. 1999; Beuther et al. 2005), we suggest that the two velocity components of SiO may arise from an outflow in the north-east–south-west direction. To confirm the
Figure 5. The integrated intensity maps of each species. Contour levels are all 3, 4, 5, 6, 7, 8, 9, 10 $\sigma$. The $1\sigma$ noise levels (Jy beam$^{-1}$ km s$^{-1}$) of various species are presented in Table 1.
were detected, are \(2.5 \pm 0.2\) \(\times 10^{-8}\) \(\pm 0.1\) \(\times 10^{-8}\). in the maximum flow velocity \(0.2\) \(\times 10^{-9}\). is the length of the begin-to-end flow extension for each lobe. From Fig. 1, we derived that the lengths of the blueshifted and redshifted lobes \(S\) are 0.15 and 0.36 pc, respectively.

Figure 6. Population temperature diagram of the observed CH$_3$OH transitions. The vertical bars mark the ln\((N_{\text{rot}}/g_e)\) errors from the integrated intensities. The linear least-squares fit (solid line) gives a rotation temperature of \(105 \pm 29\) K.

Table 2. The parameters derived from molecular lines.

| Molecule     | \(T_{\text{rot}}\) (K) | \(N_T\) (cm\(^{-2}\)) | \(f_{\text{H}_2}\) |
|--------------|-------------------------|-------------------------|-----------------|
| SO$_2$       | 112                     | \((2.5 \pm 0.1) \times 10^{16}\) | \((3.2 \pm 0.1) \times 10^{-8}\) |
| $^{34}$SO$_2$| 192                     | \((3.2 \pm 0.2) \times 10^{16}\) | \((4.2 \pm 0.2) \times 10^{-8}\) |
| SO           | 143                     | \((3.7 \pm 0.2) \times 10^{17}\) | \((4.8 \pm 0.2) \times 10^{-7}\) |
| C$^{34}$S    | 50                      | \((5.1 \pm 0.1) \times 10^{14}\) | \((6.5 \pm 0.2) \times 10^{-10}\) |
| NS           | 71                      | \((3.3 \pm 0.1) \times 10^{15}\) | \((4.2 \pm 0.2) \times 10^{-9}\) |
| HCN          | 307                     | \((7.8 \pm 0.2) \times 10^{15}\) | \((1.0 \pm 0.1) \times 10^{-8}\) |
| NH$_2$CHO    | 100                     | \((4.4 \pm 0.5) \times 10^{14}\) | \((5.7 \pm 0.3) \times 10^{-10}\) |
| C$^{17}$O    | 33                      | \((7.0 \pm 0.2) \times 10^{17}\) | \((9.0 \pm 0.2) \times 10^{-7}\) |
| SiO          | 75                      | \((1.8 \pm 0.1) \times 10^{15}\) | \((2.3 \pm 0.2) \times 10^{-9}\) |
| H$^{13}$CO$^+$| 28                     | \((2.2 \pm 0.2) \times 10^{14}\) | \((2.9 \pm 0.2) \times 10^{-10}\) |
| CH$_3$OH     | 105 $\pm$ 29           | \((3.1 \pm 2.1) \times 10^{17}\) | \((4.0 \pm 2.7) \times 10^{-7}\) |
| $^{13}$CH$_2$OH| 170                    | \((3.5 \pm 0.7) \times 10^{15}\) | \((4.5 \pm 0.8) \times 10^{-9}\) |
| HCOOCH$_3$   | 165                     | \((3.5 \pm 0.3) \times 10^{13}\) | \((4.5 \pm 0.4) \times 10^{-7}\) |

Moreover, the velocities of regions F and G at the peak position are 39.0 and 44 km s$^{-1}$, respectively, both of which may have a velocity gradient of \(\sim 2.0\) km s$^{-1}$ with respect to \(V_{\text{sys}}\). The velocity gradient is coincident with the inward velocity found in the NH$_3$ absorption line at smaller scale (Galván-Madrid et al. 2009), while the velocity of both regions E and H with respect to \(V_{\text{sys}}\) is \(\sim 4.0\) km s$^{-1}$, which is associated with the rotation velocity at larger scale (Galván-Madrid et al. 2009). Additionally, from Fig. 7(c) and (d) we also find that the PV diagram of C$^{13}$S shows a velocity gradient at PA = 135$^\circ$ and 45$^\circ$. C$^{13}$S is used to trace Keplerian rotation (Beuther et al. 2009). Galván-Madrid et al. (2009) also observed a velocity gradient in molecular lines at PA = 45$^\circ$, which they interpret as rotation in a torus/disc, the plane of which is oriented north-east–south-west. Our measurements, however, provide clear indication of an outflow along the same north-east–south-west direction. Therefore, we favour a model where the detected velocity gradients at PA = 135$^\circ$ are caused by rotation motions (and possibly infall) in the direction perpendicular to the outflow. However, in this model we cannot explain the velocity gradients detected at PA = 45$^\circ$ in regions E–H of Fig. 7(a) and (c).

4.2 Chemistry

From Table 1, we can see that 11 species were detected. The emission peaks for different molecules are located at different positions in the core (Fig. 5), hence each molecule may be produced via a different mechanism. The individual molecules are discussed below.

4.2.1 Sulphur-bearing molecules

The sulphur chemistry is of specific interest because of its rapid evolution in warm gas and since the abundances of sulphur-bearing species increase significantly with temperature, both by ice evaporation and by shock interaction.

Sulphur dioxide (SO$_2$): eight transitions of SO$_2$ were detected, containing four ground-state and four vibrationally excited lines. SO$_2$(19$_{17}$–18$_{16}$) at 346.652 16 GHz is the strongest unblended line. Because SO$_2$ is an inorganic asymmetric molecule, adopting a rotation temperature of \(T_{\text{rot}} = 2/3E_g\) estimated that the column density and abundance of SO$_2$ are \((2.5 \pm 0.1) \times 10^{-6}\) and \((3.2 \pm 0.1) \times 10^{-8}\), respectively. The derived abundance of SO$_2$ is consistent with those in Sgr B2, G29.26 and G19.61–0.23 (Nummelin et al. 2000; Beuther et al. 2009; Qin et al. 2010) but larger than that in Orion KL (Beuther et al. 2009). It has recently been suggested that the Orion KL hot core may be only a pre-existing density enhancement heated from the outside by shocks (Zapata, Schmid-Burgk & Menten 2011; Goddi et al. 2011). Via shock-induced chemical models, Hartquist et al. (1980) estimated that the abundance of SO$_2$ is \(3.7 \times 10^{-11}\). The highest fractional abundance relative to H$_2$ in G20.08–0.14N can be explained by grain-surface chemistry, not by shock interaction of a molecular outflow with the ambient dense gas. Two transitions of the $^{34}$SO$_2$ isotopologue were detected. In Orion, SO$_2$ dominates the appearance of the millimetre-wave spectrum (Schilke et al. 1997a), accounting for approximately 28 per cent of all the detected lines. Because of its asymmetric geometry, it has a rich spectrum of lines that are typically very strong because of the large abundance and high dipole moment of the molecule. In G20.08–0.14N, 10 of the detected 41 transition lines belong to SO$_2$ and its isotopologue, which is similar to the case in Orion.

Sulphur monoxide (SO): sulphur monoxide was detected in the (10$_{17}$–10$_{16}$) transition at 336.553 75 GHz. The derived column density and abundance are \((3.7 \pm 0.2) \times 10^{17}\) and \((4.8 \pm 0.2) \times 10^{-7}\),
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Figure 7. PV diagrams of SiO and C\textsuperscript{34}S. The upper diagrams are for a cut at PA = 45\degree (north-east–south-west), while the lower diagrams are at PA = 135\degree (north-west–south-east). Cuts are across the position of H\alpha region A. The black dashed line indicates \( V_{\text{sys}} \). Other lines (blue and red in the online article) are used to mark the beginning and end of each velocity component.

respectively. Charnley (1997) has investigated the formation of SO and SO\(_2\). When \( t \leq 10^4 \) yr, the evolution of the sulphur chemistry in the models shows that sulphur monoxide is produced by reaction \( \text{SH} + \text{O} \rightarrow \text{SO} + \text{H} \). When \( t \geq 2 \times 10^4 \) yr, the reaction \( \text{S} + \text{OH} \rightarrow \text{SO} + \text{H} \) is also important at 100 K, along with \( \text{S} + \text{O}_2 \rightarrow \text{SO} + \text{O} \). For increasing core temperature, reaction \( \text{S} + \text{O}_2 \rightarrow \text{SO} + \text{O} \) dominates. Considering a SO\(_2\) abundance of \((3.2 \pm 0.1) \times 10^{-8}\), we obtained an SO/SO\(_2\) abundance ratio of \( 15 \pm 0.2 \) in G20.08–0.14N, which can be explained by the ‘evaporated mantles’ model without \( \text{O}_2 \) injection at 200 K. From this model we estimated that the age of the G20.08–0.14N hot core is about \( 8 \times 10^3 \) yr, which is less than the dynamical time-scale of the outflow identified by SiO. In Fig. 5, the emission peak of SO is located to the north-west of the continuum peak, which is perpendicular to the direction of the outflow. Hence, although the outflow can excite the formation of SO from the time-scales, SO may be produced by reaction \( \text{SH} + \text{O} \rightarrow \text{SO} + \text{H} \). After some time, we may detect the SO excited by the outflow.

Carbon monosulphide (CS): the rare carbon–sulphur isotopologue \( \text{C}^{34}\text{S} \) (7–6) is detected at 337.396 46 GHz. The estimated column density and fractional abundance of \( \text{C}^{34}\text{S} \) are \((5.1 \pm 0.1) \times 10^{14}\) and \((6.5 \pm 0.2) \times 10^{-10}\), respectively. The derived column density of \( \text{C}^{34}\text{S} \) is similar to the one observed in Orion KL (Beuther et al. 2009). Beuther et al. (2009) considered that the formation of \( \text{C}^{34}\text{S} \) can be successfully explained by gas chemistry models. Moreover, the PV diagrams of \( \text{C}^{34}\text{S} \) show inflow and rotation motions, further confirming that \( \text{C}^{34}\text{S} \) should be a better tracer of the rotational disc at very early evolutionary stages.

4.2.2 Nitrogen-bearing molecules

Theoretical models and observations suggest that nitrogen-bearing molecules have higher gas temperatures and lower fractional abundances on a time-scale of \( \sim 10^5 \) yr (Blake et al. 1987; Miao et al.
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In the G20.08−0.14N hot core, Galván-Madrí et al. (2009) detected NH$_3$ and CH$_3$CN molecules. They derived that the fractional abundances of both molecules are about 5 x 10$^{-7}$ and 5 x 10$^{-9}$ to 2 x 10$^{-8}$. NH$_3$ and CH$_3$CN are the best tracers of hot cores (e.g., Wilner, Wright & Plambeck 1994; Wright, Plambeck & Wilner 1995; Wilson et al. 2000). NH$_3$ may originate from the evaporation of grain mantles (Pauls et al. 1983), driving a nitrogen-rich chemistry and producing many complex nitrogen-bearing molecules (Caselli, Hasegawa & Herbst 1993). Here we detected three nitrogen-bearing molecules, cyanoacetylene, nitrogen sulphone and formamide, towards the G20.08−0.14N hot core.

Cyanoacetylene (HC$_3$N): we detected the two ground-state and three vibrationally excited state lines of HC$_3$N, HC$_3$N (38−37$\tau$) at 346.455 73 GHz is the strongest and is unblended. Using this transition line, we obtained a HC$_3$N column density and fractional abundance of (7.8 ± 0.2) x 10$^{15}$ and (1.0 ± 0.1) x 10$^{-8}$, respectively. The derived fractional abundance of HC$_3$N is one order of magnitude larger than that in Orion KL and Sgr B2 (Beuther et al. 2009; Nummelin et al. 2000), but is consistent with that in G19.61−0.23 (Qin et al. 2010) and IRAS 20126+4104 (Xu, Wang & Ning 2012). Qin et al. (2010) and Xu et al. (2012) suggest that the higher fractional abundance of CH$_3$OH with respect to H$_2$ can be explained by grain-surface chemistry. Grain-surface chemistry models predict that the abundance of CH$_3$OH is larger than 10$^{-8}$ (van der Tak, van Dishoeck & Caselli 2000), while gas chemical models predict an abundance of < 10$^{-9}$ (Lee et al. 1996). In G20.08−0.14N, the higher fractional abundance of CH$_3$OH cannot be interpreted simply by gas-phase emical reactions and may originate from grain-surface chemistry. The 12$^{13}$C/$^{12}$C ratio from CH$_3$OH and 13$^{15}$CH$_3$OH is ~9. Milam et al. (2005) concluded that the 12$^{13}$C/$^{12}$C ratio obtained from CO indicates a gradient in Galactic distance of 12$^{13}$C/$^{12}$C = 5.41D + 19.03, where D is the distance from the Galactic centre in kpc. Using the 12$^{13}$C/$^{12}$C ratio from CH$_3$OH, we derived that the distance of G20.08−0.14N is 12.9 kpc, which is close to the values reported by Fish et al. (2003) and Anderson & Bania (2009).

Silicon monoxide (SiO): SiO J = 7−6 (ν = 0) was detected at rest frequencies of 347.330 63 GHz with an upper-level energy of 75 K. The column density and fractional abundance derived from a single line of SiO (1.8 ± 0.1) x 10$^{15}$ and (2.3 ± 0.2) x 10$^{-8}$, respectively. The derived column density of SiO is an order of magnitude higher than that of Orion KL and G29.96 (Beuther et al. 2005). One explanation for the SiO abundance enhancements in shocked gas is that SiO is produced by destruction of grain cores in shocks (Caselli, Hartquist & Haynes 1997; Schilke et al. 1997b). Another possibility is that SiO is embedded in icy grain mantles, which are evaporated. Hence, we suggest that SiO may be produced by the destruction of grain cores in the shocks of an outflow.

Formyl ion (HCO$^+$) and methyl formate (HCOOCH$_3$): we detected the (4−3) transitions of the H$^{13}$CO$^+$ isotopologue. The estimated column density and fractional abundance of H$^{13}$CO$^+$ are (2.2 ± 0.2) x 10$^{14}$ and (2.9 ± 0.2) x 10$^{-10}$. In Fig. 5, the emission of HCO$^+$ shows an elongated structure with two cores. Since the HCO$^+$ is blended with the line from CH$_3$CN at 346 983.8 MHz, the latter could be responsible for the complex structure of HCO$^+$. HCOOCH$_3$ is a heavy asymmetric rotor with hindered internal rotation of the methyl group. Two transitions of HCOOCH$_3$ were detected with relatively weak emission. Using the transition of HCOOCH$_3$ at 347.478 24 GHz, we obtained a column density and fractional abundance of (3.5 ± 0.3) x 10$^{17}$ and (4.5 ± 0.4) x 10$^{-7}$, respectively. Our obtained column density of HCOOCH$_3$ is consistent with that of Sgr B2 (N) (Liu et al. 2001), but larger than that (~10$^{-8}$) produced by gas-phase chemistry.

In the Orion KL hot core, the hot molecular gas is not associated with any self-luminous millimetre, radio or embedded infrared source, Goddi et al. (2011) and Zapata et al. (2011)
suggested that the Orion KL hot core may be only a pre-existing density enhancement heated from the outside by shocks from a molecular outflow. On the other hand, in G20.08–0.14N the molecular gas is associated with a millimetre source and an H II region and clearly shows star-formation activity. This indicates that the G20.08–0.14N hot core is heated by a protostar forming at its centre. Based on the chemical models discussed here, we concluded that the age of the G20.08–0.14N hot core should be about $10^5$–$10^6$ yr.

5 SUMMARY

Submillimeter Array observations towards the high-mass star-forming region G20.08–0.14N are presented in the submillimetre continuum and in the form of molecular line transitions. From the SMA data, 0.9-mm continuum emission reveals an extended structure associated with an H II region and HC H II regions. 41 molecular transitions were detected related to 11 molecular species, including SO$_2$, SO, C$^{13}$S, NS, C$^{17}$O, SiO, CH$_3$OH, HC$_3$N, H$_2$CO$^+$, HC$_3$COOH, NH$_2$CHO and their isotopic species. In addition, six molecular transitions are unidentified. 10 transition lines of the detected 41 transition lines belong to SO$_2$, which dominates the appearance of the submillimetre-wave spectrum. The channel maps of C$^{13}$S and SiO show velocity gradients. In their PV diagram, C$^{13}$S emission shows rotation motions, while SiO emission not only presents two rotation motions at smaller and larger scales respectively but also reveals for the first time a collimated outflow along the north-east–south-west direction. The average dynamical time-scale of the outflow is about $2.6 \times 10^4$ yr. An H II region is situated in the central position of the outflow, which may drive the collimated outflow. Eight transitions of CH$_3$OH are unblended; we derived a rotational temperature and column density of 105 K and $3.1 \times 10^{17}$ cm$^{-2}$ for CH$_3$OH lines, respectively, further indicating that a hot core coincides with G20.08–0.14N. The hot core is heated by a protostar at its centre with an age of $10^5$–$10^6$. The emission peaks of different molecules are located at different positions of the hot core. By comparing the abundances of different species with chemical models and previous observations of other hot cores, we concluded that each species may be produced by a different mechanism. Nitrogen sulphide (NS) is detected in G20.08–0.14N for the first time.

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