INFALL AND OUTFLOW MOTIONS IN THE HIGH-MASS STAR-FORMING COMPLEX G9.62+0.19

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ABSTRACT

We present the results of a high-resolution study with the Submillimeter Array toward the massive star-forming complex G9.62+0.19. Three submillimeter cores are detected in this region. The masses are 13, 30, and 165 $M_\odot$ for the northern, middle, and southern dust cores, respectively. Infall motions are found with HCN (4–3) and CS (7–6) lines at the middle core (G9.62+0.19 E). The infall rate is $4.3 \times 10^{-3} M_\odot$ yr$^{-1}$. In the southern core, a bipolar outflow with a total mass about 26 $M_\odot$ and a mass-loss rate of $3.6 \times 10^{-5} M_\odot$ yr$^{-1}$ is revealed in SO (8–7–7). CS (7–6) and HCN (4–3) lines trace higher velocity gas than SO (8–7). G9.62+0.19 F is confirmed to be the driving source of the outflow. We also analyze the abundances of CS, SO, and HCN along the redshifted outflow lobes. The mass–velocity diagrams of the outflow lobes can be well fitted by a single power law. The evolutionary sequence of the centimeter/millimeter cores in this region is also analyzed. The results support that ultracompact H II regions have a higher blue excess than their precursors.

Key words: ISM: individual objects (G9.62+0.19) – ISM: kinematics and dynamics – ISM: molecules – stars: formation – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

High-mass stars play a major role in the evolution of the Galaxy. They are the principal sources of heavy elements and UV radiation (Zinnecker & Yorke 2007). However, the formation and evolution of high-mass stars are still unclear. A possible evolution sequence of high-mass stars from infrared dark clouds to classic H II regions has been suggested (Van der Tak & Menten 2005). But one of the major topics—whether high-mass stars form through accretion-disk outflow, like low-mass objects (Shu et al. 1987), or via collision coalescence (Wolfire & Cassinelli 1987; Bonnell et al. 1998)—is still far from being solved.

Yet more and more observations at various resolutions seem to support the accretion-disk-outflow models rather than the collision-coalescence models. Disks are detected in several high-mass star-forming regions (Patel et al. 2005; Jiang et al. 2005; Sridharan et al. 2005). Outflows are found with high detection rate as in low-mass cores in single-dish surveys (Wu et al. 2004; Zhang et al. 2005; Qin et al. 2008b). High-resolution studies have also confirmed that molecular outflows are common in high-mass star-forming regions (Su et al. 2004; Qiu et al. 2007, 2009; Qin et al. 2008a, 2008c). Searching for inflow motions has also made large progress in recent years (Wu & Evans 2003; Fuller et al. 2005; Wyrowski et al. 2006; Klaassen & Wilson 2007; Wu et al. 2007, 2009; Furuya et al. 2011). Both infall and outflow motions in the massive core JCMT 18354–0649S are detected (Wu et al. 2005) and further confirmed by higher resolution observations (Liu et al. 2011). Although accretion-disk-outflow systems are found in high-mass star-forming regions, there may be differences between low- and high-mass formation.

The infall motion can be detected via “blue profile,” a double-peaked profile with the blueshifted peak being stronger for optically thick lines and a single peak at the absorption part of optically thick lines for optically thin lines, which is caused by self-absorption of the cooler outer infalling gas toward the warmer central region (Zhou et al. 1993). In contrast, the “red profile” where the redshifted peak of a double-peaked profile is stronger for optically thick lines is suggested as an indicator for outflow motions. Mardones et al. (1997) defined the “blue excess” in a survey, E, as $E = (N_B - N_R)/N_T$, where $N_T$ is the number of sources and $N_B$ and $N_R$ mark the number of sources with blue and red profiles, respectively. The blue excess seems to have no significant differences among the low-mass cores in different evolutionary phases. However, using the IRAM 30 m telescope, Wu et al. (2007) found that ultracompact (UC) H II regions show a higher blue excess than their precursors, indicating fundamental differences between low- and high-mass star-forming conditions. The searches need to be expanded.

Located at a distance of 5.7 kpc (Hofner et al. 1994), G9.62+0.19 is a well-studied high-mass star-forming region containing a cluster of H II regions, which are probably at different evolutionary stages. Multiwavelength Very Large Array observations have identified nine radio continuum sources (denoted from A to I; Garay et al. 1993; Testi et al. 2000); components C to I are very compact (<5″) in diameter; Garay et al. 1993; Testi et al. 2000). As revealed in NH3 (4,4), (5,5), and CH3CN (J = 6–5), component F is a hot molecular core (HMC) and hence likely the youngest source in the region (Cesaroni et al. 1994; Hofner et al. 1994, 1996). G9.62+0.19 E is a young massive star surrounded by a very small UC H II region and a dusty envelope (Hofner et al. 1996), while G9.62+0.19 D is a small cometary UC H II region excited by a B0.5 zero-age main-sequence star (Hofner et al. 1996; Testi et al. 2000). Both G9.62+0.19 F and G9.62+0.19 D seem to be at a more evolved stage than G9.62+0.19 F. Thus, G9.62 complex is an ideal...
sample to examine massive star-forming activities including outflow and infall motions.

Maser emissions of NH$_3$, H$_2$O, OH, and CH$_3$OH, as well as the strong thermal NH$_3$ emissions, were detected along a narrow region with projected length 20″ and width ≤2″ (Hofner et al. 1994). A possible explanation for this alignment is compression of the molecular gas by shock front originating from an even more evolved H II region to the west of the star-forming front (Hofner et al. 1994). High-velocity molecular outflows have also been detected in this region, and G9.62+0.19 F is believed to be the driving source (Gibb et al. 2004; Hofner et al. 2001; Su et al. 2005). However, most of the previous work was carried out at low frequencies, probing low excitation conditions. To examine the hot dust/gas environment and dynamical processes in this region, higher resolution studies at high frequencies are needed. In this paper, we report the results of the Submillimeter Array (SMA) observations toward the G9.62+0.19 region at 860 μm.

2. OBSERVATIONS

The observations of G9.62+0.19 with the SMA were carried out on 2005 July 9 with seven antennas in its compact configuration at 343 GHz for the lower sideband (LSB) and 353 GHz for the upper sideband (USB). The $T_{\text{sys}}$ ranges from 210 to 990 K with a typical value of 380 K at both sidebands during the observations. The observations had two fields for the G9.62+0.19 complex to cover the entire region with emissions. One phase reference center was R.A. (J2000) = 18°06′14″21 and decl. (J2000) = −20°31′46″2, and the other was R.A. (J2000) = 18°06′15″00 and decl. (J2000) = −20°31′34″20. Uranus and Neptune were observed for antenna-based bandpass calibration. QSOs 1743-038 and 1911-201 were employed for antenna-based gain correction. Neptune was used for flux-density calibration. The frequency spacing across the spectra band was 0.8125 MHz corresponding to a velocity resolution of ~0.7 km s$^{-1}$.

MIRIAD was employed for calibration and imaging (Sault et al. 1995). The imaging was done to each field separately and the mosaic continuum map was made using a linear mosaicing algorithm (task “linmos” in MIRIAD). The 860 μm continuum data were acquired by averaging over all the line-free channels in both sidebands. The spectral cubes were constructed using the continuum-subtracted spectral channels smoothed into a velocity resolution of 1 km s$^{-1}$. Additional self-calibration with models of the clean components from a previous imaging process was performed on the continuum data in order to remove residual errors due to phase and amplitude problems, and the gain solutions obtained from the continuum data were applied to the line data. The synthesized beam size of the continuum emission with robust weighting of 0.5 is 2′′.76 × 1′′.88 (P.A. = 21′′.4).

3. RESULTS

3.1. Continuum Emission

The 860 μm continuum image combining the visibility data from both sidebands is shown in Figure 1. Three submillimeter cores are detected. The known centimeter and millimeter continuum components (Testi et al. 2000) of B, C, D, E, F, G, H, and I are marked by plus signs. Water masers (Hofner & Churchwell 1996) are marked by open squares and methanol masers (Norris et al. 1993) by triangles. The near-IR sources (Persi et al. 2003; Testi et al. 1998; Linz et al. 2005) are marked by filled circles. IRAC sources are marked with asterisks.

I are marked by plus signs. Water masers (Hofner & Churchwell 1996) are marked by open squares and methanol masers (Norris et al. 1993) by triangles. The near-IR sources (Persi et al. 2003; Testi et al. 1998; Linz et al. 2005) are marked by filled circles. IRAC sources are taken from the database of the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) and labeled with asterisks. The northern core is located at the southeast of G9.62+0.19 C, and the middle core is associated with G9.62+0.19 E. The 860 μm continuum emission at the southern core is concentrated on the HMC G9.62+0.19 F and extends to G9.62+0.19 D in the south and to G9.62+0.19 G in the north.

Gaussian fits were made to the continuum. The northern core seems to be a point-like source. The middle core is very compact with a deconvolved size of ~1′′.4. The southern core is found to be elongated from north to south with an average size of 2′′.4, containing at least three sources, D, F, and G. F is at its peak position. The peak positions, sizes, peak intensities, and total fluxes of these three submillimeter cores are listed in Columns 2–5 in Table 1. The physical properties of these cores will be further discussed in Section 4.2.

3.2. Line Emission

Tens of molecular transitions including hot molecular lines CH$_3$OH, HCOOCH$_3$, and CH$_3$OCH$_3$ are detected toward both the middle and southern submillimeter cores, indicating these two cores are hot and dense (Qin et al. 2010). Figure 2 presents the full LSB and USB spectra in the UV domain over the shortest baseline. The strongest lines are identified and labeled on the plots. Only HCN (4–3) and CS (7–6) line emissions are detected toward the northern core with our sensitivity. Thus, we mainly focus on the middle and southern cores in this paper.

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6 Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

7 http://irsa.ipac.caltech.edu/data/SPITZER/GLIMPSE/
The systemic velocities of 2.1 km s\(^{-1}\) for the middle core and 5.2 km s\(^{-1}\) for the southern core are obtained by averaging the \(V_{lsr}\) of multiple singly peaked lines. Six transitions of the thioformaldehyde (H\(_2\)CS) and molecular transitions SO (87–77), CS (7–6), HC\(_{15}\)N (4–3), and HCN (4–3) are analyzed here, while the others will be discussed in another paper. We have made Gaussian fits to the beam-averaged spectra and present the observed parameters of these lines in Table 2. The strongest lines are identified and labeled on the plots.

### 3.2.1. Line Emission at the Middle Submillimeter Core

The integrated intensity maps of four transitions of H\(_2\)CS toward the middle core are shown in the upper panels of Figure 3. From panels (a) to (d), the upper level energy of H\(_2\)CS transitions varies from \(~90\) K to \(~400\) K from panels (e) to (h). As the upper level energy increases, the emission peak of the different transitions of H\(_2\)CS moves from southeast to northwest, indicating a temperature gradient in the southern core.

The integrated intensity maps of four transitions of H\(_2\)CS toward the middle core are shown in the upper panels of Figure 3. From panels (a) to (d), the upper level energy of H\(_2\)CS transitions varies from \(~90\) K to \(~400\) K from panels (e) to (h). As the upper level energy increases, the emission peak of the different transitions of H\(_2\)CS moves from southeast to northwest, indicating a temperature gradient in the southern core.

### 3.2.2. Line Emission at the Southern Core

The integrated intensity maps of four transitions of H\(_2\)CS at the southern core are shown in the lower panels of Figure 3. The upper level energy of H\(_2\)CS transitions varies from \(~90\) K to \(~400\) K from panels (e) to (h). As the upper level energy increases, the emission peak of the different transitions of H\(_2\)CS moves from southeast to northwest, indicating a temperature gradient in the southern core.

The integrated intensity maps of four transitions of H\(_2\)CS at the southern core are shown in the lower panels of Figure 3. The upper level energy of H\(_2\)CS transitions varies from \(~90\) K to \(~400\) K from panels (e) to (h). As the upper level energy increases, the emission peak of the different transitions of H\(_2\)CS moves from southeast to northwest, indicating a temperature gradient in the southern core.

The spectra and integrated intensity maps of HC\(_{15}\)N (4–3) and SO (87–77) are presented in Figure 5. The two spectra seem to be symmetric and their cores are associated with that of the continuum emission very well.

Figure 6 presents the spectra and P–V diagrams of HCN (4–3) and CS (7–6) emissions of the middle core. HCN (4–3) and CS (7–6) show asymmetric profiles. The blue and red emission peaks of HCN (4–3) are around 0 and 6 km s\(^{-1}\), respectively. The blueshifted emission of CS (7–6) peaks around 1 km s\(^{-1}\), while the redshifted one around 4 km s\(^{-1}\). We can see that the blueshifted emission of both HCN (4–3) and CS (3–2) is always stronger than the redshifted emission and the absorption is also redshifted, which are blue profiles (see Section 1). Besides the “blue profile,” some weak absorption dips are found around 10 km s\(^{-1}\) in both the spectra and P–V diagrams of HCN (4–3) and CS (7–6), and further observations are needed to determine the properties of these absorption dips. In this paper, we only pay attention to the “blue profile” found in CS (7–6) and HCN (4–3) emissions.

The integrated intensity maps of HCN (4–3) and CS (7–6) toward the middle core are presented in Figure 7. The HCN (4–3) and CS (7–6) are associated with the dust emission.

### Notes.

a The dust temperature is assumed to be the same as the rotational temperature of H\(_2\)CS transitions.

b The opacity index \(\beta\) is obtained from Su et al. (2005).
Table 2
Observed Parameters of the Lines

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition a</th>
<th>Frequency (GHz)</th>
<th>$E_u$ (K)</th>
<th>rms (Jy beam$^{-1}$)</th>
<th>$V_{lsr}$ b (km s$^{-1}$)</th>
<th>Intensity b (Jy beam$^{-1}$)</th>
<th>FWHM b (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
<td>D</td>
</tr>
<tr>
<td>H$_2$CS</td>
<td>10$<em>{0,10}$--9$</em>{0,9}$</td>
<td>342.946</td>
<td>90.6</td>
<td>0.3</td>
<td>5.5 ± 0.2</td>
<td>2.7 ± 0.2</td>
<td>5.9 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>10$<em>{0,9}$--9$</em>{0,8}$</td>
<td>343.322</td>
<td>143.3</td>
<td>0.3</td>
<td>4.0 ± 0.5</td>
<td>2.2 ± 1.1</td>
<td>4.9 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>10$<em>{0,8}$--9$</em>{0,7}$</td>
<td>343.813</td>
<td>143.3</td>
<td>0.3</td>
<td>6.0 ± 0.3</td>
<td>2.5 ± 0.4</td>
<td>4.9 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>10$<em>{0,7}$--9$</em>{0,6}$</td>
<td>343.410</td>
<td>209.1</td>
<td>0.3</td>
<td>6.2 ± 0.8</td>
<td>2.4 ± 0.7</td>
<td>5.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>10$<em>{0,6}$--9$</em>{0,5}$</td>
<td>343.414</td>
<td>209.1</td>
<td>0.3</td>
<td>5.8 ± 2.8</td>
<td>2.6 ± 0.2</td>
<td>5.5 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10$<em>{0,5}$--9$</em>{0,4}$</td>
<td>343.203</td>
<td>419.2</td>
<td>0.2</td>
<td>1.8 ± 0.4</td>
</tr>
<tr>
<td>SO</td>
<td>8$_{7}$$-$$7_7$</td>
<td>344.311</td>
<td>87.5</td>
<td>0.2</td>
<td>4.9 ± 0.1</td>
<td>2.2 ± 0.1</td>
<td>5.0 ± 0.1</td>
</tr>
<tr>
<td>HC$_{15}$N $v = 0$</td>
<td>4--3</td>
<td>344.200</td>
<td>41.3</td>
<td>0.2</td>
<td>6.1 ± 0.4</td>
<td>2.6 ± 0.1</td>
<td>5.2 ± 0.1</td>
</tr>
<tr>
<td>CS</td>
<td>7--6</td>
<td>342.883</td>
<td>65.8</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCN $v = 0$</td>
<td>4--3</td>
<td>354.505</td>
<td>42.5</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes.

a Not all the detected lines are listed in this table. The others will be presented in another paper.
b The $V_{lsr}$, intensity, and FWHM of each transition are derived from single Gaussian fit toward the beam-averaged spectra.
c Blended with H$_2$CO (5$_{1,4}$--4$_{1,3}$) at 343.325713 GHz.
d Blended with H$_2$CS (10$_{3}$--9$_{3}$).
e Blended with H$_2$CO (10$_{3}$--9$_{3}$).
f Blended with H$_2$CS (10$_{0,8}$--9$_{0,6}$).

The two transitions of H$_2$CS (10$_{0,8}$--9$_{0,6}$) and (10$_{0,9}$--9$_{0,8}$) have the same frequency, line strength, and permanent dipole moment. Therefore, they have the same contributions to the observed line profile.
Figure 3. Integrated intensity maps of four transitions of H$_2$CS at the middle (upper panels) and southern cores (lower panels). The known centimeter and millimeter continuum components are marked by plus signs as in the continuum map. The contour levels in all the panels are from 3$\sigma$ in steps of 3$\sigma$. The rms levels are 0.3, 0.3, 0.3, and 0.2 Jy beam$^{-1}$ km s$^{-1}$ for H$_2$CS (10$_{10}$--9$_{0,9}$) in panels (a) and (e), H$_2$CS (10$_{2,8}$--9$_{2,7}$) in panels (b) and (f), H$_2$CS (10$_{3,7}$--9$_{3,6}$) in panels (c) and (g), and H$_2$CS (10$_{5}$--9$_{5}$) in panels (d) and (h), respectively.

Figure 4. P–V diagram (left) and first moment map (right) of H$_2$CS (10$_{2,8}$--9$_{2,7}$) emission at the middle core. (a) The contours of the P–V diagram are from 0.6 to 1.4 in steps of 0.2 Jy beam$^{-1}$ (1$\sigma$). (b) Contour plot of H$_2$CS (10$_{2,8}$--9$_{2,7}$) integrated intensity image overlaid on the first moment map. The contours are from 0.9 (3$\sigma$) in steps of 0.9 Jy beam$^{-1}$ km s$^{-1}$. The first moment map is constructed from the data after imposing a cutoff of 3$\sigma$.

Figure 10. The high-velocity emission of both HC$^{15}$N (4–3) and SO (8$_7$–7$_7$) is associated with core F, indicating that core F is the driven source of the outflow. The blue and red wings of SO (8$_7$–7$_7$) overlap to a large extent in the contour maps, and hence the molecular outflow revealed by SO (8$_7$–7$_7$) is observed close to its flow axis.

Figure 11 presents the channel maps of CS (7–6) emission. The redshifted high-velocity gas seems to be elongated from northeast to southwest, while the blueshifted high-velocity gas from north to south. The high-velocity gas revealed by CS...
Figure 5. Spectra and integrated intensity maps of HC15N (4–3) (upper panels) and SO (8–7) (lower panels) at the middle core. The systemic velocity is marked with the thick vertical dashed lines at the spectra panels. The known centimeter and millimeter continuum components of C and E are marked by plus signs at the integrated maps as the continuum map. (a) The beam-averaged spectrum of HC15N (4–3) at E, (b) the integrated intensity map of HC15N (4–3); the contour levels are $-1.2 (6\sigma), 1.2, 2.4, 4.2, 6.6, \text{and } 9.6 \text{ Jy beam}^{-1} \text{ km s}^{-1}$, (c) the beam-averaged spectrum of SO (8–7) at E, and (d) the integrated intensity map of SO (8–7). The contour levels are $-1.2 (6\sigma), 1.2, 2.4, 4.2, 6.6, 9.6, 13.2, 17.4, \text{and } 22.2 \text{ Jy beam}^{-1} \text{ km s}^{-1}$.

Figure 6. Beam-averaged spectra and position–velocity (P–V) diagrams of HCN (4–3) (upper panels) and CS (7–6) (lower panels) at the middle core. The P–V diagrams are cut along a position angle of $0^\circ$. (a) The beam-averaged spectrum of HCN (4–3) at E. (b) The P–V diagram of HCN (4–3). The contour levels are $-1.5 (5\sigma), -0.9, 0.9, 1.5, 2.1, 2.7, 3.3, 3.9, \text{and } 4.5 \text{ Jy beam}^{-1} \text{ km s}^{-1}$. (c) The beam-averaged spectrum of CS (7–6) at E. (d) The P–V diagram of CS (7–6). The contour levels are $-1.5 (5\sigma), -0.9, 0.9, 1.5, 2.1, 2.7, 3.3, 3.9, \text{and } 4.5 \text{ Jy beam}^{-1}$. (7–6) is also very obvious in the P–V diagram in Figure 13(d). As shown in the P–V diagram, the blueshifted high-velocity gas extends about 8″ from north to south. The high-velocity emission integrated over the wings ($-12 \text{ km s}^{-1} \leq V \leq -5 \text{ km s}^{-1}$ for the blue wing and $15 \text{ km s}^{-1} \leq V \leq 22 \text{ km s}^{-1}$ for the red wing) is presented in Figure 13(e).

Figure 12 shows the channel maps of HCN (4–3) emission. The maximum of absorptions appears at around $0 \text{ km s}^{-1}$. The redshifted high-velocity gas seems to be elongated from west to east, while the blueshifted high-velocity gas is from north to south. At very high velocity channels ($V \leq -16 \text{ km s}^{-1}$), the blueshifted emission is totally located at the southeast. By comparing the channel maps and P–V diagrams (see Figure 13) of HCN (4–3) and CS (7–6) at velocity intervals $-12 \text{ km s}^{-1} \leq V \leq -5 \text{ km s}^{-1}$ and $15 \text{ km s}^{-1} \leq V \leq 22 \text{ km s}^{-1}$, we find similar structures in CS (7–6) and HCN (4–3) emissions. The high-velocity emission of HCN (4–3) integrated from $-12$ to $-5 \text{ km s}^{-1}$ for the blue wing and from $15$ to $22 \text{ km s}^{-1}$ for the red wing is presented in panel (b) of Figure 13. As of CS (7–6), the blueshifted gas revealed by HCN (4–3) is elongated from north to south with the emission center located between G9.62+0.19 F and G9.62+0.19 D, while the redshifted gas is from northeast
Figure 7. Integrated intensity maps of HCN (4–3) (left) and CS (7–6) (right) at the middle core. The contour levels in both maps are from 1.5 (5σ) in steps of 3 Jy beam$^{-1}$ km s$^{-1}$. HCN (4–3) is integrated from −3 to 7 km s$^{-1}$, while CS (7–6) from −1 to 6 km s$^{-1}$.

Figure 8. Averaged spectra of SO (87–77) (upper left), HCN$^{15}$N (4–3) (lower left), HCN (4–3) (upper right), and CS (7–6) (lower right) at the southern core. The spectra of SO (87–77) and HCN$^{15}$N (4–3) are averaged over a region of 4", while HCN (4–3) and CS (7–6) are averaged over a region of 6". HCN ν2 = 1 (4–3) emission is marked by the arrow in the upper right panel, which can be clearly distinguished from the red wing of HCN (4–3).

Figure 9. Integrated intensity maps of HCN$^{15}$N (4–3) (left panel) and SO (87–77) (right panel) at the southern core. To avoid the influence of outflow motions, both the maps are integrated from 2 to 8 km s$^{-1}$. The contour levels are (a) −1.2 (6σ), 1.2, 2.4, 4.2, 6.6, 9.6, 13.2, and 17.4 Jy beam$^{-1}$ km s$^{-1}$ for HCN$^{15}$N (4–3) and (b) −1.2 (6σ), 1.2, 2.4, 4.2, 6.6, 9.6, 13.2, 17.4, 22.2, 27.6, and 33.6 Jy beam$^{-1}$ km s$^{-1}$ for SO (87–77).
Figure 10. P–V diagrams and integrated intensity maps of SO (87–77) (upper panels) and HC15N (4–3) (lower panels) at the southern core. The P–V diagrams are cut along the N–S direction. The vertical solid line in P–V diagrams labels the systemic velocity. The dashed and solid contours in the right panels show the redshifted and blueshifted emissions, respectively. The integral velocity intervals are marked by thick dashed lines in the P–V diagrams. For both SO (87–77) and HC15N (4–3), the blueshifted emission is integrated from $-4$ to $0$ km s$^{-1}$, while the redshifted emission is from 10 to 14 km s$^{-1}$ in the integrated intensity maps. (a) The P–V diagram of SO (87–77). The contours are from 0.6 (3$\sigma$) in steps of 0.6 Jy beam$^{-1}$. (b) The P–V diagram of HC15N (4–3). The contours are from 0.6 (3$\sigma$) in steps of 0.4 Jy beam$^{-1}$. (c) Integrated intensity maps of SO (87–77) at line wings. The contours are from 1 (5$\sigma$) in steps of 1 Jy beam$^{-1}$ km s$^{-1}$ for both redshifted and blueshifted emissions. (d) Integrated intensity maps of HC15N (4–3) at red wings. The contours are 0.6 (3$\sigma$), 1.2, 2, and 3 Jy beam$^{-1}$ km s$^{-1}$.

Figure 11. CS (7–6) channel maps at the southern core, which is smoothed to a velocity resolution of 3 km s$^{-1}$. The contours are $-0.6$ (3$\sigma$), 0.6, 1.2, 2.4, 4.8, 7.2, and 9.6 Jy beam$^{-1}$. 
Figure 12. HCN (4–3) channel maps at the southern core, which is smoothed to a velocity resolution of 4 \( \text{km s}^{-1} \). The contours are \(-0.6 (3\sigma), 0.6, 1.2, 2.4, 3.6, 4.8, \) and \(7.2 \text{ Jy beam}^{-1}\).

Figure 13. P–V diagrams and integrated intensity maps of HCN (4–3) (upper panels) and CS (7–6) (lower panels) at the southern core. The P–V diagrams are cut along the N–S direction. The vertical solid line in P–V diagrams labels the systemic velocity. The dashed and solid contours in the right panels show the redshifted and blueshifted emissions, respectively. The blueshifted and redshifted emissions in the integrated maps are integrated from \(-12 \text{ to } -5 \text{ km s}^{-1}\) and 15 to 22 \( \text{ km s}^{-1}\), respectively, in panels (b) and (e). (a) The P–V diagram of HCN (4–3). The contours are from 0.9 \((3\sigma)\) in steps of 1.2 \( \text{ Jy beam}^{-1}\). (b) Integrated intensity maps of HCN (4–3) at line wings. The contours are 1.5 \((5\sigma)\), 4.5, 7.5, and 10.5 \( \text{ Jy beam}^{-1} \text{ km s}^{-1}\). (c) The integrated intensity maps of HCN (4–3) at extremely high velocities. The blueshifted and redshifted emissions in the integrated maps are integrated from \(-20 \text{ to } -13 \text{ km s}^{-1}\) and 23 to 39 \( \text{ km s}^{-1}\), respectively. The contours are from 1.5 \((5\sigma)\) in steps of 3 \( \text{ Jy beam}^{-1} \text{ km s}^{-1}\) for both blueshifted and redshifted emissions. (d) The P–V diagram of CS (7–6). The contours are from 0.9 \((3\sigma)\) in steps of 1.2 \( \text{ Jy beam}^{-1}\). (e) Integrated intensity maps of CS (7–6) at line wings. The contours are 1.5 \((5\sigma)\), 4.5, 7.5, and 10.5 \( \text{ Jy beam}^{-1} \text{ km s}^{-1}\).
to southwest. Two clumps are found in the blueshifted high-velocity emission of HCN (4–3), which are located at northwest and southeast of F, respectively.

In order to reveal the very high velocity emission traced by HCN (4–3) but not CS (7–6), we integrate over the wings at much higher velocities (−20 km s⁻¹ ≤ V ≤ −13 km s⁻¹ for the blue wing and 23 km s⁻¹ ≤ V ≤ 39 km s⁻¹ for the red wing) and present the integrated emission map in Figure 13(c). The redshifted emission is elongated from northeast to southwest with the emission center located between G9.62+0.19 F and G9.62+0.19 D. It is clearly seen that the high-velocity gas traced by SO (87–77), CS (7–6), and HCN (4–3) have different spatial distributions, which should be caused by the complicated interactions between the outflow and the ambient gas. It may also indicate a change of the outflow axis. The change of outflow axis is also found in IRAS 20126+4104 (Su et al. 2007) and JCMT 18354−0649S (Liu et al. 2011).

From the integrated emission maps of SO (87–77), HCN (4–3), and CS (7–6) high-velocity gas, it is clearly seen that G9.62+0.19 F is located at the middle of the redshifted and blueshifted lobes, suggesting that G9.62+0.19 F is the outflow driving source.

4. DISCUSSION

4.1. Rotational Temperature of H₂CS Transitions

Six transitions of H₂CS have been detected in the middle and southern cores, enabling us to estimate the rotational temperature. Under the assumptions that the gas is optically thin under local thermodynamic equilibrium and the gas emission fills the beam, the rotation temperature and beam-averaged column density can be estimated using the rotational temperature diagram (RTD) by (Cummins et al. 1986; Turner 1991; Liu et al. 2002)

\[
\ln \left( \frac{N_u}{g_u} \right) = \ln \left( \frac{N_T}{Q_{\text{rot}}} \right) - \frac{E_u}{T_{\text{rot}}} = \ln \left[ 2.04 \times 10^{20} \frac{\int I(\text{Jy beam}^{-1})dv(\text{km s}^{-1})}{\theta_d \theta_b (\text{arcsec})^2 g_1 g_k v^3 (\text{GHz}^3) S \mu^2 (\text{debye}^2)} \right],
\]

where \( N_u \) is the observed column density of the upper energy level, \( g_u \) is the degeneracy factor in the upper energy level, \( N_T \) is the total beam-averaged column density, \( Q_{\text{rot}} \) is the rotational partition function, \( E_u \) is the upper energy level in K, \( T_{\text{rot}} \) is the rotation temperature, \( \int I dv \) is the integrated intensity of the specific transition, \( \theta_d \) and \( \theta_b \) are the FWHM beam size, \( g_k \) is the K-ladder degeneracy, \( g_1 \) is the degeneracy due to nuclear spin, \( v \) is the rest frequency, \( S \) is line strength, and \( \mu \) is the permanent dipole moment. For H₂CS, the interchangeable nuclei are spin \( \frac{1}{2} \), leading to ortho and para forms with \( g_1 = \frac{3}{2} \) and \( \frac{1}{2} \), respectively (Blake et al. 1987; Turner 1991). The partition function \( Q_{\text{rot}} \) of H₂CS is (Blake et al. 1987)

\[
Q_{\text{rot}} = 2 \left[ \frac{\pi (kT_{\text{rot}})^{\frac{3}{2}}}{h^3 ABC} \right],
\]

where \( k \) and \( h \) are the Boltzmann and Planck constants, respectively, and \( A, B, \) and \( C \) are the rotation constants. Thus, the rotation temperature \( T_{\text{rot}} \) and total column density \( N_T \) can be estimated by least-squares fitting to the multiple transitions. We applied the RTD method toward D, E, F, and G (see Figure 14), and the fitting results are listed in the second and third columns of Table 3. The rotational temperature of the middle core (E) is 83 ± 21 K. In the southern core, the rotational temperature estimated decreases from G (91 K) to F (83 K) and D (43 K), suggesting the temperature gradient in the southern core. The total column density of H₂CS ranges from 1.3 × 10¹⁵ (G) to 3.8 × 10¹⁵ cm⁻² (D).

However, the filling factor and the optical depth correction were not taken into account in the RTD method. To investigate their effect we applied the population diagram (PD) analysis (Goldsmith & Langer 1999; Wang et al. 2010). In the PD analysis, we have

\[
\ln \left( \frac{\hat{N}_u}{g_u} \right) = \ln \left( \frac{N_T}{Q_{\text{rot}}} \right) - \frac{E_u}{T_{\text{rot}}} + \ln(f) - \ln \left( \frac{\tau}{1 - e^{-\tau}} \right),
\]

where \( \hat{N}_u \) is the inferred column density of the upper energy level from the PD analysis, \( f \) is the source filling factor, and \( \tau \) is the optical depth. The optical depth \( \tau \) can be expressed by (Remijan et al. 2004)

\[
\tau = \frac{8\pi^3 S \mu^2 \nu}{3k \Delta v T_{\text{rot}}} e^{-\frac{\nu}{\Delta v}},
\]

where \( \Delta v \) is the FWHM line width. Under LTE, the upper-level populations, \( \hat{N}_u \), can be predicted according to the right-hand side of Equation (3) for a given set of total column density, \( N_T \), rotational temperature, \( T_{\text{rot}} \), and source filling factor, \( f \). The expected \( \hat{N}_u \) were evaluated for the parameter space of \( T_{\text{rot}} = 10–500 \text{ K}, N_T = 10^{14}–10^{17} \text{ cm}^{-2}, \) and \( f \) between 0.01 and 1.0.

To compare the observed \( N_u \) and the inferred \( \hat{N}_u \), we calculate the \( \chi^2 \) as

\[
\chi^2 = \sum \left( \frac{N_u - \hat{N}_u}{\delta N_u} \right)^2,
\]

where \( \delta N_u \) is the 1σ error of observed upper-state column density. Although the \( \chi^2 \) is a good representation of the goodness of fit, the parameter set with the lowest \( \chi^2 \) may not actually represent physical parameters very well due to the uncertainties of the observed data. In order to find a representative parameter set, we compute a weighted mean and standard deviation for all the parameters, with the weights being the inverse of the \( \chi^2 \). All the parameter sets where the inferred upper-level population \( \hat{N}_u \) corresponds with the observed upper-level population \( N_u \) within 3σ are used to compute the weighted means and standard deviations. The derived rotational temperature, total column density, and filling factor of each component are listed in Columns 3–5 of Table 3. The inferred optical depths of each line transition are listed in the last six columns of Table 3. The rotational temperatures of D, E, F, and G are estimated to be 42 ± 34, 92 ± 74, 51 ± 23, and 105 ± 37 K, respectively. A temperature gradient in the southern core is also revealed as in the RTD method. The four components D, E, F, and G have similar total column density as the inferred \( \hat{N}_u \), which are much larger than one, while the other transitions are always optically thin except H₂CS (10₂,9−9₂,8) line at G.
### Table 3
Physical Parameters of H2CS Transitions Obtained with the Rotational Temperature Diagram (RTD) Method and Population Diagram (PD) Analysis

<table>
<thead>
<tr>
<th>Core</th>
<th>RTD</th>
<th>PD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{\text{rot}}$ (K)</td>
<td>$N_{\text{tot}}$ ($10^{15}$ cm$^{-2}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(10$<em>{10}$−9$</em>{10}$)</td>
<td>(10$<em>{10}$−9$</em>{9}$)</td>
</tr>
<tr>
<td>D</td>
<td>43 ± 9</td>
<td>3.8 ± 2.9</td>
</tr>
<tr>
<td>E</td>
<td>83 ± 21</td>
<td>2.5 ± 1.6</td>
</tr>
<tr>
<td>F</td>
<td>83 ± 7</td>
<td>2.6 ± 0.6</td>
</tr>
<tr>
<td>G</td>
<td>91 ± 17</td>
<td>1.3 ± 0.7</td>
</tr>
</tbody>
</table>

**Note.** The rotational temperature and total column density of H2CS transitions derived from the RTD analysis are presented in the second and third columns, while those derived from the PD analysis are shown in the fourth and fifth columns. The sixth column gives the filling factor of each source inferred from the PD analysis. The last six columns exhibit the optical depth of each transition using the PD analysis.
**Figure 14.** Population diagrams of H$_2$CS toward four centimeter/millimeter cores. The names of the cores are labeled in the upper right corners of each panel. Open circles in blue represent the observed data. The vertical bars present $3\sigma$ errors of $\ln(N_u/g_u)$ due to the uncertainties of integrated intensities. The solid line shows the linear least-squares fitting using the RTD method. Crosses in red mark the weighted mean results from the PD analysis. The inferred parameters from the PD analysis are presented in the upper right corners of each panel. (A color version of this figure is available in the online journal.)

**4.2. Core Properties**

In the optically thin case, the total dust and gas masses of the three submillimeter cores can be obtained with the formula $M = S_\nu D^2/\kappa_\nu R B_\nu(T_d)$ (Hildebrand 1983), where $S_\nu$ is the flux at 860 $\mu$m, $D$ is the distance, $R = 0.01$ is the mass ratio of dust to gas, and $\kappa_\nu$ is dust opacity per unit dust mass. $B_\nu(T_d)$ is the Planck function at a dust temperature of $T_d$. We assume that $T_d$ equals the rotational temperature of H$_2$CS. For the northern core, since only CS (7–6) ($E_u = 65.8$ K) and HCN (4–3) ($E_u = 42.5$ K) exhibit strong emission lines, we assume $T_d$ to be 50 K. Together with the measurements at centimeter and millimeter wavelengths, Su et al. (2005) extrapolated the ionized gas emission at millimeter/submillimeter wavelengths and found that the 0.85 mm continuum associated with components D, E, and F is dominated by thermal dust emission. They have derived an opacity index $\beta$ of components E and F to be 1.2 and 0.8, respectively. For the northern submillimeter core, $\beta = 1.5$ is assumed. Using the above dust opacity indexes, we adopt $\kappa_\nu = 2.0, 1.8,$ and $1.5$ cm$^2$ g$^{-1}$ for the northern, middle, and southern cores, respectively (Ossenkopf & Henning 1994). At the distance of 5.7 kpc, we get the total dust and gas masses for these three cores and list all the parameters in Table 1. The deduced masses for the northern, middle, and southern cores are 13, 30, and $165 M_\odot$, respectively. The column density of H$_2$ is $1.2 \times 10^{24}$ and $2.1 \times 10^{24}$ cm$^{-2}$ for the middle and southern submillimeter cores, respectively.

**4.3. Infall Properties in the Middle Core**

In the middle core, both CS(7–6) and HCN(4–3) emissions exhibit “blue-profile” features, indicating infall motions of the gas envelope toward the central star (Keto et al. 1988; Zhou et al. 1993; Zhang et al. 1998; Wu & Evans 2003; Wu et al. 2005, 2007; Fuller et al. 2005; Wysowsky 2008; Sun & Gao 2008). The velocity difference (0.9 km s$^{-1}$) between the absorption dip in the CS (7–6) spectrum (3 km s$^{-1}$) and the systemic velocity (2.1 km s$^{-1}$) is taken as the infall velocity $V_{in}$. Since both HCN (4–3) and CS (7–6) emissions are not resolved toward the middle core, we simply take the dust core size as the radius of the infall region, which may underestimate the infall rate.
derived below. The kinematic mass infall rate can be calculated using
\[ \frac{dM}{dt} = 4\pi R_\odot^2 \rho \mu V_{\text{in}}, n = 1.5 \times 10^7 \text{ cm}^{-3} \]
the density of this dust core. Taking helium into account, the mean molecular mass \( m \) is 1.36 times the H$_2$ molecule mass. The infall rate calculated is \( 4.3 \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \). For comparison, the \( V_{\text{in}} \) from pure free-infall assumption is also derived using the formula \( V_{\text{in}}^2 = 2GM/R_{\text{in}} \). The pure free-infall velocity is \( V_{\text{in}} = 3.6 \, \text{km s}^{-1} \) and thus the “gravitational” mass infall rate is \( 1.7 \times 10^{-2} \, M_\odot \, \text{yr}^{-1} \), which is larger than the kinematic infall rate.

### 4.4. Outflow Properties in the Southern Core

#### 4.4.1. Shock Chemistry in the Outflow Region of the Southern Core

Observations have shown that there are important differences in molecular abundances in different outflow regions (Bachiller & Perez Gutiérrez 1997; Choi et al. 2004; Jørgensen et al. 2004; Codella et al. 2005). Significant abundance enhancements are found in the shocked region for sulfur-bearing molecules (Bachiller & Perez Gutiérrez 1997; Jørgensen et al. 2004), and the abundance of HCN in outflow regions is related to atomic carbon abundance (Choi 2002). However, previous studies of the chemical impact of outflows are confined to the well-collimated outflows around Class 0 sources, while such studies, especially high-resolution studies on massive outflows, are rare (Bachiller & Perez Gutiérrez 1997; Jørgensen et al. 2004; Arce et al. 2007).

A red and bright IRAC source is found to be associated with the southern core. The magnitudes of the IRAC source at 3.6, 4.5, and 5.8 μm are 10.102 ± 0.093, 8.361 ± 0.108, and 7.778 ± 0.302 mag, respectively. The [3.6 – 4.5] color is as large as 1.74, indicating shocked emission in the southern core (Takami et al. 2010). Maser emissions of NH$_3$, H$_2$O, OH, and CH$_3$OH as well as the strong thermal NH$_3$ emissions also uncover the existence of the shocked gas (Hofner et al. 1994). Outflows can be revealed from shocked H$_2$ emission probed by the strong and extended emission at the 4.5 μm band (Qu et al. 2008; Takami et al. 2010). Thus, the massive outflow in the southern core of G9.62 complex provides an ideal sample to study shock chemistry.

The fractional abundance of a certain molecule is defined as \( \chi = N_T/N_\text{H}_2 \), where \( N_T \) is the total column density of a specific molecule and \( N_\text{H}_2 \) is the H$_2$ column density. Assuming that the gas is optically thin and the emission fills the beam, the beam-averaged total column density of a specific molecule can be obtained from

\[ N_T = 2.04 \times 10^{20} \int I(\text{Jy beam}^{-1})dv(\text{km s}^{-1})Q_{\text{rot}}E_\nu/T_{\text{rot}} \theta_e \theta_h (\text{arcsec}^2) g(\text{GHz}) S \mu^2(\text{debye}^2) \]  

(6)

Assuming that \( T_{\text{rot}} \) of HC$_{15}$N equals that of H$_2$CS and the gas is optically thin, \( N_T \) of HC$_{15}$N is calculated to be \( 3.0 \times 10^{13} \, \text{cm}^{-2} \) at the core region. At the galactocentric distance of 3 kpc for G9.62+0.19 (Scoville et al. 1987; Hofner et al. 1994), the abundance ratio [C$^+$]/[C$^+$] \approx 350 (Wilson and Rood. 1994). Thus, the total column density of HCN at the core region should be \( 1.1 \times 10^{10} \, \text{cm}^{-2} \). Therefore, the fractional abundance of HCN relative to H$_2$ at the core region is \( 5.2 \times 10^{-9} \). HCN appears to be greatly enhanced in the outflow regions of the L1157 (Bachiller & Perez Gutiérrez 1997), while it has similar abundances in the outflow region and the ambient cloud of NGC 1333CIRAS 2A (Jørgensen et al. 2004). Owing to the lack of a direct estimation of the H$_2$ column density toward the outflow region, the fractional abundance of HCN in the outflow region is also assigned to \( 5.2 \times 10^{-9} \) in calculating the outflow parameters. Since the HC$_{15}$N emission traces outflowing gas at much lower velocity than HCN, perhaps HCN could be more enhanced in the high-velocity component. With the possibility of higher opacity and the lack of direct H$_2$ column density measurement, the derived fractional abundance is perhaps a lower limit anyway. Su et al. (2007) estimate an HCN abundance of \( \sim 1 \times 10^{-8} \) in the massive outflow lobes of IRAS 20126+4104, which is comparable to our estimation here.

Since the blueshifted outflow gas traced by CS (7–6) and HCN (4–3) suffers self-absorption, the abundance ratios among SO (87–77), CS (7–6), and HCN (4–3) were inferred from the beam-averaged spectra taken from the redshifted outflow lobe. The abundance ratio as a function of flow velocity (the outflow velocity relative to the systemic velocity) of [CS/SO] is obtained assuming five different excitation temperatures in the left panel of Figure 15. It can be seen that the abundance ratio of [CS/SO] increases with the excited temperature. At each excitation temperature, the abundance ratio of [CS/SO] has lower values at flow velocities less than 6 km s$^{-1}$, and higher values when \( V_{\text{flow}} > 8 \) km s$^{-1}$, whereas the abundance ratio seems to be constant at flow velocities between 6 and 8 km s$^{-1}$. There are two reasons for the lower abundance ratio when \( V_{\text{flow}} > 6 \) km s$^{-1}$: first, the flux missing of CS (7–6) due to the interferometer is more serious than SO (87–77); second, CS (7–6) may be more optically thick at lower flow velocities than SO (87–77). As shown in the P–V diagrams, the emission region of CS (7–6) is much larger than SO (87–77) at high velocities. The higher abundance ratio when \( V_{\text{flow}} > 8 \) km s$^{-1}$ is due to the smaller filling factor of SO (87–77) emission. We propose that the mean observed value between 6 and 8 km s$^{-1}$ can represent the actual abundance ratio of [CS/SO]. Assuming a typical excitation temperature of \( T_{\text{ex}} = 30 \) K (Wu et al. 2004), the abundance ratio of [CS/SO] at the redshifted lobe is inferred as 0.7. Nilsson et al. (2000) find that the [SO/CS] abundance ratios are strongly enhanced in the Orion A and NGC 2071 outflows where the [SO/CS] ratios are estimated to be about 24 and 2.2, respectively. However, the [SO/CS] abundance ratio in the outflow of G9.62+0.19 is found to be 1.4, much lower than that found in Orion A outflow.

As shown in the right panel of Figure 15, the abundance ratio of [CS/HCN] decreases linearly with the flow velocity. To avoid the missing flux difficulty, the abundance ratio is calculated at high flow velocities larger than 7 km s$^{-1}$. The decreasing of the abundance ratio with velocity is because the emission region traced by CS (7–6) is always smaller than HCN (4–3), leading to a smaller filling factor for CS (7–6), which can be verified easily by comparing the channel maps between CS (7–6) in Figure 11 and HCN (4–3) in Figure 12 at high velocities. We fitted the observed data with a linear function, and adopted the value at flow velocity of 10 km s$^{-1}$ as the actual abundance ratio of [CS/HCN] in the outflow region, which is [CS/HCN] = 1.2. Since HCN fractional abundance is \( 5.2 \times 10^{-9} \), the fractional abundances of CS and SO are deduced to be \( 6.2 \times 10^{-9} \) and \( 8.9 \times 10^{-9} \), respectively.

#### 4.4.2. Properties of the Bipolar Outflow Traced by SO (87–77) Emission

The SO (87–77) emission in the southern core shows line wings, suggesting outflow motions. From the integrated intensity map in Figure 10(c), we find the outflow lobes revealed by SO (87–77) emission peak at different positions with
different position angles compared with previously reported H2S (2,2,0−2,1,1) (Gibb et al. 2004) and HCO+ (1−0) data (Hofner et al. 2001). But in the same sense, the blue and red lobes revealed by SO overlap to a large extent as well as HCO+ (1−0) and H2S (2,2,0−2,1,1) data, consistent with the argument of the outflow being viewed pole-on (Hofner et al. 2001).

The total mass of each outflow lobe is given by

\[ M_{\text{flow}} = 1.04 \times 10^{-4} D^2 \frac{Q_{\text{rot}} E/\tau_{\text{ex}}}{\chi v^3 S \mu^2} \int \frac{\tau}{1 - e^{-\tau}} S_{\nu} dv, \]

where \( M_{\text{flow}} \), \( D \), \( S_{\nu} \), \( \chi \), and \( \tau \) are the outflow gas mass in \( M_\odot \), source distance in kpc, line flux density in Jy, relative abundance of H2, and optical depth, respectively. The other parameters have the same units as in Equation (1). The fractional abundance of SO is taken as 8.9 × 10^{-5} (see Section 4.4.1). Assuming an excitation temperature of 30 K and the outflowing gas as optically thin, the inferred outflow masses are 13 \( M_\odot \) for each of the redshifted and blueshifted lobes. Thus, the momentum can be calculated by \( P = \sum M(v) \nu dv \), and the energy by \( E = \sum \frac{1}{2} M(v) \nu^2 dv \), where \( \nu \) is the flow velocity. The derived parameters are listed in Table 4. The momentum and energy of the red lobe are 82 \( M_\odot \) km s^{-1} and 5.4 × 10^{45} erg, respectively. For the blue lobe, the momentum and energy are calculated to be 86 \( M_\odot \) km s^{-1} and 5.8 × 10^{45} erg, respectively. The dynamical timescale \( t_{\text{dyn}} \) is estimated as \( R / V_{\text{chan}} \), where \( R \sim 0.06 \) pc is adopted as the mean size of the outflow lobes assuming a collimation factor of unity, and \( V_{\text{chan}} \sim 5.5 \) km s^{-1} is assumed as the mass-weighted mean velocity. Thus, the dynamic timescale is estimated to be 1 × 10^{4} yr, which may be underestimated due to the uncertainty of the outflow scale. The mechanical luminosity \( L \) and the mass-loss rate \( M \) are calculated as \( L = E/\tau \) and \( M = P/(\Omega \nu_a) \), respectively, where the wind velocity \( \nu_a \) is assumed to be 500 km s^{-1} (Lamers et al. 1995). The mechanical luminosity \( L \) and the total mass-loss rate are estimated to be 9.3 \( L_\odot \) and 3.6 × 10^{5} \( M_\odot \) yr^{-1}, respectively.

4.4.3. Very High Velocity Gas Detected in CS (7−6) Emission

The CS (7−6) emission at the southern core shows a “red profile” with wide wings. We take 6.2 × 10^{-9} as the fractional abundance of CS relative to H2 along the outflow lobes. Assuming \( T_{\text{ex}} = 30 \) K, we derive the parameters for the CS outflow (Table 4) with the same method used for SO (8−7). The outflow masses at very high velocities (\( V_{\text{flow}} > 10 \) km s^{-1}) are 3.7 \( M_\odot \) and 5.5 \( M_\odot \) for the blueshifted and redshifted lobes, respectively. The momentum and energy of the blueshifted lobe at very high velocities are calculated to be 47 \( M_\odot \) km s^{-1} and 6.0 × 10^{45} erg, respectively. For the redshifted lobe, the momentum and energy at extremely high velocities are calculated to be 68 \( M_\odot \) km s^{-1} and 8.7 × 10^{45} erg, respectively, which are similar to those of the blueshifted lobe.

4.4.4. Very High Velocity Gas Detected in HCN (4−3) Emission

As discussed before, HCN (4−3) has a velocity extent of at least 60 km s^{-1}, which traces extremely high velocity gas. Adopting an excited temperature of 30 K, and an HCN-to-H2 abundance ratio of 5.2 × 10^{-9}, the parameters of the outflow are calculated and listed in Table 4. The outflow mass at very high velocities (\( V_{\text{flow}} > 10 \) km s^{-1}) are 5.2 \( M_\odot \) and 17.6 \( M_\odot \) for the blueshifted and redshifted lobes, respectively. The momentum and energy of the blueshifted lobe at very high velocities are 85 \( M_\odot \) km s^{-1} and 1.4 × 10^{49} erg, respectively. For the redshifted lobe, the momentum and energy at very high velocities are 294 \( M_\odot \) km s^{-1} and 5.5 × 10^{49} erg, respectively, which are larger than those of the blueshifted lobe.

4.4.5. Mass–Velocity Diagrams

A broken power law, \( dM(v)/dv \propto v^{-\gamma} \), usually exhibits in molecular outflows near young stellar objects (Chandler et al. 1996; Lada & Fich 1996; Ridge & Moore 2001; Su et al. 2004; Qiu et al. 2007, 2009). The slope \( \gamma \), typically ranging from 1 to 3 at low outflow velocities, often steepens at velocities larger than 10 km s^{-1}—with \( \gamma \) as large as 10 in some cases (Arce et al. 2007). Assuming optically thin, the mass–velocity diagrams of the outflow at the southern core of the G9.62+0.19 complex are shown in Figure 16. SO (8−7), CS (7−6), and HCN (4−3) results were all used in the mass spectra. We calculate the outflow mass traced by CS (7−6) and HCN (4−3) from \( V_{\text{flow}} \) of 10 km s^{-1} to avoid the absorption of the spectra. Instead of broken power-law appearance, the mass–velocity diagram of the blueshifted lobe can be well fitted by a single power law with a power index of 2.
the redshifted lobe can be well fitted by a single power law with a power index of \(1.70 \pm 0.17\) even though the mass drops more rapidly after 25 km s\(^{-1}\). As marked by the dashed ellipse in the right panel, the outflow mass revealed by CS (7–6) is much lower than that revealed by HCN (4–3) at very high velocities. Despite the CS data, the mass–velocity diagram of the redshifted lobe at velocities smaller than 25 km s\(^{-1}\) can be fitted by a single power law with a much smaller power index of \(1.08 \pm 0.09\). However, no significant slope changes are found in both the redshifted and blueshifted lobes of the outflow at the southern core, which are very different from those previous works.

### 4.5. Different Evolutionary Stages of the Three Dust Cores

The northern core has the smallest diameter and mass among the three cores. It seems likely to be a point source after deconvolution. It is located south of the nominal radio UC H\(\text{II}\) region G9.62+0.19 C. In this region, eight near-IR sources are detected in a diffuse near-IR nebulosity at the west of the radio emission peak (Persi et al. 2003). The reddest one, c7 (18°06\(^{m}\)14\(^{s}\)34,−20°31′25′′0), is located within 1′′ of the radio peak, while the faintest one, c8 (18°06\(^{m}\)14\(^{s}\)42,−20°31′27′′4), seems to be associated with the submillimeter core detected in SMA observation. Source c8 is too faint to be detected even at \(H\) band and also shows no emission at 12.5 μm. In contrast to the bright, rich molecular spectrum forest in the middle and southern submillimeter cores, the northern submillimeter core lacks strong molecular emissions. There is also no other early star-forming signature such as masers associated with it. Since it is with near-IR emission and at the edge of the UC H\(\text{II}\) region G9.62+0.19 C, the northern core may be just a remnant core in the envelope of the UC H\(\text{II}\) region G9.62+0.19 C, which needs further observations.

The middle core is associated with the hypercompact H\(\text{II}\) region G9.62+0.19 E (Garay et al. 1993; Kurtz & Franco 2002). OH, H\(_2\)O, and NH\(_3\) (5,5) masers have been detected near the radio emission peak (Forster & Caswell 1989; Hofner et al. 1994; Hofner & Churchwell 1996). Periodic class II methanol masers are also found in G9.62+0.19 E (van der Walt et al. 2009; Goedhart et al. 2005; Norris et al. 1993). Methanol masers are believed to be a good tracer of young massive star-forming regions at stages earlier than relatively evolved UC H\(\text{II}\) regions (Longmore et al. 2007). No infrared source coincides with G9.62+0.19 E (Persi et al. 2003). Hot molecular CH\(_3\)CN lines are detected in this region, and a kinematic temperature of \(T_k = 108\) K was obtained from CH\(_3\)CN emission with a large velocity gradient model (Hofner et al. 1996), which is coincident with the rotational temperature (\(T_{rot} = 92\) K) obtained from H\(_2\)CS emission. A spectrum forest including hot molecular lines, such as CH\(_3\)OH, is detected toward G9.62+0.20 E, suggesting that this core is in a hot phase. Infall motions are traced by CS (7–6) and HCN (4–3) lines indicating active star forming in this region. All of the above suggest that G9.62+0.20 E is forming a massive young star.

The 860 μm dust emission of the southern core peaks at G9.62+0.19 F and extends from north to south. A hump structure is found to the southeast of the emission peak, indicating another possible submillimeter core. The previously recognized millimeter/centimeter cores (G9.62+0.19 D, G) are at the edges of the southern core. G9.62+0.19 G is a weak radio source (Testi et al. 2000), while G9.62+0.19 D is consistent with an isothermal UC H\(\text{II}\) region excited by a B0.5 star (Hofner et al. 1996).
1996). Weaker radio emission was found at core F. H_2O and OH masers are found across the whole submillimeter core from north to south (Forster & Caswell 1989; Hofner & Churchwell 1996). A near-IR source with large NIR excess is found to be associated with G9.62+0.19 F (Testi et al. 1998; Persi et al. 2003). With higher resolution observations, Linz et al. (2005) found four near-IR objects (F1–F4) in this core. F4 has little emission at K band but becomes redder at longer wavelengths, which seems to correspond to the bright IRAC source with a large excess at 4.5 μm. This object is the dominating and closest associated source of core F. Core F is also confirmed to be the driving source of an active outflow. All of the above imply that G9.62+0.19 F is a very young massive star-forming region.

4.6. Blue Excess in High-mass Star-forming Regions

Wu et al. (2007) found that UC H II regions show a higher blue excess than UC H II precursors with the IRAM 30 m telescope. Wyrowski et al. (2006) also detected a large blue excess in UC H II regions. A “blue profile” was detected with CS (7–6) and HCN (4–3) lines in the UC H II region G9.62+0.19 E, while, a “red profile” was detected in the HMC G9.62+0.19 F, which coincides with their argument. The detection of infall signature in G9.62+0.19 E also coincides with the interpretation that material is still accreted during the UC H II phase (Wu et al. 2007; Keto 2002). Around younger cores, the outflow is more active and cold than UC H II regions, which leads to a more “red profile,” while in UC H II regions, the outflows become weak, the surrounding gas of UC H II regions is thermalized, and the temperature gradient toward the central star is more likely to cause a “blue profile,” which results in the higher blue excess than UC H II precursors.

5. SUMMARY

We have observed the G9.62+0.19 complex with the SMA in the 860 μm continuum and molecular line emission. The main results of this study are as follows.

1. Dust continuum at 860 μm reveals three submillimeter cores in the G9.62+0.19 star-forming complex. With H2CS as the rotational temperature probe, the temperatures of E and F are estimated to be 92 ± 74 and 51 ± 23 K, respectively. The masses calculated are 13, 30, and 165 M☉ for the northern, middle, and southern cores, respectively.

2. In the middle core, HCN (4–3) and CS (7–6) spectra exhibit infall signature. The infall rate calculated is 4.3 × 10^{-3} M☉ yr^{-1}. The detection of infall signature in G9.62+0.19 E coincides with the interpretation that material is still accreted after the onset of the UC H II phase (Wu et al. 2007).

3. In the southern core, high-velocity gas is detected in SO (8_{8}–7_{7}), CS (7–6), and HCN (4–3) lines. A bipolar outflow with a total mass about 26 M☉ and a mass-loss rate of 3.6 × 10^{-5} M☉ yr^{-1} is revealed in SO (8_{8}–7_{7}) line wing emission. G9.62+0.19 F is confirmed to be the driving source of the outflows in the southern submillimeter core. The abundance ratios of [CS/SO] and [CS/HCN] in the outflow region are found to be 0.7 and 1.2, respectively. The abundance ratio [CS/HCN] decreases with the flow velocity, indicating smaller outflow regions revealed by CS (7–6) than that revealed by HCN (4–3). The mass–velocity diagrams of the blueshifted and redshifted outflow lobes can be well fitted by a single power law. The power indexes for the blueshifted and redshifted lobes are 2.28 ± 0.23 and 1.70 ± 0.17, respectively. No significant slope changes are found in the mass–velocity diagrams.

4. The evolutionary sequence of the centimeter/millimeter cores in this region is also analyzed. The northern core may be just a remnant core in the envelope of the UC H II region G9.62+0.19 C, which needs further observations. The middle core (G9.62+0.19 E) is in a hypercompact H II region. Core G9.62+0.19 F is confirmed to be an HMC.

5. The detection of blue profiles at the hypercompact H II region E and the red profiles at the HMC F supports the results of single-dish observations that UC H II regions have a higher blue excess than their precursors.

We are grateful to the SMA staff for making the observations. This work is funded by grants of NSFC nos. 10733030 and 10873019.

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