Outflow activities in the young high-mass stellar object G23.44-0.18

Jeremy Zhiyuan Ren¹, Tie Liu¹, Yuefang Wu¹, and Lixin Li¹,²

¹Department of Astronomy, Peking University, 100871, Beijing China, E-mail: rzy,ywu@pku.edu.cn
²The Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Lu 5, Hai Dian Qu, Beijing 100871, P. R. China

2 July 2013

ABSTRACT
We present an observational study towards the young high-mass star forming region G23.44-0.18 using the Submillimeter Array. Two massive, radio-quiet dusty cores MM1 and MM2 are observed in 1.3 mm continuum emission and dense molecular gas tracers including thermal CH₃OH, CH₃CN, HNCO, SO, and OCS lines. The $^{12}$CO (2–1) line reveals a strong bipolar outflow originated from MM2. The outflow consists of a low-velocity component with wide-angle quasi-parabolic shape and a more compact and collimated high-velocity component. The overall geometry resembles the outflow system observed in the low-mass protostar which has a jet-driven fast flow and entrained gas shell. The outflow has a dynamical age of $6 \times 10^3$ years and a mass ejection rate $\sim 10^{-3} M_\odot$ year$^{-1}$. A prominent shock emission in the outflow is observed in SO and OCS, and also detected in CH₃OH and HNCO. We investigated the chemistry of MM1, MM2 and the shocked region. The dense core MM2 have molecular abundances of 3 to 4 times higher than those in MM1. The abundance excess, we suggest, can be a net effect of the stellar evolution and embedded shocks in MM2 that calls for further inspection.

Key words: stars: pre-main sequence — ISM: molecules — ISM: abundances — ISM: kinematics and dynamics — ISM: individual (G23.44-0.18) — stars: formation

1 INTRODUCTION
The outflows take place in high-mass star forming regions at very early evolutionary stages (e.g. Birkmann et al. 2006; Beuther & Sridharan 2007; Longmore et al. 2011). They inject large amount of hot gas and kinetic energy into the molecular cloud, causing intense shock waves that dramatically alter the chemistry of the surrounding environment (van Dishoeck & Blake 1998). However, the morphological and dynamical properties of the outflows on smaller scales, as well as their chemical effect to the young high-mass stellar cores are still to be further characterized.

The high-mass star forming region G23.44-0.18 (G23.44 hereafter) was previously detected as a group of strong CH₃OH masers (Walsh et al. 1998) which indicate the presence of young massive stars. It has a trigonometric-parallax distance of 5.88 kpc (Brunthaler et al. 2009). In this letter, we report an observation of the massive dusty cores MM1 and MM2 associated with the CH₃OH masers, as well as a high-velocity, intense bipolar outflow revealed in CO (2–1). The outflow is causing a shock emission and may be affecting the chemistry in MM2. Section 3 presents the observational results. A further discussion on the outflow is given in Section 4.1 and 4.2. The properties of the dusty cores are discussed in Section 4.3. A summary is given in Section 5.

2 OBSERVATIONS AND DATA REDUCTION
The observational data is taken from the released SMA data archive. The observation toward G23.44 was carried out in September 2008. The phase tracking center is RA.(J2000)=18h34m39.25s, Dec.(J2000)=−8°31′36.2″. The pointing accuracy of the SMA is $\sim 3''$. The observation employed 8 antennas in their compact configuration. The correlator has a total bandwidth of 4 GHz, centered at 220 GHz (LSB) and 230 GHz (USB). The on-source integration time is 80 min. The SMA primary beam size (field of view) at this waveband (1.3 mm) is 55''×3.7''.

Images of the G23.44 region at other wavelengths were also...
3 RESULTS

Figure 1 shows the 1.3 mm continuum emission (white contours) overlayed on the RGB image of the three IRAC bands. It reveals two dust cores aligned from the north to south, denoted as MM1 (northern core) and MM2 (southern core). Deconvoluted with the beam size, MM1 has an mean diameter of 7.3'' (0.2 pc) while MM2 is more elliptical, with an extent of 9.7'' × 6.7'' (0.27 × 0.19 pc) and position angle PA = 45° northeast. The strongest 6.7 GHz CH$_3$OH masers coincide with the centers of MM1 and MM2. We referred to the MAGPIS 6 cm survey for the potential radio continuum emission from the ionized gas. It turns out that neither MM1 nor MM2 has detectable emission above the sensitivity level of 2.9 mJy, indicating both cores being prior to forming an Ultra-Compact Hii (UCH ii) region. The fluxes (or magnitudes) of MM1 and MM2 at near- to far-Infrared are drawn from the 2MASS and IRAC point-source catalogues. The 450 µm fluxes are measured directly from the JCMT images. The obtained values are shown in Table 1.

The J = 2 − 1 transition of $^{12}$CO, $^{13}$CO and C$^{18}$O and a number of molecular species tracing dense gas are detected in our sidebands, including HNCO (10$_{0,10}$−9$_{0,9}$), SO (65−54), OCS (19−18), CH$_3$CN 12$_K$ − 11$_K$ (K = 0 to 6), and four thermally excited CH$_3$OH lines. In the online material, their spectra and physical parameters are provided in Figure S1 and Table S1. The 2MASS $K_S$ and JCMT 450 µm images are presented in Figure S2 and S3.

Figure 2a shows the integrated images of the C$^{18}$O, CH$_3$CN, HNCO, CH$_3$OH (8$_{0}−7_{1}$), SO, and OCS lines. The C$^{18}$O has a broad distribution, with the emission peaks reasonably coincident with the dust cores. The other species show more compact emissions closely associated with the dust cores. The C$^{18}$O emission has comparable intensities for MM1 and MM2, while the emissions of other dense-gas tracers are much brighter in MM2. Since the dust continuum and C$^{18}$O emission all closely follow the H$_2$ distributions, the intensity contrast suggests that MM2 have higher molecular abundances than MM1, as discussed in Section 4.3.

A strong bipolar outflow is observed in $^{12}$CO (2−1). Figure 2b presents the CO (2−1) image integrated in the four velocity intervals. The outflow can be divided into a pair of low-velocity component (LVC) and high-velocity component (HVC) based on their distinct morphologies. The HVC roughly has |v| \> 20 km s$^{-1}$ from the systemic velocity (101 km s$^{-1}$). The bulk of the outflow emission is in the southeast-northwest direction, with a position angle of PA = 40° northwest. Figure 2c shows the beam-averaged SO and OCS spectra at MM1 and MM2 center, and the shocked region (Δα = −11′′, Δδ = 10′′). The $^{13}$CO emission shows a similar feature with $^{12}$CO despite being weak in the HVC. We present the channel maps of $^{12}$CO and $^{13}$CO in Figure S4 and S5, respectively.

4 DISCUSSION

4.1 The physical properties of the outflow

The presence of intense bipolar outflow in G23.44 suggests that the central stars are likely being formed via a disk-mediated accretion [Zhang et al. 2007]. The HVC is well collimated along the outflow axis, while the LVC, especially its red wing, has a more opened parabolic shape with a decreasing brightness from the edge to the center. The overall geometry of the outflow is reminiscent of the outflow system in the low-mass protostar HH211 [Gueth & Guilloteau 1999]. HH211 consists of a high-velocity jet-driven flow and an entrained low-velocity gas shell. The G23.44

Table 1. Physical parameters of the cores.

| parameter | MM1          | MM2          | Unit  |
|-----------|--------------|--------------|-------|
| $m_I$     | $12.315 \pm 0.049$ | > 15.8       | mag   |
| $m_H$     | 11.702 ± 0.028 | > 15.1       |       |
| $m_K$     | 11.435 ± 0.023 | > 14.3       |       |
| $F(3.6\mu m)^b$ | 1.42 ± 0.28   | 0.63 ± 0.08  | mJy   |
| $F(4.5\mu m)^b$ | 25.65 ± 2.23 | 14.48 ± 1.96 |       |
| $F(8.0\mu m)^b$ | 47.84 ± 2.22 | 53.16 ± 2.11 |       |
| $F(1.3\mu m)c$ | 32.92 ± 2.04 | 46.04 ± 2.86 |       |
| $F(450\mu m)c$ | 27.3 ± 1.5   | 38.6 ± 1.5  | Jy    |
| $T_{rot}$(CH$_3$CN) | 65 ± 10     | 110 ± 10    | K     |
| $T_{rot}$(CH$_3$OH) | 66 ± 5      | 60 ± 6      |       |
| Mass      | 120 ± 30     | 140 ± 10    | $M_\odot$ |
| $N$(H$_2$) | $1.9 \pm 0.2$ | $2.5 \pm 0.2$ | 10$^{21}$ cm$^{-2}$ |

Note. The flux densities at IR and sub-millimeter wavebands are taken from $^a$2MASS, $^b$Spitzer/IRAC, $^c$JCMT/SCUBA. The remaining data all come from the SMA observation.

extracted from several public archives. The Spitzer/IRAC images and the point-source catalogue are taken the database of the GLIMPSE sky survey in the NASA/IPAC Infrared Science Archive. We looked for the near-infrared counterparts in the 2MASS point-source catalogue$^2$. The continuum image at JCMT 450 µm was also obtained to measure the flux densities. They are taken from the Canadian Astronomy Data Center (CADC) repository of the SCUBA Legacy Fundamental Object Catalogue.$^3$

2 http://irsa.ipac.caltech.edu/
3 http://www4.cadc-ccda.hia-iha.nrc-cnrc.gc.ca

4 http://third.ucllnl.org/gps/index.html
outflow may represent a scaled-up version of this system, despite its collimation and shell structure being much less perfect than HH211. However, the size of the outflow in HH211 is only \( \sim 10^4 \) AU, while the G23.44 outflow (10^2 AU) has a 10-time larger spatial extent. On such a large scale, the outflow structure might begin to deteriorate due to increased turbulence in its environment.

The CO outflow, especially the LVC also exhibits a weak emission feature in opposite direction to the major one, i.e. a blueshifted emission in the NW and a redshifted one in the SE. This can be a second flow by chance aligned in the same position angle with the major one. Alternatively, once the outflow direction is close to the plane of the sky and its inclination angle becomes smaller than the opening angle (\( \sim 30^\circ \)), its front and back sides will exhibit opposite Doppler shift. This scenario is well demonstrated by [Yen et al. (2010) Figure 10 therein]. We speculate the second case to be more plausible.

Assuming a local thermal equilibrium (LTE) and low optical depth for the \(^{12}\)CO line-wing emission, the CO column density and the outflow mass can be inferred following the approach of [Garden et al. (1991)]. The excitation temperature of the outflow is speculated to be slightly lower than in the dense core MM2 (\( \sim 70 \) K, Section 4.3). A value of \( T_{\text{ex}} = 50 \) K is adopted here. The outflow mass is estimated in each 1 km s\(^{-1}\) interval, then the total mass, momentum, and kinetic energy are calculated from \( M = \Sigma \nu m(\nu)\), \( P = \Sigma \nu m(\nu)\nu^2\), and \( E_k = \Sigma \nu m(\nu)\nu^2/2\). In calculation, we assume an inclination angle of \( \theta = 20^\circ \) to correct the velocity projection. The outflow turns out to have \( M \approx 5.5 \) \( M_\odot \), \( P \approx 360 M_\odot \) km s\(^{-1}\), \( E_k = 9 \times 10^{46} \) erg.

Each of the blue and red wings in the HVC is resolved into two major clumps (Figure 2b, lower panel) denoted B1, B2 and R1, R2. These clumps in the outflow may indicate an episodic mass ejection (e.g. [Qiu et al. 2009]). The average central distance is 240 (0.68 pc) for the pair of B1-R1, and 50 (0.14 pc) for B2-R2. The two pairs both show a reasonable geometrical symmetry. However, the clumps are not exactly aligned across the MM2 center, instead with an offset to its west. This may indicate that the driven agent, or the stellar disk system is also displaced from the MM2 center. The dynamical age of the outflow \( t_{\text{dyn}} \) is estimated by dividing its spatial extent with the typical velocity (\( \nu = 40/\sin\theta \) km s\(^{-1}\)). That yields \( t_{\text{dyn}} = 6.1 \times 10^3 \) years for the B1-R1 pair and \( t_{\text{dyn}} = 1.3 \times 10^4 \) years for B2-R2. Adopting the first value, we calculate the mass ejection rate to be \( M = M_\odot \approx 1.0 \times 10^{-3} M_\odot \).
yr\(^{-1}\). One can see that the outflow is young and performing an intense mass ejection.

### 4.2 Chemical enhancement in the outflow and shock

In both low- and high-mass young stellar objects the outflows have led to a rich chemistry in CH\(_3\)OH, HNCO, and sulphides [Blake et al. 1987; van der Tak et al. 2003; Jørgensen et al. 2004; Rodríguez-Fernández et al. 2010; et al.]. In G23.44, the SO and OCS emission shows a noticeable emission clump at offset\((-11''\), 10''\) (Figure 2a). The clump is almost perfectly aligned with the HVC axis of the CO (2–1), and reasonably coincides with the peak R2, despite being closer to MM2 center. This strongly suggests that the clump traces a shock within the jet/outflow. The clump is also weakly detected in HNCO and CH\(_3\)OH (spectra shown in Figure S1). Their column densities are estimated using Equation (1) and (2) in Section 4.3. In calculation a temperature of \(T_{\text{ex}}\) = 50 K [same with that of CO (2–1)] is adopted, and the C\(^{18}\)O abundance is taken to be a constant of \(2 \times 10^{-7}\) as the typical ISM abundance which is close to \(f_{\text{C^{18}O}}\) measured in MM1 and MM2. The abundances of other molecules are then inferred from their intensity ratio relative to C\(^{18}\)O (2–1). The abundances of the shocked clump are listed in Table 2.

In the low-mass protostars, the outflows often lead to a rich chemistry. In a few cases, the column density of HNCO and S-bearing molecules can be enhanced for orders of magnitude (e.g. L1157 and L1448, Rodríguez-Fernández et al. 2010; Taffala et al. 2017). In comparison, the shocked region at \((-11'', 10'')\) shows moderate abundances which are comparable or even slightly lower than in MM2. The enhancement level can be limited by the temperature and density in the shocked region, as well as the efficiency of the previous grain-surface chemistry. In addition, since the outflow has a short \(t_{\text{dyn}}\), the shock chemistry may still be undergoing and have not yet attained its maximum level.

The blue lobe of CO (2–1) outflow are devoid of the SO and OCS emissions. As a possible explanation, the S-bearing species (e.g. H\(_2\)S and CS as their progenitors) would be rather tightly bound to the dust grains [Blake et al. 1987], and a threshold shock velocity may be required for their desorption. Higher resolution and primary shock products like SiO and H\(_2\)S may better reveal the shock chemistry.

### 4.3 The dense core properties

The dust cores MM1 and MM2 coincide with dark patches on the extended 8 \(\mu\)m emission (Figure 1). The two cores are slightly connected with each other, suggesting that they might be the fragmentation products from the same natal cloud.

The CH\(_3\)CN (12\(K\) – 11\(K\)) lines provide a temperature diagnosis for the cores (Figure 3a). We take an LTE radiative transfer model with a uniform rotation temperature and gas density (Chen et al. 2006; Zhang et al. 2007) to reproduce the observed CH\(_3\)CN spectra at the dust-core center. We found the best fit at \(T_{\text{rot}}\) = 65 K for MM1 and \(T_{\text{rot}}\) = 110 K for MM2. The modeled spectra of \(K = 0\) and 1 towards MM2 is much lower than the observed line profile while the \(K > 1\) lines are all well fitted. The excess emission in \(K = 0\) and 1 lines may largely arise from the cold outer-envelope gas.

The rotation temperature is also evaluated from the thermally excited CH\(_3\)OH lines at the core center using the rotation diagram method [Goldsmith & Langer 1999; Liu et al. 2001; Bisschop et al. 2007]. The column density of the upper level \(N_u\) is related to the line intensity in the form

\[
\frac{N_u}{g_u} = \frac{3k}{8\pi^3 v_S \mu^2} \int T_b \, d\nu
\]

where \(g_u\) is the upper-level degeneracy, \(S\) is the line strength, \(\mu\) is the dipole moment. \(N_u\) depends on the total column density \(N_T\) in the form

\[
\ln \left( \frac{N_u}{g_u} \right) = \ln \left( \frac{N_T}{Q_{\text{rot}}} \right) - \frac{E_u}{T_{\text{rot}}}
\]

where the partition function \(Q_{\text{rot}}\) can be adopted from [Blake et al. 1987]. \(T_{\text{rot}}\) is then estimated from a least-square fit (Figure 3b). The derived values are listed in Table 1.

The \(T_{\text{rot}}\) derived from CH\(_3\)OH and CH\(_3\)CN are remarkably similar for MM1. For MM2, however, the \(T_{\text{rot}}\) of CH\(_3\)OH is lower than that of CH\(_3\)CN. As a probable reason, the CH\(_3\)OH lines generally have lower \(E_u\) than CH\(_3\)CN (12\(K\) – 11\(K\)), then the cooler outer-part gas would contribute more significantly to the CH\(_3\)OH lines than to the CH\(_3\)CN (in particular \(K = 2\) to 6). In addition the CH\(_3\)OH can be easily released from the dust grains by the shocks while the CH\(_3\)CN production requires subsequent gas-phase reactions and stellar heating [van Dishoeck & Blake 1998]. CH\(_3\)CN may therefore be distributed closer to the MM2 center (as seen in Figure 2a), and showing a higher \(T_{\text{rot}}\).

For the other species, an independent temperature estimation is currently unavailable. We adopt \(T_{\text{ex}}\) = 60 K for MM1 and \(T_{\text{ex}}\) = 70 K for MM2 assuming an LTE excitation, the column density of the molecules are calculated from their spectral lines towards the dust-core center, using equation (1) and (2).

Assuming optically thin 1.3 mm dust continuum emission, the total dust-and-gas mass can be estimated using \(S_v = \frac{2}{3} \frac{d^2}{c}\)
The outflow in G23.44-0.18

5 SUMMARY

We present a multi-wavelength study towards the young high-mass star forming region G23.44-0.18. Two dusty cores, MM1 and MM2 are observed in 1.3 mm continuum emission and the molecular lines of CH$_3$OH, CH$_3$CN, HNCO, SO, and OCS. The two cores have a pre-UC HII evolutionary stage. A strong bipolar outflow is arising from MM2 as revealed by CO (2–1). The outflow consists of a collimated, bi-velocity component and a more extended, parabolic flow at lower velocities. A clump of shocked gas is observed in SO (6$_{2}$S–5$_{1}$) and OCS (19–18) lines and also detected in HNCO and CH$_3$OH. The outflow shows a high momentum and mass-loss rate, and a short timescale of $t_{\text{dyn}} \sim 6 \times 10^3$ years.

In MM2 the high-density tracers CH$_3$OH, CH$_3$CN, HNCO, SO, and OCS show abundances of 3 to 4 times higher than those in MM1. To explain this difference, we suggest a combined effect of the stellar heating and underlying shock interactions in MM2. A further study with higher excited lines and improved resolution can be performed to probe the chemistry, possible disk-jet system and mass accretion close to the MM2 center.

ACKNOWLEDGMENT

We are grateful to the SMA observers and the SMA data archive. We would thank the anonymous referee for the useful comments that helped to improve the presentation and interpretation. This work is supported by grants of No.10733033, 10873019, 10973003, 2009CB24901, and the Doctoral Candidate Innovation Research Support Program (kjdb201001-1) from Science & Technology Review.

REFERENCES

Arce, H. & Sargent, A. 2004, ApJ, 612, 342
Beuther, H., & Sridharan, T. K. 2007, ApJ, 668, 348
Birkmann, S. M., Krause, O., Lemke, D. 2006, ApJ, 637, 380
Bisschop, S. E., Jorgensen, J. K., van Dishoeck, E. F., & de Wachter, E. B. 2007, A&A, 465, 913
Blake, G., Sutton, E., Masson, C., & Phillips, T. 1987, ApJ, 315, 621
Brunthaler, A., Reid, M. J., Menten, K. M., Zheng, X. W., Moscadelli, L., & Xu, Y. 2009, ApJ, 693, 424
Chen, H., Welch, W. J., Wilner, D. J., Sutton, E. C. 2006, ApJ, 639, 975
Garden, P. R., Hayashi, M., Gatley, I. et al., 1991, ApJ, 374, 540
Goldsmith P. & Langer, W. 1999, ApJ, 517, 209
Gueth, F. & Guilloteau, S. 1999, A&A, 343, 571
Jørgensen, J. K., Hogerheijde, M. R., Blake, G. A., van Dishoeck, E., Mundt, L., & Schöier, F. & A&A, 415, 1021
Liu, S.-Y., Mehringer, D., & Snyder, L. 2001, ApJ, 552, 654
Longmore S. N., Pillai, T., Keto, E., Zhang, Q., & Qi, K. 2011, ApJ, 726, 97
Ossenkopf, V., & Henning, T. 1994, A&A, 291, 943
Qi, K., Zhang, Q., Wu, J., & Chen, H. 2009, ApJ, 696, 66
Rodriguez-Fernández, N., Tafalla, M., Gueth, F., & Bachiller, R. 2010, A&A, 516, 98
Robitaille, T. P., Whitney, B. A., Indebetouw, R., Wood, K., & Denzmore, P. 2006, ApJS, 167, 256
van der Tak, Boonman, A., Braakman, R., van Dishoeck, E. 2003, A&A, 412, 133
Tafalla, M., Santiago-Garcia, J., Hacar, A., & Bachiller, R. 2010, A&A, 522, 91
van Dishoeck, E. & Blake, G. 1998, ARA&A, 36, 317
Walsh, A. J., Burton, M. G., Hyland, A. R., Robinson, G. 1998, MNRAS, 301, 640
Wu, Y., Qin, S. L., Guan, X., Xue, R., Ren, Z., Liu, T., Huang, M., Chen, S. 2009, ApJ, 697, L116
Yen, H., Takakuwa, S., Ohashi, N. 2010, ApJ, 710, 1786
Zhang, Q., Hunter, T. R., Beuther, H., Sridharan, T. K., Liu, S.-Y., Su, Y.-N., Chen., H.-R., & Chen, Y. 2007, ApJ, 658, 1152
Table S1. Parameters of the molecular lines.

| Frequency (GHz) | Species | Transition | \( V_{\text{lsr}} \) (km s\(^{-1}\)) | \( T_{\text{peak}} \) (K) | \( \gamma_{\text{peak}} \) (K) | \( \Delta V_{\text{FWHM}} \) (km s\(^{-1}\)) |
|----------------|---------|------------|---------------------------------|-----------------|-----------------|-----------------|
| MM1 (\( -1''_1, 10''_1 \)) |          |            |                                 |                 |                 |                 |
| 219.5603...   | C\(^{18}\)O | 2 – 1      | 102.2                           | 11 ± 0.4        | 3.2 ± 0.5       |                  |
| 219.7982...   | HNCO     | 10\(_{0,10} - 9_{0,9}\) | 101.4                           | 1.8 ± 0.1       | 3.6 ± 0.4       |                  |
| 219.9494...   | SO       | 6\(_{5} - 5_4\) | 101.3                           | 4.2 ± 0.1       | 3.4 ± 0.4       |                  |
| 220.0784...   | CH\(_3\)OH | 8\(_{0,8} - 7_{1,6}\) | 101.5                           | 1.0 ± 0.3       | 4.2 ± 0.6       |                  |
| 220.7302...   | CH\(_3\)CN | 12\(_{2} - 11_2\) | 101.6                           | 1.3 ± 0.2       | 5.5 ± 0.8       |                  |
| 229.7588...   | CH\(_3\)OH | 8\(_{1} - 7_0\) | 101.8                           | 3.9 ± 0.1       | 3.5 ± 0.5       |                  |
| 230.0270...   | CH\(_3\)OH | 3\(_{2,2} - 4_{1,4}\) | 102.1                           | 1.3 ± 0.3       | 2.9 ± 0.6       |                  |
| 231.0609...   | OCS      | 19 – 18    | 102.1                           | 1.9 ± 0.2       | 4.5 ± 0.4       |                  |
| 231.2810...   | CH\(_3\)OH | 10\(_{2,9} - 9_{3,6}\) | 101.3                           | 0.6 ± 0.2       | 2.3 ± 0.4       |                  |

| MM2 (\( 1''_1, -3''_1 \)) |          |            |                                 |                 |                 |                 |
|-----------------|---------|------------|---------------------------------|-----------------|-----------------|-----------------|
| 219.5603...   | C\(^{18}\)O | 2 – 1      | 99.8                            | 6.4 ± 0.5       | 10.5 ± 1.5      |                  |
| 219.7982...   | HNCO     | 10\(_{0,10} - 9_{0,9}\) | 100.6                           | 3.5 ± 0.1       | 8.8 ± 0.6       |                  |
| 219.9494...   | SO       | 6\(_{5} - 5_4\) | 101.5                           | 6.0 ± 0.1       | 11.3 ± 0.7      |                  |
| 220.0784...   | CH\(_3\)OH | 8\(_{0,8} - 7_{1,6}\) | 100.5                           | 3.5 ± 0.3       | 6.7 ± 0.8       |                  |
| 220.7302...   | CH\(_3\)CN | 12\(_{3} - 11_3\) | 101.7                           | 2.8 ± 0.1       | 6.6 ± 0.7       |                  |
| 229.7588...   | CH\(_3\)OH | 8\(_{1} - 7_0\) | 102.1                           | 15.0 ± 0.1      | 8.5 ± 0.8       |                  |
| 230.0270...   | CH\(_3\)OH | 3\(_{2,2} - 4_{1,4}\) | 102.1                           | 2.0 ± 0.2       | 4.3 ± 0.5       |                  |
| 231.0609...   | OCS      | 19 – 18    | 102.1                           | 3.2 ± 0.1       | 6.7 ± 0.4       |                  |
| 231.2810...   | CH\(_3\)OH | 10\(_{2,9} - 9_{3,6}\) | 102.1                           | 1.4 ± 0.3       | 4.3 ± 0.3       |                  |

| Shock (\( -1''_1, 10''_1 \)) |          |            |                                 |                 |                 |                 |
|-----------------|---------|------------|---------------------------------|-----------------|-----------------|-----------------|
| 219.5603...   | C\(^{18}\)O | 2 – 1      | 102.1                           | 8.0 ± 0.3       | 2.7 ± 0.4       |                  |
| 219.7982...   | HNCO     | 10\(_{0,10} - 9_{0,9}\) | 96.3                            | 0.8 ± 0.2       | 1.3 ± 0.4       |                  |
| 219.9494...   | SO       | 6\(_{5} - 5_4\) | 102.3                           | 4.9 ± 0.3       | 5.6 ± 0.5       |                  |
| 220.0784...   | CH\(_3\)OH | 8\(_{0,8} - 7_{1,6}\) | 102.1                           | 0.9 ± 0.2       | 3.7 ± 0.6       |                  |
| 220.7302...   | CH\(_3\)CN | 12\(_{2} - 11_2\) | –                              | –               | –               |                  |
| 229.7588...   | CH\(_3\)OH | 8\(_{1} - 7_0\) | 103.2                           | 8.0 ± 0.2       | 4.2 ± 0.4       |                  |
| 230.0270...   | CH\(_3\)OH | 3\(_{2,2} - 4_{1,4}\) | –                              | –               | –               |                  |
| 231.0609...   | OCS      | 19 – 18    | 102.1                           | 2.0 ± 0.2       | 3.3 ± 0.5       |                  |
| 231.2810...   | CH\(_3\)OH | 10\(_{2,9} - 9_{3,6}\) | –                              | –               | –               |                  |
Figure S1. The molecular lines detected in the observational sidebands at the three positions.
Figure S2. The near to mid-IR RGB-coded image of G23.44. The blue is the 2MASS Ks, the green and red colors are IRAC 3.6 and 4.5 micron, respectively. The image center is RA.(J2000)=18\textdegree 34\text{m} 39.25\text{s} and Dec.(J2000)=−8\textdegree 31′ 36.2″. The contour levels are -5, 5, 15, 25, 35, 45, and 55 σ (0.013 Jy beam\(^{-1}\)). The synthesized beam (4.1″ × 3.7″) with PA = 7° to the west. The squares are the two strongest CH\(_3\)OH masers. The crosses are the centers of the IRAC sources.

Figure S3. The SCUBA 450 \(\mu\)m image of G23.44. Contours are 10 to 90 per cent of the peak brightness (34.5 Jy beam\(^{-1}\)). The beam size is 7.5″. The cross denotes the center position RA.(J2000)=18\textdegree 34\text{m} 39.25\text{s} and Dec.(J2000)=−8\textdegree 31′ 36.2″.
Figure S4. The $^{12}$CO (2–1) channel images. The contours are -10, 20 to 90 percent of the peak intensity, which is 45 Jy beam$^{-1}$ for the velocity range of [63,90] km s$^{-1}$ and 18.9 Jy beam$^{-1}$ for $v=\{110,152\}$ km s$^{-1}$. Gray is the SMA 1.3 mm continuum emission.
Figure S5. The $^{13}$CO (2–1) channel images. The contours are -10, 20 to 90 percent of the peak intensity which is 12.2 Jy beam$^{-1}$ for the velocity range of $[84,93]$ km s$^{-1}$ and 8.8 Jy beam$^{-1}$ for $v=[108,117]$ km s$^{-1}$. 