

The total column densities and fractional abundances of CH₃CN, CH₃OH, HCOOCH₃ and ¹³CS in W51 cores

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Abstract We present interferometric observations of the W51 region at 2.7 mm and 3.3 mm with the Berkeley-Illinois-Maryland Association Array. The lines of CH₃CN ($J = 6 - 5$, $K = 0, 1, 2, 3, 4$), CH₃OH ($15_{-2} - 15_1$ E), HCOOCH₃-A ($7_{1,6} - 6_{1,5}$), HCOOCH₃-E ($7_{1,6} - 6_{1,5}$) and ¹³CS (2-1) as well as the 2.7 mm continuum toward W51 have been observed. The derived total beam-averaged column densities N_T and fractional abundances of CH₃CN, CH₃OH, HCOOCH₃ and ¹³CS in W51 cores have been obtained.

Keywords: massive star formation, interstellar molecular lines, column density, fractional abundance.

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W51 is an HII region complex in Sagittarius spiral arm about 7.5 kpc away. There are three dense molecular cores identified in the 1' region^[1-3]. Massive stars form in these hot, dense, molecular cloud cores. These cores are characterized by small sizes, high temperature, and high gas densities. Although substantial effort has been invested in the study of hot cores, their role in the evolution of massive stars is not well understood. Observations of molecules in hot cores can be used to deduce the physical properties of the hot gas.

The methyl cyanide (CH₃CN) has properties that make it an appealing probe of hot cores. The molecule is a symmetric top which has $K = 0$ to J components closely spaced in frequency for each rotational transition $J+1$ to J . The relative intensities of the K -components can be used to infer the rotation temperature T_{rot} and beam-averaged column densities N_u based on observations of a single rotational transition^[4]. The closely spaced K -components can be observed simultaneously in a single spectrum, thereby minimizing calibration uncertainties in relative line strengths. The methanol (CH₃OH) and methyl formate (HCOOCH₃) are simple organic molecules displaying hindered internal rotation. They are also slightly asymmetric top. Therefore, there are many transitions in the centimeter and millimeter wavelength range^[5-9]. Because of the three iden-

tical H atoms in the CH₃ group, they are separated into two noninterchangeable torsional substates, E and A. ¹³CS is one isotope of CS. It is also a simplest linear molecule. Observation of ¹³CS can help us understand the ratio of ¹³C/¹²C.

This paper presents interferometric observations of CH₃CN (*J*=6—5, *K*=0, 1, 2, 3, 4), CH₃OH (15₋₂—15₁ E), HCOOCH₃-A (7_{1,6}—6_{1,5}), HCOOCH₃-E (7_{1,6}—6_{1,5}) and ¹³CS (2-1) toward W51 region with the Berkeley-Illinois-Maryland Association (BIMA) Array. These line parameters observed are used to estimate the column densities and fractional abundances of the W51 molecular cores.

1 Observations

The observation was conducted in June 02 and 05, 1998 using the ten-element BIMA Array. Two tracks of data were taken with the C configuration, which had baselines ranging from 2 kλ to 29 kλ. The system temperatures typically ranged between 250 and 400 K. The pointing center position was coincident with the continuum source W51-IRS1 at RA(2000)=19^h23^m41^s.87, Dec(2000)=14°30'36".2. The molecular parameters for observations, such as quantum numbers, rest transition frequency, energy for the upper state and line strength of molecules are listed in table 1. The integration time was 6 h. Jupiter was used as flux density calibrator, 3C345 was used as passband responses, and 1925+211 was used as phase references. The data were imaged and self-calibrated using the MIRIAD software package of the BIMA consortium. The typical rms noise was 0.1 Jy beam⁻¹ in a line-free channel and 0.2—0.3 Jy beam⁻¹ in a channel with significant signal. The beam sizes were 9"×6" with P.A.=12° and 7"×5" with P.A.=10° for 90 GHz track and 110 GHz track. The detailed observational parameters are listed in table 2. The conversion factor between specific intensity and brightness temperature is 0.30—0.34 Jy beam⁻¹ K⁻¹ for different windows.

2 Results and discussion

Fig. 1 shows (a) the continuum image of W51 at 110 GHz (2.7 mm), (b) the

Table 1 Molecular parameters for observed transitions^[6-9] in W51

Molecule	Transition <i>J_k</i> — <i>J'_{k'}</i>	Rest frequency <i>ν</i> /GHz	Energy above ground <i>E_u</i> /K	Line strength <i>S_{ul}</i> <i>μ</i> ² /debye ²
CH ₃ CN	6 ₀ —5 ₀	110.38352	18.542	92.291
CH ₃ CN	6 ₁ —5 ₁	110.38138	25.687	89.727
CH ₃ CN	6 ₂ —5 ₂	110.37505	47.123	82.037
CH ₃ CN	6 ₃ —5 ₃	110.36447	82.843	69.219
CH ₃ CN	6 ₄ —5 ₄	110.34966	132.839	51.273
CH ₃ OH	15 ₋₂ —15 ₁ E	107.15979	296.9	2.605
HCOOCH ₃ -A	7 _{1,6} —6 _{1,5}	88.851479	17.940	18.031
HCOOCH ₃ -E	7 _{1,6} —6 _{1,5}	88.843240	17.958	18.031
¹³ CS	2—1	92.494299	6.659	3.914

Table 2 W51 observational parameters

Molecule	Transition $J_K - J'_K$	Channels	Beam size /arcsec ²	Bandwidth /MHz	Resolution /km·s ⁻¹	Channel rms /Jy beam ⁻¹
CH ₃ CN	6 ₀ —5 ₀	128	6.4×4.7	50	1.06	0.2
CH ₃ CN	6 ₁ —5 ₁	128	6.4×4.7	50	1.06	0.2
CH ₃ CN	6 ₂ —5 ₂	128	6.4×4.7	50	1.06	0.2
CH ₃ CN	6 ₃ —5 ₃	128	6.4×4.7	50	1.06	0.2
CH ₃ CN	6 ₄ —5 ₄	128	6.4×4.7	50	1.06	0.2
CH ₃ OH	15 ₂ —15 ₁ E	128	6.6×4.9	50	1.09	0.2
HCOOCH ₃ -A	7 _{1,6} —6 _{1,5}	256	8.6×6.2	25	0.33	0.3
HCOOCH ₃ -E	7 _{1,6} —6 _{1,5}	256	8.6×6.2	25	0.33	0.3
¹³ CS	2 — 1	256	8.3×5.9	25	0.32	0.3

intensity of the CH₃CN $J_K=6_3-5_3$ emission line at 57 km·s⁻¹, (c) the intensity of the CH₃OH $J_K=15_2-15_1$ E emission line at 57 km·s⁻¹, (d) the intensity of the HCOOCH₃-A $J_K=7_{1,6}-6_{1,5}$ emission line at 57 km·s⁻¹, (e) the intensity of the HCOOCH₃-E $J_K=7_{1,6}-6_{1,5}$ emission line at 57 km·s⁻¹, (f) the intensity of the ¹³CS $J=2-1$ emission line at 57 km·s⁻¹. The contour levels are -0.3, 0.3, 0.6, 0.9, 1.2, 1.8, 2.4, 3, 3.6 and 4.8 Jy beam⁻¹. The mapping center position is coincident with the continuum source W51-IRS1 at RA(2000)=19^h23^m41^s.87, Dec(2000)=14°30'36".2. The pixel space equals one arcsecond. In addition, we have labeled the positions of the regions e1, e2, IRS1, and IRS2 in fig. 1(a). The emission from the other CH₃CN $J=6-5$ lines (including $K=0,1,2,4$) originates from the same region of W51 as the $K=3$ transition. In comparing fig. 1(b)—(f) with fig. 1(a), the distribution of CH₃CN, CH₃OH, HCOOCH₃ and ¹³CS is found to be very compact. They peak at W51e and near W51 IRS2. Fig. 2(a)—(c) shows the spectra of the CH₃CN $J=6-5$ lines toward W51 e1, W51 e2 and W51 IRS2 respectively. Fig. 3(a)—(c) shows the spectra of the ¹³CH₃CN $J=6-5$ and CH₃OH $J_K=15_2-15_1$ E lines toward W51 e1, W51 e2 and W51 IRS2 respectively. Fig. 4(a)—(c) shows the spectra of the HCOOCH₃-A&E $J_K=7_{1,6}-6_{1,5}$ lines toward W51 e1, W51 e2 and W51 IRS2 respectively. And fig. 5(a)—(c) shows the spectra of the ¹³CS $J=2-1$ line toward W51 e1, W51 e2 and W51 IRS2 respectively. Parameters of the observed CH₃CN $J_K=6_3-5_3$, CH₃OH $J_K=15_2-15_1$ E, HCOOCH₃ $J_K=7_{1,6}-6_{1,5}$ and ¹³CS $J=2-1$ transitions are given in table 3.

By assuming all levels are populated in LTE and the observed transitions are optically thin, one can use^[10]

$$\frac{N_u}{g_u} = \frac{2.04W}{\theta_a\theta_b} \times \frac{1}{\langle S\mu^2 \rangle \nu^3} \times 10^{20} \text{ cm}^{-2} \quad (1)$$

with the definition of upper level column densities N_u from Boltzmann population distribution

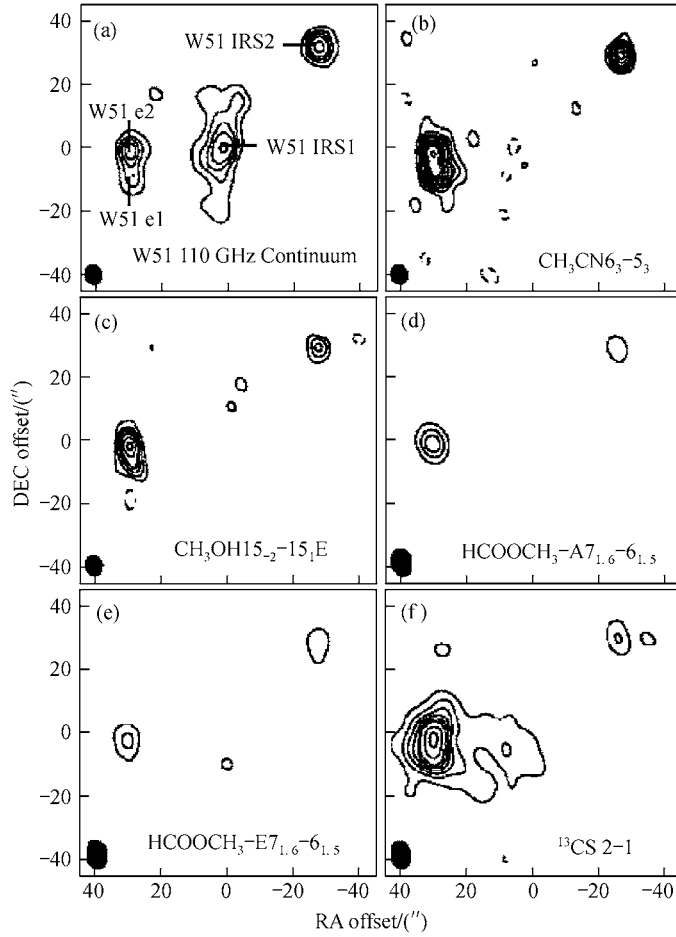


Fig. 1. Images of (a) the continuum emission toward W51 at 110 GHz, (b) the intensity of the CH₃CN $J_K=6_3-5_3$ emission line at 57 km s⁻¹, (c) the intensity of the CH₃OH $J_K=15_2-15_1$ E emission line at 57 km s⁻¹, (d) the intensity of the HCOOCH₃-A $J_K=7_{1,6}-6_{1,5}$ emission line at 57 km s⁻¹, (e) the intensity of the HCOOCH₃-E $J_K=7_{1,6}-6_{1,5}$ emission line at 57 km s⁻¹, (f) the intensity of the ¹³CS $J=2-1$ emission line at 57 km s⁻¹. The contour levels are -0.3, 0.3, 0.6, 0.9, 1.2, 1.8, 2.4, 3, 3.6 and 4.8 Jy beam⁻¹. The beam size is shown on the lower left.

$$\frac{N_u}{g_u} = \frac{N_T}{Q_{rot}} \exp\left(-\frac{E_u}{T_{rot}}\right). \quad (2)$$

Then the total beam-averaged column densities N_T are proportional to the integrated line intensities W in the following sense:

$$N_T = \frac{2.04W}{\theta_a \theta_b} \times \frac{Q_{rot} \exp(E_u/T_{rot})}{\langle S\mu^2 \rangle \nu^3} \times 10^{20} \text{ cm}^{-2}, \quad (3)$$

where

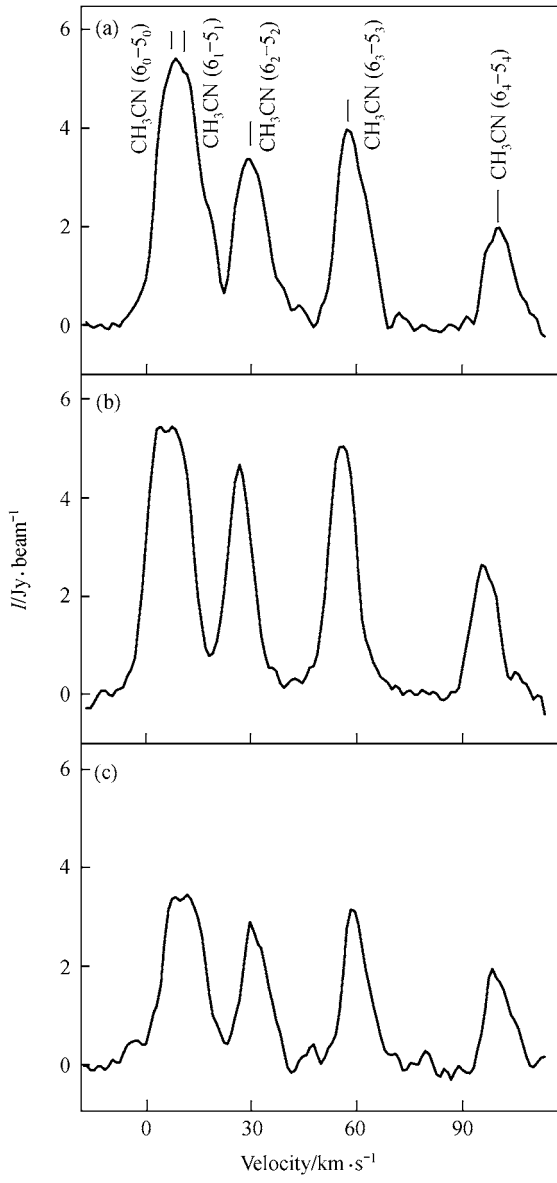


Fig. 2. Line profiles of the CH₃CN *J*=6—5 from W51 e1, W51 e2 and W51 IRS2.

$$Q_{rot}(CH_3CN) = \frac{2}{3} \times \sqrt{\frac{\pi(kT_{rot})^3}{h^3 ABC}} = 0.9717 \times T_{rot}^{1.5}, \tag{4a}$$

$$Q_{rot}(CH_3OH) = 2 \times \sqrt{\frac{\pi(kT_{rot})^3}{h^3 ABC}} = 1.2327 \times T_{rot}^{1.5}, \tag{4b}$$

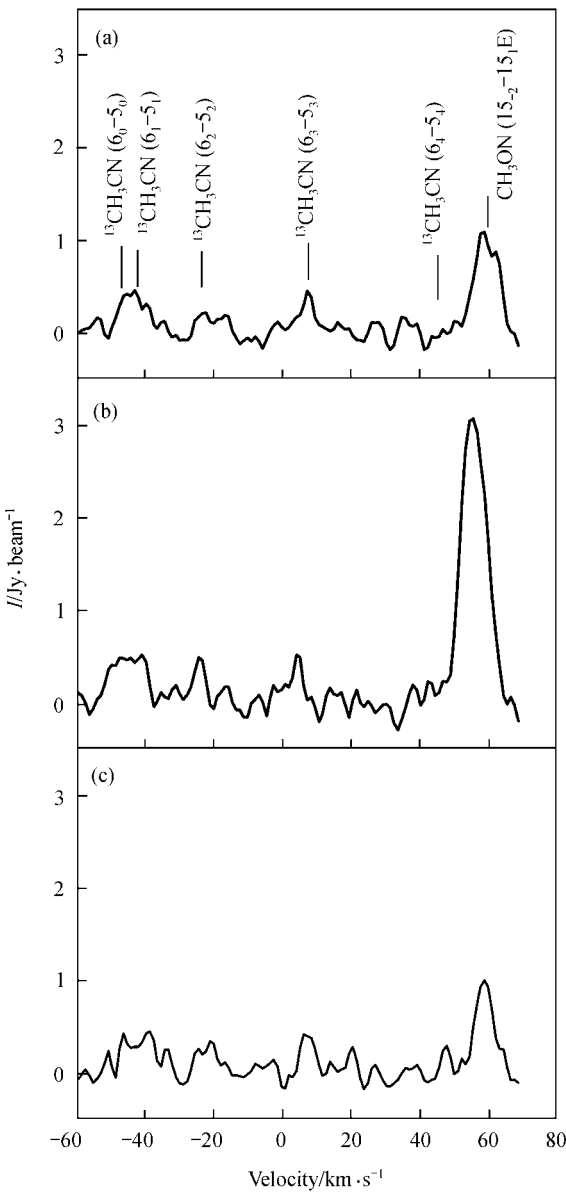


Fig. 3. Line profiles of the ¹³CH₃CN J=6—5 and CH₃OH J_K=15₂—15₁ E from W51 e1, W51 e2 and W51 IRS2.

$$Q_{rot}(\text{HCOOCH}_3 - A) = 2 \times \sqrt{\frac{\pi(kT_{rot})^3}{h^3 ABC}} = 12.453 \times T_{rot}^{1.5}, \tag{4c}$$

$$Q_{rot}(\text{HCOOCH}_3 - E) = 2 \times \sqrt{\frac{\pi(kT_{rot})^3}{h^3 ABC}} = 12.455 \times T_{rot}^{1.5}, \tag{4d}$$

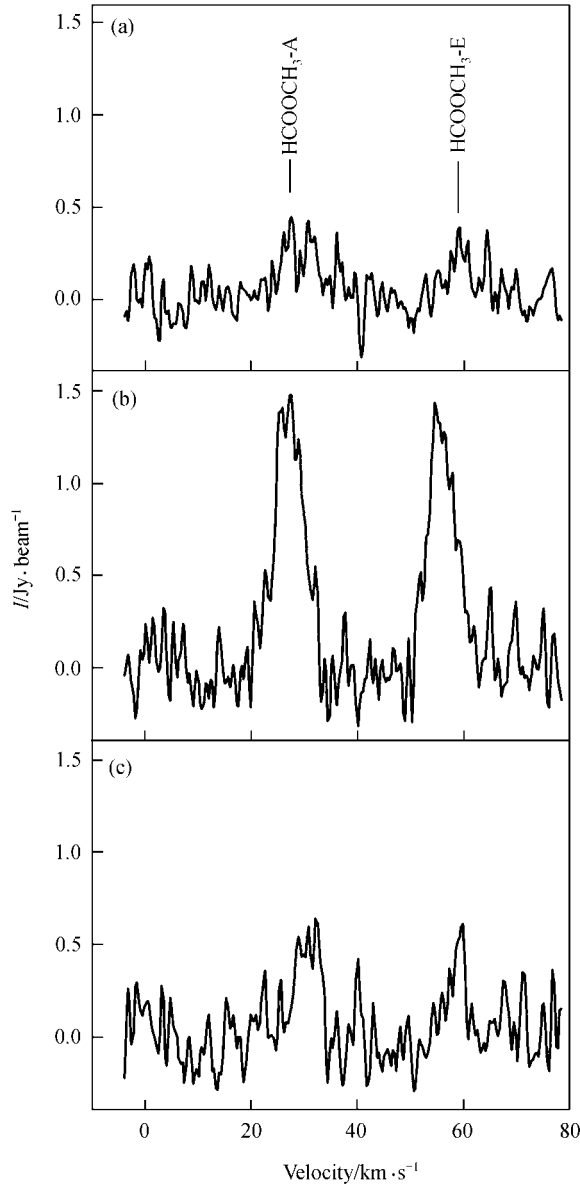


Fig. 4. Line profiles of the $\text{HCOOCH}_3\text{-A\&E } J_K=7_{1,6}-6_{1,5}$ from W51 e1, W51 e2 and W51 IRS2.

$$Q_{\text{rot}}(^{13}\text{CS}) = \frac{kT_{\text{rot}}}{hB} = 0.9011 \times T_{\text{rot}}. \quad (4e)$$

For the observed transitions in eqs. (1)—(4) and tables 1, 2 and 3, ν is the rest frequency in GHz, θ_a and θ_b are the FWHM dimensions of a Gaussian beam in arcseconds, E_u is the upper energy level of the transitions in K, $\langle S\mu^2 \rangle$ is the total rotational line

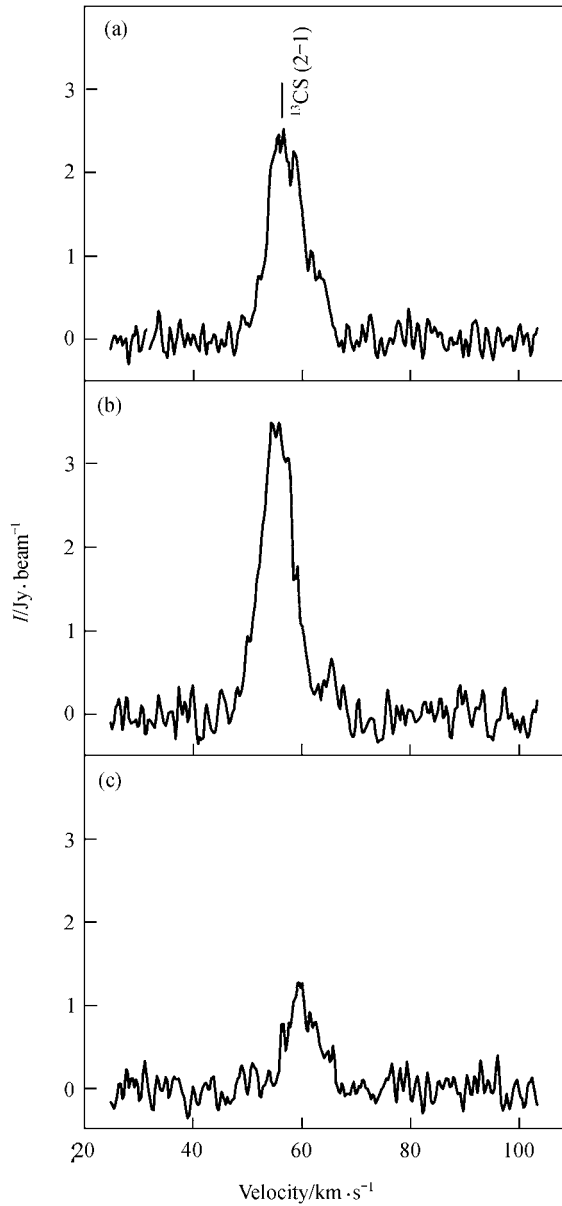


Fig. 5. Line profiles of the ¹³CS $J=2-1$ from W51 e1, W51 e2 and W51 IRS2.

strength in debye², $W = \int I_v dv$ is the integrated line intensity in Jy beam⁻¹ km·s⁻¹, g_u is the rotational degeneracy of the upper level, and Q_{rot} is the partition function. Using rotational temperature $T_{rot} = 150$ K^[2], the derived beam-averaged column densities from observed transitions are listed in table 4. The values of HCOOCH₃ are the average of HCOOCH₃-A and HCOOCH₃-E. The total H₂ column density is reported to be 1×10^{24} cm⁻²^[11]. Therefore, the fractional abundances X have been calculated. They are also

Table 3 The velocity V_{LSR} and integrated line intensities W in W51 cores

Molecule	Transition	$V_{LSR}/\text{km}\cdot\text{s}^{-1}$			$W/\text{Jy beam}^{-1}\text{ km}\cdot\text{s}^{-1}$		
		W51 e1	W51 e2	W51 IRS2	W51 e1	W51 e2	W51 IRS2
CH ₃ CN	6 ₃ —5 ₃	58.6 (1.0)	55.9 (1.0)	59.6 (1.0)	41.9 (1.1)	49.0 (1.2)	26.4 (1.0)
CH ₃ OH	15 ₂ —15 ₁ E	59.1 (1.0)	55.6 (1.0)	58.6 (1.0)	9.1 (0.6)	29.1 (0.9)	7.8 (0.6)
HCOOCH ₃ -A	7 _{1,6} —6 _{1,5}	58.6 (0.3)	55.6 (0.3)	58.9 (0.3)	2.0 (0.3)	8.7 (0.4)	2.1 (0.3)
HCOOCH ₃ -E	7 _{1,6} —6 _{1,5}	58.6 (0.3)	55.6 (0.3)	58.9 (0.3)	3.0 (0.4)	9.6 (0.4)	2.9 (0.3)
¹³ CS	2—1	57.1 (0.3)	55.5(0.3)	60.0(0.3)	20.5(0.5)	26.4(0.5)	8.0(0.4)

Table 4 The total beam-averaged column densities N_T and fractional abundances X of W51 cores

Molecule	Total column density $N_T/\times 10^{15}\text{ cm}^{-2}$			Fractional abundance $X/\times 10^{-9}$		
	W51 e1	W51 e2	W51 IRS2	W51 e1	W51 e2	W51 IRS2
CH ₃ CN	9.5(0.3)	11.1(0.3)	6.0(0.3)	9.5(0.3)	11.1(0.3)	6.0(0.3)
CH ₃ OH	293.5(19.4)	938.6(29.1)	251.6(19.4)	293.5(19.4)	938.6(29.1)	251.6(19.4)
HCOOCH ₃	19.5(2.8)	71.4(3.2)	19.5(2.4)	19.5(2.8)	71.4(3.2)	19.5(2.4)
¹³ CS	3.9(0.1)	5.0(0.1)	1.5(0.1)	3.9(0.1)	5.0(0.1)	1.5(0.1)

listed in table 4.

3 Conclusions

From interferometric observations with the BIMA array, we can draw the following conclusions:

The observed transitions are optically thin. The distribution of CH₃CN, CH₃OH, HCOOCH₃ and ¹³CS was found to be very compact. They peak at W51e and near W51 IRS2. The large difference of total column density and the fractional abundance is probably a result of different evolutionary stages of the W51 e1, W51 e2 and W51 IRS2 cores.

The nondetection of CH₃CN, CH₃OH, HCOOCH₃ and ¹³CS toward W51 IRS1 further demonstrates the chemical differentiation between W51 IRS1 and other cores. The continuum at W51 IRS1 is from free-free emission.

Using the rotational temperature T_{rot} =150 K and the total H₂ column density $N_T(\text{H}_2)$ = $1\times 10^{24}\text{ cm}^{-2}$, the total column densities and the fractional abundances of CH₃CN, CH₃OH, HCOOCH₃ and ¹³CS in the W51 e1, W51 e2 and W51 IRS2 cores have been calculated (see table 4).

The large column densities of organic molecules CH₃OH and HCOOCH₃ at W51 e2 show that W51 e2 is one of the best targets for searching for large organic molecules.

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