



# Tracing the Evolutionary Stage of Low-mass Dense Cores by Using the Abundance Ratio of SO to SO<sub>2</sub>

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## Abstract

Sulfur-bearing molecules are frequently detected in star-forming regions. The abundance ratio of SO to SO<sub>2</sub> (hereafter, SO/SO<sub>2</sub> ratio) has been proposed as a potential evolutionary tracer of star formation because tentative correlations have been found between SO/SO<sub>2</sub> ratio and evolutionary stages. Nonetheless, the lack of high-resolution observations and extensive statistical analyses of large samples raises questions regarding its efficacy as an evolutionary tracer. In this study, we analyze 31 protostellar cores with both SO and SO<sub>2</sub> detection to investigate the relationship between the SO/SO<sub>2</sub> ratio and two evolutionary parameters of chemical richness factor and gas temperatures. The correlations between SO/SO<sub>2</sub> ratio and evolutionary parameters have been found, but these correlations are mainly contributed by low-mass cores rather than high-mass cores. Our findings suggest that the SO/SO<sub>2</sub> ratio serves as a reliable evolutionary tracer for low-mass dense cores. In high-mass cores, the relationship between the SO/SO<sub>2</sub> ratio and evolutionary stage remains ambiguous. This likely arises from both vigorous stellar feedback effects and the potential absence of distinct evolutionary stages analogous to those in low-mass cores. Consequently, higher-resolution observations with expanded statistical samples are required to assess the viability of SO/SO<sub>2</sub> ratio as an evolutionary tracer for high-mass cores.

*Key words:* stars: formation – stars: evolution – submillimeter: ISM – ISM: molecules

## 1. Introduction

Sulfur-bearing molecules are frequently detected in star-forming regions and are typically used to study molecular clouds (e.g., Charnley 1997; Hatchell et al. 1998; Bachiller et al. 2001; van der Tak et al. 2003; Wakelam et al. 2005; Vidal & Wakelam 2018; Artur de la Villarmois et al. 2019, 2023; Oya et al. 2019; Zapata et al. 2019; Fuente et al. 2021; Tychoniec et al. 2021; Tang et al. 2024). Sulfur predominantly exists as S<sup>+</sup> in translucent gas, and rapidly freezes onto negatively charged grains during cloud collapse (Ruffle et al. 1999). Given that hydrogen (H) is the most abundant element, hydrogenation occurs most efficiently on grain surfaces, making H<sub>2</sub>S the primary sulfur reservoir in icy mantles (Charnley 1997). As the protostar heats its surroundings, H<sub>2</sub>S desorbs from grain mantles into the gas phase, increasing gaseous sulfur abundance. Oxygen atoms react with H atoms to form OH, and the liberated sulfur then reacts with OH and O<sub>2</sub> to form SO. SO subsequently reacts with OH to form SO<sub>2</sub>. Consequently, the SO/SO<sub>2</sub> ratio serves as an evolutionary clock in hot cores.

Buckle & Fuller (2003) investigated 24 Class 0/I low-mass protostellar cores and found that the abundances of SO and SO<sub>2</sub> varied at different rates throughout the core evolutionary sequence. Their findings are consistent with the suggestion that the SO/SO<sub>2</sub> ratio may serve as a potential chemical clock from Charnley (1997). However, the chemical model (Wakelam et al. 2004) gave a different opinion that the SO/SO<sub>2</sub> ratio cannot be easily used as a chemical clock because the SO/SO<sub>2</sub> ratio strongly depends on the physical conditions, grain mantle composition, and the abundance of atomic oxygen in the gas phase. Observational studies have further demonstrated that SO and SO<sub>2</sub> abundances are significantly influenced by energetic star-forming activities, particularly those associated with high-velocity gas motions such as outflow and infall processes (e.g., Viti et al. 2001; van der Tak et al. 2003; Artur de la Villarmois et al. 2023; Zhang et al. 2023). These findings consequently challenge the reliability of the SO/SO<sub>2</sub> ratio as a tracer of evolutionary stages.

Herpin et al. (2009) observed four massive dense cores (two mid-infrared quiet and two brighter) using Institut de Radio Astronomie Millimétrique (IRAM), discovering only minor

variations among them. Wakelam et al. (2011) conducted one-dimensional modeling of these four massive cores and noted a clear decrease in the SO/SO<sub>2</sub> ratio as the cores evolved. They attributed the minor differences in the SO/SO<sub>2</sub> ratio observed by Herpin et al. (2009) to the cores being at similar evolutionary stages, rendering them indistinguishable based on the SO/SO<sub>2</sub> ratio. Recently, Fontani et al. (2023) studied 15 massive cores classified as high-mass starless cores (HMSCs), high-mass protostellar objects (HMPOs), and ultra-compact H<sub>II</sub> regions (UC H<sub>II</sub>), which contain at least one zero-age main-sequence star). Their results showed SO/SO<sub>2</sub> ratios of 6.0, 2.4, and 2.0 for HMSCs, HMPOs, and UC H<sub>II</sub> regions, respectively. In another study, Artur de la Villarmois et al. (2023) investigated 50 low-mass cores (Class 0/I) using ALMA Band 6 observations with approximately 0.5 angular resolution, but found no correlation between the SO/SO<sub>2</sub> ratio and core evolution. Therefore, the relationship between the SO/SO<sub>2</sub> ratio and the evolutionary stages of dense cores remains unclear.

Previous studies have failed to yield consistent conclusions, primarily because most investigations relied on low-resolution single-dish observations and limited sample sizes. Although Artur de la Villarmois et al. (2023) studied 50 protostars with an excellent angular resolution, they obtained only six samples with concurrent detections of SO and SO<sub>2</sub>. Such a small effective sample size is insufficient for robust statistical studies of chemical evolution mechanisms. On the other hand, previous research has mainly concentrated on either high- or low-mass dense cores, with few studies investigating the SO/SO<sub>2</sub> ratio differences between them with high-resolution observations and identical configuration. The primary motivation of this work is to examine the relationship between the SO/SO<sub>2</sub> ratio and the evolutionary stages of dense cores without bias, and to assess whether there is a significant difference in the SO/SO<sub>2</sub> ratio between high- and low-mass dense cores in massive star-forming regions. Additionally, we will verify whether the SO/SO<sub>2</sub> ratio serves as a reliable tracer of evolutionary stages.

## 2. Observations and Samples

### 2.1. 870 $\mu\text{m}$ Observations

This study utilizes ALMA Cycle 5 observations conducted from 2018 May 18 to 20, (UTC), under project ID 2017.1.00545S (PI: Tie Liu). A total of 11 massive protoclusters were observed, with 8 included in this analysis (I14382-6017, I16071-5142, and I17204-3636 are excluded due to the lack of molecular emissions of SO<sub>2</sub>). Detailed information on these targets is provided in Table 1. The C43-1 antenna configuration was adopted to perform the observations, and a mosaic mode was employed to extend the field of view. The final images offer 46'' field of views with angular resolutions of approximately 0.8.

Calibrations of phase, bandpass, and amplitude were conducted by using ALMA pipeline based on CASA 5.1.15 version

(CASA Team et al. 2022). The pipeline-processed visibility data underwent self-calibration, including three rounds of phase-only self-calibration and one round of amplitude self-calibration, to enhance image quality. During processes, the phase-only self-calibration starts with a solution interval of a single scan length and terminates with an integration time of 6.05 s. The signal-to-noise ratio of the self-calibrated images ranges from 218 to 838, with percentage improvements in self-calibration between 5% and 47%. The amplitude self-calibration did not introduce systematic errors. Given that self-calibration improved the continuum image quality, solutions derived from continuum self-calibration were applied to the spectral line data to enhance the signal-to-noise ratio of the spectra. The rms noise levels ( $\sigma$ ) for both continuum and spectral cube data of each protocluster are summarized in Table 1.

During imaging, the TCLEAN task in CASA was employed to generate images. We applied the “hogbom” deconvolution algorithm with “briggs” weighting (robust = 0.5) to balance image sensitivity and angular resolution. Four spectral windows were used for spectral line data, each with 1920 uniform channels. Two spectral windows have a bandwidth of 1.875 GHz with a resolution of 0.976 MHz (corresponding to a velocity resolution of  $\sim 0.85 \text{ km s}^{-1}$ ), while the other two have a bandwidth of 468.75 MHz with a resolution of 0.244 MHz (corresponding to a velocity resolution of  $\sim 0.21 \text{ km s}^{-1}$ ). To ensure consistency in subsequent analysis and parameter calculations, we smoothed the narrow-band spectra to match the spectral resolution of the broad-band data.

### 2.2. Sample Selection

A total of 248 dense cores were identified in 11 massive protoclusters (Xu et al. 2024). Tang et al. (2024) investigated the sulfur-bearing molecular lines in these cores, identifying 31 cores that exhibit both SO and SO<sub>2</sub> emissions, with their column densities, abundances, and temperatures reported. While all 31 cores are classified as protostellar cores, exhibiting differing properties (e.g., with or without detection of complex organic molecules), making them ideal for studying the relationship between the SO/SO<sub>2</sub> ratio and core evolutionary stages. The core samples are summarized in Table 2, with basic information sourced primarily from Xu et al. (2024) and Tang et al. (2024). In this work, we follow the nomenclature established by these authors. Detailed information and spatial distributions of the dense cores can be found in Xu et al. (2024) and Tang et al. (2024). The estimations of parameters (and their uncertainties) will be introduced in Section 3.1.

## 3. Results

### 3.1. Parameters

This study utilized a well-characterized sample of dense cores described in Xu et al. (2024), where the authors reported

**Table 1**  
Information of the Observations

| Source      | Center<br>(R.A., Decl.)  | $T_d$<br>(K) | Distance<br>(kpc) | Beam Size<br>( $" \times "$ ) | Signal-to-noise Ratio | Improvement <sup>a</sup> | $\sigma_{\text{cont}}^b$<br>(Jy beam <sup>-1</sup> ) | $\sigma_{\text{line}}^c$<br>(Jy beam <sup>-1</sup> ) |
|-------------|--------------------------|--------------|-------------------|-------------------------------|-----------------------|--------------------------|------------------------------------------------------|------------------------------------------------------|
| I14498-5856 | 14:53:42.81, -59:08:56.5 | 26.7         | 3.2               | $1.065 \times 0.785$          | 501                   | 35%                      | $1.0 \times 10^{-3}$                                 | $6.0 \times 10^{-3}$                                 |
| I15520-5234 | 15:55:48.84, -52:43:06.2 | 32.2         | 2.6               | $0.852 \times 0.699$          | 296                   | 47%                      | $1.5 \times 10^{-3}$                                 | $5.6 \times 10^{-3}$                                 |
| I15596-5301 | 16:03:32.29, -53:09:28.1 | 28.5         | 4.4               | $0.824 \times 0.691$          | 353                   | 29%                      | $5.0 \times 10^{-4}$                                 | $4.9 \times 10^{-3}$                                 |
| I16060-5146 | 16:09:52.85, -51:54:54.7 | 32.2         | 5.2               | $0.820 \times 0.681$          | 616                   | 26%                      | $2.5 \times 10^{-3}$                                 | $5.1 \times 10^{-3}$                                 |
| I16076-5134 | 16:11:27.12, -51:41:56.9 | 30.1         | 5.0               | $0.734 \times 0.628$          | 360                   | 20%                      | $6.0 \times 10^{-4}$                                 | $4.5 \times 10^{-3}$                                 |
| I16272-4837 | 16:30:59.08, -48:43:53.3 | 23.1         | 3.2               | $0.799 \times 0.662$          | 838                   | 10%                      | $1.4 \times 10^{-3}$                                 | $4.5 \times 10^{-3}$                                 |
| I16351-4722 | 16:38:50.98, -47:27:57.8 | 30.4         | 2.9               | $0.771 \times 0.651$          | 370                   | 9%                       | $1.2 \times 10^{-3}$                                 | $5.0 \times 10^{-3}$                                 |
| I17220-3609 | 17:25:24.99, -36:12:45.1 | 25.4         | 7.6               | $0.813 \times 0.653$          | 281                   | 5%                       | $1.7 \times 10^{-3}$                                 | $7.2 \times 10^{-3}$                                 |

**Notes.** Due to the fact that only eight massive protoclusters exhibit detections of both SO and SO<sub>2</sub>, only these eight sources are included in the table. Comprehensive details regarding all 11 massive protoclusters are presented in Xu et al. (2024) and Tang et al. (2024).

<sup>a</sup> The percentage improvement in the signal-to-noise ratio of the continuum image compared to the one without self-calibration.

<sup>b</sup> The rms noises of continuum images.

<sup>c</sup> The rms noises of spectral data, which is an averaged value over all spectral windows.

essential physical parameters. Based on the information from Xu et al. (2024), the mass of dense cores was estimated by the following equation under optically thin assumption of continuum emissions.

$$M_{\text{core}} = R \frac{F_{\nu}^{\text{int}} D^2}{\kappa_{\nu} B_{\nu}(T_{\text{dust}})}, \quad (1)$$

where  $R$ ,  $F_{\nu}^{\text{int}}$ ,  $D$ , and  $\kappa_{\nu}$  are gas-to-dust ratio, integrated flux of continuum emission, distance, and dust opacity, respectively.  $B_{\nu}(T_{\text{dust}})$  is Planck function at a dust temperature  $T_{\text{dust}}$ .

The H<sub>2</sub> column density ( $N_{\text{H}_2}$ ) of dense cores was estimated as follows:

$$N_{\text{H}_2} = R \frac{F_{\nu}^{\text{peak}}}{\Omega \mu_{\text{H}_2} m_{\text{H}} \kappa_{\nu} B_{\nu}(T_{\text{dust}})}, \quad (2)$$

where  $F_{\nu}^{\text{peak}}$  is the peak flux density over the core's region.  $\Omega$  is the solid angle of synthesized beam.  $\mu_{\text{H}_2} = 2.81$  and  $m_{\text{H}}$  are the molecular weight per hydrogen molecule and mass of a hydrogen atom, respectively. The uncertainty in parameter estimation is dominated by gas-to-dust ratio (28%), dust opacity (23%), core flux ( $\sim 14\%$ ), temperature ( $\sim 20\%$ ), and distance (10%). Monte Carlo methods were adopted for uncertainty estimations with  $1\sigma$  confidence intervals for core mass and H<sub>2</sub> column density. The core parameters and uncertainties of our samples, including position, mass, and H<sub>2</sub> column density ( $N_{\text{H}_2}$ ), were taken from Xu et al. (2024) and are listed in Table 2.

### 3.1.1. Parameters of Sulfur-bearing Species

The dense core samples analyzed herein originate from Xu et al. (2024). Tang et al. (2024) subsequently conducted a comprehensive survey of sulfur-bearing molecules within these cores, systematically probing the observed bandwidth and detecting ten sulfur-bearing species (CS, SO, H<sub>2</sub>CS, NS,

SO<sub>2</sub>, <sup>33</sup>SO <sup>34</sup>SO<sub>2</sub>, <sup>33</sup>SO<sub>2</sub>, SO<sup>18</sup>O, and OC<sup>34</sup>S) across 248 dense cores.

The spectrum at the continuum emission peak of the dense core was extracted for molecular line identification and parameter derivation, both performed using the SLIM module within the MADCUBA package<sup>7</sup> (Martín et al. 2019). The optimal molecular parameters (e.g., column density  $N$ , excitation temperature  $T_{\text{ex}}$ , line width  $\Delta v$ , and systemic velocity  $v_{\text{lsr}}$ ) of sulfur-bearing species were determined by fitting the local thermodynamic equilibrium (LTE) model to observed spectra (the fitting results are presented in Figure 1). During the fitting process, multiple Gaussian velocity components are considered in cases where a spectrum cannot be well-fitted by a single component. These components are denoted as colored curves in Figure 1. The fitting uncertainties of the derived parameters are given by SLIM. Additionally, ALMA calibration pipeline gives 10% flux calibration uncertainty (Braatz 2020). Therefore, the uncertainties of estimated molecular parameters are combined by the uncertainty from SLIM LTE fitting (90%) and flux calibration (10%). The abundances relative to H<sub>2</sub> of SO ( $f(\text{SO})$ ) and SO<sub>2</sub> ( $f(\text{SO}_2)$ ) for each dense core from Tang et al. (2024) are adopted in this work and listed in Table 2. Abundance ratio of SO/SO<sub>2</sub> is estimated, and its uncertainty is calculated using an uncertainty propagation formula that incorporates the uncertainties of  $N_{\text{H}_2}$ ,  $f(\text{SO})$ , and  $f(\text{SO}_2)$ .

<sup>7</sup> Madrid Data CUBE Analysis (MADCUBA, <https://cab.inta-csic.es/madcuba/>) is a software package for analyzing observational spectral data. Designed with an interface and a data processing engine based on the ImageJ infrastructure, it provides functions for data visualization, spectral analysis, line identification, and parameter estimation. The SLIM module of MADCUBA implements a four-parameter (column density  $N$ , excitation temperature  $T_{\text{ex}}$ , line width  $\Delta v$ , and systemic velocity  $v_{\text{lsr}}$ ) local thermodynamic equilibrium (LTE) model with automatic corrections for optical depth and beam dilution effects. The AUTO-FIT tool within SLIM estimates these parameters and their uncertainties by fitting the LTE model to observed spectra.

**Table 2**  
Parameters of Dense Cores

| Core      | Center <sup>a</sup><br>(R.A. , Decl.) | Mass <sup>a</sup><br>$M_{\odot}$ | $N_{\text{H}_2}$ <sup>a</sup><br>( $\text{cm}^{-2}$ ) | $f(\text{SO})$ <sup>b</sup> | $f(\text{SO}_2)$ <sup>b</sup> | $T_{\text{H}_2\text{CS}}$ <sup>b</sup><br>(K) | $\frac{f(\text{SO})}{f(\text{SO}_2)}$ | $T_{\text{CH}_3\text{OCHO}}$<br>(K) | CRF <sup>c</sup> |
|-----------|---------------------------------------|----------------------------------|-------------------------------------------------------|-----------------------------|-------------------------------|-----------------------------------------------|---------------------------------------|-------------------------------------|------------------|
| (1)       | (2)                                   | (3)                              | (4)                                                   | (5)                         | (6)                           | (7)                                           | (8)                                   | (9)                                 | (10)             |
| I14498-7  | (14:53:42.6802, −59:08:52.9861)       | 9.7(5.2)                         | 6.5(2.3)E+23                                          | 2.9(1.1)E-08                | 1.5(0.7)E-07                  | 105.5(11.0)                                   | 0.2(0.1)                              | 178.0(20.0)                         | 0.51(0.02)       |
| I15520-4  | (15:55:49.0562, −52:42:59.3895)       | 1.7(1.0)                         | 1.4(0.6)E+23                                          | 9.7(4.5)E-09                | 2.1(1.0)E-09                  | 45.3(4.7)                                     | 4.7(3.1)                              | ...                                 | 0.02(0.01)       |
| I15520-15 | (15:55:48.4511, −52:43:04.4500)       | 2.8(1.6)                         | 5.0(2.1)E+23                                          | 5.5(2.3)E-09                | 5.0(2.3)E-10                  | 55.6(6.1)                                     | 11.0(6.8)                             | 78.3(5.4)                           | 0.07(0.01)       |
| I15520-16 | (15:55:49.0298, −52:43:05.3468)       | 1.0(0.6)                         | 2.7(1.2)E+23                                          | 5.7(2.6)E-09                | 6.2(3.6)E-10                  | 60.2(6.2)                                     | 9.3(6.9)                              | ...                                 | 0.03(0.00)       |
| I15520-18 | (15:55:48.6540, −52:43:06.0751)       | 2.6(1.4)                         | 5.8(2.3)E+23                                          | 1.8(0.8)E-08                | 5.6(2.8)E-08                  | 47.3(5.3)                                     | 0.3(0.2)                              | 86.8(10.8)                          | 0.16(0.01)       |
| I15520-19 | (15:55:48.8662, −52:43:06.4520)       | 3.8(1.9)                         | 4.1(1.7)E+23                                          | 7.5(3.1)E-09                | 1.8(0.8)E-09                  | 45.4(3.6)                                     | 4.3(2.6)                              | ...                                 | 0.04(0.01)       |
| I15520-21 | (15:55:48.3768, −52:43:06.6352)       | 1.5(0.8)                         | 2.3(1.0)E+23                                          | 3.3(1.5)E-08                | 2.5(1.1)E-08                  | 53.8(6.8)                                     | 1.3(0.8)                              | 99.3(5.2)                           | 0.25(0.01)       |
| I15520-22 | (15:55:48.5410, −52:43:06.6687)       | 1.1(0.6)                         | 4.0(1.6)E+23                                          | 4.2(1.7)E-08                | 9.9(4.0)E-08                  | 55.5(4.2)                                     | 0.4(0.2)                              | 94.2(4.2)                           | 0.24(0.01)       |
| I15520-34 | (15:55:48.7529, −52:43:16.7775)       | 0.2(0.1)                         | 3.9(2.3)E+22                                          | 2.0(1.2)E-08                | 4.5(3.3)E-08                  | 64.8(7.9)                                     | 0.5(0.4)                              | ...                                 | 0.03(0.01)       |
| I15596-14 | (16:03:32.6424, −53:09:26.6198)       | 1.6(0.8)                         | 1.2(0.4)E+23                                          | 4.5(1.6)E-08                | 6.3(2.7)E-08                  | 54.0(5.2)                                     | 0.7(0.4)                              | 88.0(2.7)                           | 0.18(0.01)       |
| I15596-19 | (16:03:32.1454, −53:09:30.1428)       | 4.3(2.1)                         | 3.5(1.1)E+23                                          | 2.7(0.9)E-08                | 8.0(4.0)E-08                  | 93.4(9.6)                                     | 0.3(0.2)                              | 134.6(13.1)                         | 0.30(0.01)       |
| I16060-2  | (16:09:52.4189, −51:54:50.8762)       | 3.5(2.4)                         | 1.2(1.1)E+23                                          | 3.2(3.1)E-08                | 4.4(4.3)E-08                  | 44.9(3.6)                                     | 0.7(1.0)                              | ...                                 | 0.06(0.01)       |
| I16060-4  | (16:09:52.7642, −51:54:53.0100)       | 10.0(4.8)                        | 5.9(2.8)E+23                                          | 5.0(2.5)E-08                | 2.0(1.0)E-07                  | 67.1(5.3)                                     | 0.2(0.2)                              | 144.5(30.8)                         | 0.27(0.01)       |
| I16060-8  | (16:09:52.6839, −51:54:53.9571)       | 35.1(15.0)                       | 2.1(0.8)E+24                                          | 1.6(0.7)E-08                | 1.0(0.4)E-07                  | 134.7(15.8)                                   | 0.2(0.1)                              | 166.7(52.3)                         | 0.49(0.02)       |
| I16060-9  | (16:09:52.6394, −51:54:54.8841)       | 52.6(22.2)                       | 1.9(0.7)E+24                                          | 1.8(0.7)E-08                | 1.2(0.6)E-07                  | 112.2(12.4)                                   | 0.1(0.1)                              | ...                                 | 0.51(0.02)       |
| I16060-10 | (16:09:52.4310, −51:54:55.6099)       | 35.6(15.1)                       | 2.4(0.9)E+24                                          | 9.8(3.8)E-09                | 3.7(1.5)E-08                  | 91.4(10.1)                                    | 0.3(0.1)                              | 264.0(18.0)                         | 0.91(0.02)       |
| I16060-11 | (16:09:52.5013, −51:54:56.7799)       | 14.5(6.5)                        | 9.0(3.7)E+23                                          | 4.3(1.9)E-08                | 1.8(0.8)E-07                  | 100.0(10.5)                                   | 0.2(0.1)                              | 347.0(116.0)                        | 0.77(0.02)       |
| I16060-13 | (16:09:52.6320, −51:54:57.3908)       | 10.8(5.1)                        | 7.2(3.2)E+23                                          | 1.8(0.8)E-08                | 1.6(0.7)E-08                  | 99.6(10.2)                                    | 1.2(0.8)                              | 95.0(27.0)                          | 0.15(0.01)       |
| I16076-11 | (16:11:26.5403, −51:41:55.5385)       | 1.7(0.9)                         | 1.6(0.8)E+23                                          | 7.8(4.0)E-08                | 1.1(0.6)E-08                  | 75.0(7.8)                                     | 7.3(5.7)                              | ...                                 | 0.07(0.01)       |
| I16076-15 | (16:11:26.5530, −51:41:57.0631)       | 9.6(4.2)                         | 4.4(1.6)E+23                                          | 4.3(1.6)E-08                | 1.4(0.6)E-07                  | 63.1(5.8)                                     | 0.3(0.2)                              | 387.0(74.0)                         | 0.74(0.02)       |
| I16272-2  | (16:30:57.2696, −48:43:40.1228)       | 3.5(1.6)                         | 4.8(1.7)E+23                                          | 2.9(1.2)E-08                | 7.4(2.8)E-08                  | 92.9(10.2)                                    | 0.4(0.2)                              | 85.3(4.1)                           | 0.74(0.02)       |
| I16351-12 | (16:38:50.4943, −47:28:00.4270)       | 2.4(1.2)                         | 6.0(2.2)E+23                                          | 9.6(3.8)E-08                | 3.7(1.5)E-07                  | 120.9(13.5)                                   | 0.3(0.1)                              | 116.0(6.8)                          | 0.94(0.02)       |
| I16351-13 | (16:38:50.6482, −47:28:00.9642)       | 1.4(0.6)                         | 1.8(0.7)E+23                                          | 4.2(1.7)E-08                | 1.9(1.0)E-08                  | 53.2(4.0)                                     | 2.2(1.5)                              | 94.0(7.2)                           | 0.16(0.01)       |
| I16351-14 | (16:38:50.2866, −47:28:01.6251)       | 0.3(0.2)                         | 1.1(0.8)E+23                                          | 2.2(1.6)E-08                | 2.9(2.3)E-09                  | 40.2(3.0)                                     | 7.6(8.1)                              | ...                                 | 0.03(0.01)       |
| I16351-15 | (16:38:50.4808, −47:28:01.6611)       | 1.7(0.8)                         | 2.1(0.8)E+23                                          | 2.2(0.9)E-07                | 1.8(0.7)E-07                  | 63.7(5.9)                                     | 1.2(0.7)                              | 85.3(2.2)                           | 0.49(0.02)       |
| I16351-17 | (16:38:50.4733, −47:28:03.0018)       | 2.4(1.1)                         | 4.1(1.6)E+23                                          | 9.1(3.6)E-09                | 2.9(1.8)E-09                  | 51.5(6.1)                                     | 3.2(2.3)                              | ...                                 | 0.11(0.01)       |
| I17220-16 | (17:25:25.3653, −36:12:44.0420)       | 26.8(11.0)                       | 6.8(2.7)E+23                                          | 5.9(2.4)E-08                | 2.1(0.9)E-07                  | 65.8(10.0)                                    | 0.3(0.2)                              | 131.0(10.0)                         | 0.76(0.02)       |
| I17220-17 | (17:25:25.2820, −36:12:44.0906)       | 48.4(19.2)                       | 1.0(0.4)E+24                                          | 3.2(2.8)E-08                | 5.2(2.4)E-08                  | 61.4(5.7)                                     | 0.6(0.6)                              | 201.0(50.0)                         | 0.78(0.02)       |
| I17220-18 | (17:25:25.2377, −36:12:45.5533)       | 52.3(19.5)                       | 1.3(0.5)E+24                                          | 2.2(0.8)E-08                | 5.6(2.2)E-08                  | 63.2(8.4)                                     | 0.4(0.2)                              | 97.8(5.0)                           | 0.82(0.02)       |
| I17220-19 | (17:25:25.3085, −36:12:45.7412)       | 26.2(10.1)                       | 7.6(2.9)E+23                                          | 4.9(2.0)E-08                | 1.7(0.7)E-07                  | 68.6(10.8)                                    | 0.3(0.2)                              | 222.0(34.0)                         | 0.83(0.02)       |
| I17220-22 | (17:25:25.1683, −36:12:46.7791)       | 7.1(3.2)                         | 2.2(1.1)E+23                                          | 1.3(0.6)E-08                | 7.4(3.8)E-09                  | 61.5(8.5)                                     | 1.7(1.2)                              | 131.0(11.0)                         | 0.19(0.01)       |

**Notes.**

<sup>a</sup> The parameters are taken from Xu et al. (2024).

<sup>b</sup> The parameters are taken from Tang et al. (2024).

<sup>c</sup> CRF represents the chemical richness factor, which is estimated by the ratio of channels with signal above  $3\sigma$  to total channels of two wide band spectral windows.

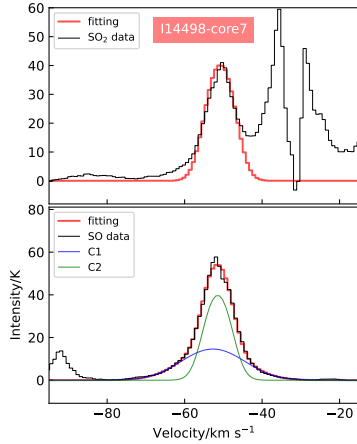


**Figure 1.** The observed spectra (gray stepped lines) are overlaid on LTE modeling results (red stepped lines) for  $\text{SO}_2$  (upper panel) and  $\text{SO}$  (bottom panel) in I14498-core7. When spectra cannot be adequately fitted with a single velocity component, multiple velocity components (colored curves) are used in the fitting process. All spectra of dense cores can be found in Figure A1 of Appendix A.

### 3.1.2. Gas Temperature of $\text{H}_2\text{CS}$ and $\text{CH}_3\text{OCHO}$

Temperature is a crucial parameter for molecular dense cores, as it closely correlates with their physical conditions and evolutionary stages. During the transition from the starless to the protostellar stage, gravitational collapse converts potential energy into thermal motion through compressional heating, elevating the gas kinetic temperature, establishing gas temperature as an indirect indicator of core evolution.

While Tang et al. (2024) provided gas temperature measurements of sulfur-bearing molecules using both  $\text{H}_2\text{CS}$  and  $^{34}\text{SO}_2$  transitions in their survey,  $^{34}\text{SO}_2$  exhibited a limited detection rate of 71% in our sample, and it seems to be only associated with high-temperature central regions. In contrast,  $\text{H}_2\text{CS}$  demonstrated universal detectability (100% detection rate) across all of our samples. Therefore, the gas temperatures of  $\text{H}_2\text{CS}$  ( $T_{\text{H}_2\text{CS}}$ ) are included in Table 2, and the fitting results of  $\text{H}_2\text{CS}$ <sup>8</sup> are presented in Figure 2.

The primary scientific purpose of this study is to investigate whether the  $\text{SO}/\text{SO}_2$  ratio can serve as a reliable tracer for the evolutionary stages of dense cores. However, the abundances of  $\text{SO}$  and  $\text{SO}_2$  are estimated based on  $T_{\text{H}_2\text{CS}}$ , creating an interdependency between the  $\text{SO}/\text{SO}_2$  ratio and temperature parameters. Such inherent coupling diminishes the statistical robustness of direct correlation analyses. Additionally,  $\text{H}_2\text{CS}$  has been reported to primarily trace the outer warm envelopes (Fuente et al. 2021; Bouscasse et al. 2022; Tychoniec et al.

2022; Tang et al. 2024). It may do not represent the temperatures of dense cores and can poorly reflect evolutionary sequence of dense cores.

To obtain a more reliable and independent gas temperature as an indirect indicator of dense core evolutionary stages. We selected a complex organic molecule (COM) of  $\text{CH}_3\text{OCHO}$  as a gas temperature tracer of dense core.  $\text{CH}_3\text{OCHO}$  is typically detected in hot cores/corinos, which are dense regions with gas temperatures exceeding 100 K and high chemical richness. Its optically thin transitions spanning upper energy levels ( $E_{\text{upper}} = 80\text{--}589\text{ K}$ ) within our observational bandwidth provide a robust Boltzmann population distribution for excitation temperature calculations. The detection of  $\text{CH}_3\text{OCHO}$  in chemically enriched hot cores/corinos has been extensively documented, establishing its reliability as a gas temperature tracer and an evolutionary stage indicator (Nummelin et al. 2000; Belloche 2013; Bergner et al. 2017,2019; Jørgensen et al. 2018; Agúndez et al. 2019; Li et al. 2024).

The gas temperatures of  $\text{CH}_3\text{OCHO}$  ( $T_{\text{CH}_3\text{OCHO}}$ ) of dense cores were derived from the fitting LTE model to spectra at  $870\text{ }\mu\text{m}$  using the SLIM. An example fitting (See footnote 2) is shown in Figure 3, where the black stepped lines represent observed spectra in two wide-band spectral windows (spw 29 and spw 31). The red stepped lines denote the optimal LTE model generated by SLIM. A total of 23 dense cores have  $\text{CH}_3\text{OCHO}$  detected, with temperatures estimated via SLIM fitting. The results of  $T_{\text{CH}_3\text{OCHO}}$  are listed in Table 2.

Certainly, while other molecular transitions in our observations can serve as temperature tracers, the selection of  $\text{H}_2\text{CS}$  and  $\text{CH}_3\text{OCHO}$  was motivated by the following reasons: (1) Their transitions in this band cover a wide range of upper-level energies ( $E_u$ ), which is critical for constructing reliable LTE models; (2) Both molecules exhibit high detection rates in our sample, which allowed us to expand the sample size significantly, enhancing the generality of our conclusions; (3) Their spectral lines suffer comparatively low contamination from line blending, reducing uncertainties in line fitting and parameter derivation. This clarity is essential for accurate radiative transfer modeling and temperature estimation.

### 3.1.3. Chemical Richness Factor

The definition of possible evolutionary sequence of the dense cores is the crucial point of this work, the samples in this study are classified as protostellar objects according to Xu et al. (2024). However, identifying the specific evolutionary stage of these dense cores remains challenging due to observational limitations (e.g., dust obscuration, molecular depletion, and resolution constraints), continuous parameter gradients (e.g., in velocity, density, and temperature), non-linear chemical evolution, and diverse dynamical processes and environments. As noted in Section 3.1.2, gas temperature

<sup>8</sup> During the fitting process for both  $\text{H}_2\text{CS}$  and  $\text{CH}_3\text{OCHO}$ , we consider multiple Gaussian components. The spectrum is initially fitted with a single Gaussian component, and the residuals are examined. If residuals for all transitions exceed  $3\sigma$ , additional components are iteratively added until all residuals fall below  $3\sigma$ . If only one transition exhibits residuals exceeding  $3\sigma$ , the anomaly is tentatively attributed to spectral line blending effects.

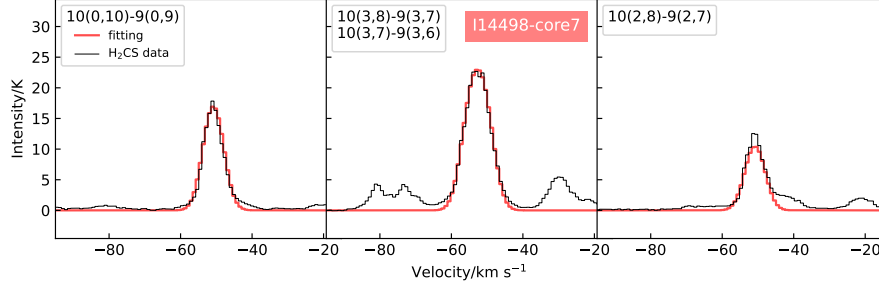


**Figure 2.** The observed spectra of three unblended transitions of H<sub>2</sub>CS (gray stepped lines) are overlaid on LTE modeling results (red stepped lines) in I14498-core7. When spectra cannot be adequately fitted with a single velocity component, multiple velocity components (colored curves) are used in the fitting process. All spectra of dense cores can be found in Figure B1 of [Appendix B](#).

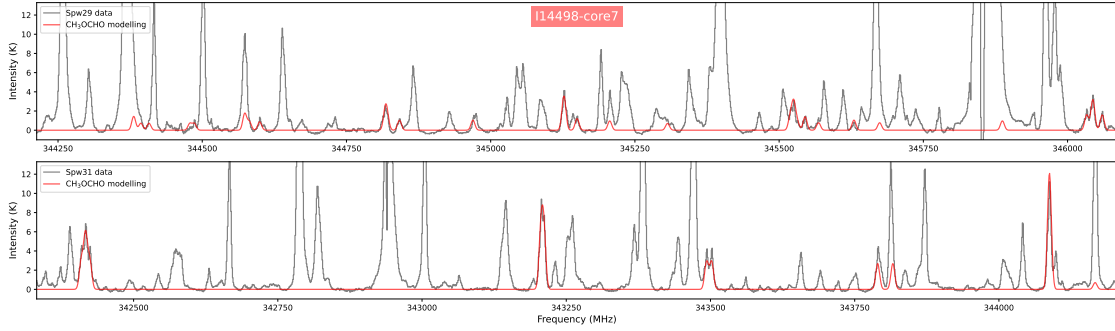


**Figure 3.** The spectra of spw 29 and spw 31 (gray stepped lines) are overlaid on the LTE modeling results (red stepped lines) for the complex organic molecule CH<sub>3</sub>OCHO in I14498-core7. All spectra of dense cores can be found in Figure C1 of [Appendix C](#).

acts as an indirect indicator of evolution of protostellar cores. As these cores evolve from an early developmental stage to a later one, they undergo a heating process, which results in a progressive rise in temperature. This rise in gas temperature results in an increased chemical reaction rate and more solid phase species evaporating to the gas phase. Consequently, the chemical richness of the dense core increases, leading to more detectable molecular transitions. To quantify this, a chemical richness factor (CRF) has been defined as follows:

$$\text{CRF} = \frac{N_{>3\sigma_{\text{line}}}}{N_{\text{total}}}, \quad (3)$$

where  $N_{>3\sigma_{\text{line}}}$  represents the number of spectral channels with signals exceeding three times the rms noise ( $>3\sigma_{\text{line}}$ ,  $\sigma_{\text{line}}$  of each source is listed in Table 1), and  $N_{\text{total}}$  is the total number of spectral channels. The estimated CRF for each core is presented in the last column of Table 2. A CRF is an unbiased factor because it only depends on original observations. A higher CRF indicates more detected molecular transitions, therefore, it can also be taken as an evolutionary parameter.

It should be noted that a CRF is introduced primarily because it is derived directly from observed spectra, making it an independent observational parameter distinct from conventional physical quantities (e.g., temperature, mass, and density). The CRF values depend on multiple transitions of complex organic molecules, meaning that dense cores with a

high CRF typically reside in the temperature-rise phase of protostellar cores or the hot core/corino phase. When complex organic molecules are extensively excited within dense cores, the CRF value rapidly approaches 1, thereby blurring distinctions between different evolutionary stages. Consequently, a CRF exhibits significantly higher sensitivity to early-stage protostellar cores than to younger cores (e.g., prestellar cores) or evolved protostellar cores.

### 3.2. Statistics and Correlations

The statistical results of the parameters in Table 2 are shown as histograms in Figure 4. The figure reveals notable differences in the statistical behaviors of high- ( $M > 8 M_{\odot}$ ) and low-mass ( $M < 8 M_{\odot}$ ) cores. For high-mass protostellar cores, no clear parameter trend is observed between those with and without COM(CH<sub>3</sub>OCHO) detection. The only difference is that the cores with COM detection exhibit wider parameter ranges. In contrast, low-mass protostellar cores display significant parameter trends: those with COM detection have a lower SO/SO<sub>2</sub> ratio, a higher CRF, and elevated gas temperatures ( $T_{\text{CH}_3\text{OCHO}}$  and  $T_{\text{H}_2\text{CS}}$ ) compared to those lacking COM detection.

Figure 5 shows the correlations among the SO/SO<sub>2</sub> ratio, CRF,  $T_{\text{CH}_3\text{OCHO}}$ , and  $T_{\text{H}_2\text{CS}}$ . The correlation coefficients ( $r$ ) for high-mass, low-mass, and all dense cores are displayed in the

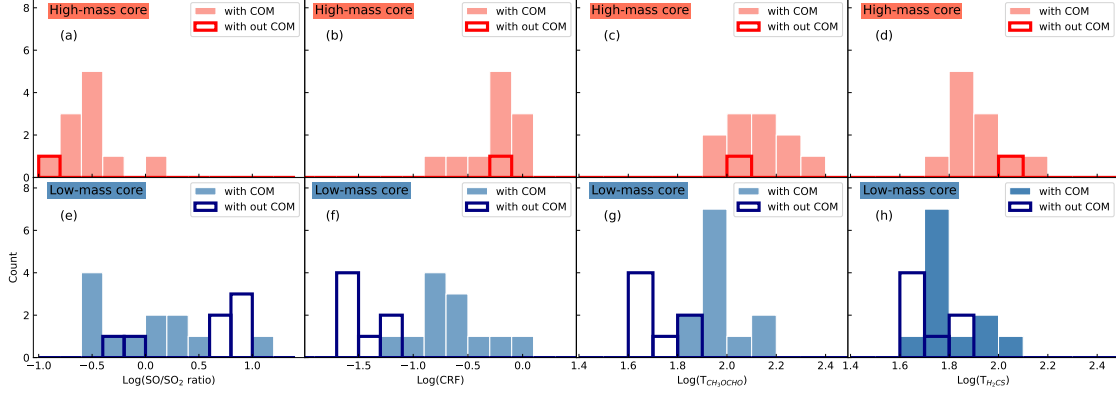


**Figure 4.** The histograms of dense core parameters. The upper panels display results for high-mass cores, while the lower panels show results for low-mass cores. Each panel separately plots cores with and without COM emissions.

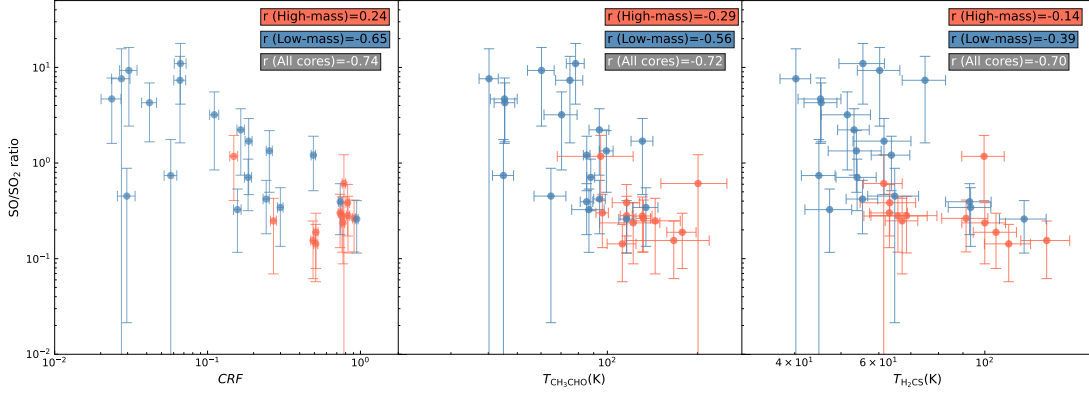


**Figure 5.** The correlations between the SO/SO<sub>2</sub> ratio and CRF (left panel),  $T_{\text{CH}_3\text{OCHO}}$  (middle panel), and  $T_{\text{H}_2\text{CS}}$  (right panel) are illustrated. High-mass cores are marked with red dots, while low-mass cores are represented by blue dots. Parameter uncertainties are indicated by error bars. The upper-right corner of each panel displays the Spearman correlation coefficients for high-mass, low-mass, and all dense cores, respectively.

respective panels. This study employs the Spearman correlation coefficient for analysis, as the parameters are not Gaussian distributed. The figure reveals anti-correlations between the SO/SO<sub>2</sub> ratio and evolutionary parameters (CRF,  $T_{\text{CH}_3\text{OCHO}}$  and  $T_{\text{H}_2\text{CS}}$ ) for all dense cores, with a correlation coefficient of approximately  $-0.7$ . When assessing high-mass and low-mass cores separately, only low-mass cores exhibit anti-correlations, albeit slightly weaker than that of all dense cores. In contrast, high-mass cores show no significant correlation.

From the correlation between SO/SO<sub>2</sub> ratio and  $T_{\text{H}_2\text{CS}}$ , a clear break of correlation slope is present at  $\sim 70$  K. We found this is due to the fact that H<sub>2</sub>CS is a good tracer of warm rather than high-temperature regions (e.g., Fuente et al. 2021; Tychoniec et al. 2021; Bouscasse et al. 2022; Tang et al. 2024), and H<sub>2</sub>CS is more sensitive to the gas temperature between 40 and 70 K than high temperature ( $>70$  K). This is also the one of the reasons why we would like to introduce another gas temperature tracer, CH<sub>3</sub>OCHO, which can cross-check the correlation between the SO/SO<sub>2</sub> ratio and gas temperature to ensure the validity of our results.

## 4. Discussion

### 4.1. The SO/SO<sub>2</sub> Ratio Can Only Trace Evolutionary Stages of Low-mass Cores

As discussed in Section 3, a core undergoes a warm-up process, leading to increases in temperature and chemical richness during its evolution.<sup>9</sup> Consequently, temperature and chemical richness may serve as indirect indicators of the evolution of a dense core from early to later stages. Based on this assumption, the relationship between the SO/SO<sub>2</sub> ratio and the evolutionary parameters of the CRF,  $T_{\text{CH}_3\text{OCHO}}$ , and  $T_{\text{H}_2\text{CS}}$  are explored. The anti-correlations between the SO/SO<sub>2</sub> ratio and the evolutionary parameters are clearly illustrated in Figure 5. For all dense cores, the correlation coefficients ( $r$ ) are

<sup>9</sup> The rich chemical composition can drive numerous endothermic/exothermic chemical reactions, which possess the potential to alter the regional gas temperature distribution. However, it should be noted that the dominant cooling mechanisms in molecular cloud cores are dust radiation and molecular line radiation. Consequently, this work is predicated on the perspective that the potential impact of microscopic chemical reactions on temperature distribution is negligible.

approximately  $-0.7$  for the  $\text{SO}/\text{SO}_2$  with evolutionary parameters, supporting the notion that the  $\text{SO}/\text{SO}_2$  ratio decreases with core evolution (Wakelam et al. 2011; Fontani et al. 2023). However, when examining low- and high-mass cores separately, moderate anti-correlations are observed only in low-mass cores (see Figure 5). In contrast, high-mass cores show no correlation between the  $\text{SO}/\text{SO}_2$  ratio and evolutionary parameters. Notably, most high-mass cores fall in the bottom-right corner of the figure, indicating they generally have lower  $\text{SO}/\text{SO}_2$  ratios and higher evolutionary parameters than low-mass cores. Additionally, as noted in Section 3.2, cores with COM detection are deemed more evolved than those without it. Clear trends are observed in low-mass cores from early to late stages, as shown in Figure 4. However, no distinct trend is found for high-mass cores. Our results show that the  $\text{SO}/\text{SO}_2$  ratio behaves differently in high- and low-mass cores.

There are two plausible reasons for this. First,  $\text{SO}$  and  $\text{SO}_2$  are commonly found in star-forming regions, with their abundances enhanced by star formation activity (e.g., Charnley 1997; Hatchell et al. 1998; Viti et al. 2001; Sakai et al. 2014, 2017; Artur de la Villarmois et al. 2019, 2023; Oya et al. 2019; Tychoniec et al. 2021; Zhang et al. 2023), in which the high-mass cores are associated with more vigorous star-forming feedback, which can significantly influence the  $\text{SO}/\text{SO}_2$  ratio (Tang et al. 2024). Therefore, this ratio may not only reflect evolutionary stages but also be significantly affected by the physical conditions of high-mass cores. Second, a well-established evolutionary sequence exists for low-mass cores from Class 0 to Class III, but the sequence for high-mass cores is controversial due to their short lifetimes and insufficient observational evidence. Consequently, our findings suggest that the  $\text{SO}/\text{SO}_2$  ratio may serve as an evolutionary tracer for low-mass cores, but it is uneasy to indicate evolutionary stages of high-mass cores.

To further verify the robustness of our conclusions, we estimated the  $\text{SO}/\text{SO}_2$  ratios of 171 and 64 for two prestellar cores (L1544 and L183, respectively) based on IRAM observations (Lattanzi et al. 2020). These ratios are markedly higher than those observed in our sample, indicating that the  $\text{SO}/\text{SO}_2$  ratio effectively traces the evolutionary stages of low-mass cores. This trend on  $\text{SO}/\text{SO}_2$  is consistently reproduced by the chemical model for L1544 (Ge et al. 2023), further corroborating the validity of our findings.

#### 4.2. Comparison

Figure 6 presents the comparison of  $\text{SO}/\text{SO}_2$  ratio between this work and the data collected from previous studies (Buckle & Fuller 2003; Wakelam et al. 2004; Tercero et al. 2010; Wang et al. 2013; Holdship et al. 2019; Rivière-Marichalar et al. 2019; Fuente et al. 2021; Möller et al. 2021; Bouscasse et al. 2022; Artur de la Villarmois et al. 2023; Fontani et al. 2023). As noted in Section 1, prior research on sulfur-bearing

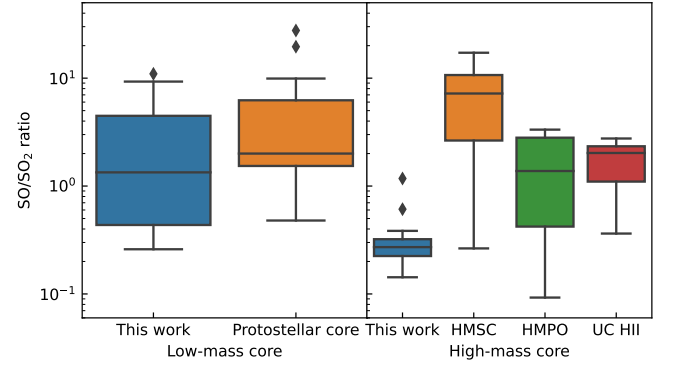


**Figure 6.** Comparison of  $\text{SO}/\text{SO}_2$  ratio between this work and the data from references. Based on the information provided by references, the possible evolutionary stages of sources are labeled on a horizontal axis. For high-mass cores, the HMPO represents the high-mass protostellar object, HMSC represents the high-mass starless core, and UC HII represents the core associated with ultra-compact  $\text{H}_{\text{II}}$  region.

molecules primarily relied on single-dish telescopes and lacked statistical analysis. Only Artur de la Villarmois et al. (2023) tested 50 dense cores using ALMA with approximately  $0.5''$  angular resolution, yet only six cores definitively detected both  $\text{SO}$  and  $\text{SO}_2$ . Consequently, this work's results are mainly compared with those from single-dish telescopes.

The  $\text{SO}/\text{SO}_2$  ratio of low-mass cores from this study aligns with previous findings. But for high-mass cores, the  $\text{SO}/\text{SO}_2$  ratio of this work (with a median value of 0.27) is lower than earlier studies (with a median value of 0.92). This discrepancy may stem from beam dilution, as prior results from references in Figure 6 were based on single-dish observations. Tang et al. (2024) analyzed 11 massive protoclusters using subarcsecond resolution and found  $\text{SO}_2$  emissions only in the central regions of protostellar cores. Thus, the  $\text{SO}_2$  in high-mass starless cores may be influenced by low-resolution observations that fail to resolve substructures containing both starless and protostellar objects. Beam dilution reduces  $\text{SO}_2$  abundance, increasing the  $\text{SO}/\text{SO}_2$  ratio because  $\text{SO}$  is more widely distributed in the envelopes of dense cores and other extended areas. This comparison suggests that low-resolution observations of distant massive star-forming regions may primarily capture outer envelopes instead of the more dense core interiors. Our findings indicate that high-resolution observations can provide more accurate data, differing significantly from single-dish results, and are essential for studying the properties of sulfur-bearing molecules.

#### 5. Conclusion

Utilizing ALMA Band 7 observations of eight massive protoclusters, we examine the relationships between  $\text{SO}/\text{SO}_2$  ratios of 31 dense cores and various evolutionary parameters. We report parameters including mass,  $N_{\text{H}_2}$ , abundances of  $\text{SO}$  and  $\text{SO}_2$ , the  $\text{SO}/\text{SO}_2$  ratio, a self-defined CRF, and gas temperatures ( $T_{\text{CH}_3\text{OCHO}}$  and  $T_{\text{H}_2\text{CS}}$ ). Notable anti-correlations

emerge between the SO/SO<sub>2</sub> ratio and the evolutionary parameters, predominantly influenced by low-mass cores. This indicates that the SO/SO<sub>2</sub> ratio may act as a reliable evolutionary tracer for low-mass cores, in contrast to its efficacy in high-mass counterparts. Furthermore, the comparison of our findings with prior studies suggests that the SO/SO<sub>2</sub> ratio in remote high-mass star-forming environments may be significantly affected by beam dilution. Consequently, high-resolution observations encompassing larger sample sizes are essential for a comprehensive investigation of sulfur-bearing molecules.

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