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The evolution of carbon-chain chemistry from prestellar to protostellar cores in Taurus Molecular Cloud

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Abstract. The discovery of abundant carbon-chain molecules in protostellar cores motivates the development of the warm carbon-chain chemistry. To understand the role of warm carbon-chain chemistry in star-forming regions, we studied C_2H and c-C_3H_2 in 15 embedded protostars in the Taurus molecular cloud, whose evolutionary stages range from prestellar to Class I/II, using data from the Submillimeter Telescope (SMT). We calculated the excitation temperature, column density, and abundance of C_2H and c-C_3H_2 in each source. We compared those properties with evolutionary indicators of the protostars. We also estimated the kinetic temperature using RADEX. Finally, we compared the abundance of C_2H and c-C_3H_2 in our survey with that in the survey of protostellar cores in the Perseus molecular cloud. While we are unable to identify new WCCCs, our results suggest that the abundances of C_2H and c-C_3H_2 could be an indicator to find WCCC candidates.

Keywords. carbon-chain molecules, protostars, Taurus Molecular Cloud, astrochemistry.

1. Introduction

The study of carbon-chain molecules in low-mass protostars helps us understand the past and evolution of carbon-chain chemistry in our solar system. Carbon-chain molecules are usually abundant in prestellar cores. As the core density increase, C^+ is converted to CO in a timescale of 3×10^5 years, reducing the production of carbon-chain molecules. Additionally the abundance of carbon-chains molecules decrease due to ionic destruction of H^+ and He^+ as well as reactions with oxygen (Sakai & Yamamoto 2013). Hence, observations often only detected carbon-chains molecules in dense cores and prestellar cores. Interestingly, Sakai et al. (2008) discovered abundant carbon-chains in a Class 0 protostar IRAS 04368+2557 in L1527. The carbon-chain molecules locate in a lukewarm region (Sakai et al. 2008) close to the embedded protostar (a few thousand AU; Sakai & Yamamoto 2013). To explain this type of chemistry, Sakai et al. (2008) proposed the warm carbon-chain chemistry (WCCC). In the WCCC scenario, the carbon-chain molecules form from gaseous CH_4, which has a sublimation temperature of 25 K. This sublimation temperature is higher than that of CO (20 K; Law et al. 2018) lower than that of H_2O (100 K; Sakai et al. 2008; Sakai & Yamamoto 2013). As the temperature increases due to accretion heating, CH_4, if presents on ices, can sublimate and react with other molecules to form carbon-chains molecules. The carbon-chain chemistry in

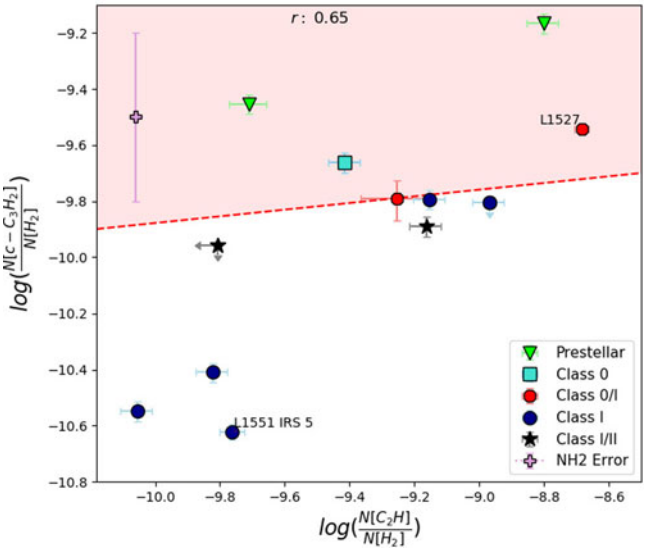

Figure 1. Abundance of carbon-chain molecules in 12 prestellar and protostellar sources in Taurus molecular cloud.

L1527 has been extensively studied (e.g., Sakai et al. 2008, 2010a, 2010c). Surveys of the carbon-chain chemistry in protostellar cores are available for 36 Class 0/I protostars in the Perseus molecular cloud and a few sources in the Taurus molecular cloud (Higuchi et al. 2018; Law et al. 2018), providing statistical characteristics of carbon-chain chemistry in the early stage of star formation. Increasing the sample size in the Taurus molecular cloud offers a great opportunity to study the carbon-chain chemistry in different environments. Thus, we conducted a survey of 15 protostars to measure the emission of C_2H and c-C_3H_2, characterizing the carbon-chain chemistry in these sources.

2. Results

For C_2H, we measured transitions of $N = 3 \rightarrow 2$, $J = 7/2 \rightarrow 5/2$, $F = 4 \rightarrow 3$, and $N = 3 \rightarrow 2$, $J = 7/2 \rightarrow 5/2$, $F = 3 \rightarrow 2$; and for c-C_3H_2, we measured transitions of $6(1, 5) \rightarrow 5(2, 4)$, $6(2, 5) \rightarrow 5(1, 4)$, and $3(2, 1) \rightarrow 2(1, 2)$. We detect C_2H in 14 sources and c-C_3H_2 in 13 sources. We calculated the excitation temperature and the column density, assuming local thermodynamic equilibrium (LTE). The excitation temperatures of c-C_3H_2 range from 5 to 11 K, where L1551 IRS 5 and L1527 have the highest excitation temperatures. C_2H and c-C_3H_2 has column density ranging from 2.6×10^{12} cm^{-2} to 1.5×10^{14} cm^{-2} and 2.6×10^{12} cm^{-2} to 2.0×10^{13} cm^{-2}, respectively. The column densities and abundances between the c-C_3H_2 and C_2H are tightly correlated (Figure 1), confirming that both species are related in the formation pathways of carbon-chain molecules, where c-C_3H_2 is a secondary product of C_2H.

The abundances of C_2H and c-C_3H_2 are generally higher in prestellar sources and lower in more evolved sources (Class 0/I-I/II); (Figure 1), except for L1527, which is a known WCCC source. Therefore, the abundance of C_2H and c-C_3H_2 could serve as an indicator for the search of WCCC candidates. Moreover, there are three pairs of sources, where each pair consists of a protostar and its adjacent cold envelope. In each pair, both sources share similar environments except for the warmer temperature in the protostar. Thus, the chemical variation within each pair provides a unique opportunity to characterize the chemical change from cold to warm environments. Figure 2 shows that the protostars have notably different chemistry of C_2H and c-C_3H_2. To further constrain

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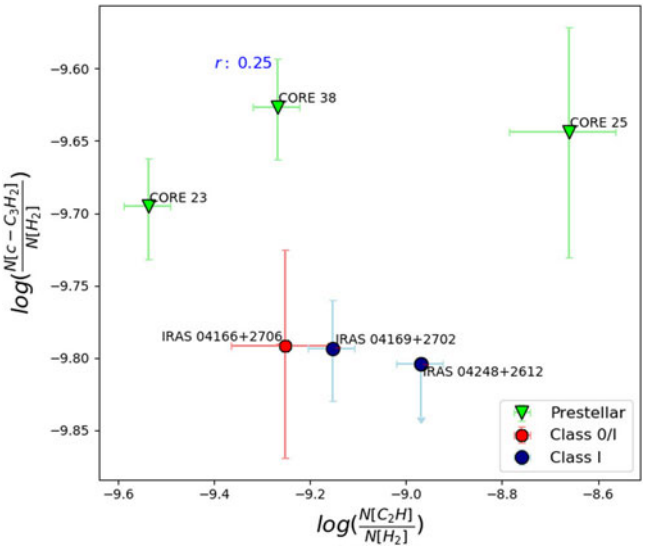

Figure 2. Abundance of carbon-chain molecules in the three pairs of protostar and cold envelope: CORE 23-IRAS 04166+2706, CORE 25-IRAS 04169+2702, and CORE 38-IRAS 04248+2612.

the chemical evolution with respect to the star formation, we compared the bolometric luminosity and bolometric temperature with the abundances of C_2H and c-C_3H_2. The bolometric luminosity and bolometric temperature are weakly negatively correlated with the abundance of C_2H and c-C_3H_2, suggesting that the protostellar evolutionary stage has no direct impact on the production of carbon-chain molecules.

We also derived the kinetic temperature of c-C_3H_2 in 4 of 15 sources using RADEX (van der Tak et al. 2007), a non-LTE radiative transfer code. The kinetic temperatures range from 10 to 28 K. L1551 IRS 5 has the highest kinetic temperature followed by L1527 with 22 K. Interestingly, the abundance of C_2H and c-C_3H_2 in the Taurus protostars is consistent with that in the Perseus protostars, both of which show correlation between these two species (Higuchi et al. 2018).

3. Conclusions

We studied the C_2H and c-C_3H_2 to characterize the carbon-chain chemistry in 15 protostars of Taurus molecular cloud. We estimated column densities and abundances of C_2H and c-C_3H_2, finding a high correlation between them. In addition, the abundances of the C_2H and c-C_3H_2 could be an indicator for identifying WCCC candidates (Figure 1). We also found significant chemical change from cold to warm environments (Figure 2). The correlation between the abundances of C_2H and c-C_3H_2 and the protostellar parameters is not very significant. Comparing with the Class 0/I protostars in the Perseus molecular cloud, the carbon-chain chemistry in Taurus sources is similar to that in Perseus (Higuchi et al. 2018). We derived kinetic temperatures for 4 of 15 sources and detected no additional WCCC source, except for L1527.

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