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Unified Picture of Chemical Differentiation in Disk-Forming Regions of Low-Mass Protostellar Sources

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Abstract. Young low-mass protostellar sources are known to show significant chemical diversity in their envelopes at a few 1000s au scale; two distinct cases are hot corino chemistry and warm carbon-chain chemistry (WCCC). It is of great interest how the chemical diversity is inherited to chemistry of disk-forming regions. With the recent ALMA observations, we found that the chemical diversity in envelopes is indeed delivered into the disk-forming regions at a 100 au scale. Moreover, the chemical composition changes drastically from envelopes to disks. We also found sources with the hybrid chemical characteristics; both hot corino chemistry and WCCC occur in spatially separated parts of a single source. This hybrid case may be a common occurrence, while hot corinos and WCCC sources are regarded as distinct cases. This unified view of chemistry in disk-forming regions will be an important clue to tracing the chemical evolution from protostellar cores to protoplanetary disks.

Keywords. astrochemistry, ALMA, ISM: IRAS 16293−2422, L1527, B335, L483

1. Introduction

In order to explore our origin in the Universe, we need to know "what kinds of molecules are delivered from interstellar space into planets". So far, single-dish observations have shown that the envelope gas around the low-mass protostars has significant chemical diversity from source to source. More specifically, two distinct cases have been known (Sakai & Yamamoto 2013); hot corino sources rich in saturated organic molecules (e.g., CH_3OH, CH_3CHO), and WCCC sources rich in unsaturated carbon-chain molecules (e.g., C_4H).

2. Chemical Changes in Young Low-Mass Protostellar Sources

Recently, ALMA allows us to investigate the physical and chemical structures near the protostar. In a prototypical hot corino source IRAS 16293–2422 Source A (Bottinelli *et al.* 2004; Jørgensen *et al.* 2012), it has been reported that the surrounding gas shows rotation motion (Pineda *et al.* 2012; Favre *et al.* 2014). We investigated the chemical structure at a few 10s au scale in this source (Oya *et al.* 2016). We revealed that the gas surrounding the protostar consists of the infalling-rotating envelope and the Keplerian disk inside it. The boundary between them is called as the centrifugal barrier. We found that these three components are traced by different molecules. The OCS line traces only the envelope gas, while the H_2CS line traces both the envelope and the disk. The COM lines highlight the centrifugal barrier. Thus, a drastic chemical change is occurring from the infalling-rotating envelope to the Keplerian disk. IRAS 16293–2422 Source B shows a similar chemical change (Oya *et al.* 2018).

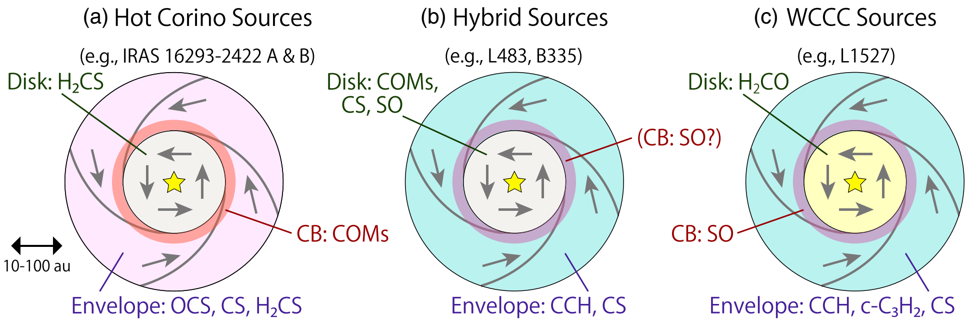

Figure 1. Chemical changes found in the young low-mass protostellar sources.

We found a similar chemical change in a prototypical WCCC source L1527 (Sakai *et al.* 2008, 2014) (Figure 1c). Interestingly, the chemical changes found in IRAS 16293–2422 and L1527 are shown by different molecular species depending on their chemical characteristics. Therefore, the chemical diversity reported for envelopes at 1000s au scale is indeed delivered into disk-forming regions at 10–100s au scale. These findings are important clues to constraining the initial condition of the disk chemistry.

3. Hybrid Chemical Characteristics

The above two sources are the distinct cases of the chemical variation. According to single-dish observations (e.g., Higuchi *et al.* 2018), most of other sources seem to have intermediate chemical characteristics. Then, how do they look like with ALMA?

B335 is a Bok globule (Keene *et al.* 1980) harboring a Class 0 low-mass protostar, and can be a standard template of chemical evolution. In the ALMA observation reported by Imai *et al.* (2016), the COM lines show a compact distribution concentrated around the protostar, while the unsaturated carbon-chain lines show an extended distribution. Figure 2 shows the spectra in two different areas; saturated COMs are prominent at the smaller scale, while unsaturated carbon-chain molecules are prominent at the larger scale. Thus, B335 shows both the chemical characteristics of hot corino chemistry and WCCC at different scales. Also, the Class 0 low-mass protostellar core L483 shows a similar chemical situation (Oya *et al.* 2017); saturated COMs trace the disk around the protostar (∼100 au), while unsaturated carbon-chain molecules are prominent in the envelope gas and the bipolar outflow (∼1000 au scale). Here, B335 and L483 are interpreted as the third case, the 'hybrid case', for the chemical diversity in disk-forming regions (Figure 1b).

4. Cause for the Chemical Diversity and the Chemical Change

The chemical structures observed in the disk-forming regions are consistent with a chemical model. Aikawa *et al.* (2018) reported a chemical model of a dynamically collapsing core. In their model, CH_3OH resides in the gas-phase near the protostar (∼100 au). It sublimates from dust grains in the hot (>100 K) region. On the other hand, CH_4 resides in the gas-phase in the warm (>25 K) region (∼1000 au), because CH_4 sublimates at a lower temperature than CH_3OH. Enhancement of CH_4 in the gas-phase triggers efficient production of carbon-chain molecules (WCCC). Thus, hot corino chemistry occurs near the protostar, while WCCC occurs in the outer region. Such a spatial separation is consistent with the observational results in the hybrid sources. This seems to be the basic picture of the chemical change in disk-forming regions (Figure 3b).

This picture will depend on the initial condition of the chemical composition of the grain mantle. If CH_4 is deficient in the grain mantle (Figure 3a), it does not sublimate

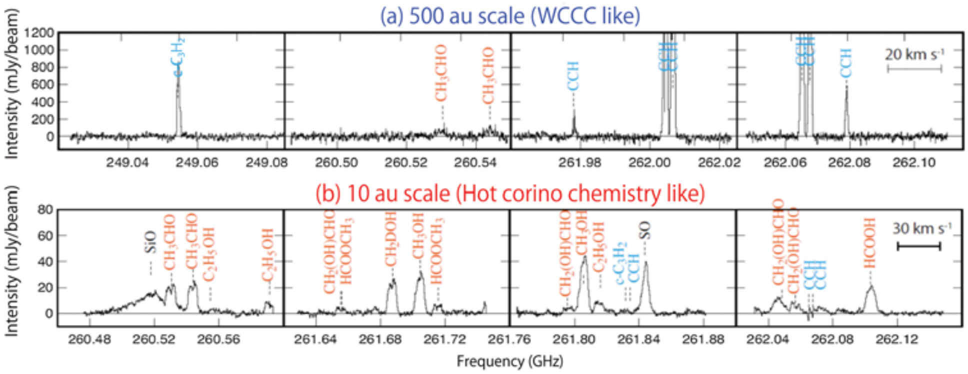

Figure 2. Spectra toward B335 averaged in the circles with the radius of (a) 500 au and (b) 10 au centered at the protostellar position (Imai *et al.* 2016).

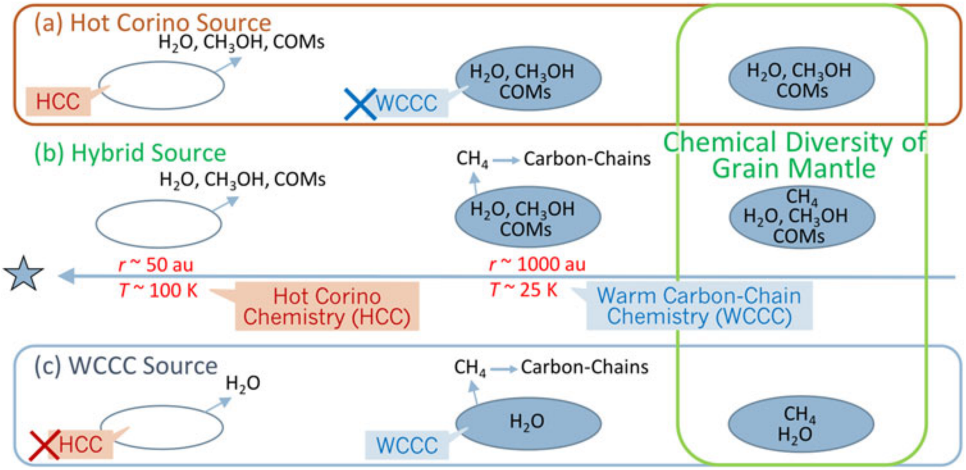

Figure 3. Schematic illustration of the scenario of the chemistry near the protostar. A dust grain falls from the right hand side toward the protostar on the left hand side. Panel (b) shows the basic picture. Panels (a) and (c) show the distinct cases deficient in CH_4 and COMs, respectively.

in the warm region, while water and COMs do in the hot region. This case results in hot corinos. On the other hand, if COMs are deficient (Figure 3c), CH_4 sublimates in the warm region and efficiently produces carbon-chain molecules. This case results in WCCC sources.

Next, why does the chemical diversity of grain mantle happen? It is proposed to depend on the duration time of the starless-core phase after the shielding of UV (Sakai & Yamamoto 2013). If the duration time is long enough compared to the time scale for chemical reactions ($\sim 3 \times 10^5$ yr), C atoms in the gas-phase are well converted to CO and deplete on dust grains. Then, CO will form CH_3OH and other COMs, resulting hot corino chemistry near the protostar. In contrast, if the duration time is too short, atomic carbon can deplete on dust grains as they are. Atomic carbon will be hydrogenated to CH_4 on the grain surface, and it will show WCCC. Of course the duration time can be intermediate; both atomic carbon and CO will exist on dust grains, and this case will result in hybrid sources. Although hot corinos and WCCC sources have extensively been studied so far because of their peculiar chemical characteristics, the intermediate case (i.e. the hybrid case) is most likely the standard case (Figure 3b).

5. Summary

We have investigated young low-mass protostellar sources with ALMA, and have reported the following new findings: (1) The physical structure near the protostar consists of the infalling-rotating envelope, its centrifugal barrier, and the Keplerian disk inside it. (2) The chemical changes from envelopes to disks were found. The centrifugal barrier seems to be the transition zone not only for the physical structure but also for the chemical composition of the gas. (3) The molecular species showing the chemical changes are different among sources.

The above results also raise new questions; (1) what is occurring around the centrifugal barrier ('transition zone')? (2) what is the chemical heritage from envelopes to disks? (3) what is the mechanisms causing the chemical diversity among sources? These questions will be addressed with our new ALMA large program 'FAUST' in the following years.

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Discussion

LINSKY: Some molecules will be ionized as the accretion from the interstellar medium approaches the inner disk. Ionized and neutral molecules can interact by dissociative recombination reactions. Including this chemistry may explain the different locations of chemical species around protostars.

OYA: It will be interesting to see how ions are distributed in the disk-forming regions. But, so far, our observations focused on neutral species and we have not yet worked on ions. Our new ALMA project 'FAUST' contains some ion lines (e.g., HCO^+, N_2H^+, and their isotopes). We will reveal the distributions of these ions in the near future.

MAURY: If COMs (complex organic molecules) are detected at small disk-like scales in B335, do you detect Keplerian-like motions from COMs kinematics?

OYA: It is unclear whether B335 harbors a Keplerian disk or not at the current stage. Although COMs trace the disk in L483, their detailed emitting region can depend on sources. Observations of the COM lines in B335 at a higher angular-resolution are awaited.