Chapter 11
Conclusion

11.1 Summary of This Thesis

Major outcomes of this thesis are summarized below. The questions raised in Introduction (Chap. 1) have been addressed, at least partly.

(1) The infalling-rotating envelope and its centrifugal barrier are common occurrences in the observed sources. These physical structures are seen regardless of the chemical characteristics (WCCC/hot corino chemistry/hybrid) of the sources. The infalling-rotating envelope model based on the simple physical assumptions (the energy and angular momentum conservation) works well to characterize the observed kinematic structure. Thus, the model seems to capture the basic physics in disk forming regions.

(2) The centrifugal barrier is most likely the transition zone from the infalling-rotating envelope to the disk inside it. The kinematic structure is discontinuously changed across the centrifugal barrier. It is expected that this physical change is also related to the launching mechanism of the outflow as an extraction mechanism of the angular momentum of the gas. Although some hints are found in this thesis, their relation is not obvious at the present stage.

(3) The fact that the observed kinematic structure is well represented by the infalling-rotating envelope model implies that the magnetic field does not effectively affect the gas motion at least in the infalling-rotating envelope at a few 100 au scale.

(4) The chemical change across the centrifugal barrier is seen in all the observed sources, which is probably caused by the accretion shock in front of the centrifugal barrier as well as the protostellar heating. The molecular species tracing each physical component of the disk forming region (the infalling-rotating envelope, the centrifugal barrier, and the disk component) is different depending on the chemical characteristics of the sources. This would result in a chemical diversity in protoplanetary disks and eventually in planets.

Y. Oya, *A Few Tens au Scale Physical and Chemical Structures Around Young Low-Mass Protostars*, Springer Theses, https://doi.org/10.1007/978-981-19-1708-0_11

(5) The chemical processes in the stagnated gas around the centrifugal barrier are expected to determine the chemical heritage passed from the infalling-rotating envelope to the disk component. Thus, the initial condition of the chemical evolution in protoplanetary disks is defined in the transition zone.
(6) Several molecular lines are recognized as good tracers for the physical components. The chemical diagnostics will be a powerful tool for star-formation studies in the ALMA era, although it is still in its infancy.

11.2 Future Prospects

11.2.1 Transition Zone from the Envelope to the Disk

In this thesis, it has been demonstrated that images at a sub-arcsecond resolution unveil unexpected phenomena. However, there are still complex physical components remained to be resolved, for instance, the detailed structure of the transition zone from the infalling-rotating envelope to the disk, the stagnation of the gas at the centrifugal barrier, and the launching points of the outflow. The physical parameters for some sources observed in this thesis are just upper limits. Higher angular resolution observations will allow us to characterize them more accurately.

Based on these motivations, such higher angular-resolution observations are going to be conducted with ALMA. These projects plan to observe the sources with which this thesis has dealt at an angular resolution of up to $0.''07$ (10 au). Some parts of these programs have already been executed in these years. With a high angular-resolution observation ($0.''2$) toward L1527, [5] has indeed confirmed the extension of the scale height of the envelope gas at the centrifugal barrier due to the gas stagnation, as described in Chap. 10. The higher angular-resolution observations will provide us with new insights into the disk formation study.

11.2.2 How about in More Evolved Sources?

The concept of the infalling-rotating envelope and its centrifugal barrier has been confirmed to be common at the evolutionary stages of Class 0 and I. Moreover, the chemical process occurring around the centrifugal barrier would determine the initial condition for the chemical evolution in the disk formation. This thesis shows that chemical diversity is already seen at its earliest stage. Then, the next question naturally rises: how does it evolve in the future? Thanks to the high sensitivity of ALMA, the weak molecular line emission of various molecular species is being detected in protoplanetary disks (e.g. [2]). For instance, the H_2CS line is detected toward MWC 480 (IAU Symposium 332). This detection is interesting, because H_2CS is detected in the disk component of IRAS 16293−2422 Source A (Chap. 6). The chemical characterization of more sources in the Class II stage is urgent to delineate the whole scenario of the chemical evolution from infalling-rotating envelopes to protoplanetary disks and eventually to planets.

11.2.3 *Chemical Heritage: Importance of Sulfur Chemistry*

Understandings of the behavior of various molecular species in the disk-forming region are essential to building the sound bases of the chemical diagnostics. The observational results in this thesis suggest that S-bearing molecules, such as CS, SO, OCS, and H_2CS, would be key species in the chemical differentiation in the disk forming region. However, their chemical behaviors are still unknown both observationally and theoretically. Since they will be sensitive to physical changes in disk formation, physical characterization of each source is required in order to understand the chemical behaviors of S-bearing molecules. In IRAS 16293−2422 Source A (Chap. 6), H_2CS traces the disk component while OCS does not in spite of their similar desorption temperature (Chap. 9). It suggests that there are some chemical mechanisms which reduces the OCS abundance and enhance the H_2CS abundance inside the centrifugal barrier. Identification of the specific chemical processes responsible for this trend is highly awaited. Such chemical processes will also affect the chemical heritage delivered into the disk. The detection of H_2CS toward the protoplanetary disk mentioned above may further indicate that it is delivered into the planets. Moreover, a recent study with Rosetta also found various S-bearing species in the coma of comet 67P/Churyumov-Gerasimenko [1]. Hence, the sulfur chemistry is the central issue for astrochemical studies of the disk formation in the next decade.

So far, sulfur chemistry has been studied for molecular clouds and star-forming regions (e.g. [3, 4, 6–8]). The most difficult point in the sulfur chemistry is that we do not exactly know the sulfur abundance available for the gas-phase reactions. In the previous models, 99% of sulfur is simply assumed to be depleted onto dust grains. However, this fraction is quite arbitrary. Moreover, we do not exactly know the major form of sulfur on dust grains, although H_2S is thought to be a potential candidate.

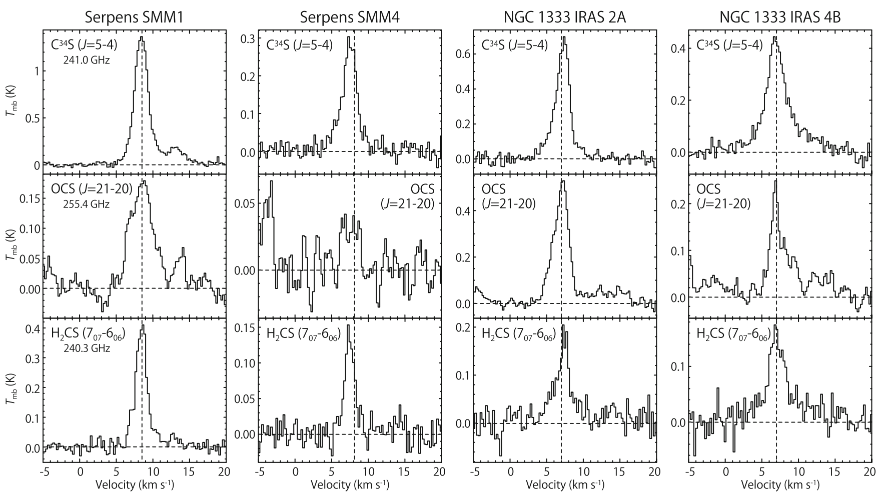

Fig. 11.1 Spectra of S-bearing molecules observed toward the four hot corino sources with the IRAM 30 m telescope. The vertical dashed line represents the systemic velocity of each source. Broad OCS lines, which would come from the vicinity of the protostar, are detected

Hence, the sulfur chemistry seems unpredictable at the present stage in hot regions like the disk forming regions, where extensive gas-grain interaction is occurring. Under such a circumstance, we need to start with understandings of abundances and distributions of various S-bearing molecules in protostellar cores.

Based on this prospect, a spectral line survey observation of S-bearing species has been started with single-dish telescopes (IRAM 30 m, NRO 45 m). The OCS and H_2CS lines were successfully detected at the wavelength of 1.2 mm toward several hot corino sources (Fig. 11.1), such as Serpens SMM1, SMM4, NGC 1333 IRAS 2A, and NGC 1333 IRAS 4B. Although these species has not been popular in the observational studies of low-mass protostellar sources, understandings of their detailed distribution in the vicinity of the protostar will be essential to the establishment of the chemical diagnostics and further exploration of the chemical evolution from molecular clouds to star-forming regions.

The above future projects are schematically illustrated in Fig. 11.2. By tackling these projects with a full use of ALMA, I would like to contribute to unveiling the whole picture of the physical and chemical evolution in formation of Solar-type stars.

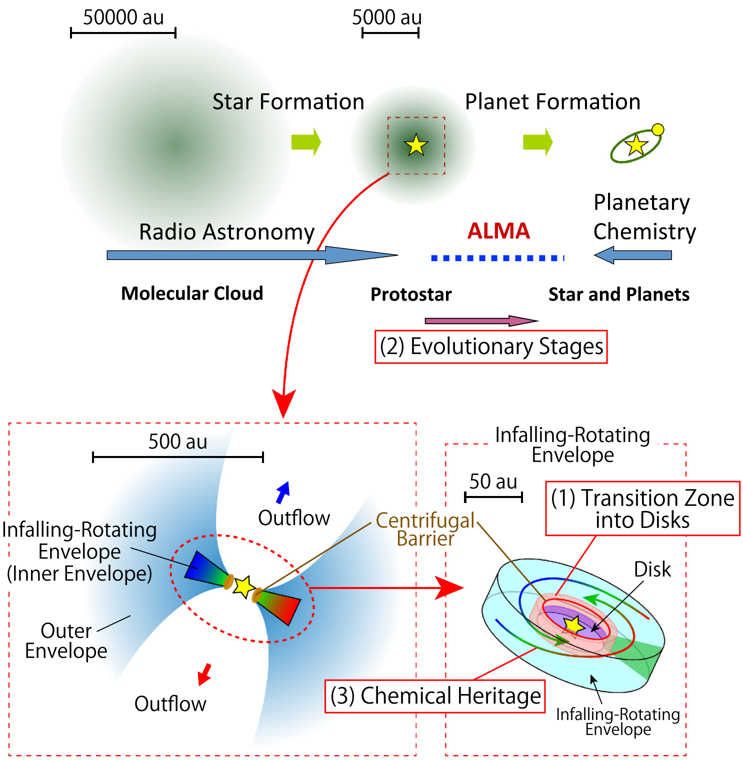

Fig. 11.2 Schematic illustration of the protostellar evolution process (top). The bottom illustrations depict the disk/envelope system of young low-mass protostellar sources, whose physical and chemical structures have been characterized in this thesis. The focusing points of the future projects mentioned in Sect. 11.2 are also shown

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