（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）

国外連携機関長期研修　報告書

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日程	西暦 2022 年　10 月　13 日　～　西暦 2023 年　2 月　3 日

To reveal how high-mass stars, which have masses of more than 8 solar mass, I'm working on the ASHES (ALMA Survey of 70 µm Dark High-mass Clumps in Early Stages) project. This project has been conducted by ALMA (Atacama Large Millimeter/submillimeter Array) toward thirty-nine high-mass clumps, that are all infrared-dark, cold, dense, and massive, the best candidates as the birthplace of high-mass stars. By analyzing the obtained dust continuum emission data, I identified more than 800 dense cores, where stars are born. This is the largest sample so far observed in infrared-dark clumps. During this project, I have analyzed molecular line emission data such as tracers of molecular outflow, dense gas, and warm gas, and studied (1) the gravitational stability of cores, (2) the star formation signatures, (3) the hierarchical fragmentation, and (4) the slope of the core mass function.

Identifying the star formation signature and estimating the stability of cores is an essential step for understanding the evolution of cores and the possibility of star formation. Using the dense gas tracer, I estimated the virial mass that is derived from the energy balance between gravity and thermal and non-thermal support (→(1)). If a core has a larger mass than the virial mass, it is unstable against the gravitational collapse, forming stars. If not, it likely keeps a stable condition or disperses in the future. Stability is one indication of star formation, and unstable cores or gravitationally bound cores are thought to be forming protostars. Additionally, I identified cores with the signature of star formation by the detection of molecular outflow and/or warm gas tracers, and defined cores with such signatures as protostellar core, and the others as prestellar core (→(2)). As a result, I reveal about 300 cores host the star formation signatures (protostellar cores). And I found the continuous sequence from prestellar to protostellar cores in terms of the gravitational stability. The ratio of the virial mass to core mass implies protostellar cores are unstable, and starting to collapse, which is consistent with the picture of star formation. Overall, I revealed protostellar cores are more massive, denser, and more gravitationally bound.

I spend the most time on the study of hierarchical fragmentation and the core mass function (CMF) during this project. Especially for the fragmentation (→(3)), we came up with the idea for hierarchical fragmentation through the discussion with the host-supervisor. The fragmentation properties in the very early stages are important to understand how cores form from the parental bodies. The simple description is known as Jeans fragmentation, which considers the condition where the perturbation grows. I compared core masses and separation with what was expected from Jeans fragmentation and revealed that core properties prefer thermal Jeans fragmentation rather than Jeans fragmentation with turbulent support. However, most cores have masses smaller than Jeans mass, implying hierarchical fragmentation; clumps fragment into smaller denser objects that form cores. I verified how statistically significant the possibility of hierarchical fragmentation is. In my idea, this study would be important because we use the largest sample so far at the early stages of high-mass star formation. I mostly completed these analyses ((1)-(4)) and continue discussing with the host supervisor and collaborators to submit the papers to the Astro Physical Journal this year.

I already presented such results at the seminar at the visiting institute (CfA) and suppose to have a talk at the ASJ annual meeting, and also at the international conference, Protostar, and Planets VII this spring. The experience of having a talk at CfA was very fruitful and meaningful for my career. I had about one hour for my talk including 15 min. discussions fully in English, and more than ten staff came both in-person and online. I got some questions from the star-forming community and from the galaxy community too. I obtained good science comments and also confidence for the English talk.

In addition to the improvement in my research, this project gave me the great experience of living in a foreign country for more than three months. There remain some effects due to COVID-19, and I suffered from the active interaction with other researchers. However, I could have a plentiful discussion with my host supervisors in a comfortable environment for the research and had a good discussion with the researchers at a neighboring university too. It may be possible to do such kind of things even in Japan using online tools, but I would like to emphasize that face-to-face discussion is more fruitful and likely to produce more new ideas for the study. Of course, such connections would be important in my career, and more conversation and discussion improved my speaking and listening English abilities. Additionally, I could study the difference in culture, and how to live in foreign countries. This long-term stay in the United States enabled me to imagine research life in foreign countries, and it broaden the vision of my next carrier. Lastly, I would like to thank all organizations that supported my visit and encourage graduate students to experience such visits outside Japan and increase their options for their next career.