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（様式３）

# 博士論文の要旨

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論文題目 Study of Dense Core Property and Core Mass Function with Simulation and Observation Data to Reveal the Core Growth with Observations

The birthplace of stars is dense cores in molecular clouds. Since the evolution process of a star strongly depends on the mass, the mass is one of the most important properties of a dense core as well. Then, the relationship between mass functions of dense cores (Core Mass Functions, CMFs) and stellar mass functions (Initial Mass Functions, IMFs) is expected to imprint information on the core evolution and star formation processes. These two mass functions have turnovers at low mass and a power-law shape above the turnovers. From previous observations of the IMF, the power-law index of the IMF is thought to be a universal feature. Many previous studies of CMFs in nearby star-forming regions have suggested that the CMFs resemble IMF. In particular, the turnover mass of CMF is larger than that of IMF and the power-law index of CMF is similar to the slope of IMF.

Several numerical simulations of the prestellar core suggest that the protostellar feedback such as outflow blows off a part of the core mass and the remaining core mass evolves into star and star formation efficiency which is a mass ratio of a star and a parental dense core becomes smaller than unity.

In the standard star formation scenario of the core-collapse model, stellar mass is determined by the mass of parental core mass with a constant star formation efficiency which is smaller than unity. Then, it has been believed that the observed relationship of the one-to-one correspondence between CMF and IMF can be explained by the core-collapse model at least in the low-mass star-forming region.

However, top-heavy CMFs are reported from recent ALMA continuum observations of distant high-mass star-forming regions (Motte et al. 2018). The observed CMF has a shallower slope at the high-mass part and this contradicts the core-collapse star formation model. The interpretation of this result is under discussion, but the time evolution of CMF is suggested as a possible idea to explain the new relationship between CMF and IMF.

To investigate the relationship, we conducted a dense core survey in the Orion Nebula Cluster (ONC) region which is a central region of Orion A to construct CMF (Takemura et al. 2021a). Orion A is the nearest giant molecular cloud (GMC) and is known as an active star-forming region. We used CARMA+NRO45-m combined C18O (J=1-0) data of Orion A which covers a wide area with high angular resolution. The wide observation area of 1 degree by 2 degrees and high angular resolution of 8 arcseconds enable us to perform the unbiased precise dense survey. We then directly compared the observed CMF and IMF derived from the stellar catalog provided by the previous observation. The highest spatial resolution is achieved in the study of the direct comparison of the two mass functions. As a result, we found that CMF and IMF have turnovers at almost the same masses and similar slopes resemble universal IMF. Since dense cores are deeply embedded into the molecular cloud, we concluded that mass accretion from surrounding material is important to explain the observed relation of the two functions. We also suggested that dense cores will grow with mass accretion.

The core growth during the star formation is proposed by other observations as well. Kong et al. (2021) compared the masses of protostellar cores and starless cores in the Dragon Infrared Dark Cloud. Then, it is found that protostellar cores tend to be more massive than starless cores. This implies that starless cores grow while acquiring mass from the outside.

In order to reveal the evolution of dense cores and CMF and core growth process with mass accretion, we extended the dense core survey in the ONC region to the entire Orion A (Takemura et al. submitted to ApJS). Prior to the observational study, we examined whether we could obtain true CMF from observation and how to get the true CMF from observation with numerical simulation data. Then, this thesis consists of the above two studies with numerical simulation (Chapter 2 of the thesis) data and observational data (Chapter 3 of the thesis).

The three-dimensional AMR, MHD simulation of the collision of two GMCs is conducted by Wu, Benjamin and we utilized the data. From the position-position-position (PPP) volume density data, we created position-position (PP) column density data and position-position-velocity (PPV) column density data. Then, we conducted the dense core survey with the volume density data in the position-position-position three-dimensional data. We treat this as a true CMF of the simulated cloud and compare this with CMFs of PP data and PPV data. For PP data, we subtracted the background column density from the column density at the core position to extract the column density of the core itself. As expected, the PP CMF without subtraction has a larger turnover mass than PP CMF. The PP CMF with subtraction has a similar turnover mass as PPP CMF but the slope above it is shallower than that of PPP CMF. The main reason may be an overlapping effect along a line of sight. Then, we think that the compensation with the completeness of CMF with subtraction may be a way to obtain true CMF from PP data. In the actual observation, it is difficult to know the actual column density due to the lack of information on temperature. In this case, we get steeper CMF when we adopt the typical clump temperature such as 20 K. In addition, we get a shallower CMF than that CMF for the entire cloud when we construct a CMF with cores near the center of the cloud. Therefore, should take into account that temperature variation and selection of the observing area can change the slope of CMF from PP data. Next, PPV CMF of C18O has a similar turnover mass to PPP CMF but the slope is shallower than that of PPP data. The result that we could get almost true turnover mass from PPV data is good for molecular line observations. We guess the reason why the slope becomes steeper is we underestimate the core mass, especially for the massive cores, due to the line broadening. It is necessary to be careful that PPV CMF becomes steeper than true CMF in actual observations.

We conducted a dense core survey in the entire Orion A using the CARMA+NRO45-m combined C18O (J=1-0) data of Orion A (Takemura et al. submitted to ApJS). Applying the Dendrogram algorithm (Rosolowsky et al. 2008) to the PPV data and we identified 2341 cores. We note that the velocity width – mass relation of identified cores with this observational data have much shallower than that of simulated PPV data. This means that the broadening of the line width as the mass increases is small in observational data than in simulated data. Then, we expect that the effect of underestimation of core mass due to the line broadening is also small in our observational data and the observed CMF is closer to true CMF. The observed CMF in Orion A has an IMF-like turnover mass and slope as well as the analysis. This result also supports the core growth with mass accretion. When we separate the Orion A into subregions, a CMF in the central region has a shallower slope than CMFs in the other subregions. Also, most of the massive cores of larger than ten solar masses are concentrated in the central region. It implies that environmental effects can affect the core properties and CMF. Next, we investigated the mass accretion process. In this thesis, we estimated the mass accretion rate in different two ways. One is the required mass accretion rate to double the core mass within a core lifetime. The other is an accretion rate of Bondi accretion. We found that Bondi accretion is too small for cores to grow within a reasonable timescale when we adopt the typical clump property. The mass accretion along filament may achieve a high mass accretion rate but specifying the concrete accretion process is difficult for now. In addition to the above discussion of CMF and the mass accretion process, we investigated the core properties.

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Results of the doctoral thesis defense

# 博士論文審査結果

Name in Full
氏 名　　竹村 英晃

Title
論文題目　　Study of Dense Core Property and Core Mass Function with Simulation and Observation Data to Reveal the Core Growth with Observations

星形成過程は、銀河の主要成分である恒星の分布を理解する上で、本質的な研究課題である。中でも、分子雲高密度コアの質量分布(コア質量関数、CMF)と星の質量分布(初期質量分布、IMF)の比較により、統計的に星形成過程を探る研究は、長年にわたり取り組まれてきた重要課題である。ハーシェル宇宙天文台による分子雲のフィラメント構造の発見や近年の高空間分解能の分子雲コアのサーベイ観測、また、分子雲の重力収縮から星形成までを扱う大規模スケールかつ高空間分解能の数値流体シミュレーション研究の発展などにもとづき、分子雲コアの CMF と星の IMF の関係と星形成過程の解釈は変化しつつある。従来は、高密度コアが重力収縮し、その一部が星形成効率 30%程度で星になる、という描像が一般的であったが、近年の観測的・理論的研究により、高密度コアへの質量降着を経て星が形成されるシナリオが新たに提唱されつつある。

本論文では、これらの研究を背景に、星団形成の数値流体シミュレーションの模擬観測とオリオン分子雲の大規模観測データの解析に基づき、CMF と IMF の関係および星形成過程に関する新たな視点を提案した。

まず、20pc(パーセク)スケールの巨大分子雲の衝突により誘起された星形成過程を 0.03pc スケールの高空間分解能で扱う数値流体シミュレーションの大規模データを、観測データの解析と同じ手法で解析することにより、観測から CMF を導出する際に生じ得る問題点を精査した。CMF の導出には、ダスト連続放射と分子輝線観測がよく用いられる。観測的には、いずれも天球面に射影された情報しか得られず、分子雲コアの視線方向の重なりの影響を考慮する必要がある。本研究では、背景放射の影響なども含め、様々な観点で模擬観測を行った。その結果、ダスト連続放射観測の場合、視線方向の重なりの影響で小さいコアを観測できず、CMF の冪を浅く見積もる可能性があること、一方、分子輝線観測の場合は速度方向に分解できるため、重なりの影響が少なくなることを示した。分子輝線の速度幅の影響なども議論し、分子輝線観測に基づき、より現実に近い CMF を導く手法を提案した。

次に、大質量星形成領域であるオリオン分子雲の CARMA 電波干渉計・野辺山電波望遠鏡(NRO45m)による $C^{18}O$ 分子輝線、ハーシェル宇宙天文台によるダスト連続波、および若い星のカタログといった大量の観測データを丁寧に解析して高密度分子雲コアの CMF を導き、また、分子雲コアの物理的性質を調べた。$C^{18}O$ 分子輝線より CMF を導出する際には、前述の手法を用いた。これまでにない高空間分解能観測を用いて CMF を導いた結果、CMF のピーク質量(~0.1 太陽質量)、冪ともに、同じオリオン分子雲に付随する星の IMF と良い一致を示すことを明らかにした。これは、従来の星形成の描像とは異なり、高

密度コアに周囲のガスが質量降着しつつ星形成するシナリオを支持する。このように CMF と IMF の比較により統計的観測の観点から星形成過程を議論する一方で、本論文ではさらに、高密度コアの物理的性質を観測的に調べることにより、星ありコアは星なしコアに比べて質量が大きく密度が高いこと、また、柱密度が高いフィラメントから高密度コアへの効率的な質量降着に対する示唆など、新たな星形成シナリオを支持する結果を得た。

以上のように、本論文は、星団形成の数値流体シミュレーションの模擬観測により、観測からより現実的な CMF を求める手法を確立し、かつ、これまでにない、広域かつ高空間分解能、高感度のオリオン分子雲の観測データに基づき、近傍の小質量星形成領域や遠方の大質量星形成領域の ALMA サーベイ観測とも比較可能な、今後の CMF 観測の基礎となる星形成領域の分子雲コアのカタログを作成した。さらに観測より導いた CMF と IMF を比較した統計的観点と、高密度コアの物理的性質の観測に基づき、フィラメントから高密度コアへの効率的な質量降着を経て星が形成されるという、新たな星形成シナリオを提案した。

本論文において、データ解析、議論、論文作成の一連の過程は、出願者が主体となって行っている。その内容は、今後の星形成研究の進展に広く有用であり、また、星形成過程に対する新たな知見を与えた。以上の理由により、審査委員会は、本論文が学位の授与に値すると判断した。