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研究課題名（和文）Understanding Accretion of Young Massive Protostars

研究課題名（英文）Understanding Accretion of Young Massive Protostars

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研究成果の概要（和文）：本研究課題では大質量原始星周囲の回転円盤を探査，同定し、その性質を明らかにすることを目的としています。実際に、いくつかの形成段階にある大質量量星周囲において回転円盤の同定に成功しました。これらの観測結果は、強力な輻射や力学的フィードバックがあったとしても、大質量量星が小質量量星と同様の過程で誕生するというシナリオを支持しています。また観測解析を通じて、ホットディスク分子輝線や水素再結合線を利用した新しい円盤探査手法を確立しました。これらの観測結果と円盤探査手法は本研究領域を発展させるもので、それらを基にした新しい観測計画提言も採択されています。

研究成果の学術的意義や社会的意義
This project improved our understanding of the formation of massive stars. In particular the results support a scenario that massive stars form in a similar way as low-mass solar type stars. The method developed in this study can be applied to more targets to study massive star formation.

研究成果の概要（英文）：The whole project is to search, identify, and study the rotationally supported disks around massive protostars. We have successfully identified several sources with rotationally supported disks around forming massive stars. These observational results support a scenario that massive stars form in a similar way as low-mass stars, despite their strong radiation and kinematic feedbacks. Based on these observations, we have developed a method that can be used to search for disks, including hot-disk molecules and recombination lines. Based on the results and developed methods, we have successfully applied new observations which will extend the research.

研究分野：Astrophysics

キーワード：Massive Star Formation

１．研究開始当初の背景

The community has agreed upon a general picture for low-mass star formation: a star forms from a molecular gas core, which collapses and feeds the protostar via a rotationally supported disk. Meanwhile the disk drives bipolar outflows. In the end, the core is dispersed by the outflows, and the remaining protostar and disk continue to evolve into the star and its planet system. The key in such a picture is the disk that redistribute the angular momentum of the accreting material to allow accretion toward the protostar.

A long-standing question in star formation research is that whether massive stars also form in such a way, i.e., via accretion through a rotationally supported disk. The observational challenges are from the large distances, and highly crowded and embedded environments. There were only very few rotationally supported disk candidates around massive protostars have been claimed. It is unknown whether this is due to a genuine lack of such disks in massive star formation or due to observational difficulties. The traditional method to detect disks relies solely on the kinematic signatures, but the Keplerian rotation of disks can be easily mixed with the non-Keplerian rotation of envelopes if the observation spatial resolution is not high enough. This question is further complicated by the fact that most massive stars form in binary or higher-order multiple systems.

In low-mass star formation, the transition from an envelope to a disk has been observed to be indeed accompanied with not only change of kinematics, but also change of chemical compositions due to the accretion shock and different temperature/density conditions in the envelope and disk. However, such methods had not yet been applied to massive star formation studies. And by then it was unknown which types of molecules are best to disentangle the disk and envelope in massive star formation.

２．研究の目的

The goal of this program is to study how the massive protostars accrete material and grow. In particular, we wanted to answer the question whether the accretion process to form massive stars are similar to the formation of low-mass solar type stars, i.e., via rotationally supported accretion disks. In order to achieve this goal, we need to identify such disks and study their kinematics and other physical properties. We also need to study how common these disks are in massive star formation. We also need to study what molecules can well trace the disks to allow us to efficiently identify and study such disks. The general goal is to understand if the massive star formation and low-mass (e.g., solar type) star formation have a common universal mechanism. Answering this question is important for better understanding not only formation of stars of different masses, but also formation of planets and compact objects, as planets are formed in the accretion disks along with the stars, and the compact objects are evolved from the massive stars.

３．研究の方法

The program mostly utilized the millimeter and sub-millimeter data obtained from the Atacama Large Millimeter/Submillimeter Array (ALMA). ALMA provided high spatial resolution which allowed us to probe the innermost region (~100 astronomical units) from the forming massive star, and high sensitivities which allowed us to detect relatively weak molecular lines and extended faint emissions. The observed continuum emission provides information about the dust and ionized gas. The detected various molecular line emission can provide kinematic information, as well as information about chemical composition, and densities/temperature conditions. Using all these information, we analyze the detailed gas structures around the forming massive stars and derive their motions and physical conditions, to test whether disks are formed and how the accretion proceeds.

４．研究成果

(1) We have successfully identified several sources with rotationally supported disks around forming massive stars. In 2019, we have published a paper on the massive protostellar source G339 in the Astrophysical Journal, which we have reported direct observation of the transition from an infalling envelope to a rotationally supported disk accompanied by change of chemical signatures. We found that the SiO molecule traces the disk and inner envelope, the CH_3OH and H_2CO trace the infalling-rotating envelope outside of the disk, and the SO_2 and H_2S appear enhanced around the transition region between envelope and disk. These results indicate that an ordered transition from an infalling-rotating envelope to a Keplerian

disk through a centrifugal barrier, accompanied by change of chemical composition, is a valid description of this massive protostellar source. This is the first time that such transition has been identified with chemical signatures in massive star formation, which provides important guide for our future search for such sources.

In 2019, we also published a paper about another massive protostar G45 in the Astrophysical Journal Letters, which we have identify the disk via observation of recombination lines of ionized gas, which provide another approach to search for disks around massive protostars. The kinematics of the ionized gas is dominated by rotation close to the disk plane, while accelerated to outflowing motion above the disk plane. In this source, we also found hints of a possible jet embedded inside the wide-angle ionized outflow with non-thermal emissions. The possible co-existence of a jet and a massive photoevaporation outflow suggests that, in spite of the strong photoionization feedback, accretion is still on-going.

In 2020, we published a paper in the Astrophysical Journal Letters about another massive protostellar source IRAS16547, in which we have identified clear chemical patterns with certain molecules exclusively trace the rotationally supported disks, which may be used as reliable disk diagnostic tools in the future. We detect salt, silicon compounds, and hot water lines as probes of the individual protostellar disks at a scale of 100 au, which are complementary to hot-core molecules tracing the circum-binary structures on a 1000-au scale. We interpret that these molecules are the products of dust destruction, which only happens in the inner disks. We also tentatively find that the twin disks are counter-rotating, which might give a hint of the origin of the massive proto-binary system.

These observational results support a scenario that massive stars form in a similar way as low-mass stars, despite their strong radiation and kinematic feedbacks.

(2) Based on these observations, combined recent observational studies of other sources, we have developed a method that can be used to search for disks, including hot-disk molecules and recombination lines. We found that the innermost regions of massive star formation can be traced by a group of characteristic molecular lines, including metal and silicon compounds (e.g., NaCl, KCl, AlO, SiO, SiS), and vibrationally-excited H_2O lines. These lines show Keplerian rotation expected for disks, in contrast to the hot-core molecular lines (e.g., SO_2, CH_3CN, and other complex organic molecules), which are not concentrated at the protostars and show infalling-rotation kinematics consistent with envelopes. The refractory metal and silicon compounds are released to the gas phase by the destruction of dust grains, caused by high temperature, strong radiation field, and dynamic flow interactions in massive protostellar disks. The hot conditions also excite H_2O molecules to high energy levels. Therefore, we proposed the new concept of *hot-disk* tracers for these lines and suggested that they are true tracers of massive protostellar disks. In addition, as the massive protostars enter the Kelvin-Helmholtz contraction phase, their surface temperatures increase, leading to higher ionizing fluxes, which ionize the inner disk and disk surface. Such regions are traced by various Hydrogen recombination lines (HRLs). Therefore, we suggest that, to fully understand the physical and chemical conditions of massive protostellar disks, one can use *hot-disk* lines to trace the neutral part of the disk, HRLs to trace the ionized part of the disk, and hot-core lines to trace the envelope. The base of outflow is co-rotating with the disk, which can also be traced by *hot-disk* lines and/or HRLs. This scenario is illustrated in Fig. 1. This summary of method will be used for future larger-scale studies of massive star formation.

(3) Based on the results and developed methods, we have successfully applied new observations which will extend the research. In 2019, we have applied following-up observations of the ALMA telescope to perform more detailed observations for G339 and G45. Both projects are approved and assigned with top rank priority. The observation and data analysis were originally planned in 2020. However, the observation is delayed to 2021 due to the pandemic.

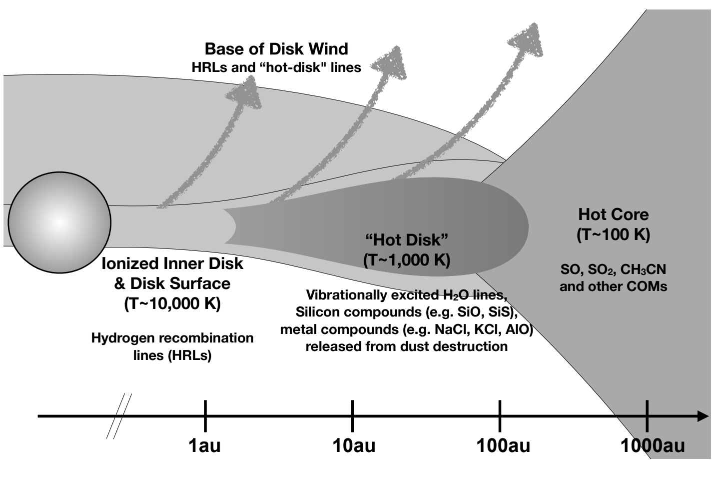

Figure 1: Schematic of a massive proto-stellar disk and surrounding structures, with typical tracers of each component. Such a scenario is based on our discovery and observations towards exemplary massive protostars with disks identified with various molecules. Based on our results, we proposed a method which can be used to efficiently identify and study disks in massive star formation, i.e., "hot-disk" tracers, combined with HRLs tracing the ionized part of the disk, and hot-core lines tracing the envelope.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　2件）

１．著者名 Kei E. I. Tanaka, Yichen Zhang, Tomoya Hirota, Nami Sakai, Kazuhito Motogi, Kengo Tomida, Jonathan C. Tan, Viviana Rosero, Aya E. Higuchi, Satoshi Ohashi, Mengyao Liu, Koichiro Sugiyama	４．巻 900
２．論文標題 Salt, Hot Water, and Silicon Compounds Tracing Massive Twin Disks	５．発行年 2020年
３．雑誌名 The Astrophysical Journal Letters	６．最初と最後の頁 L2
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/2041-8213/abadfc	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Mengyao Liu, Jonathan C. Tan, James M. De Buizer, Yichen Zhang, Emily Moser, Maria T. Beltran, Jan E. Staff, Kei E. I. Tanaka, Barbara Whitney, Viviana Rosero, Yao-Lun Yang, Ruben Fedriani	４．巻 904
２．論文標題 The SOFIA Massive (SOMA) Star Formation Survey. III. From Intermediate- to High-mass Protostars	５．発行年 2020年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/abbefb	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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２．論文標題 Discovery of a Photoionized Bipolar Outflow toward the Massive Protostar G45.47+0.05	５．発行年 2019年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 L4～L4
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/2041-8213/ab5309	査読の有無 有
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〔学会発表〕　計7件（うち招待講演　0件／うち国際学会　4件）

１．発表者名 Yichen Zhang, Eva Greco, Yao-Lun Yang, Jonathan Tan, Kei Tanaka, James De Buizer, Ruben Fedriani, Mengyao Liu, Maite Beltran
２．発表標題 ALMA 1.3mm observations of massive star forming region G35.2-0.74
３．学会等名 237th Meeting of the American Astronomical Society（国際学会）
４．発表年 2021年

１．発表者名 Yichen Zhang, Kei Tanaka, Jonathan Tan, Nami Sakai, Viviana Rosero, James De Buizer, Mengyao Liu, Diego Mardones, Maria Beltran, Kaitlin Kratter, Diego Mardones, Guido Garay
２．発表標題 ALMA View of the Innermost Regions of Massive Star Formation
３．学会等名 大質量星形成ワークショップ2020
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４．発表年 2021年

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２．発表標題 Discovery of a Photoionized Bipolar Outflow toward the Massive Protostar G45.47+0.05
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３．学会等名 The Evolution of Massive Stars and Formation of Compact Stars: from the Cradle to the Grave（国際学会）
４．発表年 2020年

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２．発表標題 Massive Star Formation in 0.03”-resolution View of ALMA
３．学会等名 From Star to Planet II（国際学会）
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３．学会等名 ALMA2019: Science Results and Cross-Facility Synergies（国際学会）
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関