氏　　名	塚越　崇
学位（専攻分野）	博士（理学）
学位記番号	総研大甲第1190号
学位授与の日付	平成２０年９月３０日
学位授与の要件	物理科学研究科　天文科学専攻 学位規則第６条第１項該当
学位論文題目	Structures and Evolution of the Circumstellar Environments around Classical T Tauri Stars in nearby Star Forming Regions
論文審査委員	主　査　准教授　関本　裕太郎 准教授　田村　元秀 准教授　林　左絵子 教授　山本　智（東京大学） 准教授　犬塚　修一郎（京都大学）

論文内容の要旨

It is fundamental to investigate the origin of low-mass stars and planets in order to answer how the sun or the earth was formed. In the widely accepted star and planet formation scenario, a dispersion process of the circumstellar material around young stellar object is recognized as one of the most important mechanisms to control the mass input to the star-disk system and the nature of the planet. In the protostar phase, although most of the systematic studies restricted their sample to the young stellar objects in Taurus, we have had some reasonable understanding of the dispersion process. However, our knowledge about the dispersal mechanism and time scale of the circumstellar gas has been poor yet in the phase of Classical T Tauri Star (CTTS). Therefore, more systematic observational data are required in order to understand the dispersion process of the circumstellar gas material in an envelope as well as a disk. The main purpose of this study presented in this thesis is to reveal the circumstellar environments and evolution of CTTSs in nearby star forming regions. We have performed two kinds of molecular line observations with radio telescopes, Atacama Submillimeter Telescope Experiment (ASTE) and Nobeyama Millimeter Array (NMA), for the purposes.

One of observations is the ^{12}CO and ^{13}CO J=3-2 line survey of CTTSs in nearby star forming regions, Taurus, Ophiuchus, and Lupus, using ASTE. We selected 26 CTTSs (22 for ^{12}CO observations and 13 for ^{13}CO observations) in the regions which have been reported to have strong 1.3mm continuum emission. Six targets in Ophiuchus were selected as our NMA observations. In the observations with ASTE, we employed five-points observations in which spectra at stellar position and surrounding four-points are obtained, which enable us to compare the central spectrum and other four surrounding ones. By subtracting an ambient cloud component, the excess emission toward the star which is embedded in their parent cloud can be evaluated (residual spectrum). The purposes of the observations are to characterize the molecular environment around CTTSs (~3000 AU scale) and to investigate the dispersion time scale of gas around CTTSs. Additionally, it is important to search for gas-rich disks suitable for future follow-up observations with interferometers.

Another observation is high-resolution interferometric ^{12}CO(1-0), ^{13}CO(1-0), and millimeter continuum observations toward eight CTTSs in the Ophiuchus molecular cloud. The six of eight targets were also observed in the five-points method with ASTE. The aims of the NMA observations are to reveal the structures and kinematics of the residual spectra obtained with ASTE by the high-resolution aperture synthesis observations (~500 AU scale), and to investigate that the external environments affect the dissipation of the circumstellar gas by observing CTTSs in two clouds of Ophiuchus which have different characters (ρ-Oph and North-Oph).

From the ASTE survey observations, ^{12}CO and ^{13}CO J=3–2 spectra over the five positions were obtained toward 26 and 13 sources, respectively. We found that all of them have

spatially extended emission over the five points. These extended emissions indicate that the all CTTSs observed here are likely to be associated with the ambient gas in the parent clouds. On the other hand, the residual spectra were found for 22 and 7 sources in ^{12}CO and ^{13}CO, respectively. Almost all the residual spectra showed the positive profile, but four sources, Sz 83, Sz 88, EL 24, and SR 21, also have the negative above 3σ in ^{12}CO. We found an evolutional trend in the total intensity of the residual spectra in ^{12}CO and ^{13}CO after the correction of the distance to the source. Although the problems about the optical depth of the ambient cloud still remains, the total intensity of 12CO seems to decrease with increasing stellar age. In addition, we found that there is variation in the corrected total intensities of the residual spectra around an age of 10^6 yr. Two sources in North-Oph, AS 209 and V2508 Oph, conspicuously show the variation, and the circumstellar material has been dissipated obviously in comparison with the sources in the other regions. This diversity probably reflects to the characteristics of the Oph-North cloud, such as the low density of the cloud and/or the effect of the nearby O type star, ζ Oph.

Our NMA observations reveal the circumstellar environments around CTTSs in ρ -Oph and North-Oph as follows. We found point-like continuum emission associated with the star toward seven of the eight targets. The spectral index, β , of 0.1-0.5, the mass of 10^{-3}-10^{-2} $M_\odot$ and the beam-deconvolved size of 400-1000 AU suggest that the emission originates from the circumstellar dust disk. Our ^{12}CO and ^{13}CO J=1–0 maps show that a large amount of the remnant envelope (and a molecular outflow) still remains around the ρ -Oph sources, EL 24, SR 21, DoAr 25, and SR 24. Surrounding gas in most case is gravitationally unbound from the central stars, suggesting that it never accretes to the star-disk system. Although we found Kepler rotating gas disk with a radius of ~800 AU around AS 205 in ^{12}CO J=1–0, we did not detect significant emission of the circumstellar envelope in ^{13}CO J=1–0 except for RNO 91, which is thought to be younger than the other sources. From the ASTE observations in ^{12}CO J=3–2, we obtained the five-points spectra for six sources in ρ -Oph and North-Oph, and the significant residual spectra were found toward four sources, AS 205, EL 24, SR 21, and DoAr 25. The important point is that circumstellar structures, gas envelope or disk, were found by our NMA observations around these sources. The spectra of ^{12}CO and ^{13}CO J=1-0 by the NMA observations were well consistent with the ^{12}CO J=3-2 spectra in terms of velocity and shape. These facts suggest that the residual spectra originate from the remnant envelope, the molecular outflow, or the gas disk.

On the basis of our results by ASTE and NMA as well as some literature, the circumstellar environments around CTTSs were categorized in the following three cases: (1) envelope with/without outflow, (2) gas disk, and (3) no clear evidence for disk/envelope. The category 1has the intensity of the ^{12}CO residual spectra is large so that it is difficult to reproduce by the emission from the disk with a size of a few hundreds AU. In addition, the ^{13}CO J=3–2 residual spectra are also seen or the spatially extended gas is found by the high-resolution observations. The category 2 has the ^{12}CO J=3–2 residual spectra whose intensity is reproducible of the disk with a few hundreds AU radius, and another evidences of the

existence of the circumstellar disk are suggested, such as a kepler rotating motion or a scattered disk. The other sources belong to the category 3.

In order to examine the evolutional trend of the categories, a plot of the total intensity after the distance correction v.s. stellar age was made. Our analysis revealed the time scale of the evolution of the circumstellar structure especially an envelope as follows. It seems that the envelope with/without outflow (category 1) remains at least 1 Myr, which is larger than the free-fall time scale ($\sim 10^5$ yr). Although we did not find an evolutional trend, the sources with a gas disk (category 2) were seen from 0.7 to 10 Myr. The category 3 was also seen up to 10 Myr. The remnant envelope of category 1 sources in most cases is likely to be gravitationally unbound from the central star, indicating that the material is never supplied to the star-disk system. These results imply that the initial condition of a protoplanetary disk is achieved by the age of 1 Myr.

論文の審査結果の要旨

現在広く受け入れられている低質量星の形成シナリオでは質量の降着と散逸のプロセスが支配しており、星周物質の散逸過程を明らかにすることは、星・惑星系形成過程の理解にとって重要である。しかしながら、若い星T タウリ型星を対象とした電波望遠鏡を用いた系統的な観測はこれまであまり行われてきておらず、この進化段階における星周エンベロープ（星の形成母体となった分子雲コアの残存物質）やケプラー回転をもつ星周円盤（原始惑星系円盤）の散逸に関する情報は少ない。このような背景のもと、出願者は古典的T タウリ型星(CTTS) に付随するガス星周環境をサブミリ波 CO 輝線及びミリ波高解像度観測によって調べた。星周エンベロープの散逸時間を見積もる目的で、近傍星形成領域である Taurus, Ophiuchus, Lupus 分子雲に存在する 26 個の CTTS を観測した。サブミリ波 ^{12}CO J=3-2、^{13}CO J=3-2 輝線は、南米チリの口径 10m の ASTE 望遠鏡により、約 3000AU (AU は天文単位で太陽と地球の距離)に相当する 20 秒角の半値幅（空間分解能）で観測した。拡がった分子雲からの放射の影響を取り除くために 5 点法をもちいて天体近傍に付随する残差スペクトルを調べた。ミリ波高解像度観測は、Ophiuchus 領域の一部である ρ-Oph と North-Oph に存在する 8 個の CTTS について、野辺山ミリ波干渉計(NMA) をもちいて、^{12}CO J=1-0、^{13}CO J=1-0 輝線を用いてさらに高空間分解能の 1~10 秒角（150-1500AU に相当）でイメージング観測(65 秒角領域をカバー)を行った。観測した 8 個の内 6 天体はサブミリ波サーベイ観測のターゲットと重なっている。

サブミリ波 CO サーベイ観測の結果、全ての観測天体で空間的に拡がった ^{12}CO 放射を検出しており、観測した CTTS は拡がった母体分子雲にまだ付随している様子を示した。残差スペクトルは ^{12}CO J=3-2 で 22/26 天体、^{13}CO J=3-2 で 7/13 天体から 3σ 以上の有意な検出であった。一方ミリ波高分解能観測からは、ρ-Oph の 4 天体にまだ多くの残存/散逸エンベロープが(2 天体は分子流も) 残っていた。このような星周エンベロープの物理状態を調べた結果、中心星に対し重力的に束縛されておらず、星-円盤への質量供給が生じない事を示した。North-Oph の CTTS では、1 天体からケプラー回転円盤を示唆する ^{12}CO 放射を検出したものの、残存/散逸エンベロープと思われる ^{13}CO 放射は検出されず、ρ-Oph とは明らかに異なる星周構造をもつことを示した。このような、残存/散逸エンベロープやガス円盤といった星周構造がミリ波高分解能観測で検出された天体は、サブミリ波 CO 観測においても残差スペクトルが得られている。また、ミリ波 ^{12}CO J=1-0、^{13}CO J=1-0 のスペクトルと、サブミリ波 ^{12}CO J=3-2 の残差スペクトルを比較したところ、検出した速度やスペクトル形状が一致した。この結果は、サブミリ波 CO の残差スペクトルが、母体分子雲の揺らぎではなく実在の星周構造を起源にしている一つの証拠である。

サブミリ波 CO 観測とミリ波高分解能観測の結果および文献を元に、星周構造の観点から、観測された全ての CTTS を以下の三つに分類した: (1) 星周エンベロープ(および分子流) を持つもの、(2) 回転ガス円盤を持つもの、(3) エンベロープやガス円盤の証拠が無いもの。上記の分類毎に残差スペクトル強度と天体年齢の相関図を作成し、星周構造の進化傾向を調べ、エンベロープを伴う天体(分類 1) は 1Myr 程度で消失することを明らかにした。またガス円盤天体(分類 2) は、強度に進化傾向は見られないものの、0.7-10 Myr の範囲に存在していた。ミリ波高分解能の観測結果も考慮すると、残存/散逸エンベロープの最終段階として、中心星に重力的に束縛されていないガスが卓越しており、1 Myr 程度で散逸するといえる。この結果が示すのは、今後惑星系形成の母体となる「原始惑星系円盤」の初期状態が、1Myr までに達成されていることである。

出願者の博士論文に示された以上の結果は、サブミリ波 CO 輝線観測やミリ波高解像度観測によって古典的T タウリ型星のガス星周環境を探り、星周エンベロープの散逸過程を示したもので、こ

の分野の研究にとって十分意義のある成果と判定された。これにより審査委員会は、本論文が博士論文として十分な価値を有し、合格であると判定した。