氏　　　　　名	新　永　　玲
学位（専攻分野）	博士(理学)
学 位 記 番 号	総研大甲第455号
学位授与の日付	平成１２年３月２４日
学位授与の要件	数物科学研究科　天文科学専攻 学位規則第４条第１項該当
学 位 論 文 題 目	An Observational Study of the Extremely Young Stage of Star Formation
論 文 審 査 委 員	主　査　教　授　觀山　正見 助教授　浮田　信治 助教授　森田　耕一郎 教　授　井上　允（国立天文台） 助教授　田中　培生（東京大学）

論文内容の要旨

Abstract

The formation of stars begins with collapse of a dense interstellar cloud core to a protostar surrounded by an accretion disk. Materials in the core falls inwards to feed further growth of the protostar through the disk. At certain point during the accretion phase, a jet of gas is generated by the forming protostar along the disk's rotation axis. Subsequently, protostellar jet drives molecular outflow, and which will destroy the core and will terminate the mass accretion. Such evolution of young stellar objects (YSOs) had been classified into three categories, Class I, II, and III, based on the slope of their infrared spectral energy distribution (SED). Recently, the new fourth class "Class 0" has been suggested for the youngest protostellar objects which have not been detected in the near-infrared and which display an SED with a peak in the submillimeter wavelength. The jet and outflow are an ubiquitous phenomenon in YSOs ranging from "Class 0" to "Class I" sources. Despite the substantial observational progress, it is still uncertain when the jets are ejected during the accretion phase because most of Class 0 sources already posses jets and outflows.

The Class 0 source, S106 FIR (d = 600 pc) is a good candidate to investigate star formation process at an extremely early stage before formation of outflow. This is because this source is known to be associated with no extensive molecular outflows, making it unique among all 40 known Class 0 sources. First, we conducted aperture synthesis observations of H_2O maser emission at 22 GHz toward S106 FIR using the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) at 60 mas (milli-arcsecond) resolution on two epochs separated by $\sim$3 months. Two compact clusters of the maser spots separated by $\sim$ 50 AU were found in the center of the submillimeter core of S106 FIR. The western cluster, which has three maser components, was blueshifted and the eastern cluster, which has a single component, was redshifted with respect to the ambient cloud velocity. Each component was composed of a few spatially localized maser spots and was aligned on a line connecting the two clusters. We found relative proper motions of the components with $\approx$ 30 mas year^{-1} along the line. In addition, a series of single-dish observations show that the maser components drifted with an accelerations of $\sim$ 1 km s^{-1} year^{-1}. We conclude that the masers are excited by a 10 AU-scale jetlike accelerating flow ejected from an assumed protostar located between the two clusters.

Second, we made the higher resolution observations to reveal the detailed structure of the jetlike flow and to track its motion using the Very Long Baseline Array (VLBA) of the NRAO on four epochs separated by $\sim$1 month. The attained angular resolution of $\sim$0.5 mas corresponds to 0.3 AU. The observations have revealed the presence of a U-shaped distribution of the masers in the western blueshifted cluster, which has a length of 4 AU and a width of 3 AU. Three-dimensional velocity of the U-shape structure was analyzed

using the transverse velocities of the masers and line-of-sight velocities. Since the masers are thought to be excited in a "micro bowshock" behind the head of the jetlike flow drilling the ambient cloud medium, we call the jetlike flow as a "*micro jet*". The U-shaped structure suggests that the micro bowshock does not comprise of interior knots but lies at the head of the Micro jet. The presence of the Micro jet and the absence of extensive molecular outflows together with the cold SED argue that S106 FIR is an object in the earliest stages of star formation just after the onset of the protostellar jet.

In order to investigate the youth of S106 FIR, we have made deep outflow search by ^{12}CO (1-0) emission using the Nobeyama Millimeter Array (NMA), and by the (3-2) and (2-1) transitions of the molecule using the Caltech Submillimeter Observatory 10.4 m telescope. We could not identify any evidence for the presence of the molecular outflow driven by the Micro jet. Our attained 10σ sensitivities are of orders of 10^{-7} $M_{\odot}$ per km s^{-1} for the (1-0), (2-1), and (3-2) transitions: these sensitivities would have detected any of the CO outflows associated with Class 0 sources. This negative detection suggest that S106 FIR is too young to sweep up the ambient cloud medium to form the molecular outflow. We discussed its age to be $\approx 0.5\text{-}1.0\times10^3$ years from an upper limit of dynamical time scale of outflow, and from the number ratio of sources without and with outflow in Class 0 sources and the lifetime of "Class 0". We conclude from these observations that S106 FIR has not swept up enough ambient gas to generate a large scale molecular outflow.

With the original definition, S106 FIR is certainly categorized into "Class 0". However, S106 FIR is obviously different from the other Class 0 sources in the sense that it has not yet generated a large scale molecular outflows. This fact might mean that the SED classification scheme is inadequate to describe in detail the evolutionary stages, which might be regulated by jets and outflows. In this sense, S106 FIR is the prototype of the earliest stage, which is characterized by the lack of an extensive molecular outflow, the presence of a Micro jet and a cold SED. Identifying similar protostars and studying their physical properties will be of great importance towards understanding the evolution from cloud cores to protostars. In addition, the physical properties of the Micro jet itself will help to clarify the acceleration and collimation mechanisms of astrophysical jets.

In addition, we conducted a multi-epoch survey of H_2O masers towards ≈ 200 known cloud cores and YSOs using the Nobeyama 45m-telescope and the VLA. The goal of this survey is to establish a general view of the maser emissions associated with low-mass YSOs. We have found that the masers have been detected for $46 \pm 8\%$ of Class 0 sources, while a detection rate of only $4 \pm 3\%$ for Class I sources. We interpreted this result as follows. Since Class 0 sources possess a large amount of circumstellar gas, the energetic jets and outflows of Class 0 sources easily enhance the maser emission.

論文審査結果の要旨

星形成過程の第一段階は、星間分子雲中のコアと呼ばれる密度の濃い領域において、重力崩壊による原始星の形成である。この原始星は、収縮したガスの重力エネルギーの開放によって光っており、周囲を質量降着円盤に囲まれていると考えられている。この質量降着期のある時点において、円盤の回転軸方向に原始星からジェットが吹き出すようになる。このジェットは、その後、周囲の分子ガスに作用して、多くの原始星天体で観測されている外向きの分子ガス流を形成する。その結果、分子雲コアは散逸し、原始星への質量降着も停止する、と考えられている。

この現在広く受け入れられている星形成のシナリオの中で、原始星からのジェットの形成についての観測的研究は、その難しさもあり、ほとんど行われて来なかった。

本申請者は、このような星形成のごく初期の描像に迫るための手段として、水メーザー放射のVLBIによる１ミリ秒角という高空間分解能観測を提案した。水メーザーは、おそらくジェットが周囲のガスと衝突してできた衝撃波領域の存在を示しており、その放射が非常に強いため、スペクトル線観測にも関わらず、非常に精度の良いVLBI観測が可能である。

本申請者は、また、星形成のごく初期の時期にあると思われる原始星天体の中から、分子流が未発達であるにも関わらず、水メーザーが検出されている天体S106FIRを観測対象として選び出した。これを米国国立電波天文台(NRAO)のVLA電波干渉計を用いて観測し、これらの水メーザーが原始星のごく近傍に付随したものであることを確認した。さらに、これをNRAOのVLBI専用アレイVLBAを使って１ミリ秒角以下の位置精度で観測を行った。こうして明らかにされた水メーザースポットの分布から、原始星から放出されたばかりのマイクロジェットとも言うべき非常に小さいジェットの存在を発見した。

申請者は、この発見により、これまで考えられていた星形成シナリオの中の謎の部分に初めて光を当てた。今後、このマイクロジェットの詳細な研究や他の天体での観測が進めば、星形成初期の物理過程の解明は大きく進むものと考えられる。

本研究で得られた成果、独創性は以下の通りである。

1) 非常に若い原始星段階であると思われるclass0天体の中でもS106FIRに着目して水メーザー線のVLA及びVLBI観測を実施し、原始星の周りの水メーザースポットの分布を明らかにした。この結果、分布の広がりから、原始星から吹き出したばかりのジェットと周囲のガスとの間の衝撃波によって、励起されたものである可能性が高いことを示した。

2) ほぼ１ヶ月づつ離した４回のVLBI観測から、1ミリ秒角以下の精度の水メーザースポットの分布の時間変化を解析した。この中から、原始星から遠ざかる方向で動いていると思われるＵ字状の形の構造を発見した。ここから申請者は、原始星がジェットを吹き出し始

めるときに、U字形状で示されるようなマイクロジェットという構造を形成することを明らかにした。

3) 申請者自身の観測や他の観測データを解析することにより、このS106FIRが従来のclass0天体よりも若い星形成段階の天体である可能性が高いことを示唆した。この結果、従来考えられていた標準的な星形成過程のシナリオを大きく書き変える可能性が出てきた。