氏　　名	楊 毅
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論 文 審 査 委 員	主　査　准教授　中村　文隆 准教授　柴田　克典 助教　廣田　朋也 准教授　武藤　恭之　工学院大学　教育推進機構 准教授　野村　英子　東京工業大学　理学院

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論文の要旨

Summary (Abstract) of doctoral thesis contents

About 4000 exoplanets have been discovered so far and among them about 200 are in binary or multiple systems. It is also known that stars tend to form in binary or multiple systems, which indicates that many planets would form in environments of binary or multiple systems. Therefore, to understand planet formation, it is quite necessary to investigate planet formation processes in binary systems.

Previous researches have made a big progress on planet formation in single star systems. However, we still do not clearly understand the planet formation process in binary systems. To understand this, we need to know the disk evolution process in binary systems. Some theories of disk evolution process in binary systems have been developed in recent years, but the observational evidence is still lacked due to the previous low spatial resolutions and low contrasts of the instruments, especially for the disk evolution process in close (separation < 100 AU) binaries. To improve current theories, observational evidence is quite important. Fortunately, as the development of high-contrast observation techniques, we can now observe the protoplanetary disk structures in close binaries.

In this thesis, we aim at finding observational evidence of the disk evolution in young binary systems by investigating the disk structures around them. To achieve this goal, we use high-contrast imaging polarimetric observations in near-infrared wavelengths and investigate the detailed disk structures around close binaries. We also used the Atacama Large Millimeter Array (ALMA) high spatial resolution data at submillimeter wavelengths to complement the near-infrared data.

We mainly investigated four young binaries. Firstly, we focused on the GG Tau A binary. By performing non-masked polarimetry imaging with the High Contrast Instrument for the Subaru Next Generation Adaptive Optics (HiCIAO) instrument mounted on the Subaru Telescope, polarized scattered light from the inner region of the disk around the GG Tau A system was successfully detected in the H-band (~1.6 μm) with a spatial resolution of approximately 0.07”, revealing the complicated inner disk structures around this young binary. An arc-like structure to the north of GG Tau Ab and part of a circumstellar structure that is noticeable around GG Tau Aa extending to approximately 28 AU from the primary star is detected in the near-infrared band for the first time. The speckle noise around GG Tau Ab constrains its disk radius to <13 AU. Based on the size of the circumbinary ring and the circumstellar disk around GG Tau Aa, the semi-major axis of the binary's orbit is likely to be 62 AU. A comparison of the present observations with previous ALMA and

near-infrared H2 emission observations suggests that the north arc could be part of a large streamer flowing from the circumbinary ring to sustain the circumstellar disks. According to the previous studies, the circumstellar disk around GG Tau Aa has enough mass and can sustain itself for a duration sufficient for planet formation; thus, this study indicates that planets can form within close (separation < 100 AU) young binary systems.

Secondly, we observed the triple-star system T Tau. We conducted high-contrast polarimetry observations in the direction of T Tau in the H-band, by using the HiCIAO instrument mounted on the Subaru Telescope, revealing structures as near as 0.1" from the stars, T Tau N and T Tau S. The whole T Tau system is discovered to be surrounded by nebula-like envelopes, and there are several outflow-related structures detected in these envelopes. After analyzing the detailed polarization patterns near each component of this triple young star system, we suggest that the face-on circumstellar disk of T Tau N should not be larger than 0.8", or 117 AU. As for T Tau S, we suggest that it is surrounded by an inclined circumbinary disk with a radius of about 44 AU which is quite misaligned with the binary orbit and is likely to trigger the famous E-W outflow, and a precessing southwest outflow. But we did not detect any cavity in the disk around T Tau S, which may be due to that the gap opened in a misaligned disk is smaller than a coplanar one, and it is hard to observe such a gap in such an inclined disk. Our observations give a much more direct view of the disk structures in this system than the previous researches; it could be quite helpful for the following researches.

Thirdly, we investigated the FS Tau A system. By analyzing the H-band image obtained by HiCIAO as well as the archived CO 2-1 data obtained by ALMA, we found out that the surrounding structures around FS Tau A can be classified as blue-shifted component 1 and red-shifted component 2. For component 1, we identify one structure representing a 56-AU nearly edge-on inner circumbinary disk which is quite misaligned with the binary orbit, and a bar-like structure located at the southeast of the central stars. For component 2, we identify a crescent-like structure in CO 2-1 image which is consistent with the structures detected in near-infrared band, which may represent a ring or an arm. We notice that the binary orbit, inner 56-AU circumbinary disk and the previous detected outer circumbinary disk are misaligned with each other. For FS Tau A holds a low-eccentric orbit, it is hard to explain this misalignment from the precession triggered by the binary. We also take a look at H-band image of the binary system Coku Tau 4 obtained by Subaru/HiCIAO, suggesting that it may have a gap with radius about 23 AU in its 70-AU circumbinary disk.

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Based on the circumbinary disks we observed, as well as the results from other telescopes, we made a brief analysis about the disk evolution in binary systems, mainly focusing on gap opening and misalignment of circumbinary disks. We found out that current gap opening and disk misalignment theory can explain most of the gaps and disk misalignment in observed circumbinary disks. However, there still exist some circumbinary disks whose gap size and misalignment cannot be explained well by the current theories, and this indicates that improving circumbinary disk evolution is still necessary. Besides, although from our observation results a detailed discussion about planet formation is hard, we can still suggest that planet formation may be possible in the circumstellar disks around the stars in binary systems and circumbinary disks, and the discovery of so many misaligned circumbinary disk implies there should exists planet whose orbital plane is misaligned with the orbital plane of its host binary.

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博士論文審査結果の要旨

Summary of the results of the doctoral thesis screening

星の大半は連星系や多重星系のメンバーとして生まれるが、これまでの惑星系形成の研究は、単独星の周りで起こる惑星系形成に集中して行われてきた。そのため、連星系や多重星系での惑星系形成については理解が進んでいない。本研究では、連星系内での惑星形成過程の理解を進めるため、近赤外線による偏光観測という手法を用いて、高空間分解能の観測を行い、惑星形成の現場となる星周構造等を明らかにした。サンプル数は 4 天体と限られてはいるが、観測天体に対して星周円盤や周連星円盤の広がり、ギャップ構造、傾きなどに強い制限を与えることに成功した。観測結果から、これまでの連星系・惑星系形成の理論モデルでは完全には説明できない点も見出され、今後の連星系内での惑星系形成の研究にも影響を与える重要な知見を得た。

出願者は、まず、太陽近傍にある比較的明るい連星系のうち、高空間分解能観測が可能な天体を 4 天体（GG Tau A, T Tau, FS Tau A, Coku Tau 4）選び出し、すばる望遠鏡に搭載された HiCIAO カメラを用いた近赤外線(H バンド)偏光観測を行った。次世代 AO システムを用いることにより、空間分解能約 10AU(約 0.1 秒角スケール)の観測をすることに成功した。本論文で示された観測は、中心星を隠すコロナグラフを用いない観測を行っていることが特徴である。このため、星のごく近傍の領域の観測に成功しており、以前の観測に比較して星周構造がより詳しくわかった。近接連星系 GG Tau A の観測では、連星を構成する星それぞれの周囲の円盤起源と考えられる構造や、周連星円盤からのガス降着に起因すると思われる弓状の構造を近赤外線で初めて検出した。さらにこの天体内の連星間距離、星周円盤のサイズ、周連星円盤の広がり、ギャップ構造の大きさなどを定量的に見積もった。

三重星系である T Tau に対しては、世界初の近赤外線偏光観測を実行し、この天体の内部構造、特に、原始星アウトフローや星周円盤の広がりなどを観測的に明らかにした。この天体の星周円盤面は軌道面とずれており、その傾きにより、星周円盤と周連星円盤の間にできるギャップが非常に小さいことなども予想し、今後のこの天体の観測・研究に対して重要な知見を得ることに成功した。

FS Tau A については、近赤外線偏光観測のほか ALMA で取得された一酸化炭素分子輝線データの解析も行い、この天体内の星周構造や速度構造を明らかにした。この天体は非常に大きな周連星円盤を持っていることが先行観測により示唆されていた。しかし出願者は、理論予想に反する、連星の軌道面から大きく傾いた半径 56AU の小さな周連星円盤の存在を新たな観測より示唆した。

Coku Tau 4 については、天体の SED から予想されていたものよりも大きい半径 23 AU のギャップ構造の存在を示唆した。

出願者は、本観測結果と他の先行観測の結果を用いて、惑星系形成に大きな影響を与えると予想されるギャップ構造、連星軌道から傾いた星周円盤の影響について深く考察した。その結果、GG Tau A は、これまでの理論モデルで説明可能な星周構造であることがわかったが、FS Tau A などで検出された連星の軌道面から大きく傾いた小さな半径の周連星円盤は、既存の連星系形成モデルでは説明することが難しいことを指摘した。さらに、今

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回検出した星周円盤や周連星円盤は、惑星系形成が起こる環境にあることを予想した。大きく傾いた星周円盤の存在から、まだ発見されていないが、連星系の軌道面から大きくずれた軌道を持つ系外惑星の存在を示唆した。今後の系外惑星系サーベイ計画にも影響を与えるかもしれない。

以上のように、出願者の観測は、先行観測に比べ格段に改善された分解能で、4つの連星系・多重星系の星周構造を明らかにすることに成功した点は高く評価できる。本研究で行われたデータ解析等は、出願者が主体的に実行したものであり、研究内容は今後の連星系内での惑星系形成過程の理解に大きく貢献するものと期待される。従って、審査委員全員が博士論文として合格であると判断した。