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論文内容の要旨

Infrared polarimetry is a powerful tool for investigating star-forming regions in molecular clouds and planet-forming regions in circumstellar disks, providing a unique method to study the geometry of circumstellar structures and environments around young stars. This is because the infrared radiation can penetrate even into the dense star forming clouds where optical studies are difficult due to heavy extinction and because the infrared wavelengths correspond the peak of spectral energy distribution (SEDs) where young cool stars radiate most of their energy.

Polarized light scattered by materials around young stars provides us important information such as identification of illuminating sources of circumstellar reflection nebulae or exciting sources of outflows associated with the sources, resulting in discovery of unresolved compact disk/outflow systems around young stars. It also provides knowledge of the size distributions and compositions of populations of dust grains in circumstellar materials. Polarimetry also enhances the imaging contrast by separating the polarized scattered light from the unpolarized light of the central source, This is especialy powerful when combined with high-resolution near-infrared (NIR) imaging with adaptive optics and coronagraph.

With these various merits of infrared polarimetry in mind, we have conducted NIR polarimetry for several star forming regions. In order to investigate the evolution of circumstellar infrared reflection nebulae (IRNe) around young stars as well as that of the young stars themselves, wide-field polarimetry has been performed. In addition, in order to investigate the magnetic fields in those star forming regions, software aperture polarimetry of the point-like sources within the same fields has been conducted. Furthermore, in order to investigate the disks around young stars, we have searched for circumstellar disks by wide-field NIR polarimetry. These are observations with a limited spatial resolution; thus their small scale structures are less explored. In order to study much smaller scale (< 100 AU) circumstellar structure, we have used the Subaru telescope with a good seeing condition. Then we have developed a new polarimetric instrument HiCIAO. I have been in charge of software development for mechanical control and its polarimeter unit. Using HiCIAO, we have studied circumstellar disks with a high-resolution ($\sim 0.''06$) NIR polarimetric technique. The results of these series of observations/developments can be summarized as follows.

The Orion Molecular Cloud 1 South region — The Orion Molecular Cloud 1 South (OMC-1S) region is situated in the Orion nebula. We conducted the polarimetry in the J, H, & Ks bands toward the OMC-1S region for the first time. The polarization images clearly show at least six infrared reflection nebulae (IRNe) which are barely seen or invisible in the intensity images. Our polarization vector images also identify the illuminating sources of the nebulae: IRN 1 & 2, IRN 3, 4, & 5, and IRN 6 are illuminated by three IR sources, Source 144-351, Source 145-356, and Source 136-355, respectively. Furthermore, our polarization vector data suggest the candidate driving sources of the optical Herbig-Haro objects; a pair of HH529 and HH269, a pair of HH202 and HH528 or HH 203/204, and HH 530 are originated from Source 144-351, Source 145-356, and Source 136-355, respectively.

The NGC 6334 region — NGC 6334 is a famous, active massive star-formation complex in the southern hemisphere. We report the detection of eighteen infrared reflection nebulae (IRNe) in the J, H, & Ks linear polarimetric observations of the NGC 6334 massive star-formation complex, of which 16 IRNe are new discoveries. Our images cover $\sim$180 square arcminutes, one of the widest near-infrared polarization data in star-formation regions so far. These IRNe are most likely associated with embedded young OB stars at different evolutionary phases, showing a variety of sizes, morphologies, and polarization properties, which can be divided into four categories. We argue the different nebula characteristics to be a possible evolutionary sequence of circumstellar structures around young massive stars.

Polarimetric Search for Disks around Young Brown Dwarfs — We conducted the first systematic near-infrared linear polarization survey of 34 M-type young brown dwarfs (YBDs) in the J, H, and K_s bands, of which 16 YBDs appear to have significant degrees (a few to $\sim$10 %) of polarization, including an M8.5-type planetary-mass ($\sim$10 M_J) object (PMO). These polarizations are most likely due to dust scattering in an asymmetric circumstellar disk around the YBDs or PMO. The size of the unresolved circumstellar disks should be smaller than $\sim$ 150AU. The degrees of polarization of the 16 YBDs decrease with increasing wavelengths, while the polarization angles of the sixteen YBDs are consistent in the J, H, and K_s bands. These behaviors of polarizations are consistent with those of dust scattering.

High-Resolution Polarimetry of NGC 6334 V — NGC 6334 V is situated in the southernmost ridge of the NGC 6334 complex. We present high spatial resolution (0.″3) polarimetric images in the H and K bands and direct images in the L' and M' bands of the NGC 6334 V infrared nebulae. The images show complex structures including the multi-shells and various knots in the nebulae. The appearances and colors of the eastern and western nebulae differ considerably. Our polarization images also show differences between the illuminating sources of the nebulae: the eastern nebula is illuminated by a deeply embedded mid-infrared source, KDJ 4, and the western nebula by our newly detected near-infrared source, WN-A1. The degree of polarization of the nebulae is very large, up to 70% at K and 60% at H, which is consistent with a single scattering of near-infrared radiation from each source at the walls of the mass outflows.

High-Resolution Polarimetry of Circumstellar Disks — We conducted high-resolution (0.″06) near-infrared (1.6 μm) polarimetry of the circumstellar disk around AB Aurigae at a radial distance 0.″15-3.″85 (20-550 AU). We reavealed highly complicated and asymmetrical structures in the inner part (r $\lesssim$ 1″: 140 AU) of the disk, while we confirmed the outer spiral structure. Such an inner region of AB Aurigae has not been investigated previously due to high speckle noises. We found a double ring structure at $\sim$ 40 and $\sim$ 110 AU and a wide gap between the rings in the polarized intensity (PI) images. Furthermore, we found seven gaps (diameter of $\sim$15 to $\sim$70 AU) within the double rings as well as three prominent PI peaks at $\sim$30 AU. Since all these gaps are unlikely to be the regions of lower degrees of polarization, we concluded that the gaps are real structures in the inner disk. Comparing our PI image with previous model calculations, we argue that the ring structures in the inner disk can be produced by gravitational instability. Alternatively, unseen planets formed by gravitational instability in the disk can explain the ring gap structures in the inner disk regions.

Developing a New Instrument of HiCIAO — HiCIAO ('Hi'gh 'C'ontrast 'I'nstrument for Subaru Next Generation 'A'daptive 'O'pics) is a new instrument for the Subaru telescope. I describe the software for mechanical control and a polarimeter unit. HiCIAO has ten mechanical devices. All ten devices are permitted to be initialized, moved to an absolute or relative position, queried for status, and stopped. I also describe the software which synchronizes between the Lyot stop and the spider rotation in order to suppress diffraction caused by the spider. I also describe the HiCIAO polarimeter and their tests in detail, including removal of instrumental polarization from the tertially mirror (TM) and mirrors of the image rotator in the Subaru adaptive optics (AO188).

Our results are one of the important progresses to understand the planet formation around various masses of young stars. We will continue the systematic survey to obtain a wider sample of circumstellar disks around not only intermediate mass stars but also solar-mass stars and brown dwarfs, and explore how a circumstellar disk evolves to a planetary system.

博士論文の審査結果の要旨

星形成領域に多数存在する若い褐色矮星および惑星質量天体の形成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。近年の赤外線による観測技術の向上により、質量降着の特徴を示すスペクトル線やスペクトルエネルギー分布の赤外超過の観測結果から、褐色矮星にも星周円盤構造があることが間接的に発見されている。しかし褐色矮星の円盤の構造を空間的に分解した報告や星周円盤の構造探査に威力を発揮する近赤外線の偏光観測結果は極めて少ない。このような背景のもと、出願者は近赤外線の偏光装置の開発に携わり、主にソフトウェア開発を担当すると共に、この偏光装置を用いた観測的研究をおこなった。出願者の博士論文では、これらの偏光装置をもちいた観測成果と装置の性能評価についてまとめられた。主な内容は以下の通りである：

1) 代表的な大質量星形成領域 NGC6334V と OMC-1 について、南アフリカにある名古屋大学 1.4m 望遠鏡と近赤外線偏光装置 SIRPOL を用いた観測をおこない、それぞれ 16 個と 6 個の新しい赤外反射星雲を発見した。また、偏光ベクトルの解析から反射星雲やハービックハロー天体の励起源である若い星の同定に成功した。さらに、NGC6334V については偏光パターンと星の進化段階との関係に相関がある可能性を示唆すると共に、すばる望遠鏡と近赤外線コロナグラフカメラ CIAO をもちいた高空間分解能の観測により、これまで一つの双極分子流と考えられていた天体が、実際には二つの若く埋もれた B 型星をそれぞれ起源とする二つの分子流であることを発見した。

2) 若い褐色矮星に付随する星周円盤について初めて系統的探査として、名古屋大学 1.4m 望遠鏡と偏光装置 SIRPOL をもちいて、34 個の褐色矮星を観測した結果、16 天体から有意な偏光成分を検出した。偏光成分の有無は、質量降着の特徴を示す輝線強度や赤外超過と相関があるため、星周円盤の内側に起因する散乱光であると結論づけた。以上(1)と(2)の研究の一部は、既に出願者が第 1 著者の 3 編の査読付き学術論文として発表されている。

3) すばる望遠鏡のナスミス焦点に新しく設置された高コントラスト赤外線カメラ HiCIAO の偏光装置について、装置を駆動するためのソフトウェアの開発と性能評価をおこなった。特に後者については、望遠鏡と観測装置に起因する器械偏光について、光学素子単体の屈折率や偏光度・偏光角の測定結果をもちいたシミュレーションをおこない、ナスミス焦点で初めて器械偏光の補正方法を確立すると共に、偏光度 0.2%以下、偏光角 5 度以下という高い測定精度が出ていることを確認した。

4) 若い星の円盤構造の詳細観測をおこなうため、すばる望遠鏡と HiCIAO をもちいてぎょしゃ座 AB 星の観測をおこなった。この天体はすばる望遠鏡と CIAO により周囲に渦巻き構造を持つ円盤があることが既に判明している。HiCIAO により約 1 秒角（実スケール 140AU）より内側の構造を探ることに成功し、星周円盤が二重のリング構造を持つことや複数のギャップがあることを初めて明らかにした。

出願者の博士論文に示された以上の結果は、自ら開発に関与した近赤外線の偏光装置をもちいた観測によって分子流や赤外反射星雲を新たに発見し、それらの起源である分子雲に深く埋もれた若い星をより正確に同定し、若い星の星周円盤の存在とその詳細な構造をより明瞭に捉えたものであり、星・惑星系形成など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。また、観測、データ制約から解析、結果のとりまとめ・議論、論文作成の一連の過程において、出願者が主体的におこなっていることが認められた。これにより審査委員会は、全員一致で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。