JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
38: 319 ~ 324, 2005

SUBARU EXPLORATIONS OF EXO-SOLAR PLANETS AND DISKS

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(Received February 1, 2005; Accepted March 15, 2005)

ABSTRACT

To date, more than 150 exo-solar planets have been observed by various methods such as spectroscopic, photometric, astrometric, gravitational lensing, pulsar timing methods. However, all these are indirect methods; they do not directly image the planets. Only free-floating planets or their 'analog' have been directly detected so far. Thus the next milestone is the direct imaging of any kinds of planetary mass objects orbiting around normal (young) stars, which might have been associated with protoplanetary disks, the sites of planet formation. I will describe some SUBARU efforts to detect self-luminous young giant planets as companions as well as direct imaging of the protoplanetary disks of ~ 100 AU size. The results of near-infrared coronagraphic imaging with adaptive optics are briefly presented on AB Aur, HD 142527, T Tau, and DH Tau. Our results demonstrate the importance of high-resolution (~0.1 arcsec) direct imaging over indirect observations such as modeling based on spectral energy distributions. The SUBARU observations are a prelude to ALMA from the morphological point of view.

Key words : infrared — exoplanet — disks — brown dwarf — coronagraph — stars: pre-main-sequence — imaging

I. INTRODUCTION

For centuries human beings have wondered if there are planets elsewhere in the universe and if there is any life on those planets. As we found that most of our system planets are not suitable for life except for the Earth, it is natural that we seek for more distant planets, that is, extrasolar planets or exoplanets orbiting around other stars. In spite of decades of intensive efforts such as astrometric searches for reflex motion conducted by van de Kamp (1963, 1969, 1975), there was not a single credible claim for an exoplanet in middle of 1995.

However, after the first discovery report of 51 Peg B by Mayor and Queloz in 1995 and its subsequent confirmation by Marcy and Butler, about 150 giant exoplanets whose $Msin(i)$ is less than ~13 M_{jup} have been discovered so far (M_{jup} = 1 Jupiter mass ~ solar mass /1000, see Schneider's web page for a latest list). They are discovered around the F, G, K, and M-type main-sequence stars, and some are around giant stars which were supposed to be intermediate-mass stars during their main sequence stage (e.g., Sato et al. 2004). Most of these planets have been detected by the radial velocity measurements, one of the most successful "indirect" methods for exoplanet detection. This method spectroscopically measures the star's velocity along the line of sight to Earth as it moves about the center of mass of the star-planet system. It has long been used to search for binary companions. With the introduction of precise wavelength calibration techniques such as gas cells or fiber spectrometers (see also Walker et al. 1995; Campbell & Walker 1979), the velocity measurements have become precise enough (a few to one meter/second!) to detect giant planets around nearby stars.

Minimum-mass, semi-major axis, orbital period, and eccentricity derived from these measurements range respectively from 0.04 M_{jup} (to ~13 M_{jup}), from 0.026 to 5.9 AU, from 1 to 5,360 days, and from 0 to 0.9. The minimum mass is almost the mass of Uranus and only ~14 times of the Earth mass (McArther et al. 2004; Santos et al. 2004)

Statistical studies based on the radial velocity measurements of more than 1,000 stars suggest that about 5 percent of the sample stars are associated with the exoplanet candidates with $Msin(i) < 10\ M_{jup}$, while very few sources are detected with $20 < Msin(i)/M_{jup} < 80$ (e.g., Marcy et al. 1999). Although the current sample is still limited (by a time span) to companions relatively near the central star, this paucity is regarded as real and called as a "brown dwarf desert". About 2/3 are very close to the central star with semi-major axis less than 0.3 AU. Because of this proximity, their temperature is much higher ($T_{eff}>$ 1,000 K) than that of Jupiter (~120 K). Therefore, they are called hot Jupiters. These features combined with the existence of planets with large eccentricity suggest the diversity of planetary systems; new planetary systems are very different from our own.

Most importantly, the G0 dwarf star HD209458,

Proceedings of *the 6th East Asian Meeting of Astronomy*, held at Seoul National University, Korea, from October 18-22, 2004.

which is suggested to have a planetary companion from the radial velocity method (Henry et al. 2000), is confirmed to have exoplanets with an independent indirect method. This method, transit, is a photometric method of detecting only a few percent of stellar light dimming by a passage of a planet across the central star. Combining the radial velocity data with the transit data, inclination, mass (not mass lower-limit), radius, density of the exoplanets are determined. The derived mass and radius are 0.63 M_{jup} and 1.27 R_{jup}, respectively, which clearly demonstrates the planet to be a gas giant (Charbonneau et al. 2000). More recently, transit searches have made success of detecting candidate planets first, then confirmed by subsequent radial velocity measurements (Konacki et al. 2004; Bouchy et al. 2004). Their rotation periods are extremely short (1-2 days); therefore the orbits are very close to the central stars and they are called 'very hot Jupiters'.

However, all these observations are "indirect". They are not detecting the light from the planets, rather detecting light from the central star. Therefore, the next milestone in planet quests might be direct imaging of any planets orbiting around a star (see Section X).

II. DIVERSITY OF PLANETARY SYSTEMS

During the observations described in Section I, a number of strange animals have been revealed such as hot Jupiters, very hot Jupiters, eccentrics planets, and so on, which are alien to our Solar system. What is the origin of the diversity of planetary systems? A planetary system is the final product of planetary formation processes. Since planets are born in protoplanetary nebulae around pre-main-sequence stars during the process of star formation (a by-product of star formation; see e.g., Greaves 2005 for a recent disk review and references therein), it is extremely important to understand the diversity of the initial stage, i.e., protoplanetary disks, if any (e.g., Tamura 2004). Of course, since the planets so far detected around main sequence stars or giants are matured, it should be kept in mind any orbital evolutions or other factors should be also taken into account to fully understand the diversity.

III. CIAO – FIRST DEDICATED INFRARED CORONAGRAPH ON 8-10 M CLASS TELESCOPES

Observationally, the direct imaging of both exoplanets and protoplanetary disks is extremely difficult: it requires a high sensitivity, a high resolution, and a high dynamic range or contrast at the same time. Both high sensitivity and high resolution are now simultaneously realized with the recent 8-10 meter class telescopes with adaptive optics (AO; e.g., Takami et al. 2004). The AO corrects for atmospheric perturbations in real-time, by the means of wavefront sensors and deformable mirrors. In the current Subaru AO system, 36-elements sensors and 36-elements mirrors are used. With the Subaru adaptive optics and infrared camera we regularly achieve a resolution of 0.07-0.10 arcsec and a sensitivity of 22 mag (5 σ in 1 hour) around 1.5-2 microns (*H* and *K* bands). However, a high contrast, that is, a capability to observe faint objects near bright objects, is another thing.

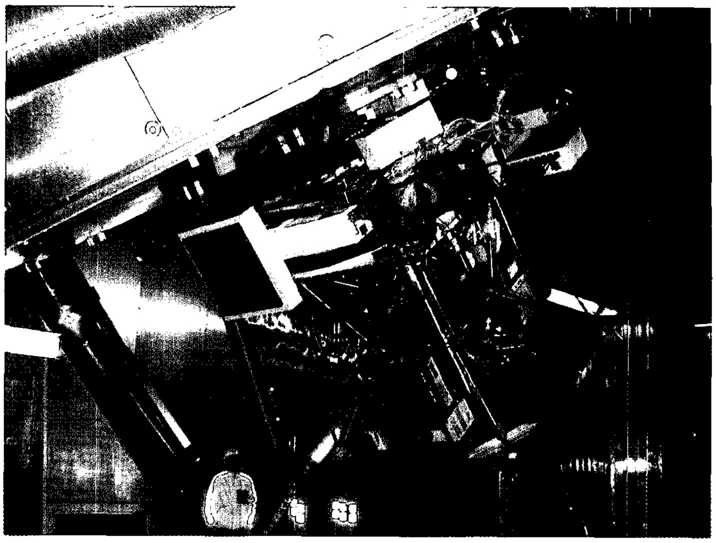

Fig. 1.— CIAO attached to the Cassegrain focus of the SUBARU telescope.

CIAO (Coronagraphic Imager with Adaptive Optics) is the first among those equipped with a full cold coronagraph mode (with various cold occulting masks and Lyot stop optics) on the world 8-10 meter class telescopes (Fig. 1). Compared to previous coronagraphs, it has unique features of near-infrared operation and small occulting masks (down to 0.2 arcsec in diameter). Therefore, CIAO is currently one of the best instruments for exoplanet and disk searches described above. See Tamura et al. (1998, 2000) and Murakawa et al. (2004) for the instrument details.

IV. CORONAGRAPHIC SURVEYS OF YOUNG STARS WITH CIAO/SUBARU

We are currently conducting an observing project "Subaru Disk and Planet Searches" (SDPS project). This is a systematic infrared coronagraphic survey of pre-main-sequence stars in and near the Taurus molecular cloud (by M. Hayashi & M. Tamura et al.; Instruments: Subaru + AO + CIAO). The aims of this survey are (1) detecting and resolving circumstellar disks and envelopes around bright central stars with a resolution of ~0.1 arcsec, and (2) detecting candidates for young planets and brown dwarfs around central bright stars as companions. The Taurus dark cloud is selected because it is one of the nearest (d= 140 pc; Elias 1978) active star forming regions with a number of YSOs; we plan to eventually observe more than 100 YSOs, while the nearest star forming regions such as TW Hya association does not offer a large enough sample of stars. YSO sample with an age span of $<10^5$ yr to $\sim 10^7$ yr can be found in and around Taurus. Similar surveys are also conducted for massive YSOs (Herbig Ae star project by M. Fukagawa et al.) and nearby stars (by T. Nakajima et al.). Here the SDPS and Herbig Ae projects are mainly described.

The surveys are conducted at H-band (1.6 micron) where the atmospheric correction with adaptive optics and the scattering efficiency are balanced; the AO correction is too poor at J (1.2 micron) and the scattering efficiency is less at K (2.2 micron). Typical resolution is 0.1 arcsec (FWHM), which corresponds to 14 AU at the distance of the Taurus cloud. The field of view is 22 arcsec × 22 arcsec (3,000 AU × 3,000 AU) with a pixel scale of 0.022 arcsec/pixel. Typical limiting magnitude for point sources is 21 mag at H in our survey, which can detect 1 Myr-3 M_{jup} young Jupiters. We have observed more than 50 objects in year 2002 and 2003. The reduction is still in progress, but some results on disks and companion sources are shown here. A preliminary result on HL Tau is described in Tamura et al. (2004).

V. AB AUR – SPIRAL DISK

AB Aur is a Herbig Ae star of A0-type with an age of 4 Myr at a distance of 144 pc (van den Ancker et al. 1997; deWarf et al. 2003). Its H-band coronagraphic image with CIAO is shown in Fig. 2 (Fukagawa et al. 2004). It shows a clear spiral structure with 3 or 4 arms, extending to r= 450 AU. The rough outer shape is an elliptical at PA=58 degrees. Previous HST/STIS optical image (Grady et al. 1999) seems affected by the scattering by the dust in the surrounding envelope, but this near-infrared light directly traces the surface structure of the AB Aur protoplanetary disk. If we assume the normal dust scattering which favors a stronger forward scattering, the south-east (lower-left) side of the disk is nearer to us. Millimeter observations by Mannings & Sargent (1997) have suggested that the disk is barely resolved and its north-east (upper-left) side is approaching to us. By combining the geometric and kinetic information, we can conclude that the spiral arms are trailing (like galaxies).

What is the cause of the spirals? Although such a spiral structure can be produced by gravitational perturbation by companions, our and previous images could not find any evidences for companion sources. Therefore, we believe gravitational instability of a relatively heavy disk is the cause of this structure; our rough estimate of the Toomre Q value (see e.g., Nelson et al. 1998) is within the weak instability regime ($Q \sim 2$ based on the radio-estimated mass). This relatively massive disk has been maintained by some infall of matter from the surrounding large envelope witnessed by the optical image. High resolution ($\sim$0.1 arcsec) millimeter and submillimeter observations are critical to reveal the true kinematics of the spiral arms.

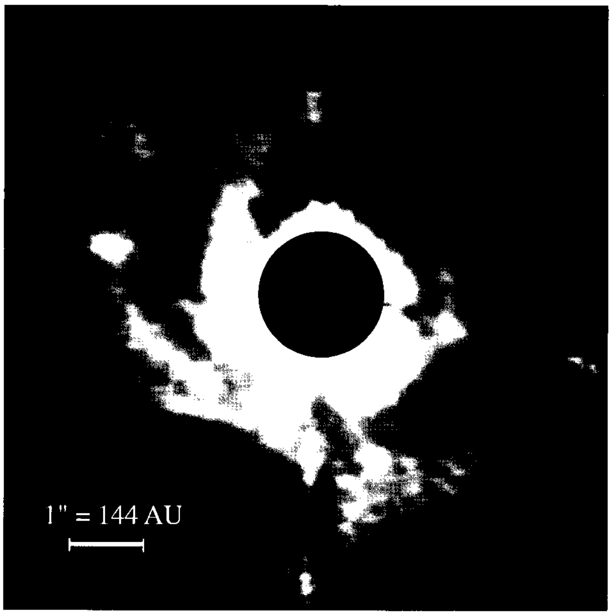

Fig. 2.— H-band image of the circumstellar disk around AB Aur after a reference PSF was subtracted. The surface brightness is multiplied by the distance squared from the center for display so that the fainter outskirts can be viewed with a high contrast. Boxcar smoothing is applied with 5x5 pixels. The inner area of 1.7 arcsec diameter (r < 120 AU; filled circle) is photometrically unusable and is masked. The field of view is 8 arcsec × 8 arcsec. North is up, and east is to the left.

VI. HD 142527 – BANANA DISK

HD 142527 is a Herbig Ae star of F-type with an age of 1 Myr at a distance of 140 pc (Nordstrom et al. 2004; Waelkens et al. 1996). Its H-band coronagraphic image with CIAO has revealed a very complex structure (Fukagawa et al. 2005, in prep.): the central star is surrounded by two split crescents or "bananas" which have slightly different radius and centers, and one arm is extending to the north from the western banana. A clear gap is seen between the central star and bananas. A similar structure is predicted only from the theory (Adams et al. 1989). If this is the case, the central star should have a companion, which has never been observed previously and in this observation.

VII. SIGNIFICANCE OF DIRECT IMAGING

What has been demonstrated by the above two observations is the need for high-resolution direct imaging. It has been conventional that SED (spectral energy distribution) is used to infer the morphology of the circumstellar structures around Herbig Ae/Be stars (and T Tauri stars). They are typically a combination of disks and envelopes whose structures are relatively simple; flat or spherical. More recent models employ somewhat detailed morphologies such as flared and truncated disks. However, the above two stars are categorized as class I Herbig Ae stars with more or less similar SEDs. Therefore, the SUBARU 0.1 arcsec observations have demonstrated that direct imaging is indispensable for revealing the true disk morphology.

Further examples of the SUBARU/CIAO images can be found in Fukagawa et al. (2003) for a disk around an Ae star with a companion, HD 151093A, and in Itoh et al. (2002) for a cicumbinary disk around GG Tau.

There are, however, limitations in our near-infrared imaging approach. It just traces the near-surface morphology of the disks, thus does not always correspond to the internal disk structures. It is also difficult to infer the mass of the disk and its kinematics. These will be explored with future sub-arcsecond submillimeter and millimeter imaging observations. Our SUBARU observations are a prelude to ALMA and SMA from the morphological point of view.

VIII. T TAU – ENIGMATIC MULTIPLE SYSTEM

T Tau has long been identified as one of the brightest low-mass pre-main-sequence objects and, as such, has been considered as the prototype for the T Tauri class of objects. However there are several features that make this star to be alien to a prototype T Tauri star as follows: (1) the presence of infrared companion from 0.7 arcsec from the optical star (Dyck, Simon, & Zuckerman 1982). T Tau S dominates the system flux at wavelengths longer than 2 micron, (2) T Tau S itself is a binary of only 0.05 arcsec separation (Koresko 2000), (3) the whole system shows a large photometric variability over decades (Kobayashi et al. 1994). Our CIAO images resolve a complex circumstellar structure around multiple system T Tau (Mayama et al. 2005, in prep.). As the structure within 300 AU is significantly different from that of over 300 AU in shape, this is interpreted as an asymmetric warped circumbinary disk or inner part of the envelope which encompasses whole multiple system T Tau.

Our coronagraphic images suggest that the two extended reflection nebulae are walls of the cavity caused by a blue-shifted outflow from T Tau. We also successfully resolved T Tau N and S as well as T Tau Sa and Sb. The curvature and orientation of path of T Tau Sb probably indicate that it has been, and is still, bound to T Tau Sa as has been suggested by Furlan et al. (2003). The flux of T Tau S at the time of the observations obviously decreased since 2001. While the flux of T Tau Sa was larger than that of Sb in November 2000, the flux of T Tau Sb is larger than that of Sa at the time of our observation. The flux decrease of the whole T Tau S system from 2000 to 2002 is mainly caused by T Tau Sa.

IX. DH TAU – YOUNG BROWN DWARF COMPANION

Companion searches are greatly merited if the targets are younger; the younger companion is brighter and the contrast between the primary and the companion becomes lower (e.g., Burrows et al. 2001). This is one of the reasons why we explore YSOs in nearby star forming regions.

DH Tau is a classical T Tauri star with an age of 0.1-4 Myr and a mass of 0.25-0.5 solar mass. CIAO coronagraphic images have revealed a companion of 15 mag at H at 2.3 arcsec (330 AU) from the central star.

This star is originally selected because it has a relatively large infrared polarization (Tamura & Sato 1989), suggestive of the circumstellar structures. However, interestingly, no significant circumstellar disks or envelopes are detected except for the companion.

The companion shows the same proper motion of the Taurus cloud members, distinct from the background stars. Its near-infrared spectra show deep absorption band due to water and other metal features, all indicating low effective temperatures, but not as low as those of planetary mass objects ($T_{eff} \sim$ 2,700 K). With recent theoretical models, the companion is concluded as a companion young brown dwarf of about 40 M_{jup} (Itoh et al. 2005). Therefore, we are near the detection of self-luminous near-planetary mass objects as companions.

X. FREE-FLOATING PLANETS

During deep near-infrared surveys of nearby star forming regions, several teams including ours have noticed the existence of very low-luminosity objects probably associated with the region (Tamura et al. 1998; Oasa et al. 1999; Lucas and Roche 2000; Zapatero-Osorio et al. 2000; Kaifu et al. 2000). The faintest of these objects are now regarded as candidates for isolated planetary-mass objects, therefore called as free-floating planets or sub-brown dwarfs. Recent deeper surveys further suggest the presence of numerous candidate free-floating planets (S106, see Fig. 3: Oasa et al. 2005; Orion: Lucas et al. 2005). They are distinct from the planetary mass objects orbiting around stars or young stars. The low-temperature and therefore low-mass natures of some of those candidates have been confirmed by recent sensitive spectroscopy and MIR-imaging at least down to $\sim$14 M_{jup} (Luhman et al. 2004, 2005).

Although they are not directly connected to the companion planets, their formation, evolution, and circumstellar structures are crucial for understanding the extremely low-mass objects (e.g., Mohanty et al. 2004). If we consider the companion planets are formed in proto-

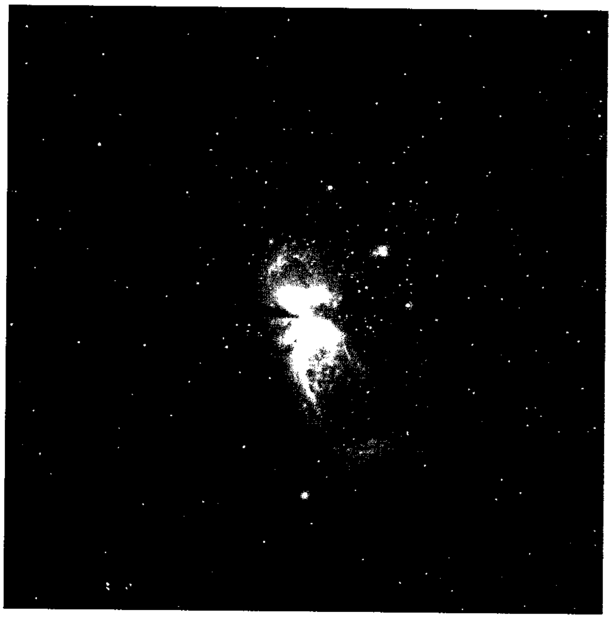

Fig. 3.— Near-infrared image of S106 star forming region obtained with SUBARU/CISCO. The field of view is $\sim 5' \times 5'$. North is up and east is to the left. Original image is in *JHKs*-composite color.

planetary disks, any planetary mass companion around brown dwarfs (such as 2M1207B) is most unlikely to be "planets" because the disk around brown dwarfs is too light to produce giant planets. It can rather be considered to be a 'binary' composed of a brown dwarf and a planetary-mass object.

Large-scale deep surveys for young brown dwarfs and even free-floating planets have also been made with other Japanese facility, IRSF 1.4 meter telescope and *JHKs*-simultaneous infrared camera SIRIUS. Monitoring observations searching for YSO variabilities are also conducted for several fields. Nearby star forming regions including the Chamaeleon, ρ Ophiuchi, R Coronae Australis, Orion, Monocerotis molecular clouds have been observed (Naoi et al. 2005;in prep., Kusakabe et al. 2005;in prep., Ishihara et al. 2005; in prep.)

XI. INDIRECT SEARCHES ON SUBARU

There are several indirect approaches for planet detections on-going on the SUBARU telescope.

T. Yamada (NAOJ) et al. have conducted transit searches with the wide-field CCD at the prime-focus (Suprime-Cam), monitoring more than 10^4 stars during several nights. The transit searches usually use small telescopes for wide field-of-views. However, the large field ($34' \times 27'$) of the Suprime-Cam and the large collecting area of SUBARU enable faint transit searches. They have already detected a number of "a few percent" variable stars with a period of 1-5 hours.

Y. Suto (University of Tokyo) et al. have conducted a high dispersion (R$\sim$50,000) spectroscopy with HDS of the transiting planet HD 209458. They searched for the planetary atmosphere from the ground-based observations, which were inferred from previous HST observations (Charbonneau et al. 2002; Vidal-Madjar et al. 2003). Several important upper limits are set for a number of atoms such as Hα, Li, and Fe (Winn et al. 2004; Narita et al. 2005, in prep.). They also try to detect 0.01 percent reflected light with a velocity shift of $\sim$50 km/s.

SUBARU, along with Keck and Magellan, is a member of the N2K (next 2,000) Consortium. This Doppler survey targets the next 2,000 stars in 3 years. The projects focus on detection of hot Jupiters and plans to observe 100 stars in every semester at each telescope. The precision on SUBARU is $\sim$3 m/s. The Japanese PIs are S. Ida (TITECH) and B. Sato (NAOJ).

XII. CONCLUSION

We have several kinds of programs on the SUBARU telescope for the explorations of the exo-solar planets, brown dwarfs, and protoplanetary disks through direct imaging. We are directly resolving disks around YSOs and finding the "diversity of disks". We are also detecting new near-planet-mass companions and many candidates around YSOs. Indirect and other kinds of direct searches for more evolved planets are also ongoing.

A prioritized study of exoplanets, "Development of Extrasolar Planetary Sciences", has just started in Japan, based on a MEXT fund. Organized and collaborative observations could be important not only in Japan but also among the East Asia Astronomy community.

ACKNOWLEDGEMENTS

The author is grateful to the collaborators on these projects; in particular, M. Hayashi, H. Suto, M. Fukagawa, Y. Itoh, S. Mayama, M. Ishii, T. Kudo, K. Murakawa, S. Hayashi, Y. Oasa, Y. Nakajima, P. Lucas, J. Hough, T. Yamashita, J. Morino, S. Oya, T. Naoi, L. Abe, T. S. Pyo, J. Nishikawa, T. Nishikawa, T. Usuda, M. Iye, H. Ando, S. Miyama, & N. Kaifu.

We also appreciate the support from the Subaru Telescope staff, especially from S. Harasawa for making our observations successful. We are also grateful to T. Nakamoto, M. Momose, T. Yamada, Y. Suto, B. Sato, N. Narita, S. Ida, and attendance to the Extrasolar Planet Seminar for valuable discussions and suggestions.

This research is supported in part Grant-in-Aids on Priority Area Nos. 16077101 and 160777204 of the MEXT.

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