Review

SEEDS — Strategic explorations of exoplanets and disks with the Subaru Telescope —

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(Communicated by Yoshihide KOZAI, M.J.A.)

Abstract: The first convincing detection of planets orbiting stars other than the Sun, or exoplanets, was made in 1995. In only 20 years, the number of the exoplanets including promising candidates has already accumulated to more than 5000. Most of the exoplanets discovered so far are detected by indirect methods because the direct imaging of exoplanets needs to overcome the extreme contrast between the bright central star and the faint planets. Using the large Subaru 8.2-m Telescope, a new high-contrast imager, HiCIAO, and second-generation adaptive optics (AO188), the most ambitious high-contrast direct imaging survey to date for giant planets and planet-forming disks has been conducted, the SEEDS project. In this review, we describe the aims and results of the SEEDS project for exoplanet/disk science. The completeness and uniformity of this systematic survey mean that the resulting data set will dominate this field of research for many years.

Keywords: exoplanet, circumstellar disk, direct imaging, coronagraph, infrared

1. Introduction

While planets are relatively tiny objects in a vast universe, they are the most promising sites for bearing life, as evidenced by our Earth. Planets are formed as by-products of star formation processes, resulting in the formation of a planetary system around a central star or central multiple stars.

Our solar system consists of one single star, the Sun, and eight planets. Mercury, Venus, Earth, and Mars are the closest to the Sun (approximately 0.4 to 1.5 AU, where 1 AU is the mean distance between the Sun and Earth) and the lowest-mass planets (approximately 0.06 to 1.0 Earth masses). They are mainly composed of rocks and are called rocky planets or Earth-like planets. Jupiter and Saturn are situated in the middle of the solar system (approximately 5.2 and 9.6 AU) and are the most massive planets (approximately 320 and 95 Earth masses). They are mainly composed of gas and are thus called gas giant planets, or Jovian planets. Uranus and Neptune are the furthest planets (approximately 19 and 30 AU) and are of median mass (approximately 15 and 17 Earth masses). They are mainly composed of ice and are thus called icy giant planets, or Neptunian planets. Pluto, recently flown-by and directly imaged in detail by the New Horizons mission, is not a planet, but rather has been categorized as a dwarf planet since 2006.

This configuration of our planets has been fairly well explained by the “standard” planet formation theory (see Section 2), which was based on the sole known example of our Solar System. We do not know whether this planetary configuration is universal or not.

The first 20 years of indirect planet hunting observations have detected about 1900 exoplanets and more than 3500 candidates (see http://exoplanet.eu/ and http://planetquest.jpl.nasa.gov/kepler). This success has largely been due to the precise radial velocity (RV) method and accurate transit photometry, especially by the Kepler mission, which discovered 4700 exoplanets including candidates. Figure 1 summarizes the distribution of exoplanets discovered by various techniques as of November
2015, except for the Kepler planets whose masses are not yet determined.

The RV method measures very small and periodic Doppler shifts of the absorption lines of the host star due to the planetary revolution with precise radial velocity measurements. Its velocity amplitude $K$ is described as:

$$K \approx \frac{1}{2} \sqrt{\frac{M_{\text{planet}} \sin i}{a^3 M_{\text{star}}}} \sqrt{\frac{M_{\text{Jupiter}}}{M_{\text{Sun}}}},$$

where $M_{\text{planet}}$ is the planet mass, $i$ is the orbital plane inclination, $M_{\text{star}}$ is the stellar mass, $M_{\text{Jupiter}}$ is the Jupiter mass, $a$ is the semi-major axis, and $M_{\text{Sun}}$ is the mass of the Sun. The RV method tends to detect massive, close-in planets. Note that the derived mass depends on the orbital inclination; if seen exactly face-on, this method cannot detect the stellar wobble along the line of sight. The first successful and convincing observation around a normal star was the discovery of 51 Peg b with the RV method. This technique has detected approximately 600 planets so far.

The transit method, in contrast, measures small and periodic photometric changes due to the eclipse of the host star by orbiting planets. Its photometric amplitude is described as:

$$\Delta B/B \approx 0.01 \left(\frac{r_{\text{planet}}}{r_{\text{star}}} \frac{r_{\text{Jupiter}}}{r_{\text{Sun}}}\right)^2,$$

where $\Delta B/B$ is the relative brightness change, $r_{\text{planet}}$ is the planet radius, $r_{\text{star}}$ is the stellar radius, $r_{\text{Jupiter}}$ is the Jupiter radius, and $r_{\text{Sun}}$ is the Sun radius. A photometric accuracy of less than 1% is necessary to detect Jovian planets around Sun-like stars. Note that this method requires a planetary orbit nearly along the line of sight and its geometric probability is small; $P \approx r_{\text{star}}/a$, where $r_{\text{star}}$ is the stellar radius and $a$ is the semi-major axis. Consequently, like the RV method, large, close-in planets tend to be more easily detected. There are also significant probabilities of false-positives in this method; such photometric changes can be made by non-planet events. Therefore, additional observations are required to confirm transit planet candidates. The first exoplanet transit paper\(^3\)\(^3\) was published in 2000 and this technique has detected approximately 1210 confirmed planets so far.

Although many planets have been discovered by these two methods, these discoveries are inherently limited in several ways. (1) Since both RV and transit studies are confined to the inner regions of exoplanetary systems, we still know very little about...
the planetary constituents in the outer regions of systems. (2) Both RV and transit surveys of young stars are complicated due to the high level of intrinsic stellar activity and thus they have traditionally targeted old and quiet stars. (3) RV surveys are not suitable for planet searches around massive main-sequence stars due to the paucity of stellar absorption lines and the reduced amplitude of the reflex stellar motion.

In contrast to the RV and transit techniques, direct imaging can be applied to both young and old stars, and can allow measurements of colors, luminosities, and spectra, thereby providing temperature and composition information. As a result, direct imaging is currently the best, if not the most efficient, way to investigate outer Jupiter-mass planets around young stars, and, especially, the initial distribution of massive planets in the outer regions where they presumably form (see below). It should be noted, however, that the mass of a directly imaged planet or any companion is conventionally estimated from its luminosity using the evolutionary models of low-mass objects (e.g., Ref. 4), assuming that the planet/companion age is the same as the host star’s age. If multi-epoch imaging observations are conducted for accurate orbital motion astrometry, a kinematical mass determination is possible.

Although attractive, the direct imaging of exoplanets is an extremely challenging observation. It simultaneously requires (a) high resolution, (b) high sensitivity, and (c) high contrast or high dynamic range. For example, if one observes our solar system at a distance of 10 pc (or ~33 light years), (a) the separation between the Sun and Jupiter is 0.5” (arc-seconds), (b) the apparent brightness of Jupiter is ~26 magnitudes, and (c) the brightness contrast between the Sun and Jupiter is about 8 orders of magnitude. Although current astronomical observations can achieve such a high resolution and high sensitivity, such a large contrast is beyond the current observation capability. However, young low-mass objects including planets are relatively bright and the contrast between a young host star and planets are smaller than that for an aged system. Therefore, current direct imaging targets are self-luminous planets around relative young (<10⁸ years) host stars.

The best wavelengths for direct imaging depend on the target age and the observing instrument. Since current direct imaging observations use adaptive optics and coronagraphs (see Section 3) that are optimized at near-infrared wavelengths, most of direct imaging is conducted at YJHK-bands (~0.9–2.1 microns), and occasionally at L’M-bands (~3–5 microns).

There are several other successful detection methods, as shown in Fig. 1, including the microlensing and timing methods (e.g., Refs. 5, 6). However, their details are beyond the scope of this paper.

2. Motivation and previous observations

As introduced in Section 1, direct imaging can explore wide-orbit (>5 AU) planets that the current RV and transit methods cannot explore. The diversity of exoplanets in the inner (<0.1 AU) regions are well and dramatically illustrated by the “close-in planets” first discovered by these methods. It is also noteworthy that since early 2000s, 8-meter-class telescopes with adaptive optics (AO) and the Hubble Space Telescope (HST) have started not only detecting but also revealing the complexity, at least morphological, and diversity of protoplanetary disks around young stars where young planets are eventually or already formed. AO technique is to improve the performance of telescope and instrument optics systems by reducing the effect of wavefront distortions. It can correct the deformations of an incoming wavefront by measuring its deformations and deforming a mirror in order to compensate for the distortions. For example, the combination of a first-generation coronagraph (a technique to suppress the effect of the central bright star) and adaptive optics (CIAO+AO36) on the Subaru Telescope7) has revealed a clear spiral structure in the “protoplanetary” disk around AB Aur at a very large distance (r > 200 AU) from the central star, which inspired discussions of gravitational scenarios for planet formation in contrast to the standard core-accretion model. HST has detected a number of “debris” dust disks around main-sequence stars in scattered light which show various types of morphology, including warps, offsets, gaps, and asymmetries (e.g., Ref. 9); see also10) for the latest debris disk survey. Note that debris disks are considered “secondary” disks produced by collisions of small bodies such as asteroids and comets, which suggests the presence of larger bodies or planets.

The link between the morphological diversity of these disks and the diversity of many known exoplanets discovered by indirect searches is not yet well understood. Therefore, we will study massive planets in the outer regions around young stars for a better understanding of both exoplanets and disks. By directly imaging young planetary-mass objects
and circumstellar structures situated at relatively large distances from the central stars, we will address the current key issues for understanding planet formation. Furthermore, so far both planets and disks have been imaged relatively far away from their central stars \((r > 100\text{ AU})\), therefore in order to compare with our solar system, it is critical to study both planets and disks of the solar system scale \((r < 100\text{ AU})\).

The current leading theory for planetary formation is the core-accretion model, in which a heavy element core is built by the accretion of planetesimals. As the core grows, its ability to accrete gas from the surrounding disk increases. When the core is sufficiently massive, rapid gas accretion occurs onto the core and a gas giant is formed. However, the problem with this scenario is that the time taken for gas giant formation is close to the upper limit estimated for the gas depletion timescale of the disk. In fact, the discovery of (nearly) planetary-mass companions around very young \((\sim 9\text{–}10\text{ Myr})\) stars such as 2M1207 B, DH Tau B, and GQ Lup B described below intensifies this timescale problem if they are formed via the core-accretion scenario. Alternatively, these wide-orbit planets can be formed like binaries, \textit{i.e.}, via gravitational instability.

The first series of direct imaging of planets were reported in 2004–2005. 2M1207 B is a very low-mass companion to a young (2–12 Myr) brown dwarf and was discovered by VLT.\(^{11} \) Brown dwarfs are the “failed stars” whose masses are too small to burn hydrogen steadily; therefore in masses they are between normal stars and planets (\((\sim 80–14\text{ Jupiter masses})\). The central star is an optically faint brown dwarf detected by 2MASS survey and the companion was discovered using an infrared wavefront sensor. Since the mass ratio between the central star and the companion is only 3, \textit{i.e.}, 24\,M\textsubscript{Jupiter}/8\,M\textsubscript{Jupiter}, it is unlikely that the companion is formed in a disk around the central star. A typical disk–star mass ratio predicts the disk mass of 2M1207 A to be only \(\sim 0.2\,M\textsubscript{Jupiter}\). DH Tau B is a very low-mass companion to a T Tauri star and was discovered by the Subaru Telescope during a survey of young stars.\(^{12} \)

If we employ the stellar age, infrared luminosity, and the standard evolutionary model, the mass of the companion is estimated to be \(\sim 10\,M\textsubscript{Jupiter}\). However, its spectral model suggests an older age and a larger mass. GQ Lup is another very low-mass companion to a T Tauri star and was discovered by a combination of VLT, Subaru, and HST data.\(^{13} \) If we employ the same estimates as for DH Tau, the mass of the companion is estimated to be \(\sim 20\,M\textsubscript{Jupiter}\). Several similar objects were reported but they are all distant from the central star (\(>100\text{ AU}\)) except for 2M1207.

The second series of direct imaging of planets was reported in 2008–2009, about when the SEEDS survey began. These are planetary-mass companions around A stars with significant infrared excesses \(\text{e.g.},\) HR 8799;\(^{14,15} \) \(\beta\) Pic\(^{16} \), but there is still a significant gap in the parameter space of masses and radial distance from our solar system planets. HR 8799 is an A5V, 1.6\,M\textsubscript{Sun} mass, 30–160\,Myr age star at a distance of 19 pc. Four massive Jovian planets (HR 8799 b, c, d, e; not the order of semi-major axis but of discovery year) have been imaged, having masses of \(5–13\,M\textsubscript{Jupiter}\) at 15, 24, 38, and 68 AU. This is still the only directly imaged multiple planetary system. \(\beta\) Pic is an A5V, 1.8\,M\textsubscript{Sun} mass, 8–30\,Myr age star at a distance of 19 pc. Its planet is situated at \(\sim 12\text{ AU}\) and its mass is estimated to be about 9\,M\textsubscript{Jupiter}. Note that all these are around A stars and no planets were directly imaged around G stars.

More than 50 planets are currently listed as directly imaged planets. However, if we restrict the masses to less than 14\,M\textsubscript{Jupiter} (below the deuterium burning limit) and the semi-major axis to less than 100 AU around normal stars other than brown dwarfs, the number of the directly imaged planets is still less than 10.

3. SEEDS survey: Sample selection and observations

The SEEDS survey\(^{17} \) is organized into two separate classes, planets and disks, each further subdivided into categories, including nearby stars (NS), moving groups (MG), debris disks (DD), young stellar objects (YSOs) (containing protoplanetary and transitional disks), and open clusters (OC). The NS category is further separated into sub-categories that include high mass stars, M-dwarfs, white dwarfs, chromospherically active stars, stars with kinematic properties suggestive of youth, and stars with known radial velocity planets. Approximately 100 targets have been selected for each category. In order to obtain high AO performance, most of the targets have a declination of more than \(\sim 40\text{ degrees}\) and \(R < 15\). For some categories, we are able to select brighter stars. Three planet search categories cover the age ranges 1–10\,Myr, \(\sim 100\,\text{Myr}\), and 100–1000\,Myr.

The SEEDS survey is the most ambitious high-contrast direct imaging survey to date. This survey was carried out with a suite of high-contrast instru-
SEEDS is a Japanese-led but international project. It consists of some 120 members; 2/3 are domestic researchers and 1/3 are in the US and EU. The project is managed by the author at The University of Tokyo, NAOJ, and NINS. The completeness and uniformity of this systematic survey will provide important statistical results to be obtained, as well as enabling the study of individual objects of particular interest. The SEEDS data set will be the dominant data in this important field of research for many years.

4. Planet results

SEEDS has reported four candidate planets to date (see Fig. 2). The first one is GJ 758 b,\(^{22,23}\) a 10–30 M\(_{\text{Jupiter}}\) companion orbiting around a Sun-like star (spectral type G9, 1.0 M\(_{\text{Sun}}\)). The projected distance from the central star to the companion is 29 AU at a distance of 16 pc. A second companion candidate has been confirmed to be a background star from the common proper motion test. Depending on the stellar age, its mass is estimated to be \(\sim 10–30\ M_{\text{Jupiter}}\).

Kappa And b was discovered from the NS category\(^{24,25}\) and is a \(\sim 12.8 (+2.0/-1.0) M_{\text{Jupiter}}\) mass planet around a B9 star (2.5 M\(_{\text{Sun}}\)). Note that both the RV and transit methods are not suitable for planet detection around such massive/large stars (unless they are evolved giants having GK-type spectra for the RV method).

GJ 504 b was discovered from the NS category.\(^{26}\) It is a very faint planet orbiting a Sun-like star. The projected distance from the central star to the companion is 44 AU at a distance of 18 pc. The central star itself is bright, visible to the naked-eye (\(V \sim 5\) mag), but the planet is very dim, 17–20 mag at infrared wavelengths (JHKL\…). The age of the central star is estimated from gyrochronology to be 100–300 Myr. It is most likely that the planet mass is only \(3–4.5 M_{\text{Jupiter}}\), estimated from its luminosity and age. If so, it is one of the lightest-mass planets ever imaged.

From seven observations, GJ 504b has been confirmed to not be a background star, but in orbit around GJ 504 A. Subsequent JHKL\… observations have also revealed that the planet has a unique blue color similar to T dwarfs.\(^{27}\) This provides useful information on its atmosphere. It appears that GJ 504b has a less cloudy atmosphere, while other imaged planets have cloudy atmospheres even though all of them are considered to be less than 1000 K or so.

In direct imaging, planet masses are estimated from the luminosity and age. All the imaged planets are younger than 50 million years, which introduces uncertainties in the mass estimates because we do not know the planet origin and consequently the models...
can provide different mass estimates. Therefore, if we use the $\sim 14 \, M_{\text{Jupiter}}$ mass boundary between planets and brown dwarfs, distinguishing between planets and brown dwarfs may suffer from this uncertainty. For example, if we consider all the imaged planets to be formed in a low-energy (more accurately, entropy) state, they are all more than $14 \, M_{\text{Jupiter}}$. On the other hand, if the planet age is old enough, this uncertainty is mitigated. Since the age of GJ 504 is old enough ($100–500 \, \text{Myr}$), either model predicts a planetary mass rather than a brown dwarf mass. If we simply use the conventional hot-start model and the age estimate based on stellar rotation, the planet mass of GJ 504b is as small as $3 \, M_{\text{Jupiter}}$.

HD 100546 b was confirmed as a planet with a disk system around a very young star ($5–10 \, \text{Myr}$) as part of the SEEDS survey. The projected distance from the central star to the companion is $47 \, \text{AU}$ at a distance of $97 \, \text{pc}$. It is a $15 \, M_{\text{Jupiter}}$ or less mass planet around a Herbig Be star ($2.4 \, M_{\odot}$). This source is also associated with a spiral arm (see Section 6).

The standard planet formation model based on our Solar system is thought to be insufficient to explain the formation of giant outer planets around Sun-like stars and massive stars. It is likely that they cannot obtain enough mass in such outer regions. It is also unlikely that a new model of gravitational instability can explain the formation of outer planets.
because they require very massive disks. We note that we have detected many gaps and spiral-arm structures at the same radial distance in disks where outer planets are discovered. These structures could be formed by the presence of planets within the disks, showing that the formation of outer planets in these disks may be possible (at least at or near their birth). Therefore, we consider that it is time to revisit the planet formation theory to include the results of outer planets and disk structures from the SEEDS results.

5. Planet early statistical results and other companions

A statistical analysis has been conducted on a combined sample of direct imaging data, totaling nearly 250 stars, from a part of the SEEDS survey and the NIRI/NICI data from the Gemini North and South telescopes. A uniform, Bayesian analysis of the ages of our entire sample was conducted, using both membership in a kinematic moving group and activity/rotation age indicators, to obtain posterior probability distributions for all target ages. As part of this study, a new statistical method for computing the likelihood of a substellar distribution function was presented. The analysis found that the entire substellar sample can be modelled as a single power law distribution of

$$p(M; a) \propto M^{-0.7}a^{-0.8},$$

where $M$ is the companion mass, ranging from massive brown dwarfs to 5 $M_{\text{Jupiter}}$, and $a$ is the orbital semi-major axis. Furthermore, it was estimated that the giant planet frequency is about 2% for planets/brown dwarfs of 5–70 $M_{\text{Jupiter}}$ at 10–100 AU.

SEEDS has also reported the detection of three brown dwarfs in the Pleiades cluster as part of the OC category survey and several stellar or substellar companions around planetary systems, from the RV detection. The latter companions are most likely to be the cause of the misaligned orbit of the RV planet around HAT-P-7. Similar companion searches are still ongoing around highly eccentric RV planets and RV planets with long-period (>10 years) trends that suggest the presence of wide-orbit planets.44,45

6. Disk results

SEEDS has detected interesting fine-structures in disks around dozens of young stars, as shown in Fig. 3. These disks exhibit gaps, spiral arms, rings, and other structures at similar radial distances where the outer planets are imaged. These structures can be considered to be “signposts” of planets. Our results on disks support the need for a new planet formation model.

The most striking result from the disk results is their small-scale structure. The SEEDS disk survey has revealed for the first time the inner 1" disk region down to 0.1", or ~10 AU in a typical protoplanetary disk or 5 AU in the nearest case. At this small scale, fine structures of many disks are revealed in Herbig Ae stars (AB Aur, SAO 206462, HD 142527, HD 169142, MWC 480, MWC 758, SR21, WLY 2-48) and T Tauri stars (LkCa 15, PDS 70, USco J1604, UX Tau, S 91, RY Tau, GM Aur, SU Aur, GG Tau, TW Hya). Several debris disks have also been detected (HR 4796A, HIP 79977) and the companion statistics around debris disks (DD category) have been published, though are not discussed in this paper.

For AB Aur, an A0, 4 Myr Herbig Ae star at a distance of 140 pc, complicated and asymmetrical structures are seen in the inner part (r < 140 AU) of the disk by HiCIAO, while confirming the previously reported outer (r > 200 AU) spiral structure detected by CIAO. A double-ring structure at ~40 and ~100 AU and a ring-like gap between the two have been discovered. The observed structures, including a bumpy double ring, a ring-like gap, and a warped disk in the innermost regions, provide essential information for understanding the formation mechanism of wide-orbit (r > 20 AU) planets.

For LkCa 15, a weak-line T Tauri star at a distance of 140 pc, sharp elliptical contours have been observed, delimiting the nebulosity on the inside as well as the outside, consistent with the shape, size, ellipticity, and orientation of starlight reflected from the far-side disk wall, whereas the near-side wall is shielded from view by the disk's optically thick bulk. This discovery confirms the disk geometry proposed to explain the spectral energy distributions of such systems, comprising an optically thick disk with an inner truncation radius of 4–6 AU enclosing a largely evacuated gap. An offset of the nebulosity contours along the major axis is also seen, which reinforces the leading theory that dynamical clearing by at least one orbiting body is the cause of the gap.

For SAO 206462, an F4, 8 Myr age, Herbig A star at a distance of 140 pc, two small-scale spiral structures lying within 0.5" (70 AU) have been discovered. Models for the spiral structures using the spiral density wave theory were used to derive a disk aspect ratio of h ~ 0.1. This model can
potentially give estimates of the temperature and rotation profiles of the disk based on dynamical processes, independently from sub-mm observations. It also predicts the evolution of the spiral structures, which can be observed at timescales of 10–20 years, providing conclusive tests of the model. Assuming a planet exists within these structures, we can predict the locations and, possibly, the masses of the unseen planets.

For PDS 70, a weak-lined T Tauri star of K5 type, 0.82 M_Sun mass, <10 Myr age, a large and sharp gap is observed. We suggest that the gap could be formed by dynamical interactions with sub-stellar companions or multiple unseen giant planets in the gap. Using a generic disk model that can simultaneously account for the general features in Spitzer, SMA, and Subaru observations, the scattered light images are computed, which agree with the general trend seen in the Subaru data. Decoupling between the spatial distributions of the µm-sized dust and mm-sized dust inside the cavity is suggested by the model. For TW Hya, a K7, 3–10 Myr age, 0.55 M_Sun mass T Tauri star, the scattered light from the disk was detected from 11 to 81 AU and a gap may exist at 30 AU from the central star, in addition to the 80 AU gap discovered by HST.

Please refer also to Takami et al. for an alternative SEEDS disk interpretation and Brandt et al. for another SEEDS data reduction method.

7. Conclusion and future prospects

The 8.2-m Subaru Telescope has successfully completed its first Subaru Strategic Program, the SEEDS survey for exoplanets and disks. Via direct imaging techniques, it has detected a few exoplanets...
and several companions including brown dwarfs, and revealed the details of many protoplanetary disks and a few debris disks.

The era has finally arrived when we can directly study planet formation sites at a resolution of much less than 0.1" at both near-infrared and submillimeter wavelengths. In fact, very recently the ALMA Long Baseline Campaign has presented submillimeter images of the disk around HL Tau, an object transitioning from a protostar to a T Tauri star at a distance of 140 pc, and detected multiple gap and ring structures with a resolution of \( \sim 0.03" \) or 4 AU.\(^{57}\)

They trace the thermal emission from the disk dust, while the near-infrared images trace the light scattered by the dust grains near the disk. These multi-wavelength studies will greatly improve our understanding of the formation and evolution of planetary systems.

Several new exoplanet instruments are now working or under development. For direct imaging and spectroscopy, both GPI for the Gemini South telescope\(^{58}\) and SPHERE for VLT\(^{59}\) have just started operations and are conducting new large scale surveys, with early results being reported.\(^{60}\)

These are equipped with extreme adaptive optics with \( \sim 1\text{−}2 \) k actuators and integrated field spectrometers (IFS). The Subaru Telescope is being upgraded to include its own extreme adaptive optics with \( \sim 2 \) k actuator (SCExAO)\(^{61},62\) and IFS (CHARIS),\(^{63}\) which will be in its full performance and available in the coming years, respectively. An infrared high-

precision radial spectrometer (IRD) equipped with a laser frequency comb is also near commissioning for earth-like planets and super-earths around nearby red dwarfs.\(^{64},65\) Such a spectrometer must be a good prospect for the next-generation high-contrast imager at the TMT observatory, such as the SEIT imager,\(^{66}\) proposed to seek for biosignatures such as oxygen 1.27 \( \mu \)m absorption features via high-contrast direct imaging and spectroscopy.

Acknowledgments

The paper is based on the SEEDS collaboration. This work is partly supported by the MEXT, JSPS, Mitsubishi fund. The help from Subaru Telescope staff and instrument development team is greatly appreciated. We recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. We hope that this strategic SEEDS survey will provide “seeds” for future terrestrial planet imaging and life detection projects in Japan.

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Profile

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(Received Aug. 29, 2015; accepted Nov. 24, 2015)