SEEDS – Direct Imaging Survey for Exoplanets and Disks

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Abstract.

Exoplanets on wide orbits ($r \gtrsim 10$ AU) can be revealed by high-contrast direct imaging, which is efficient for their detailed detections and characterizations compared with indirect techniques. The SEEDS campaign, using the 8.2-m Subaru Telescope, is one of the most extensive campaigns to search for wide-orbit exoplanets via direct imaging. Since 2009 to date, the campaign has surveyed exoplanets around stellar targets selected from the solar neighborhood, moving groups, open clusters, and starforming regions. It also surveys exoplanets in planetary systems with debris disks. The survey is designed to perform observations of ∼500 stars, covering the age range of 1 Myr to a few Gyr. As a result of the observations performed so far, SEEDS has detected new sub-stellar companions, including planets with properties that are unique compared with the previously directly imaged exoplanets. High-contrast imaging by SEEDS has also provided better characterizations of exoplanet systems identified by indirect techniques.

1. The SEEDS project

The *Strategic Exploration of Exoplanets and Disks with Subaru* (SEEDS; PI: M. Tamura) is the first Subaru Strategic Program. Its aim is to conduct a direct imaging survey for giant planets and protoplanetary disks from a few to few tens of AU, around ∼500 nearby stars. The survey was awarded 120 Subaru nights in 5 years. The SEEDS team includes 115 members from 35 institutes. The main goals of the project are:

– Detection and census of exoplanets around solar-mass stars (part of the survey also includes lower- and higher-mass objects)

– Studying evolution of protoplanetary, transitional and debris disks

– Direct link between planets and disks – studying the disk morphology and origin of planets at the same radial distance

Through August 2014 about 30 publications on SEEDS data have been published, few more submitted, and several press releases issued. Section 2. presents several science highlights that have been reported by the SEEDS survey.

1.1 Instrumentation

The primary imaging instrument used in SEEDS is the *High Contrast Coronographic Imager for Adaptive Optics* (HiCIAO; Tamura et al. 2006). It works with the AO188 adaptive optics (Hayano et al. 2008, 2010), both with natural and laser guide stars. The main characteristics of HiCIAO are shown in Table .1. To check the SEEDS contrast performance, see Brandt et al. (2014).

Some follow-up observations in the L', and narrow-band (for example CH_4, H_2O ice) filters have also been carried out with the *Infra-Red Camera and Spectrograph* (IRCS; Kobayashi et al. 2000). In early 2014 the first test observations were made with the new *Subaru Coronagraphic Extreme AO* (SCExAO; Martinache & Guyon 2009), which will produce high Strehl ratios that enables better starlight suppression with coronagraphy and therefore higher contrast at smaller inner working angles.

1.2 Targets

The SEEDS project aims to target about 500 stars, over 400 of which have been observed by June 2014. They are divided into 5 categories, depending on their age, distance, characteristics and the exact goal of the observations. They are summarized in the Table .2.

The SEEDS categories were designed to sample ages that cover the epoch of planet formation and early evolution. The luminosity of sub-stellar objects is determined by mass

Table .1: Main characteristics of the HiCIAO

Focus	IR Nasmyth (w/ AO188)
Wavelength	0.85 - 2.50 microns
Observation modes	DI, PDI, SDI, ADI (w/ & w/o coronagraph)[a]
Resolution	0.03″(J), 0.04″(H), 0.055″(Ks)
Strehl ratio	0.2 (J), 0.4 (H), 0.7 (Ks) w/ AO188
Field of view	20″×20″(DI), 20″×10″(SDI), 5″×5″(SDI)
Pixel scale	0.0095 ″/pix
Occulting masks	0.2, 0.3, 0.4, 0.6 and 1.5 arcsec diam.
Filters	Y, J, H, Ks (DI, PDI), CH4, FeII, H2 (SDI)

[a] DI: Direct Imaging, PDI: Polarimetric Differential Imaging, SDI: Spectral Differential Imaging, ADI: Angular Differential Imaging

Table .2: Main characteristics of the SEEDS targets

Category	Dist. (pc)	Age (Myr)	Properties
Young Stellar Object (YSO)	<300	1∼10	Molecular clouds (Taurus, Upper Sco, ρ Oph, Lupus, R CrA) and binaries, HAeBe stars
Debris Disk (DD)	∼130	10∼600	Selected from Spitzer and AKARI data
Open Cluster (OC)	∼125	120	Pleiades and Ursa Major members
Moving Group (MG)	∼20-100	<100	βPic (20 Myr), AB Dor (100 Myr), Columba (30 Myr), Tuc-Hor (30 Myr), and TW Hydrae (20 Myr)
Nearby Stars (NS)[a]	<30	100∼ 1000	Chromospheric Age (CA), M-dwarf (Mdf), Kinematic Age (Kin), High-mass (High), White Dwarf (WD), Radial Velocity (RV)

[a]Divided to six sub-categories

and age, which makes age an important parameter to understand the SEEDS discoveries. Each category thus probes different mass regimes. The luminosity evolution models of Burrows et al. (1997) vs. SEEDS target category are presented on Fig. .1. One can see that the planetary-mass objects are predicted to be more luminous around YSO's than around nearest stars.

2. Examples of companion and disk detections

Below, we present some highlights of SEEDS-detected companions and circumstellar disks. It is worth noting that the SEEDS observations are not only used for discovery papers, but SEEDS papers have also included new theoretical modeling and statistical analysis.

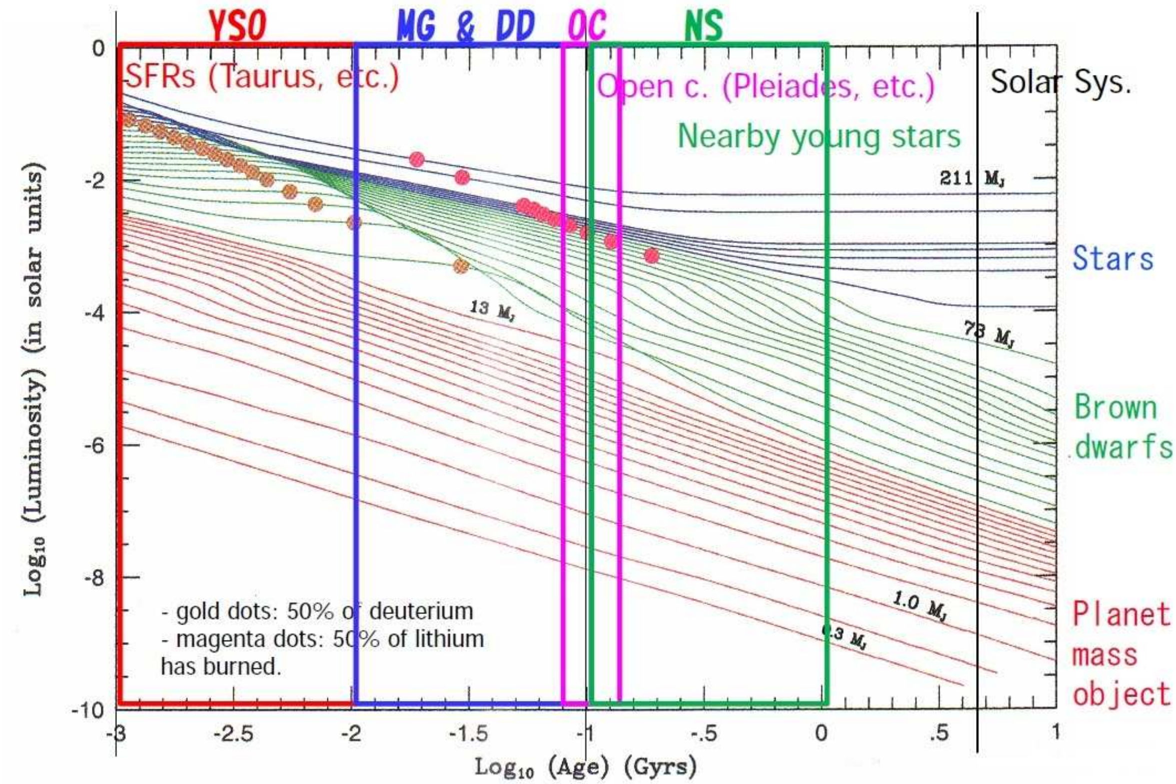

Figure .1: The (approximate) ages of targets of each SEEDS category plotted over luminosity evolution models of sub-stellar objects of Burrows et al. (1997). (Courtesy A. Burrows; http://www.astro.princeton.edu/∼burrows/)

GJ 758

The first published SEEDS result was the discovery of a companion to a sun-like star GJ 758 (Thalmann et al. 2009, Fig. .2). The discovery paper included common proper motion for GJ 758 B, but a following paper showed that the candidate companion "C" was actually a background star (Janson et al. 2011). It is likely a low-mass brown dwarf or a massive planet, and its separation from the star (29 AU) places it between the regions at which sub-stellar companions are expected to form by core accretion (∼5 AU) or direct gravitational collapse (typically >100 AU).

HAT-P-7

The HAT-P-7 hosts a transiting planet on a retrograde orbit (Narita et al. 2009; Winn et al. 2009), and another body responsible for a linear trend in radial velocities (Winn et al. 2009; Narita et al. 2012). High-contrast SEEDS observations revealed a common-proper-motion stellar companion (Narita et al. 2010, 2012, Fig. .2). The stellar companion can't be responsible for the RV trend, nor the orbit of planet "b", so a sequential Kozai mechanism has been proposed (Narita et al. 2012). First, the imaged stellar companion influences the

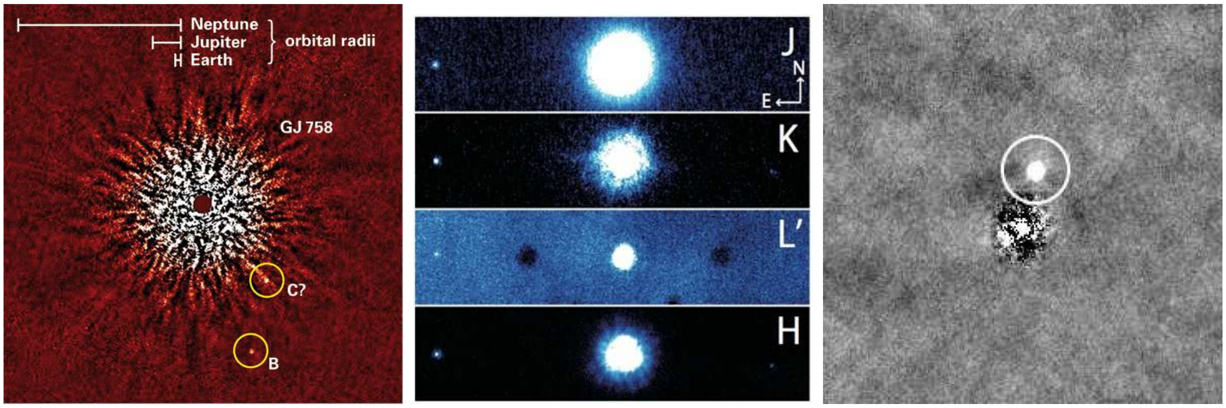

Figure .2: Left: The image of GJ 758 B (Thalmann et al. 2009, credit: NAOJ), the source "C" is a background star. Center: Four-band imaging of the stellar companion to HAT-P-7 (Narita et al. 2012, credit: NAOJ). Right: Brown dwarf companion to HII 1348, a member of the Pleiades cluster (Fig. 5m in: Yamamoto et al. 2013, by permission of Oxford University Press).

orbit of the body responsible for the RV trend, then this object influences the orbit of the transiting planet, making it retrograde.

HII 1348, HD 23514 and Pleiades

HII 1348 and HD 23514 are members of the Pleiades open cluster, which was surveyed by Yamamoto et al. (2013) as part of the SEEDS project. The HiCIAO imaging revealed $\sim$60 M_J brown dwarfs around both targets (Fig. .2), confirming previous detections of Geissler et al. (2012) and Rodriguez et al. (2012). The SEEDS observations placed an upper limit of 17.9% on the frequency of massive (6-12 M_J) planets around stars in the cluster.

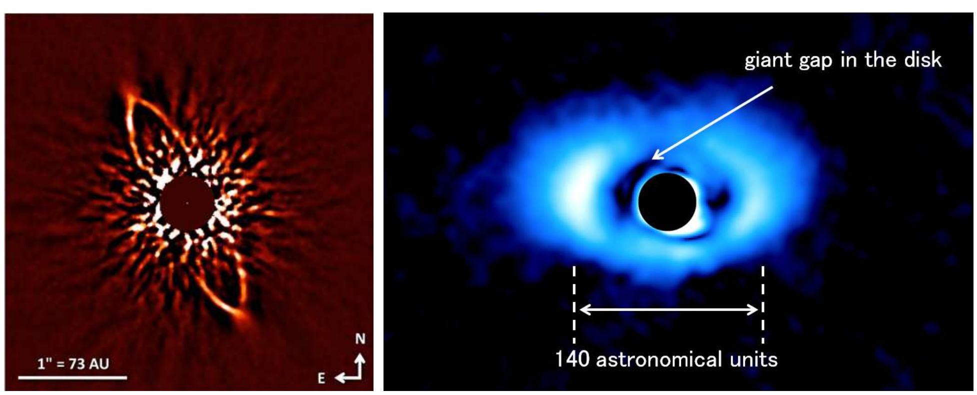

Figure .3: Left: Debris disk around HR 4796 A (Thalmann et al. 2011, credit: NAOJ). Right: Polarized light image of the disk around PDS 70 (Hashimoto et al. 2012, credit: NAOJ).

HR 4796 A

SEEDS observations of a young star HR 4796 A revealed an extended debris disk around it (Thalmann et al. 2011, Fig. .3), and confirmed a center slightly offset from the star's position. Such displacements are commonly explained by a presence of unseen planets within a disk's cavity. The observed disk morphology is well explained by a narrow ring formed in a collisional cascade, and made of grains of a wide range of sizes.

PDS 70

This weak-lined T Tauri star is surrounded by a pre-transitional protoplanetary disk. Polarimetric H-band imaging with HiCIAO revealed large cavity structures and a gap reaching ~70 AU (Hashimoto et al. 2012, Fig. .3). Evidences for a smaller, optically-thick disk have also been found. The whole outer structure is offset from the star's position, suggesting an unseen companion with a mass lower than 30-50 M_J.

U-Sco J1604

Mayama et al. (2012) presented scattered light images of a protoplanetary disk around J1604 in the U-Sco association. The disk stretches over 60 AU, is clearly resolved and several structures are seen (Fig. .4), such as an asymmetric dip east of the star.The morphology of this disk suggests that there is a planetary-mass object being formed.

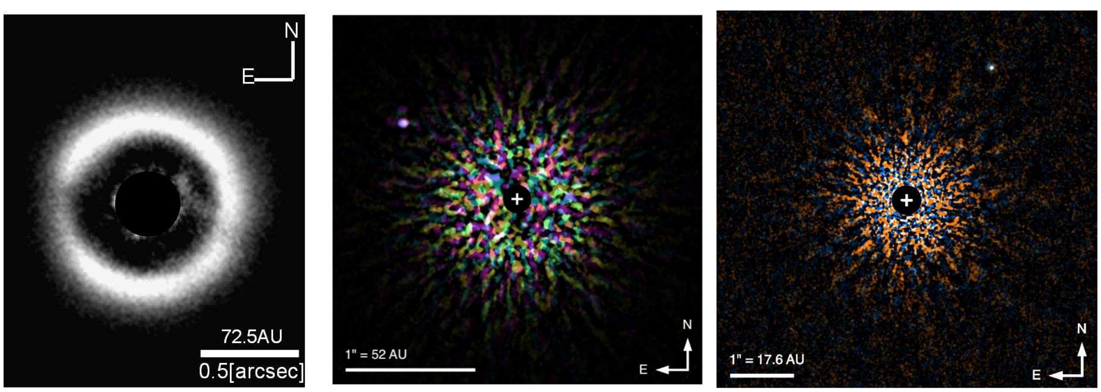

Figure .4: Left: Face-on disk around U-Sco J1604, whose morphology suggests the ongoing planet formation (Mayama et al. 2012, credit: NAOJ). Center: False-color signal-to-noise image of of κ And b (Carson et al. 2013, credit: NAOJ). Right: False-color image of GJ 504 b (Kuzuhara et al. 2013).

κ And

This B9 star is the most massive one to have a sub-stellar companion discovered with direct imaging (Carson et al. 2013, Fig. .4), at the projected distance of 55 AU. Initially estimated to have ~12.5 M_J at 30 Myr, the companion's properties were later revised by Hinkley et al. (2013) and Bonnefoy et al. (2014). The latest mass, and temperature estimations are 14^{+25}_{-2} M_J, and 1900^{+100}_{-200} K, respectively, highly dependent on the age of the system.

GJ 504

Kuzuhara et al. (2013) reported discovery of a cold planetary companion at 2.48″(∼43.5 AU) from the Sun-like star GJ 504 (Fig. .5), whose age of 160^{+350}_{-60} is older than all the hosts with other directly imaged planets previously identified. The luminosity measurements and age of GJ 504 b were compared with the commonly used models of Baraffe et al. (2003), and a mass of GJ 504 b was estimated to be $4^{+4.5}_{-1}$ M_J (one of the lowest among directly imaged exoplanets). Furthermore, the same models were used to derive the effective temperature ($T_{\rm eff}$) of 510^{+30}_{-20} K. The planet has a cooler $T_{\rm eff}$ and bluer $J-H$ color (~ -0.23) than previously imaged exoplanets, implying significant cloud depletions in its atmosphere. The further Spectral Differential Imaging (SDI) observations showed deep methane absorption features around 1.6 μm, allowing us to report that the planet's atmosphere has substantial amount of methane (Janson et al. 2013), and proving the planet's cold temperature.

HIP 79977

HiCIAO observations of HIP 79977, a young star in Upper Scorpius, revealed an edge-on debris disk (Thalmann et al. 2013, Fig. .5), confirming previous predictions based on the infrared excess. The disk is mainly made of dust produced by collisional cascades, pushed outward later by stellar radiation pressure. Two point-like sources are also visible in the images, one after subtraction of the model disk.

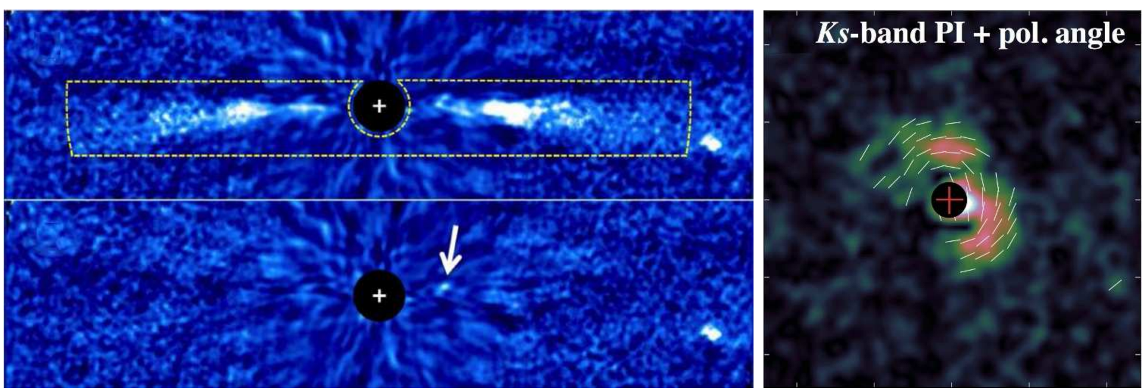

Figure .5: Left: Signal-to-noise map (top) of ADI-processed discovery image of the debris disk around HIP 79977 (Fig. 2c and 2d in: Thalmann et al. 2013). The source on the right is likely a background star. After subtraction of the disk model (bottom), another point-like source is revealed. Right: Polarized-light, Ks-band image of the low-mass transitional disk around Sz 90 (Fig. 4b in: Tsukagoshi et al. 2014).

Sz 91

Tsukagoshi et al. (2014) reported high-contrast, polarized light imaging of a transitional disk around a late-type, young star Sz 91 in Lupus (Fig. .5). These observations were combined with data taken in the sub-millimeter continuum and CO line at 870μm with SMA. The disk is possibly in an evolutionary stage immediately after the formation of proto-planets because of the large inner gap and mass (2.4×10^{-3} $M_\odot$) lower than the other transitional disks studied so far.

3. Summary

In this conference proceeding we presented selected results of the first strategic program of the Subaru telescope. Since 2009 the SEEDS project has been producing exciting results, including the discoveries of exoplanets and brown dwarfs of different characteristics, and protoplanetary and debris disk. The SEEDS projects contributes to our understanding of formation and evolution of disks and extrasolar planets.

Acknowledgements. KGH acknowledges support provided by the National Astronomical Observatory of Japan as Subaru Astronomical Research Fellow, and by the Polish National Science Center grant 2011/03/N/ST9/01819.

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Kevin Covey works on the poster judging during some CS18 downtime.