Subaru Telescope "Strategic Observations" Proposal

Subaru Strategic Exploration of Exoplanets and Disks with HiCIAO/AO188 (SEEDS)

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ABSTRACT

Since the first detection of exoplanets orbiting normal stars in 1995, many exciting discoveries have been made, but our understanding of planetary systems and their formation is far from complete. A census of companions to stars over a wide range of ages will provide important clues to the formation and evolution of stars, brown dwarfs, and planets. Armed with a much better performance than that of the CIAO-AO36 combination, we propose to conduct a Subaru-HiCIAO-AO188 imaging survey, searching for giant planets (1 M_J < mass <~13 M_J) and protoplanetary/debris disks mainly around ~500 nearby solar-type or more massive young stars. The ages of our exoplanet target stars span ~1-10 Myr for YSOs in nearest star forming regions, through ~100-500 Myr old stars in nearby open clusters, to ~1 Gyr old nearby stars. Direct imaging is indispensable for the detection of such "young" planets, especially planets in outer circumstellar regions (a few AU - 100 AU), complementary to radial velocity searches. The protoplanetary disk targets are the YSOs in nearby star forming regions, some being new targets with large IR intrinsic polarization, while the debris disk candidates include both well known and newly discovered ones from *Spitzer/AKARI* satellites. Among the planned imaging surveys of exoplanets and disks with next generation instrumentation, SEEDS will be at least 3 years earlier than others. The goals of our survey are to address the following key issues in exoplanet/disk science: (1) the detection and census of exoplanets in the outer circumstellar regions around solar-mass stars and massive stars, (2) the evolution of protoplanetary and debris disks including their morphological diversity, and (3) the link between exoplanets and circumstellar disks. The completeness and uniformity of this systematic survey will provide important statistical, or even useful null, results to be obtained as well as enabling the study of individual objects of particular interest. The SEEDS data set will be a dominant one in this important field of research for a period of many years.

1. Introduction and Scientific Question

The first 12 years of indirect observations have detected more than 240 exoplanets and yielded many important discoveries and scientific results. This success has largely been due to the accurate radial velocity (RV) method, which discovered more than 90% of the known exoplanets as well as their surprising dynamical diversity. However, these discoveries are inherently limited in several ways. (1) Since RV studies are confined to the inner regions of exoplanetary systems (<6 AU for a 15-yr survey), we still know very little about the planetary constituents in the outer regions. (2) RV surveys of "young" stars are complicated due to the high level of intrinsic stellar activity; they have thus traditionally targeted old and quiet stars. They are also not suitable for planet searches around massive stars due to the paucity of stellar absorption lines and reduced amplitude of the reflex stellar motion.

In contrast to the RV technique, direct imaging can be applied to both young and old stars, and can allow measurement of colors, luminosities and spectra, thereby providing temperatures and compositions. As a result, direct imaging is the best way to investigate Jupiter-mass planets around young stars, especially the "initial" distribution of massive planets in the outer regions where they presumably form. It is encouraging that recent RV results with the longest time spans hint at a major giant planet population in the outer regions after correcting the RV detection bias (Marcy 2007).

Furthermore, recent 8-m class telescopes with adaptive optics (AO) and HST have finally started not only detecting but also revealing the (at least morphological) complexity and diversity of protoplanetary disks around young stars where the above-mentioned young planets are eventually formed (see Fig. 1). CIAO-AO36 on the Subaru telescope has revealed a clear spiral structure in the protoplanetary disk around AB Aur (Fukagawa et al. 2004), which inspired anew the discussion of gravitational scenarios for planet formation in contrast to the standard core-accretion model. The same instrument combination has also discovered a completely new type of disk, a "banana split" morphology of radial and azimuthal structures, around HD142527 (Fukagawa et al. 2006), which might originate from an unknown companion. Recently, HST has detected a number of (~18 in total) debris disks in scattered light, which show various types of morphology, including warps, offsets, gaps, and asymmetries (e.g., Kalas et al. 2007).

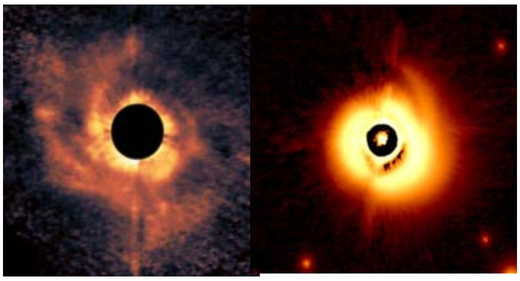

Fig. 1: Subaru coronagraphic NIR images of Herbig Ae stars, AB Aur and HD142527. The field-of-view is 8" (1120 AU) on a side for AB Aur and 12" (1680 AU). These are some representative results of the Subaru Disk and Planet Searches (SDPS) project, which was conducted in 18 nights of 2002-2004 led by Masa Hayashi.

The link between the morphological diversity of these disks and the diversity of known exoplanets discovered by the RV searches is not yet well understood. Therefore, we propose to study the massive planets in the outer regions around young stars for the purpose of both exoplanet and disk science. By directly imaging young planetary-mass objects and circumstellar structures situated at relatively large distances from the central stars, we would like to answer the following specific scientific questions, which are in fact the current key issues for our understanding of planet formation.

- When, where and how do planets form?

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 disks (Haisch et al. 2001). In fact, the discovery of (nearly) planetary-mass companions around very young (~1-10 Myr) stars such as 2M1207 B, DH Tau B, and GQ Lup B intensifies this timescale problem.

On the other hand, observations of a spiral structure in the circumstellar disk of AB Aur suggests the effect of a weak gravitational instability. In addition, Boss (1997) concluded that the timescale for gas giant formation in the disk instability process (several hundred years) is much shorter than that in the core-accretion process (several Myrs) (e.g., Pollack et al. 1996). Therefore, once the condition for disk instability is satisfied, gas giants would be formed very rapidly by the disk instability. Examining the conditions for gas giant formation in two models with respect to metallicity dependence, Matsuo et al. (2007) revisited this issue and concluded that although most of the planets detected so far were probably formed by core-accretion, the disk instability process is more likely for some.

In reality, there is probably a combination of mechanisms involved during planet formation. However, the time span of the current RV surveys is still insufficient to make a census of giant planets in the outer regions (5-100 AU). Therefore, determining when and where giant planets form by direct imaging is the central issue of our proposed survey. Even an unlikely null result (no detection) would put a stringent constraint on these models due to the uniform survey strategy.

- What are the initial exoplanet mass distribution and its evolution?

Discovery of even a single (but very certain) planet by direct imaging would be a major finding, but our goal is to obtain (at least a rough estimate of) the initial planetary mass distribution as a function of orbital radius. Besides the orbital evolution at later stages, this directly links to the diversity of known exoplanets such as close-in planets and eccentric orbit planets. Furthermore, once we know the initial distribution of exoplanets, we can directly compare it with the protoplanetary disk distribution which will be derived from our disk investigations.

- Is the brown dwarf desert real?

The RV searches (e.g., Marcy and Butler 2000) suggest a "brown dwarf desert" - a deficit in the frequency of brown dwarf companions to Sun-like hosts relative to the frequency of both less massive planetary companions and more massive stellar companions. However, recent direct imaging surveys of main sequence stars have produced somewhat inconsistent results; one supports the desert (McCarthy and Zuckerman 2004) but the others do not (Lowrance et al. 2005; Metchev 2005; Chauvin et al. 2006). The latter suggests that ~4% of young solar analogs have brown-dwarf companions, which is comparable to the exoplanet frequency. Since our surveys are deep enough to detect even giant planets, we can automatically answer this question for the young brown dwarf companion population orbiting from below 10 AU to beyond 100 AU.

- What is the disk-planet connection? What does detailed disk morphology tell about (unseen) planets or companions?

Coronagraphic imaging is a powerful tool to investigate structures in disks at high angular resolutions (~0".1). Since the scattered light from the disk is extremely faint compared with the parent star, such observations are extremely challenging. Even so, observations using Subaru-CIAO and HST have allowed us to probe their complex morphology such as warps, gaps, bananas, and asymmetries probably due to the interaction with yet unseen planets or brown dwarf companions. Therefore, our disk survey programs with a better spatial resolution (0.03") and a better inner working angle (~0.1") can provide not only crucial morphological data on disks but also an indirect approach to planet detection.

Furthermore, polarimetric imaging of such disks is even more powerful since it allows us to investigate grain composition, size, and their radial distribution. It permits This investigation of how an asteroid belt, like the Kuiper Belt, forms and evolves, as well as how common such a component is among extrasolar systems. Indeed, a non-uniform distribution of polarization has recently been observed in the Beta Pic disk using CIAO (Tamura et al. 2006).

In summary, when HiCIAO+AO188 become operational, Subaru will deploy by far the world's most powerful and sophisticated instrumentation for high resolution and high dynamic range imaging. We propose to exploit this extraordinary capability immediately, before other observatories achieve comparable facilities, with an ambitious strategic observing program intended to produce a major qualitative advance in our understanding of the nature, formation and evolution of massive planets, brown dwarfs and disks in the outer circumstellar regions of young solar-type stars and related objects of special interest. This is one of the most important, active and fundamental areas of current astronomical research, and the proposed SEEDS program is designed to also have the potential for breakthrough scientific discoveries as it explores large new areas of parameter space. Specifically, we propose to use 120 nights of Subaru time spread over a period of five years to survey ~500 total targets distributed over 5 carefully selected categories (3 types of exoplanet searches and 2 circumstellar disk investigations) and to carry out extensive follow-up observations of the most interesting systems identified in the survey. The completeness and uniformity of this systematic survey will provide important statistical, and even null, results to be obtained as well as enabling the study of individual objects of particular interest. The SEEDS data set will be a dominant one in this important field of research for a period of many years.

2. Sample Selection and Science Merits

We select three main kinds of targets for planet searches (YSOs, open cluster stars, and nearby main-sequence stars) and two for disk searches (protoplanetary and debris disks). About 100 targets are selected for each category (see the table below for details). In order to obtain high adaptive optics (AO) performance, all the targets have a declination of more than -40 deg., and R<15. For some categories we are able to select brighter stars with higher declinations for even better AO performance. All the targets have a distance within 200 pc, thereby allowing us to observe planets and disks at close proximity to each target. A summary of our sample is shown the table below. Their RA-DEC, magnitude, and central star mass distributions are also summarized in Fig. 2. In the following subsections, we describe the target selection for individual categories in detail.

Category	Planet searches			Disk searches		*Total*
	(a)	(b)	(c)	(d)	(e)	
	YSOs	Open Cl.	Nearby Stars	P.P. Disks	Debris Disks	
Number	120	116	100	105	80	521
Comments	Tau/Sco	UMa/Hyades/ Pleiades/α Per	<30 pc; Several types	Tau; HAeBe; polarized sources	SST/AKARI sample	

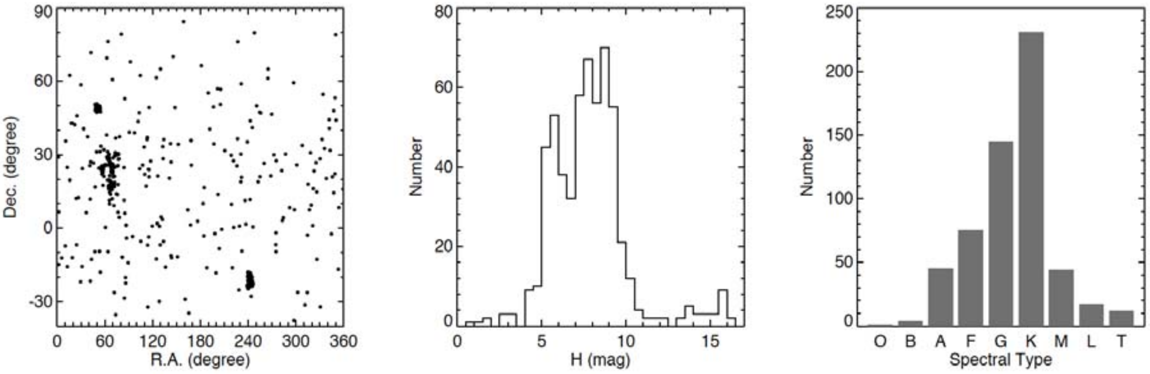

Fig. 2: RA-DEC, magnitude, and central star spectral-type distributions of our sample.

=== Targets for planet searches ===

HiCIAO and AO188 are both optimized for use at near-infrared (NIR) wavelengths. In particular, the 1-2 micron range has the maximum gain relative to the previous CIAO-AO36 combination. Therefore, our exoplanet sample should be young, warm planets rather than old, cold ones. In addition, standard evolutionary models show an advantage to detecting planets around young stars since planets are more luminous at a young age as they are still in a phase of accretion and initial cooling. It also ensures a more manageable contrast with the host star. Although very recent models based on a core-accretion scenario predict significantly fainter luminosities for young planets, they still show a short but sharp luminosity peak at some "young" age (Marley et al. 2007). Furthermore, observing stars in young clusters has the advantage of knowing the age, distance, metallicity and, therefore, of more precisely determining the companion mass. Thus, a significant fraction of our targets will be selected from such well-defined clusters.

According to the core-accretion models and recent RV surveys of M stars (e.g., Marcy 2007), the detection rate of giant planets around low-mass stars is significantly lower (<1%) than that around solar-type stars (~5%) or more massive stars (>5%). Therefore, our sample for HiCIAO+AO188 study is primarily comprised of solar-type or more massive stars.

Since observationally we do not know the duration of giant planet formation, our sample should span a large range of ages, but not beyond about 1 Gyr. These include YSOs (1-10 M yr), stars in open clusters (100-500 M yrs) and nearby main-sequence stars (~1 Gyr). Any planetary mass objects around stars older than a few Gyr would be too faint to be detected at near-infrared wavelengths.

(a) YSO (age~1-10 Myr) sample

Planets and brown dwarfs are expected to be more luminous when newly formed and to have advantageous contrast relative to the primary stars. Thus, observations toward the youngest stars would have the greatest chance of detecting low mass companions (at fixed distance, etc). Indeed, previous surveys toward pre-main sequence stars revealed the presence of such companions with masses down to several Jupiter masses. These include DH Tau B discovered using Subaru-CIAO (Itoh et al. 2005) and GQ Lup in which Subaru-CIAO archived data were also utilized (Neuhauser et al. 2005).

We thus propose to survey two nearby star-forming regions, Taurus-Auriga and Upper Scorpius A. Taurus-Auriga is one of the nearest (d~140 pc) T-associations, and also one of the best studied star-forming regions. Upper Scorpius A is one of the nearest (d~150 pc) OB associations. These two regions have different stellar mass ranges and densities, albeit similar distances. Thus, observing these regions will illuminate how the formation of extremely low-mass (sub-stellar) companions depends on the star formation environment.

Our target list covers all the A to K-type stars in Taurus (~60 targets) and the central region of the Upper Scorpius A (~60 targets) with R<15. The proposed observations will thus be an almost unbiased survey towards stars with stellar masses of 0.5-2 Mo. We will study how the frequency of extremely low-mass companions depends on the stellar masses and ages, disk signatures (e.g., IR-radio excess emission and H-alpha emission) and the presence/absence of the stellar companions.

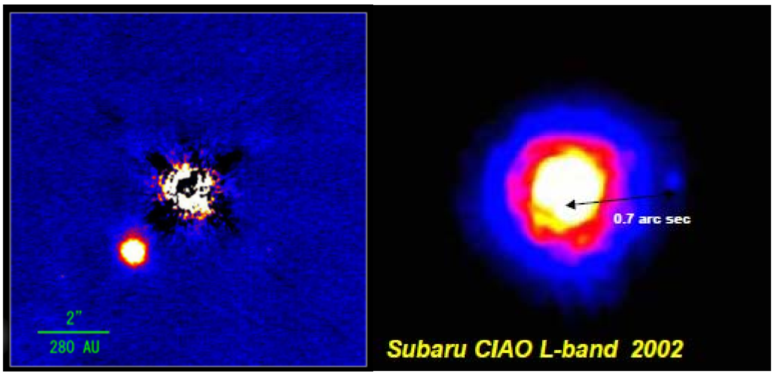

Fig. 3: Subaru-CIAO images of DH Tau and GQ Lup (Itoh et al. 2005; Neuhauser et al. 2005). These "boundary objects" between planets and brown dwarfs are orbiting around T Tauri stars of ages~1 Myr. This is also one of the most important results of the SDPS project.

(b) Open cluster sample (age~100-500 Myr)

In order to cover still young, but older than the YSOs above, stars we choose a sample from nearby open clusters. We have selected 116 targets to detect planets with masses below 10 M_J and semi-major axes less than 100 AU. The selection criteria are as follows: (1) Expected planet flux > 5-sigma point source detection limit. (2) Declination > -40 degrees, (3) V(host star) < 12. (4) The planet flux is larger than the stellar halo remaining after the suppression by the coronagraph. (5) No other bright star (< 10mag in JHKs) in the field of 6”×6”. (6) The host star is a single star.

The first selection criterion gives the upper limits for the ages and the distances of open clusters. We derived the upper limits, using the planet flux calculated by Baraffe et al. (2003) and expected HiCIAO direct imaging limiting magnitudes mentioned in the section 5. The open clusters satisfying the first and second selection criteria are only four: Ursa Major, Hyades, Pleiades, and Alpha Per.

The third and the fourth criteria set the lower and upper limits for the effective temperature of the host star, respectively. Based on the first, the third, and the fourth selection criteria, the conditions of the ages and the distances of the host stars for each stellar spectral type are derived.

The major data sources for the catalog of open cluster stars are Soderblom et al. (1993) for Ursa Major, Schwan et al. (1991) for Hyades, Belikov et al. (1998) for Pleiades, and Patience et al. (2002) for Alpha Per.

(c) Nearby star sample (age~1Gyr) and related stars

The nearby stars sample consists of relatively-young nearby stars with distances less than 30 pc and with ages of ~100 Myr to 1 Gyr, which covers the oldest segment of stellar ages (~1 Myr to 1 Gyr) in our overall sample. We also included a variety of sub-samples of special interest in the nearby stars category; these are, (i) solar-type stars, (ii) less massive stars, (iii) brown dwarfs, (iv) particularly interesting stars with known planets, and (v) likely targets for future space mission study. The nearby star sample is ~170 in total. We plan to observe ~100 stars from the "master list". All the stars are located within 30 pc from the Sun. We selected the stars with H magnitudes fainter than 5 in order to detect planetary mass companions within the range of achievable contrast by HiCIAO (ΔH ~ 13.5 mag). The declination of most targets in this category is greater than -20 degree. More details of each sub-sample are explained below.

We include 90 young solar-type stars: (i). They are F-K type stars with an age younger than 1 Gyr based on the chromospheric activity index and/or kinematic indicators. For category (ii) we select 19 young M type stars. The contrast between the primary star and companions are expected to be particularly low for M-stars. As indices of youth, we use coronal activity (X-ray luminosity), kinematic age (< 700 Myr), and association with a young moving group (~600 Myr). For category (iii) we select 25 young L and T dwarfs (L type: 15, T type: 10). These objects are expected to be younger than 1 Gyr based on various indicators (Hα and X-ray luminosity, existence of Li absorption, low surface gravity). Unlike exoplanets around bright primary stars, we can directly investigate the companions and circumstellar environment of these brown dwarfs with virtually no scattered light contamination. For category (iv) we select 24 nearby stars with known planetary companions detected using the RV method. Some of them are expected to be accompanied by outer giant planet or brown dwarfs from their long-term (> 10 yr) RV trends. We will aim to directly image these companions and obtain their physical properties. Finally we select 13 nearby stars from the target list for the NASA-TPF (Terrestrial Planet Finder) mission. They are basically the nearest (4-13 pc) solar-type (F-K) stars. The scientific motivation to add these targets are (1) to extend the main sample of young systems, as "TPF" targets have ages somewhat larger than 1 Gyr, and (2) to obtain the greatest sensitivity to circumstellar disks, envelopes, companions etc. that can be obtained by ground-base telescopes. The information should also be useful for future searches from space (TPF, SPICA).

=== Targets for disk searches ===

The discovery of hundreds of exoplanets, and also dozens of brown dwarf companions, raises a number of questions. How are these, and the Solar System, formed? Is the Solar System a common, or rather rare, type of planetary system? Are free-floating planetary-mass objects formed in the same way, and ripped off by tidal interaction with a stellar companion or other stars? The best tests for formation theories require the observation of circumstellar disks in active planet (and brown dwarf) formation. Observations of our YSO samples will allow for tackling this issue, together with the results of planet searches described above. On the other hand, the presence of debris dust around main sequence stars provides indirect evidence that planetesimals are present in these systems, i.e. that the first steps of planetary formation have taken place around stars other than the Sun. We select these two kinds of targets with the criteria described below.

(d) Protoplanetary disk sample

Following major successes with the SPDS survey (see Section 1), we propose an extensive survey of protoplanetary disks with a significantly higher sensitivity. We select all the classical T Tauri stars in the Taurus-Auriga star-forming region, with spectral types B-M0 and R<15 (40 targets). The observations will allow us to investigate how the outer disk structure is related to mass, evolutionary stage and also disk signatures (e.g., excess emission at IR-radio wavelengths, optical polarization towards the star). The selected star-forming region (Taurus) is one of the nearest (140 pc) and best studied regions, and we expect the best performance for AO correction due to its high elevation.

We also propose to observe (1) Taurus YSOs (T Tauri stars) in which disks have previous been detected using HST and CIAO (~15 targets), (2) YSOs for which our NIR polarimetric surveys have detected intrinsic polarization (Tamura et al. 2006; PASJ SIRPOL special feature issue 2007, V59, No3) (~20 targets), and (3) nearby Herbig Ae/Be (HAeBe) stars (~30 targets). The targets (1) and (2) will allow us to observe the known disks with high S/N, thereby allowing us to test planet formation theories on a variety of points, *e.g.* how gravitational instability or tidal interaction with a stellar companion functions, and how the dust size and composition evolves in the outer disk region. The targets (3) will allow us to complement the understanding of intermediate-mass YSOs, which are only several in the Taurus region.

(e) Debris disk sample

There have been many surveys carried out with the *Spitzer Space Telescope* to search for dust around main sequence stars (A-M). To take advantage of the capabilities of HiCIAO and minimize the number of non-detections, rather than carrying out a "blind'" survey, we propose to search for starlight-scatting dust around stars that are already known to harbor debris disks (detected in thermal emission), i.e. our target list is thus derived from *Spitzer* detected disks.

In some cases, HiCIAO sub-arcsec resolution will allow us to study the structure of the debris disk. This is of particular interest because, when combined with dynamical simulations, it can reveal the processes shaping the disk (e.g. the dynamical perturbation of embedded planets). The study of debris disk structure can also teach us about the diversity of planetary systems. In addition, the wavelengths and spatial scales that could be probed with HiCIAO may be relevant for the study of the occurrence and timing of Late Heavy Bombardment type events, with implications for the habitability of any terrestrial planets the system might harbor.

In total we have identified 80 targets from the literature that fulfill the following selection criteria: (1) Debris disks detections confirmed by *Spitzer*. (2) Spectral Types F, G, K (there is one very interesting M star - AU Mic - which is spatially resolved), and (3) No known binaries.

We also plan to include new debris disk targets likely to be discovered by *AKARI*, in collaboration with the *AKARI* "Vega team".

3. Observations Strategy

Equipped with HiCIAO, SEEDS should be conducted with full use of new observing modes for the Subaru telescope: polarization differential imaging (PDI) and spectral differential imaging (SDI) modes. The basic concept of such differential imaging is to split up the image into two or more images, and then use either different planes of polarization or different spectral filter band-passes to produce a signal that distinguishes faint objects near a bright central object from scattered halo or residual speckles (see Section 5 for more details). Great care is being taken to minimize the non common-path error of the differential optics and its critical components (single and double Wollaston prisms made from high-quality birefringent YLF); thus it is expected that the performance of HiCIAO will be better than that of previous PDI/SDI instruments (see also Section 5). Primary observation modes for our surveys are as follows:

- **SDI mode for planet searches**

We will use the SDI mode of HiCIAO with "methane filters" to select T_{eff}<1400K objects. These correspond to <12 M_J objects for 1-100 Myr age and <45 M_J objects even for 1 Gyr. Our "differential" filters are tuned at 1.575, 1.600, and 1.625 microns (R~64). The spatial resolution at these wavelengths is ~0.04". We can also apply the Angular Differential Imaging (ADI) mode to enhance the contrast (Marois et al. 2006) and to detect warmer objects even without methane features.

Any objects with the methane feature or lying close (<300 AU) to the central star will be re-observed as a proper motion test (PMT). The time span depends on the target category (from several months for nearby stars to several years for nearby YSOs).

Any object with the methane feature or that has passed the PMT will be followed up with low-resolution spectroscopy for better constraints on its surface temperature and gravity.

- **PDI mode for disk searches**

We will use the PDI mode for both protoplanetary and debris disk searches. This enables us to obtain the highest resolution of 0.03" and provides the sharpest polarization images of disks available with any telescope. This will be an ideal prelude to future disk studies with ALMA. The PDI contrast is expected to be comparable to the SDI contrast, much better than that of the CIAO single beam polarimetry. We will use J-band for the disk survey because of the highest resolution and the higher dust scattering efficiency; disks are generally brighter at J than at H or K.

- **Any targets for which a disk is discovered in planet searches will be followed up with standard disk protocol observations and vice versa.**

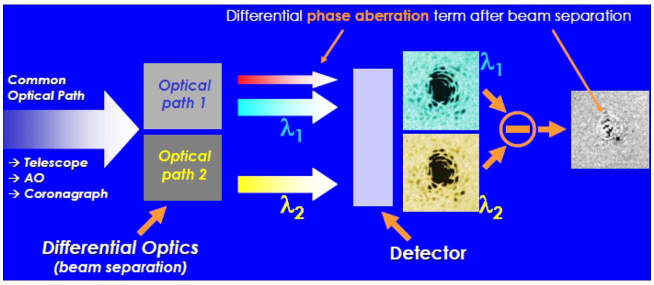

Fig. 4: Concept for the spectral differential imaging (SDI). HiCIAO uses a double Wollaston prism for producing beams at four wavelengths with a minimum non common path error

4. Why strategic observations? Why Subaru? Why HiCIAO/AO188?

Technical Advantages — AO188 is the curvature sensing AO with the largest format in the world. Together with a high quality of the mirrors on Subaru, it will arrow for excellent wavefront correction. Furthermore, HiCIAO will be the only sophisticated SDI/PDI system with coronagraphic capability, thereby minimizing the common-path error and the speckle noise better than ever. Throughout, the combination of these facilities/instruments will be the most powerful for the Northern Hemisphere targets for the foreseeable future. We also plan upgrades to the MEM-based AO and PIAA coronagraph, which will allow improved follow-up of the most interesting targets.

Number of nights required — A large sample (>300 stars) is "critical" for planet detection, and the telescope time must be requested as the strategic program. SEEDS will be by far the largest and most uniform imaging survey of both exoplanets and disks to date and for years to come. We recall that the current giant planet detection rate is ~5% and that the 1st CHFT exoplanet search of only 21 stars detected zero planets despite adequate sensitivity. The ongoing Gemini/NICI (85 element AO coronagraph system) planet-finding campaign will observe 150 stars in 50 nights with an emphasis upon southern M stars. The Subaru SDPS survey observed only ~80 YSOs without any differential imaging capability, but resulted in a discovery of several new disks and one "boundary-mass" companion object as already described.

Timeliness — The timing of HiCIAO and AO188 development compared to the competing Gemini/GPI and VLT/SPHERE instruments is such that Subaru will have the world's most powerful high-resolution and high-contrast imaging system for a period of 3 years or more, starting in 2008. Extensive, aggressive and early use of these capabilities will allow Subaru to make a dominant, potentially breakthrough, scientific contribution to one of the most important research areas in modern astrophysics.

5. Instruments - Expected Sensitivity and Contrast

Because of the higher performance of AO188 compared to AO36 and the differential capabilities (SDI/PDI), HiCIAO+AO188 has a much better contrast (about one order of magnitude) and a better spatial resolution (up to twice) than CIAO+AO36 (see also Tamura et al. 2006, Hodapp et al. 2006).

HiCIAO utilizes one HgCdTe HAWAII 2-RG array (2024x2024 pixels) with a pixel scale of 0.01 arcsec/pixel. The ASIC "Sidecar" array controller allows us a very flexible readout. We summarize the photometric sensitivities at each filter and the contrast in the SDI mode below. The contrast in the PDI mode is expected to be similar to that in the SDI mode.

From the HiCIAO sensitivity (alone), the exoplanets we can detect are: (1-10 Myr, <1 M_J) planets in Taur, (100 Myr, 4 M_J) planets in Pleiades, and (1 Gyr, 6 M_J) planets at 30pc in one hour integration time.

HiCIAO contrast will be 4x10^{-6} (13.5 mag) which is one order better than CIAO, and is enough to detect (10 Myr, 3 M_J) or (100 Myr, 7 M_J) planets orbiting a G2 V star at 5 AU (Barman et al. 2001) and to detect one-zodi debris disks (~18 mag arcsec^{-2} at 1AU) around nearest stars (Potter 2003).

Band	J	H	Ks	CH_4 low	CH_4 high	[FeII]
5σ (1 hour)	24.3	24.2	23.8	23.3	23.5	24.3

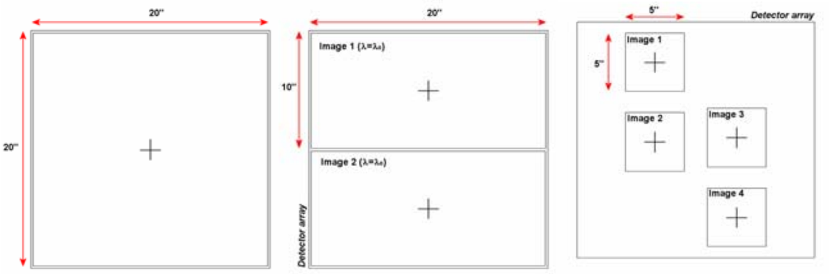

Fig. 5: Field-of-views in direct, PDI, and SDI modes.

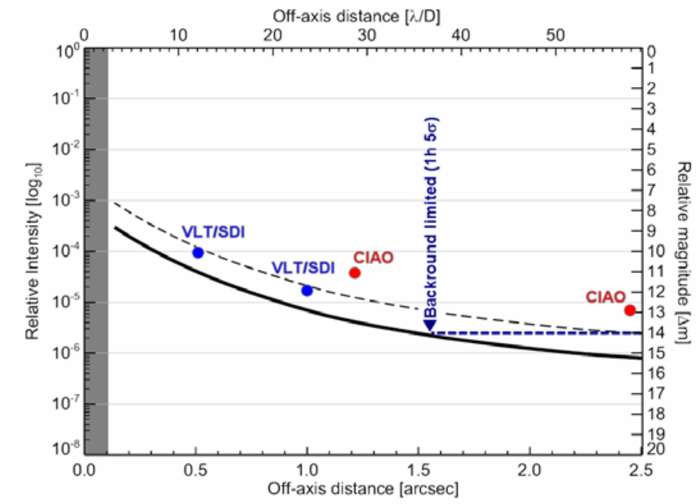

Fig. 6: HiCIAO detection limit in SDI mode. Plain curve is for a bright guide star (V=7) while the dashed curve is for V=11. The background limit is given here for an H=4 star. Plain and dashed line represent static residual noise level (see notice below).

Notice: Photometric sensitivities given in the Table are NOT the achievable contrast in SDI, because they are SNR based on photon noise only. In SDI (or PDI) mode, there is a quasi-static residual speckle background which will not improve with longer exposure times. This static speckle noise is the ultimate limitation to SDI/PDI modes.

6. Requested Nights, Scheduling and Periods

We plan to observe 521 stars described in Section 2 with an integration time of 1 hour each. This is enough to detect exoplanets/disks around the proposed sample (See Section 5). Although the central ~1" region is speckle-noise limited (its limiting magnitude depends on the brightness of the central star), the single integration time ensures a "uniform survey" over most of the field-of-view. Note that the typical integration time in the SDPS survey was only 20 min. Assuming a 50% time overhead, it will take ~75 nights to finish the survey. We also request ~45 nights for follow-up of detections, including the proper motion test for planet candidates (15 nights for 1/3 of the planet sample) and additional spectroscopy for best candidates (15 nights for 1/10 of the planet sample) as well as additional HKs polarimetric and COMICS-MIR imaging (15 nights for 1/10 of the disk sample). See also Section 10 for other follow-up observations in consideration. Therefore, we request 120 nights in total, without counting down nights.

The observing runs will be split into 4 slots per year to cover the various RA distributions. Since YSO members are concentrated in Taurus and Scorpius, one possible allocation per year is that 8-9 nights in winter and summer, 4 nights in spring and autumn. It is likely that we would wish to alter this pattern near the end of the project when there will inevitably be more targets left in some parts of the sky than others due to weather etc.

7. Team and Observers Plan

Our team is an excellent combination of the HiCIAO/AO188 instrument builders who are most familiar with conducting such a larger survey with these new and complicated instruments and experienced observers at the Subaru Observatory who can maximize the observation efficiencies; it also includes observational, instrumental, and theoretical experts in exoplanet/disk science in Japan and among established foreign collaborators, which includes AKARI, SST, SMA, ALMA, ASTE, and VLT collaborators.

It is proposed and practical to observe 120 nights (~25 nights per year) for the well-defined team, composed of postdocs and NAOJ-based students from the instrument team and Observatory. Other students from universities will also help with the observations and thus receive valuable training and experience. This SEEDS observing team, rather than a collection of many independent observers, will make it sure that the survey maintains in a uniform and high quality throughout.

8. Data Archive and Data Reduction Plan

- Data archiving is automatically made via SOSS. We will follow the Subaru standard.
- Data reduction is in two stages. The first step is quick look (QL) reduction at the time of observation. Even at this stage, our goal is to obtain semi paper-quality images after co-adding individual exposure frames in order to monitor data quality and to judge 1) if there are companion candidates, what are their methane indices, and 2) if there are disks or other circumstellar structures, what their polarization patters are. The second step is the photometry and other necessary analysis by individual team members. The team will devote its efforts to developing the necessary reduction pipeline software.
- A very short description of the data reduction procedures for the SDI mode is given here, but in fact the pipeline for SDI/PDI will be easier than the CIAO PSF-subtraction reduction because no time-dependent changes in the PSF are expected in the image subtraction. Since speckle patterns are very similar between different filter images, an effective subtraction of speckles can be obtained between the filters. First, short exposure data are co-added, flat-fielded and sky subtracted. A square aperture around each of the four images is extracted. They are then scaled, translated and rotated with an FFT algorithm. Additionally, the flux in each filter image is scaled. We then calculate two differences which are sensitive to substellar companions of spectral types (see also Biller et al. 2006). The reduction procedure for the PDI mode is more or less similar, except for two polarization images to obtain the Stokes parameters.

9. Data Release Policy

- Data release with SMOKA will be made after the proper motion test. Since some targets might require a longer time span for the test, we hope to extend the data-release policy from 18 months to 24 months.
- The planet/disk candidate data will be released after the data are published.

10. Follow-up and Supplementary Observations

- IRCS-AO188 and COMICS will be used for some spectroscopic follow-up.
- Keck or VLT or Gemini AO-spectroscopic follow-up will also be considered.
- Disk follow-up will be made with SMA and partial ALMA by radio collaborators.
- We will also make use of some near future upgrades of HiCIAO and the Subaru AO system, as necessary and as they become available; these include (1) laser guide star, (2) IR wavefront sensor, (3) MEM-based AO or PIAA coronagraph updates.

Acknowledgement

Although not listed as CoIs, several students have contributed to the target selection procedures/discussions. We would like to thank K. Yamamoto, A. Ohkubo, M. Suzuki, H. Morishita, M. Tanabe, A. Nakashima, in particular. We hope that this strategic survey, SEEDS, will provide "seeds" for future terrestrial planets and life detection projects.

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