Direct Imaging of Giant Exoplanets and Disks

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Talk Outline

- Why direct imaging (DI)?
- DI observation techniques
- Subaru/SEEDS project
  - Planet and other companion results
  - Disk results
  - Post-SEEDS activities
- Gemini/GPI & VLT/SPHERE surveys
- Future plans (space and ground)
- Summary
Various Planets detected by Various Techniques

- Wide-Orbit Planets
  - Directly Imaged
- Jovian Planets
  - Hot Jupiters
  - Mini-Neptunes
  - Super-Earths
- Radial Velocity
  - Transits
  - Microlensing
  - Imaging
  - Timing Variations
  - Orbital Brightness Modulation
  - Astrometry
Challenges with Direct Imaging

- **Huge contrast ratio** between planet and star
  - ~$10^9$ for Earth-Sun
  - ~$10^8$ for Jupiter-Sun
  - ~$10^6$ for *young* Jupiter-Sun

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**Self-luminous giant planets are main targets for direct imaging (at present)**

![Graph showing the relationship between luminosity and age for different types of celestial objects, including stars, brown dwarfs, and planets.](graph.png)

**How to suppress bright star light?**

*Present Sun*
Directly Imaged Planets
(Mass $\leq 13 \, M_{\text{JUP}}$)

Formed as BD binaries

Accretion or Gravitational Instability

Scattered?
SEEDS – Strategic Explorations of Exoplanets and Disks with Subaru

- The first “Subaru Strategic Program (SSP)” – An open-use category
- 120 nights from 2009; finished in 2015 Jan, only <1 night loss due to HiCIAO
- NIR direct imaging and census of giant planets in the outer regions (10-100AU) around ~500 solar-type and massive stars
- Exploring protoplanetary disks and debris disks for the origin of their diversity and evolution at the same radial (10-100AU) regions
- Direct linking between planets and protoplanetary disks

Resolution = 0.1-0.2”
Resolution = 0.05-0.1”
Contrast Improved by ~10

Solar-System Scale (<100AU) w/ HiCIAO
>100AU scale w/ CIAO
## SEEDS Main Survey Summary

<table>
<thead>
<tr>
<th>Item</th>
<th>Number</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total nights</td>
<td>125 nights</td>
<td>Incl. 5 night compensation</td>
</tr>
<tr>
<td>Loss due to Tel+AO</td>
<td>5.5 nights</td>
<td>HiCIAO time-loss is negligible.</td>
</tr>
<tr>
<td>Loss due to weather</td>
<td>32 nights</td>
<td>26 %, poor seeing data not included</td>
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<tr>
<td>Success rate</td>
<td>74 %</td>
<td>Typical at Mauna Kea</td>
</tr>
<tr>
<td>Observed targets</td>
<td>428 (~500 planet+disk data)</td>
<td>Follow-up removed. ~80 sources in ADI+PDI, so used as planet and disk data, respectively</td>
</tr>
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## Individual Main Results in Each Category

56 refereed papers published/accepted so far.

<table>
<thead>
<tr>
<th>Category</th>
<th>Target</th>
<th>Discovery</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>NS</td>
<td>GJ 504 b</td>
<td>Planet</td>
<td>Kuzuhara+13</td>
</tr>
<tr>
<td>NS</td>
<td>Kappa And b</td>
<td>Planet</td>
<td>Carson+13</td>
</tr>
<tr>
<td>NS</td>
<td>GJ 758 b</td>
<td>Planet/BD</td>
<td>Thalmann+13</td>
</tr>
<tr>
<td>YSO</td>
<td>HD 100546 b conf.</td>
<td>Planet/disk</td>
<td>Currie+13, Uyama+16</td>
</tr>
<tr>
<td>OC</td>
<td>HD23514 B, HII1348 B, etc.</td>
<td>3xBD</td>
<td>Yamamoto+13, Konishi+16</td>
</tr>
<tr>
<td>NS</td>
<td>HAT-P-7 B, KOI-94 B, etc.</td>
<td>M star</td>
<td>Narita+10, Ryu+16</td>
</tr>
<tr>
<td>YSO</td>
<td>~30 resolved disk imaging</td>
<td>Disks w/ gap/ring</td>
<td>Hashimoto+11 + many</td>
</tr>
</tbody>
</table>
SEEDS’ Imaging Discovery of a Cold Jovian Planet – one of the lowest mass planets ever imaged

As a highlight, we report an exoplanet detection around the Sun-like star GJ 504. A unique cold Jovian planet imaged (Kuzuhara, Tamura et al. 2013).

- Primary GJ 504 A
  - G0 star at 17.6 pc
  - age ~160 Myr (oldest among imaged planets; less model dependence)

- Planet GJ 504 b
  - m=3-4.5 M(Jupiter)
  - a~44AU
  - methane (only T-type, others are all L-type)
  - T<600K expected
Other Discoveries and Findings

- SEEDS published three planet candidates, other than GJ 504b

Kappa And (13MJUP@55au)
- A planet candidate around a B-type star (2.5 Msun)
  - (Carson+2013, note recent results, Bonnefoy+2014; Hinkley+2013)

HD100546 (18MJUP@53au)
- A planet around a YSO and induced arm?
  - (Currie+2014)

- Hard to observe via radial velocity except for giants

- SEEDS published papers summarizing the 2 or 3 year planet survey results of each category (e.g., debris disk, Janson+2013; open cluster, Yamamoto+2013, Moving Group, Brandt+2014).
Studies for Origin of misaligned RV Planets and Long-Term RV Trend

SEEDS searches for stellar companions around stars with inner planets

A stellar companion may be a cause of such an inner planet (Kozai-effect; Wu et al. 2007; Fabrycky & Tremaine 2007)

=> Probed by SEEDS imaging

- Companions were indeed discovered

- Confirmation of a M-type stellar companion orbiting HAT-P-7

HAT-P-7

M-type companion

Narita+09, 12

1200 AU

- Companions causing the RV trend

Gamma Hydrae

HD 109272

Ryu+16

HD 5608

1° 41 AU

1° 49.3 AU

0.5° 28 AU
SEEDS Statistics on Wide Orbit Giant Planets

~250 stars (MG, DD, OC) are used for statistical analysis (Brandt+2014).
~100 YSOs are used for statistical analysis (Uyama+2016).

□ Model
- Mass-Semi-major axis distribution
  \[ dN/(dMda) = k(M^\alpha)(a^\beta) \]
- Mass-Luminosity relation

□ Data
- Stellar age
- Stellar distance
- Stellar type/mass
- Contrast maps

Frequency: 5–70 M_{Jup} at 10-100 AU ~ 2%  Red=SEEDS, Green=NICI
Major Results of Planet Formation Sites

SEEDS has observed **scattered light** from disks and revealed many disk structures of less than 100AU scale that are possible signs of planet formation in such young (a few Myr) systems! Many directly-maged small gaps/spirals in disks since 2010.

- **Gaps**
  A disk gap may be evidence for dynamical interactions between a planet and its gaseous disk.

- **Spirals**
  A gravitational perturbation from an embedded planet generate spiral density waves.
SEEDS has revealed gaps & rings of <100AU scale in many disks by polarimetric imaging (Res.~0.06'', IWA~0.1'')

Note that ALMA HL Tau image (2015) is thermal emission.
Gemini Survey-GPIES: 600 stars in 890 hrs

1st Planet: 51 Eri b

Credit: Gemini

Gemini Planet Imager Extra Solar Survey

Macintosh et al. 2015
VLT/SPHERES’s Survey: 800 stars in 200 nights

HD 131399 Ab, A star, 16 Myr
- An alien planet orbits in a triple-star system
- Aagner+2016, Science

HIP 65426b, A star, 14 Myr
- SPHERE’s first planet
- Chauvin+17, A&A

But it turns out a Background star!
- Niesenson+2017

HIP 65426 (VLT/SPHERE)

Credit: SHINE (SpHere INfrared survey for Exoplanets)
Subaru’s Next Steps in Exoplanet Sciences

- **SCExAO: 2014-** (Science phase)
  - 2000 MEMS deformable mirror
  - PIAA coronagraph
  - IR bench for HiCIAO & CHARIS
  - OPT bench for FIRST & VAMPIRE

- **CHARIS: 2016-** (FL done)
  - IFU Combined with SCExAO
  - R19/R70 JHK spectroscopy
  - Small (λ/D) inner working angle!

- **IRD: 2017-** (FL done; IR Doppler)
  - IR echelle-grating spectrometer
  - R~70,000, fiber-fed
  - 1m/s accuracy w/ laser-comb
  - Habitable earths and super-earths around late M stars
  - Planet formation around M stars
CHARIS First Light Images

HR8799 cde ↓

Neptune ↓

Princeton CHARIS team
Future Surveys and Future Missions

Future Ground-based Surveys:
- GPI survey
- SPHERE survey

Future missions:
- JWST coronagraph
- WFIRST coronagraph
- Exo-C

Earth-like planets:
- TMT+SEIT (M stars)
- TPF-C or TPF-O (G stars)
- $10^8$ at 0.01" & $10^9$ at 0.1"

From Exo-C interim report (Stapelfeldt+14)
SEEDS and other surveys has explored the wide-orbit giant planets.

From SEEDS, 3 direct imaging discovery of planet and boundary mass objects (GJ 504, Kappa And, GJ 758) and 3 brown dwarfs detection in Pleiades.

GJ 504b is a cold Jovian planet orbiting a relatively old Sun-like star and has unique atmospheric features. One young planet is also confirmed (HD 100546).

Many circumstellar disks are detected down to r=0.1”. Fine structures such as gaps and spirals of <100 au scale are discovered for the first time, which are possible signs of planet formations. With the latest ALMA performance, these NIR scattering data will complement the submillimeter thermal emission from various disks.

Wide-orbit planets population can be explained as a single distribution and its frequency is ~2% from SEEDS preliminary results.

We will keep our activities with the Subaru extreme AO (SCExAO), IFU (CHARIS), and IRD and extend to TMT era with the help of the ABC activities.