Exoplanets and Disk Imaging with Subaru

November 17  14:10 - (15+5 min)

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Figure Credit: S&T, Grady, Currie
Various methods have led >1800 planet discovery in 20yr & they are diverse!
Jovian Planets

Wide-Orbit Planets (Directly Imaged)

Targets for Current Exoplanet Direct Imaging

Targets are Young Jovian Planets
- $M > 1 \text{ M}_J$
- $a > \sim 5 \text{ AU}$

You can derive:
- Mass from Luminosity (Phot.)
- Mass+ from Astrometry
- Color from Phot
- Atmosphere from Spect.
- $\text{Teff, g}$ from Spect.
Wide-orbit planets can be detected currently only by direct imaging; many are $a \geq 100$ AU; only a handful for Solar system-scale orbit planets.

Some Directly Imaged Planets (Candidates) around BD first, then A stars & YSOs, and finally G & B stars:

- **HR 8799 bcde** (A star; Marois+08,10)
- **β Pic b** (A star; Lagrange+10)
- **Fomalhaut b** (A star; Kalas+08,13)
- **GJ504 b** (G star; Kuzuhara, Tamura+03)
- **HD 95086 b** (A star; Rameau+13)
- **2M1207 b** (BD; Chauvin+04,05)
- **1RXJ 1609 b** (YSO; Lafrenière+08,10)
- **ROX 42B b** (YSO; Currie+14)

(not full list & SEEDS planets introduced in detail later)
Only 6 imaged planetary systems w/ mass <14$M_{\text{Jup}}$ and $a<100$ AU excluding BD binary, of which 3 from SEEDS.

Wide-orbit planets can be detected currently only by direct imaging; Many are $a>100$ AU; only handful for Solar-system-scale orbit planets.
Difficulties with Direct Imaging

- Huge contrast ratio between planet and star
  - $\sim 10^9$ for Earth-Sun
  - $\sim 10^8$ for Jupiter-Sun
  - $\sim 10^6$ for young Jupiter-Sun
  - Self-luminous giant planets are current main targets
  - How to suppress bright star light?
- Speckle noise from bright central star
  - Not photon-noise but speckle – noise limited observations
  - How to remove static speckle?
- Coronagraph
  - Ex. CIAO (previous) & HiCIAO (current)
- Various differential imaging techniques (PDI, SDI, ADI)
SEEDS – Strategic Explorations of Exoplanets and Disks with Subaru

- First “Subaru Strategic Program (SSP)” – An open-use category
- 120 Subaru nights in 5 years from 2009; ~110 finished by now
- NIR direct imaging and census of giant planets in the outer regions (10 AU – 100 AU) 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 (orbital) 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 Scientific Category

SEEDS has 5 categories that cover targets of various ages.

<table>
<thead>
<tr>
<th>Category</th>
<th>YSO</th>
<th>Moving Group</th>
<th>Open Cluster</th>
<th>Nearby Star</th>
<th>Debris Disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>YSOs in Taurus, Oph, Upper Sco, etc</td>
<td>Young Stars in Nearby Moving Groups</td>
<td>Stars in Open Clusters</td>
<td>Various-type stars in solar neighborhood</td>
<td>Stars with debris disks</td>
</tr>
<tr>
<td>Age coverage</td>
<td>1–10 Myr</td>
<td>10– ~100 Myr</td>
<td>130 Myr</td>
<td>100–1000 Myr</td>
<td>10 Myr– ~1 Gyr</td>
</tr>
<tr>
<td>Distance</td>
<td>~130 pc</td>
<td>10 – 50 pc</td>
<td>~130 pc</td>
<td>10 – 50 pc (except RV targets)</td>
<td>10 – 100 pc</td>
</tr>
<tr>
<td>Obs. #</td>
<td>~80</td>
<td>~70</td>
<td>~40</td>
<td>~150</td>
<td>~50</td>
</tr>
</tbody>
</table>

- focusing on solar-type (GK) but also cover higher- (BAF) & lower-mass (M) stars
- cover age range from ~1 Myr to a few Gyrs to prove planet evolution history
- planets and disks are simultaneously surveyed in YSO and debris disk categories
## Individual Main Results in each category

34 refereed papers so far

<table>
<thead>
<tr>
<th>Category</th>
<th>Target</th>
<th>Discovery</th>
<th>Reference</th>
</tr>
</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>OC</td>
<td>HD23514 B, HII1348 B independent dis.</td>
<td>BD</td>
<td>Yamamoto+13</td>
</tr>
<tr>
<td>NS</td>
<td>HAT-P-7 B, KOI-94 B, etc.</td>
<td>M star</td>
<td>Narita+10</td>
</tr>
<tr>
<td>YSO</td>
<td>~30 resolved disk imaging</td>
<td>Disks w/ gap/ring</td>
<td>e.g., Hashimoto+11</td>
</tr>
</tbody>
</table>
SEEDS Planet Discovery: GJ 504 b

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).

Properties of GJ 504

- Distance: 17.6 pc
- Spectral type: G0
- Mass: $1.2 M_{\text{sun}}$
- Age: 160 [conservative range; +350, -60] Myr
- Metallicity [Fe/H]: 0.1–0.3 (Valdes+04, Takeda+07, Valenti & Fischer 05)

9 detections so far

⇒ Confirmation of common proper motion and partial orbital motion
GJ 504b: a Jovin planet of ~160 My age

- Mass estimate via evolutionary model (Baraffe+03) w/gyro-age
  
  $\Rightarrow$ 3-4 $M_{\text{Jup}}$

  This estimated mass is among the lowest of directly imaged planets.

- Mass estimate less affected by Hot vs. Cold start problem

  - Because the planet is older than 100 Myr, the mass estimate less depends on the choice of initial conditions (Hot vs. Cold start) in evolution models. But also see Mordasini+14 for initial condition uncertainties.
GJ 504b: not L-type but T-type planet

- Unique blue J-H color
- Coldest temperature (< 600 K) among the directly imaged planets
- Photometry: J, H, Ks, L'-band (1-4 um) and SDI (CH4-off, -on; 1.56, 1.72 um)

Deep absorptions by CH$_4$ in atmosphere (like T-dwarf; Janson+2013)

Comparison with Brown dwarf colors

Comparison to T-dwarf spectra
Other Discoveries and Findings

☐ SEEDS detected two planet candidates, other than GJ 504b

☐ A planet candidate around a B-type star
   (Carson+2013, note recent results, Bonnefoy+2014;  Hinkley+2013)

☐ A discovery of a brown dwarf or massive planet orbiting a nearby G star
   (Thalmann+2009; Janson+2011)

☐ 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).

☐ Other categories’ summaries and statistics will be submitted.

☐ Data reduction software paper (Brandt+2013).
SEEDS has observed scattered light from disks and revealed many disk structures of less than 100AU scale that are **possible signs of planet formations**.

- **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 have revealed gaps & rings of <100 AU scale in many disks (no details today)
Future Surveys and Future Missions

- **Future Gr. Surveys:**
  - GPI survey
  - SPHERE survey
  - SCExAO/CHARIS (Olivier, Kasdin)

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

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

From Exo-C interim report (Stapelfeldt+14)

Star-Planet Contrast vs. Apparent Separation (arcsec)
Deep direct imaging such as SEEDS has detected a handful wide-orbit planets of the Solar system scale. More wide-orbit (>100au) planets also discovered by imaging both around stars and brown dwarfs.

From SEEDS, 3 direct imaging discovery of planet candidates (GJ 504, Kappa And, GJ 758) and 2 brown dwarfs detection in Pleiades;
- GJ 504b is a cold Jovian planet orbiting a relatively old Sun-like star and has unique atmospheric features.

A few dozens of detections of circumstellar disks, and found/characterized disk structures that are possible signs of planet formations.

Wide-orbit planets frequency is less than 10% from NICI survey and SEEDS preliminary results.

Various future plans for direct imaging both from ground and space. Earth-like planet imaging is still challenging but could be possible with 30-m telescopes with ExAO+corona or 2-4m class space high-contrast telescopes.