Direct Explorations of Exoplanets and Disks with Subaru

Joint Subaru/Gemini Science Conference
2009.5.20 10:00-10:30

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National Astronomical Observatory of Japan
Talk Outline

1. Highlights of Subaru high-contrast sciences so far
   - Diversity of protoplanetary disk morphology
   - Low-mass companions
2. Next step
   - HiCIAO & SEEDS
   - SEEDS status
3. Summary
1. Clouds collapse under gravity

Current Paradigm of Star and Planet Formation

DIRECT OBS. Need < 1” resolution
Currently best studied at NIR

2. Protoplanetary disks

10,000 yr
IRSF/SIRIUS

3. Comets & asteroids form or Vega-like stars

1 Myr
Subaru/CIAO

10 Myr
Subaru/CIAO/POL

4. Planetary system

Kaguya

100 Myr

~270 systems known

0. Cloud and cloud cores (NRO)
Subaru has an AO Coronagraph since 2001

- CIAO + 36-actuator AO at Cass.
  - First dedicated cold coronagraph on 8-m telescopes

Diversity of proto-Planetary disks

Young very low-mass Companion

Compact disk around massive YSOs
**Subaru+CIAO+A036 Science Summary**

- **Disk - morphological diversity of young and debris disks**
  - **AB Aur**: spiral structure in protoplanetary (PP) disk revealed (Fukagawa et al. 2004).
  - **HD142527**: new-type of PP disk morphology discovered (Fukagawa et al. 2006) & imaging of ice (Honda et al. 2009).
  - **FN Tau**: first PP disk around lowest-mass (0.1 Mo) star directly imaged (Kudo et al. 2007).
  - **Beta Pic**: First NIR polarimetry with coronagraph revealed nature of debris disk dust (Tamura et al. 2006).
  - **Binary disks**: GG Tau, UY Aur, etc. (Itoh, Hioki, Mayama)

- **Exoplanets/brown dwarfs - new types of companions?**
  - **DH Tau, GQ Lup, EK60**: "boundary objects" between planets and brown dwarfs around T Tauri stars discovered (Itoh et al. 2005; Neuhauser et al. 2005; Kuzuhara et al. 2009 - see his poster).
  - **HR8799** image in 2002 (Fukagawa et al. 2009).

- **Massive star disk - evidence for formation by accretion**
  - **BN, S140IR, IRAS23033, S255IRS1&3, N7538IRS1**: Ubiquity of compact disks around massive (at least up to ~10 Mo) YSOs (Jiang et al. 2005, 2007).
Spiral-shape disk around 2Mo-4Myr Herbig Ae star: AB Aur


1.6 μm
(d=144 pc)

Corder+2006
OVRO

12CO Velocity field

100 AU

700 AU

100 AU

near-side

brighter

fainter

star

flared disk

disk with spiral arms (r=450 AU)

trailing arm ← com. w/radio data + brighter forward scattering

no nearby companions in our images; but see Oppenheimer+08
Submm follow-up and planet formation scenario revisited

Gravitational instability? (instability condition):

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \leq 1$$

Probably supplies of matter from the envelope maintain the weak instability.

⇒ $Q \sim 2$; “weak” instability

A suggestion of planet formation by gravitational instability? (for some systems)

Also note recent imaging discovery of outer (>10AU) planets around A stars (Marois; Kalas).

White contours:

White contours:

Also note recent imaging discovery of outer (>10AU) planets around A stars (Marois; Kalas).
NEW type of disk: HD142527 – banana split
Herbig Ae star in Lupus (d=200pc)

disk gap
central gap
disk asymmetry
confirmed at MIR

\( \lambda = 1.65 \) micron
Subaru/CIAO

\( \lambda = 24.5 \) micron
Subaru/COMICS
Where is the snow line in protoplanetary disks?

- ice absorption everywhere
  - $T(\text{dust})=82-85\text{K}$ (by MIR; Fujiwara+2006)
  - cold enough
- Snow line is much inner
  - $R_{\text{snow}} << \sim 140\text{AU}$

Honda+2009
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DH Tau B & GQ Lup B & EK60: Planets or Brown Dwarfs?

- Very low-mass companions around T Tauri Stars; what are they?
- Spectroscopic temperature estimate is still not reliable
- Thus, we use age/luminosity
- Then DH Tau, GQ Lup, EK60 are three of the lowest and nearly planetary-mass companions.
- But they are very far from star (>100AU)

Itoh, Tamura, Hayashi+05
Neuhauser+05
Luhman+06
Kuzuhara+09
Then, finally "planets" imaged around A stars: HR8799, Fomalhaut, b Pic
Subaru new coronagraph - HiCIAO

Nasmyth platform

Telescope

Common Optics + AO Module

Coronagraph Module

High Contrast Optics Module

IR Camera Module

Wollaston Prism

Camera

188 actuators AO
Future: Complementary MEM DM (32×32)

Coronagraph
Focal masks
Pupil stops

Differential optics
(Wollaston prisms - single/double)

Hawaii 2-RG
2k×2k array
ASIC Sidecar Controller

Filters
Common+Differential
## HiCIAO Specifications

<table>
<thead>
<tr>
<th>Focus</th>
<th>IR Nasmyth (w/ AO188)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.85 – 2.50 microns</td>
</tr>
<tr>
<td>Observation modes</td>
<td>DI, PDI, SDI, ADI (w/ &amp; w/o coronagraph)</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.03&quot; (J), 0.04&quot; (H), 0.055&quot; (K)</td>
</tr>
<tr>
<td>Strehl ratio</td>
<td>0.2 (J), 0.3 (H), 0.5 (K) with AO</td>
</tr>
<tr>
<td>Field of view</td>
<td>20&quot;x20&quot; (DI), 20&quot;x10&quot; (PDI), 5&quot;x5&quot; (SDI)</td>
</tr>
<tr>
<td>Contrast</td>
<td>$10^{3.8}$ at 0.1&quot;, $10^{5.5}$ at 1.0&quot; (SDI w/ coronagraph)</td>
</tr>
<tr>
<td>Pixel scale</td>
<td>0.010&quot;/pix</td>
</tr>
<tr>
<td>Occulting masks</td>
<td>0.2&quot;, 0.3&quot;, 0.4&quot;, 0.6&quot;, 1.5&quot; diameter</td>
</tr>
<tr>
<td>Filters</td>
<td>Y, J, H, Ks (DI, PDI), CH4, FeII, H2 (SDI)</td>
</tr>
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SEEDS – Subaru Strategic Exploration of Exoplanets and Disks with HiCIAO/AO188

- First "Subaru Strategic Observations"
- 120 nights in 5 years on Subaru
- Direct imaging and census of giant planets around solar-type stars in the outer regions (~4-40 AU)
- Exploring protoplanetary disks and debris disks for origin of their diversity and evolution at the same radial regions
- Direct linking between planets and protoplanetary disks

HiCIAO
0.6" mask coronagraph images in ADI mode
# SEEDS Target Summary as of Jan 09

<table>
<thead>
<tr>
<th>Category</th>
<th>Planet searches (in methane SDI/ADI mode)</th>
<th>Disk Searches (in PDI mode)</th>
<th>Total number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>(c)</td>
</tr>
<tr>
<td>SFR YSOs &amp; Open cluster &amp; Moving Group</td>
<td>90</td>
<td>100</td>
<td>140+37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number</th>
<th>~140 pc</th>
<th>&lt;125 pc</th>
<th>&lt;30 pc</th>
<th>~140 pc</th>
<th>&lt;130 pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>~140 pc</td>
<td>&lt;125 pc</td>
<td>&lt;30 pc</td>
<td>~140 pc</td>
<td>&lt;130 pc</td>
</tr>
<tr>
<td>Age</td>
<td>1-10 Myr</td>
<td>10~100 Myr</td>
<td>100 Myr - 1 Gyr</td>
<td>1-10 Myr</td>
<td>5 Myr - 6 Gyr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comment</th>
<th>Tau/Sco</th>
<th>UPlieades/ several MGs</th>
<th>subcategory</th>
<th>TTS/HAeBE/ polarized sources</th>
<th>SST/AKARI sample</th>
</tr>
</thead>
</table>

![RA-DEC](image1.png) ![H-mag](image2.png) ![R-mag](image3.png) ![Sp-Type](image4.png)
SEEDS Members & Status

- 24 institutes 91 members (20 foreigners).
- Principal Investigator (PI): M. Tamura (NAOJ)
- Co-PI: T. Usuda, H. Takami (NAOJ)

SAC and TAC already approved!
SEEDS will start in 09B as soon as PV finished.
SUMMARY

- Various results with Subaru CI AO+AO36 have been reviewed: disk diversity, disk ice, nearly planetary mass companions at distance, massive star disks, and polarimetry.

- SEEDS will conduct a 5-year legacy survey of \( \sim 500 \) solar-mass and massive young stars for direct imaging of exoplanets and disks in 120 nights with a "all-Japan" team collaborating with foreign researchers.

- Our targets consist of 5 categories, each of which includes about \( \sim 100 \) stars (enough for statistics).

- We believe that we can image at least a handful of giant (\(<13 \text{ MJ})\) exoplanets in a few to 10s AU regions and the similar radial regions of many disks in each category.

- Various follow-up programs should be organized, including spectroscopy with various instruments and telescopes.