Protoplanetary Disks around Intermediate-Mass Stars

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Outline of this talk

1. Disks around young intermediate-mass stars
2. Spatially resolved images of protoplanetary disks
3. Temporal change of disk structure
4. Primordial to debris disks
5. Direct imaging of extra-solar planets
Planets form in circumstellar disks

Disks are by-products of star formation

“minimum mass solar nebula” \( R > 50 \text{ AU} \), \( \Sigma(r) \propto r^{-1.5} \), \( M \sim 0.01 M_\odot \)

From the solar system to extra-solar ones

How to study planet formation

- Establishing the initial conditions for planet formation
  - Multi-wavelength, multi-epoch observations are important to understand the disk

- Searching for footprints of planets
  - Morphology of disks (massive planets can significantly alter the structure)

- Studying ingredients of planets:
  - Ices, silicates, organic molecules etc.

- Detecting forming planets in disks
  - Young stars are good targets to search for planets at their birthplaces, and to constrain their formation mechanism.
  - RV might be difficult for young stars (e.g., TW Hya)
  - Direct imaging only reveal outer planets
  - Currently we cannot directly access to terrestrial planets, but we can for giant planets (younger planets are brighter).
Infrared excess as a disk diagnostic

Evolution of disks

PMS (age ~ 1 Myr)

MS
Disks around young intermediate-mass stars

- "Intermediate-mass stars" → Herbig Ae/Be stars
- Be and Ae/Fe are different:
  - Disks are ubiquitous around TTS, Herbig Ae, and Fe stars with IR excesses
    - $M_{\text{disk}} \sim 1$–$10\%$ of $M$ with significant scatter
    - $R \sim 10$ – $1000$ AU
- How about Herbig Be stars?
- In general, observations are difficult for massive stars due to fast evolution and large distances (> kpc)

Palla & Stahler (1999)

Rapid dispersal due to photoevaporation?

- Disks (+ envelopes) are detected for some cases, but $M_{\text{disk}}$ are lower ($x5$–$10$) for younger Herbig Be stars.

Alonso-Albi et al. (2009)
Imaging of protoplanetary disks in scattered light

Targets

<table>
<thead>
<tr>
<th>Source</th>
<th>Sp. Type</th>
<th>d (pc)</th>
<th>Age (Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbig Ae stars (The et al. 1994)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>AB Aur</td>
<td>A1</td>
<td>144</td>
<td>3</td>
</tr>
<tr>
<td>MWC 480</td>
<td>A5</td>
<td>170</td>
<td>5</td>
</tr>
<tr>
<td>HD 34282</td>
<td>A3</td>
<td>350</td>
<td>6</td>
</tr>
<tr>
<td>HD 139614</td>
<td>A7</td>
<td>140</td>
<td>10</td>
</tr>
<tr>
<td>HD 142527</td>
<td>F6</td>
<td>140</td>
<td>2</td>
</tr>
<tr>
<td>HD 144432*</td>
<td>A9</td>
<td>145</td>
<td>4</td>
</tr>
<tr>
<td>HD 149914*</td>
<td>B9.5</td>
<td>165</td>
<td>&lt;1</td>
</tr>
<tr>
<td>HD 150193*</td>
<td>A2</td>
<td>150</td>
<td>6</td>
</tr>
<tr>
<td>KK Oph*</td>
<td>A8</td>
<td>160</td>
<td>5</td>
</tr>
<tr>
<td>Vega-like stars (e.g., Sylvester et al.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD 163296</td>
<td>A1</td>
<td>122</td>
<td>4</td>
</tr>
<tr>
<td>HD 169142</td>
<td>A5</td>
<td>145</td>
<td>8</td>
</tr>
<tr>
<td>VV Ser</td>
<td>B6</td>
<td>310</td>
<td>5</td>
</tr>
<tr>
<td>HD 176386*</td>
<td>B9</td>
<td>140</td>
<td>2</td>
</tr>
<tr>
<td>HD 179218</td>
<td>A0</td>
<td>240</td>
<td>1</td>
</tr>
<tr>
<td>HD 190073</td>
<td>A2</td>
<td>&gt;290</td>
<td>1</td>
</tr>
</tbody>
</table>

(*) known binaries

HD 131885 A0 121 –
HD 184761 A5 65 ZAMS
HD 191089 F5 54 <100
HD 218396 A5 56 30
Imaging with Subaru

- Subaru 8.2m + CIAO (Coronagraphic Imager with Adaptive Optics)
- H-band (1.6 μm) imaging
- spatial resolution ~0''.1
- occulting mask $\phi = 0''.5 - 1''.0$

We can observe...
- outer disk ($r > 50$ AU)
- scattered light
dust grains in the upper layer of a flared optically thick disk ($L_{IR}/L_{\odot} \sim 0.1$)
- detailed morphology

Resolved Protoplanetary Disks
AB Aur (A1, 3 Myr)  HD 169142 (A5, 8 Myr)

HD 142527 (F6, 2 Myr)  HD 163296 (A1, 4 Myr)

**HD 142527  “Banana-Split”**

( d=140 pc, 2 Myr, 1.5 M$_\odot$)

- large inner hole → binary?
- two components facing with each other + outer arm
  - east: r ~100 – 400 AU
  - west: r ~150 – 490 AU
- “banana-split” (Adams et al. 1989) suggests an eccentric disk
  - central binary with e > 0.2 (Nelson et al. 2003)
  - two bananas ...?
- companion star was not observed → q < 0.25

Fukagawa et al. (2006)
AB Aur “Spiral Arms”
(d=144 pc, 4 Myr, 2.4 M\(_\odot\) )

- disk (r = 580 AU)
  + envelope (>1000 AU in optical)
- spiral arms
  - firstly suggested by the HST optical imaging (Grady et al. 1999)
  - NIR imaging is not so much affected by scattered light from the envelope
  - CO disk (e.g., Corder et al. 2005) → arms are trailing

NIR (1.6 \(\mu\)m)

UH2.2m, opt (0.6 \(\mu\)m)
Spiral Structure

- What is the cause of spiral?
  - perturber (companions): not observed
  - gravitational instability?
    \[ Q = \frac{c \Omega}{\pi G \Sigma} \leq 1 \]
    \[ M_d = \frac{F_v d^2}{\kappa_v B_v (T)} \]
    → Q could be ~2; marginally unstable
    mass supply from the surrounding envelope onto the outer disk may play a role
- How common?
  - envelope → at most ~10% of Herbig Ae disks
  - planet formation in spiral disks ...? (e.g., Rice et al. 2004)

Resolved Disks at 1.6 μm

<table>
<thead>
<tr>
<th>source</th>
<th>( \frac{L_{\text{disk}}}{L_{\text{Crisp}}} )</th>
<th>observed radii</th>
<th>morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>optically thick (protoplanetary) disks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB Aur</td>
<td>( (1.2 \pm 0.2) \times 10^{-2} )</td>
<td>120–580 AU</td>
<td>spiral</td>
</tr>
<tr>
<td>HD 150193</td>
<td>( (1.3 \pm 0.3) \times 10^{-2} )</td>
<td>59–225 AU</td>
<td>truncated by companion?</td>
</tr>
<tr>
<td>HD 142527</td>
<td>( (3.2 \pm 0.2) \times 10^{-2} )</td>
<td>105–420 AU</td>
<td>banana</td>
</tr>
<tr>
<td>HD 163296</td>
<td>( \sim 2 \times 10^{-4} )</td>
<td>232–430 AU</td>
<td>ring (ansae at opt.)</td>
</tr>
<tr>
<td>HD 169142</td>
<td>( (1.5 \pm 0.2) \times 10^{-3} )</td>
<td>123–200 AU</td>
<td>without structure</td>
</tr>
<tr>
<td>HD 100546 (1)</td>
<td>( (1.6 \pm 0.2) \times 10^{-2} )</td>
<td>46–380 AU</td>
<td>(spiral at opt.)</td>
</tr>
<tr>
<td>optically thin (debris) disks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD 141569 A (2)</td>
<td>( (2.2 \pm 0.2) \times 10^{-3} )</td>
<td>190–891 AU</td>
<td>ring, (spiral at opt.)</td>
</tr>
<tr>
<td>HR 4796 A (3)</td>
<td>( (2.4 \pm 0.5) \times 10^{-3} )</td>
<td>44–104 AU</td>
<td>ring</td>
</tr>
<tr>
<td>( \beta ) Plc</td>
<td>( (1.8 \pm 0.4) \times 10^{-3} )</td>
<td>50–140 AU</td>
<td>warp, (rings at opt./ MIR)</td>
</tr>
</tbody>
</table>

(1) Augereau et al. (2001), (2) Weinberger et al. (1999), (3) Schneider et al. (1999)
Detection in Scattered Light

prediction: SED classification by Meeus et al. (2001)

- group I: flared disk → detected in scattered light
- group II: flat disk → not detected in scattered light

\[\text{Variability of disk sources}\]

- group I → II evolution? No.: Many of the detected Group I objects have lower accretion rates than the Group II, do not drive jets, and in several cases are older than the Group II.
Detection of a very faint disk, but...

- HD 163296 (Herbig Ae star, 4 Myr, A1)
- Keplerian disk has been known, bright in (sub-)millimeter
- Disk radius ~430 AU
- $L_{\text{scat}}/L_{\text{total}}$ (1.6 $\mu$m) ~ $2 \times 10^{-4}$ ($\leftrightarrow 2 \times 10^{-3}$ for $\beta$ Pictoris)

Variability in Scattered Light

- HD 163296
- Near-infrared imaging (detecting light scattered at the surface of the optically thick disk)
- Disk is brighter in 2007 and 2008 than in 2004.
Variability of Thermal Infrared Emission

- Brightness change of ~30% was observed in 2002
- This kind of event might happen in a timescale of years (time sampling is not enough)

![Graph showing Variability of Thermal Infrared Emission](image1)

Variability for a Pre-Transitional Disk

- SAO 206462 (Age ~ 8 Myr, F-type stars)
- Pre-transitional disk
  - Transitional disk: few NIR excess + abundant MIR excess
- Gap at 3—10 AU (e.g., Pontoppidan et al. 2008, Fedele et al. 2008)

![Image showing Pre-Transitional Disk](image2)
Variability for a Pre-Transitional Disk

- Variability ($>3\sigma$) observed from NIR to 10 micron region
- Color is variable
- Warm state: small grains confined in a narrow belt from 0.08-0.2 AU
  → dust production due to mutual collisions of planetesimals...?

Grady et al. (2009)

Summary

- "Diversity" of disk morphology has been revealed by AO imaging.
- Disk brightness in scattered light is not correlated with stellar age and millimeter flux/infrared excess: detection simply means that the disk is vertically flared to intercept the stellar light.
- Bright & highly structured disks are still surrounded by the remnants of envelopes.
- The significant diversity of disk structure can be attributed to the multiplicity and the initial condition of the local star-forming environments.
- "Variability" of disk structure is another key factor that can affect the planet formation.
- Systematic study on variability has just begun...
Primordial to debris disks

Disk lifetime

- Lifetime
  → constrain the timescale for planet formation
  → may affect inward migration

\[ t_{\text{disk}} = \exp(-t/\tau_{\text{disk}}) \]
\[ \tau_{\text{disk}} = 2.5 \text{ Myr} \]

Disk fraction vs. Age

Mamajek (2009)
Evolution Depends on Stellar Mass

- For higher-mass stars, giant planet formation should occur by 3 Myr and terrestrial planet formation could occur in ~3 Myr.
- Rapid dispersion → photoevaporation?

What infrared excess tells us

**Protoplanetary Disks**
- Disk fraction appears to decay with timescale of 2.5 Myr (exponential decay), but the lifetime could be stellar-mass dependent. Disks around lower mass stars can live longer.
- Large scatter in disk morphology and lifetime indicates significant dispersion in initial conditions of planet formation.
- Evolution could proceed from inside-out.

**Transitional Disks**
- Transition time from primordial to debris might be less than or similar to 1 Myr. The number of transition disks relative to primordial disks tends to increase with stellar age.
- Higher mass stars move to the debris disk phase faster than lower mass stars.

**Debris Disk**
- Higher frequency were observed for higher mass stars.
- Evolution appears to proceed from inside-out. Warm dust (< 30 micron) is rare for > 300 – 500 Myr stars.
- Connection to planetary systems is still unclear.
Direct Imaging of Planets

Images of planetary companions

Planets Orbiting HR 8799 (Sept. 2008)

Marois et al. (2008)

PA=30 deg

Kalas et al. (2008)

Lagrange et al. (2008)
Planetary Companion Candidates Imaged so far

<table>
<thead>
<tr>
<th>Star</th>
<th>Age (Myr)</th>
<th>Stellar mass (M_\odot)</th>
<th>Companion mass (MJ)</th>
<th>Projected Separation (AU)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fomalhaut</td>
<td>100—300</td>
<td>2.0</td>
<td>\leq 3</td>
<td>98 (~119)</td>
<td>Kalas et al. (2008)</td>
</tr>
<tr>
<td>HR 8799</td>
<td>60—150</td>
<td>1.5 ±0.3</td>
<td>7[5–11], 10[7–13], 10[7–13]</td>
<td>68, 38, 24</td>
<td>Marois et al. (2008)</td>
</tr>
<tr>
<td>β Pictoris</td>
<td>12</td>
<td>1.8</td>
<td>~8</td>
<td>8</td>
<td>Lagrange et al. (2008)</td>
</tr>
<tr>
<td>CT Cha</td>
<td>2±2</td>
<td>0.7</td>
<td>17±6</td>
<td>440</td>
<td>Schmidt et al. (2008)</td>
</tr>
<tr>
<td>AB Pic</td>
<td>~30</td>
<td>K2</td>
<td>~13</td>
<td>~260</td>
<td>Chauvin et al. (2004)</td>
</tr>
<tr>
<td>GQ Lup</td>
<td>&lt; a few</td>
<td>0.7</td>
<td>1 ~ 40</td>
<td>114±33</td>
<td>Neuhaeuser et al. (2005)</td>
</tr>
<tr>
<td>2M1207</td>
<td>8 ±4</td>
<td>0.024</td>
<td>5±2</td>
<td>55</td>
<td>Chauvin et al. (2004)</td>
</tr>
</tbody>
</table>

HR 8799b in 2002

Fukagawa et al. (2009)
Planet imaging with Subaru/HiCIAO

- Project: SEEDS (Subaru Strategic Explorations of Exoplanets and Disks Survey)
- 2 + 3 years
- AO188 + coronagraph
- Jupiter-mass bodies can be imaged
- contrast: $10^{-5.5}$ at 1"
- observing techniques optimized for planet detection (ADI, SDI) can be used
- Targets: PMS stars in SFRs, debris disks, nearby stars, open cluster members, nearby moving groups
- Science run starts from this fall