Fine Structures of Giant Planet Forming Regions around a Young Star of AB Aur

Jun Hashimoto
(National Astronomical Observatory of Japan),
M. Tamura, T. Muto, T. Kudo, M. Fukagawa,
T. Fukue, C. Grady, T. Henning, K. Hodapp, M. Honda,
S. Inutsuka, E. Kokubo, G. Knapp, M. W. McElwain,
M. Momose, N. Ohashi, Y. K. Okamoto, M. Takami,
E. L. Turner, J. Wisniewski, M. Janson,
and HiCIAO/AO188/SEEDS members
Introduction

• One of the key issues in planetary science is to understand “how planets form in disks”.
  – Core accretion model can successful explain giant planets at several AU (e.g., Pollack et al. 1996)
  – Recent direct detections of giant planets with $\sim 10 \, M_J$ at beyond the planet forming zone ($r > 20 \, \text{AU}$) (e.g., Marois et al. 2008)

• Difficulty of inner regions ($r < 100 \, \text{AU}$) of circumstellar disks.
  – Typical star forming regions (e.g., Taurus) : $\sim 100 \, \text{pc}$
    • Need to access the disk within 1 arcsec.
• Very little is known about inner regions ($r < 100$AU) of circumstellar disks.
  – Direct imaging at near-infrared has explored beyond $r > 100$AU.
  – Inner regions have not been easily accessible due to speckle noise.
• Dual-beam polarimetry allows us to investigate the inner regions of the disk.
  – Non-polarized speckle noise is automatically suppressed.
  – Only polarized light scattered at disks is detected.
Observations

- **Date:** Oct. 29th, 2009 at the beginning of SEEDS
  - SEEDS: Strategic observation of Subaru Telescope
- **Instrument:** 8m Subaru/HiCIAO
- **Target:** AB Aurigae (144 pc)
- **Mode:** Dual-beam polarimetry
- **Wavelength:** $H$ band (1.6 μm)
- **Resolution:** 0.06" (9 AU)
- **Occulting mask:** 0.3" diameter
- **Exposure time:** 189.6 seconds
- **PSF reference star:** HD282411
- **Accuracy:**
  - degree of polarization $\delta P < \sim 0.3\%$
  - polarization angle $\delta \theta < \sim 5^\circ$
AB Aurigae

• Well studied Herbig Ae star
  – distance 144 pc, age 3-5Myr, mass 2.4$M_\odot$
    (van der Ancker et al. 1997; deWarf et al. 2003)
• Rotating CO disk ($r \sim 450$AU) with mass of $\sim 20M_J$
  (Henning et al. 1998).
• Large nebula with $r > 1000$ AU (Grady et al. 1999)
• Spiral structures in the outer part ($r > 130$ AU) of the disk
  (Fukagawa et al. 2004)
Recent direct imaging of AB Aur

- Revealed inner disk structures \((r < 130 \text{ AU})\) by polarimetry
  - The disk at \(r < 40 \text{ AU}\) has not been accessible.
- **Planet candidate with** \(5 < M < 37 \text{ } M_J\) **was found in a gap region at** \(r \sim 100 \text{ AU}\) (Oppenheimer et al. 2008)
- No point source was found in a gap (Perrin et al. 2009)
Results of the outer structure

- Spiral arms (S1-8) are detected in Polarized Intensity (PI) image.
  - The morphology of the outer part in those images are consistent.
- Structures near the midplane of the disk
  - These images of scattering light trace surface of the disk due to optically thick.
  - Sub-millimeter observations reveal the some of spiral arms (Lin et al. 2006)
  - Our PI image also reflects the structures of the midplane of the disk
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The inner working distance ($r \sim 20$ AU) with the high resolution (9 AU)

- **Double ring** (dashed lines) and **ring-like gap** (solid line)
  - Ellipse shape due to the inclination
  - The inner ring ($i \sim 43^\circ$) might be warped relative to the outer ring ($i \sim 27^\circ$).
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Near side

Far side

Inclination
inner ring: \( 43.1^\circ \pm 6.8^\circ \)
outer ring: \( 26.8^\circ \pm 1.9^\circ \)
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- Ellipse shape due to the inclination
- The inner ring (\( \approx 43.1^\circ \pm 6.8^\circ \)) might be warped relative to the outer ring (\( \approx 26.8^\circ \pm 1.9^\circ \)).

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outer ring: \( 26.8^\circ \pm 1.9^\circ \)
Seven dips (Dip A to G) and three PI peak (P1 to 3)
- Newly found except Dip A
- No point-like source in Dip A, which is consistent with HST/NICMOS polarimetry (Perrin et al. 2009).
- The upper limit of companion masses at 5 $\sigma$ of the photon noise in Dip A are 5 and 6 $M_J$ for an age of 3 and 5 Myr, respectively (COND model; Baraffe et al. 2003).
- Dip A is confirmed in the total intensity image ($\sim 3 \sigma$).
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The origin of fine structures of the disk

- Gravitational Instability
  - Toomre Q parameter of \( \sim 10 \) (Lin et al. 2006) is not favored

- Disk-planet interactions
  - Planet in the disk excites the spiral density wave (e.g., Papaloizou et al. 2007)
    - High-mass planet can open the gap.
    - Resemble structures with our ring gap.

Simulation with the FARGO code (Masset 2000) by T. Muto.
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  – Observed warp in the inner ring can be explained by
    gravitational perturbation from unseen planets
    (Mouillet et al. 1997)

• Fine structures of disk including a double ring, a warp,
  and a ring gap are most likely due to planetary
  perturbation.
How to confirm?

- The pattern caused by a planet co-rotates with a planet.

\[
\omega = 0.78 \left( \frac{M}{2.4 \ M_\odot} \right)^{1/2} \left( \frac{r_p}{80 \ \text{AU}} \right)^{-3/2} \text{ (deg yr}^{-1}\text{)}
\]

- \( M \) is a mass of central star, \( r_p \) is an orbital radius of a planet

- We can observe this variability in the next several years
Summary

• We have conducted the dual-beam polarimetry of the prototype young star AB Aur.
  – Both the inner working distance ($r \sim 20$ AU) and the resolution (9 AU) are better than previously achieved.
  – A double ring, a ring gap, and a warp structures discovered in the disk.
  – These fine structures of the disk suggest giant-planet formation in the disk.

• We demonstrate that we are able to investigate the planet forming regions of wide-orbit planets ($r > 20$ AU)

Future Work

• Revealing fine structures of more disks at $r > 20$ AU.
• Understanding the formation mechanisms of the wide-orbit planets