Near-Infrared Polarimetric Imaging of Disks around Young Intermediate-mass Stars in SEEDS

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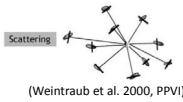
Abstract. We present our recent results to directly image circumstellar disks around Herbig Fe/Ae stars in scattered light with Subaru. Observations of such young disks are critically important to understand how disks evolve possibly under the mutual interaction with new-born planets. One of the observational approaches is direct imaging in scattered light, and the progress in this field since PPV can be found in the ability to prove inner regions of disks. This improvement largely owes to the technique of polarization differential imaging (PDI). The SEEDS PDI observations have newly uncovered rich structures such as spiral arms, inner holes, and gaps for (pre-)transitional disks while suggested the variably illuminated disks for primordial systems. The highlight is the discovery of two spiral arms each for SAO 206462 and MWC 758. The spiral feature has been uniquely found toward Herbig Fe/Aes so far, which might be due to their warmer disks producing arms loosely wound and more easily detected. The observed morphology can be interpreted by the density-wave model, and those disks are implied to harbor Jupiter-mass companions as the exciting sources of the spiral structures according to these models.

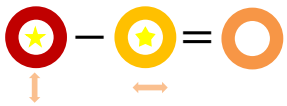
Observations - PDI

- Project: Strategic Exploration of Exoplanets and Disks with Subaru (SEEDS)
- Subaru/HiCIAO + AO188
- Polarization differential imaging (PDI), two-beam
- *H* band (1.64 μm)
- FWHM = 0.06" = 8 AU at 140 pc (typical)
- Coronagraphic mask of 0.3" in diameter (w/o a mask only for HD 142527)
- Inner working angle r ~ 0.2" = 30 AU at 140 pc (typical)
- PDI in *J* and *Ks* band, and ADI (total intensity) observations were supplementary obtained for a few sources.



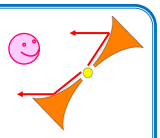
(Weintraub et al. 2000, PPVI)

Scattered light is polarized, while starlight is unpolarized.



Observable: Polarized intensity (PI) = (Intensity) × (Pol. degree)

Direct imaging in scattered light



- High-angular-resolution is the key to unveil detailed structure. The resolution of less than 0.1" can be obtained in opt/NIR with a large aperture telescope and adaptive optics from the ground.
- Light scattered by dust grains in the upper layer of an optically thick disk
  → disk structure (dynamics): radial: hole, gap etc., vertical: flat vs. flared
  → grain property (material): size, composition

Sample summary

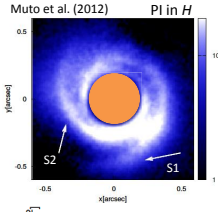
Targets consist of Herbig Fe/Aes with ages of ~2–8 Myr. Most of the Meeus group I sources (Meeus et al. 2001) are pre-transitional systems, and showed gaps and /or spiral arms in our observations.

Source	Sp	d (pc)	*i* (CO)*	*R* range of PI detection	Index (p) of radial surface brightness; r^{-p}	Observed structure
Meeus group I						
AB Aur	A1	140	~30	0.15"—3.85"	1.5±0.1 (PA~60°; major) 2.0±0.2 (PA~330°; minor)	gap, spiral, envelope
MWC 758	A8	200/280	21±2	0.2"—0.8"	5.7±0.1 (east) 2.8±0.1 (west)	spiral
HD 34282	A0	350	56±3	0.2"—1.1"	2.2—2.5 (major)	envelope
SAO 206462	F4	140	~11	0.2"—1.0"	1.7—2 (PA=55°; major) 3.1—3.6 (PA~145°; minor)	spiral
HD 142527	F6	140	~30	0.55"(IWA)—1.7"	5.1±0.2 (PA=60°, >1") 7.2±0.4 (PA=–120°, >1.1")	hole, spiral, envelope (low-res. optical data)
HD 169142	A9	140	13	0.2"—1"	2 (azimuthally averaged)	gap
Meeus group II						
MWC 480	A5	170	38	0.2"—1"	2.8/2.0 (PA=150°; major) 3.1/1.7 (PA=30; major)	no distinctive structure
HD 163296	A0	120	45	—	—	non-detection

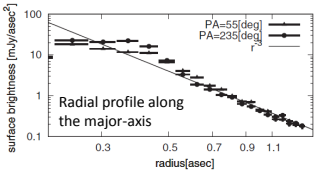
* Inclination from CO measurements: Tang et al. (2012), Isella et al. (2007, 2010) , Pietu et al. (2003, 2007), Panić et al. (2008)

SAO 206462

Muto et al. (2012) PI in *H*



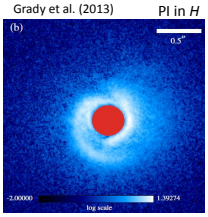
Two non-axisymmetric spiral structures are indicated by white arrows.



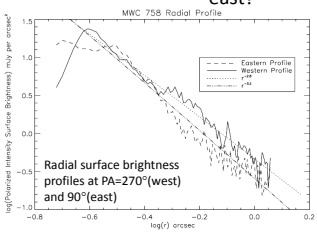
- ✓ Spiral arms were detected
- ✓ Total PI of 9.87 mJy ± 0.06%. Combined with HST NICMOS data of total intensity, the disk's total polarization fraction is ~20—40%.
- ✓ Scattered light found within the submm cavity

MWC 758

Grady et al. (2013) PI in *H*



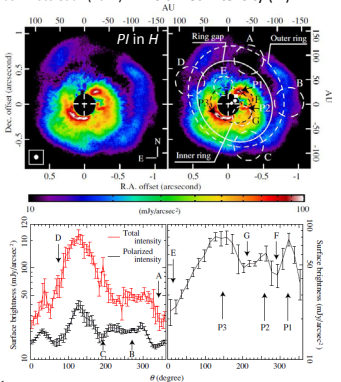
- ✓ Two arms were detected
- ✓ Asymmetric distribution: greater extent toward west. Shadowing by the arm in east?



- ✓ Integrated PI (r > 0.2") = 0.09% relative to the star
- ✓ Scattered light found within the submm cavity

AB Aur

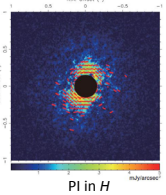
Hashimoto et al. (2011) Polarized intensity (PI) in *H*.

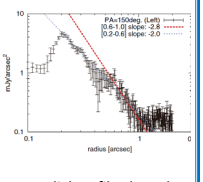


- ✓ A double ring structure at r~40 AU and ~110 AU and a wide gap at r ~ 80 AU between the rings
- ✓ The inner ring (i=43°±7°) might be warped relative to the outer ring (i=27°±2°)
- ✓ Scattered light found within the submm cavity

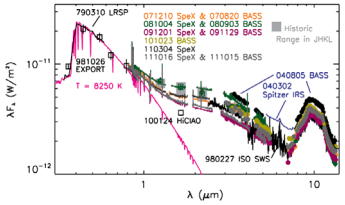
MWC 480

Kusakabe et al. (2012)





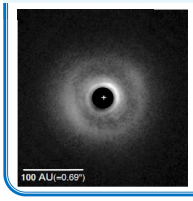
Radial profile along the major-axis



- ✓ At the epoch of the disk detection, the NIR excess was at a historic low. The only marginal detection was obtained in 1998 by HST/NICMOS.
  → Variable illumination?

HD 169142

Momose et al. in prep.



- ✓ A gap between 0.35"—0.6"
- ✓ Azimuthally-averaged radial profile in the inner (r < 0.35") or outer (r > 0.6") regions can be fitted well with a power-law of r^{-2}, but that between the gap) is almost flat.
- ✓ At r ~ 0.25", the northwestern part is much brighter than the southeastern part. The opposite trend is found at r ~ 0.55".

Spiral arms (SAO 206462, MWC 758)

Muto et al. (2012), Grady et al. (2013)

- Fitting based on density-wave theory

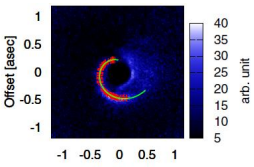
$$\theta(r) = \theta_0 + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left[\left(\frac{r}{r_c} \right)^{1+\delta} \left\{ \frac{1}{1+\delta} - \frac{1}{1-\gamma+\delta} \left(\frac{r}{r_c} \right)^{-\gamma} \right\} - \left(\frac{1}{1+\delta} - \frac{1}{1-\gamma+\delta} \right) \right]. \quad (4)$$

(r_c, θ_0) : corotation point (~launching point of the spiral)
$\Omega(r) \propto r^{-\gamma}$: disk rotation profile (1.5 for Keplerian)
$c(r) \propto r^{-\delta}$: disk sound speed profile
hc : disk aspect ratio (H/r) at the corotation radius

- Mass of a putative perturber; assuming a perturbing body excites the spiral arm

$$M_p / M_* = (\text{Pattern Amplitude}) (h_c)^3$$

A pattern amplitude from the surface brightness contrast of the arm
→ a perturber mass: 0.5 M_{Jupiter} for SAO 206462, 5^{+3}_{-4} M_{Jupiter} for MWC 758



The fitting was performed on the surface brightness of the scattered light normalized by r^2. The points that represent the spiral shape are shown by red points, the shape of the spiral given by Equation (4) with the best-fit parameters is shown by green curves.

Best-fit external perturber

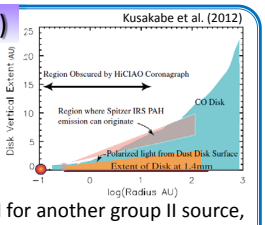
	SAO 206462 S1	SAO 206462 S2	MWC 758 South
r_c	0.39"	0.9"	1.55"
θ_0	204°	353°	9°
h_c	0.08	0.24	0.18

Note: It is *assumed* here that scattered light traces the surface density. ALMA will enable us to study the density structure.

Variable illumination (MWC 480, HD 163296)

- An anti-correlation between the height of the dust disk near the sublimation radius and the degree of illumination of the outer disk is expected only when the dust disk has settled toward the midplane. Our data constrain the opening half angle for the disk of MWC 480 to lie between 1.26° ≤ θ ≤ 2.2°. When compared with similar measures in CO for the gas disk from literature, the dust disk subtends only ~30% of the gas disk scale height (h/r ~ 0.03), much flatter than gapped transitional disks.

Kusakabe et al. (2012)



- PDI for another group II source, HD 163296, resulted in a non-detection of the disk. It may also be due to variable illumination (Wisniewski et al. 2010).