Discovery of a Nearly-Edge-On Disk around the Young Fe Star PDS 453

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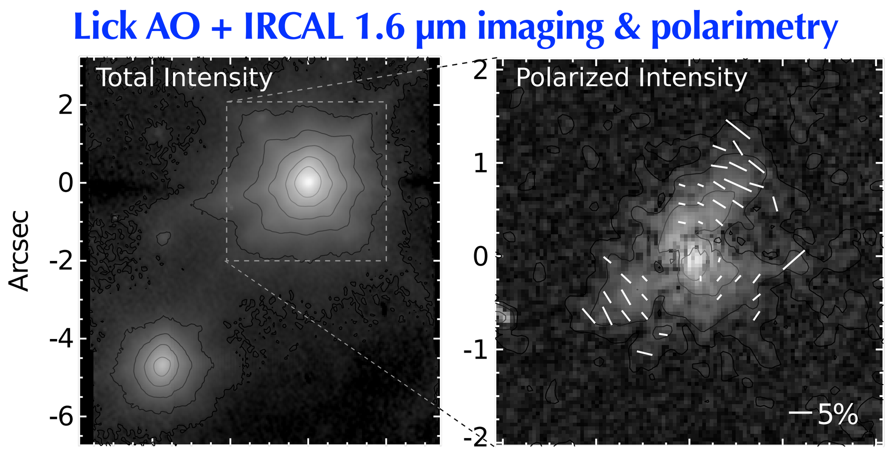
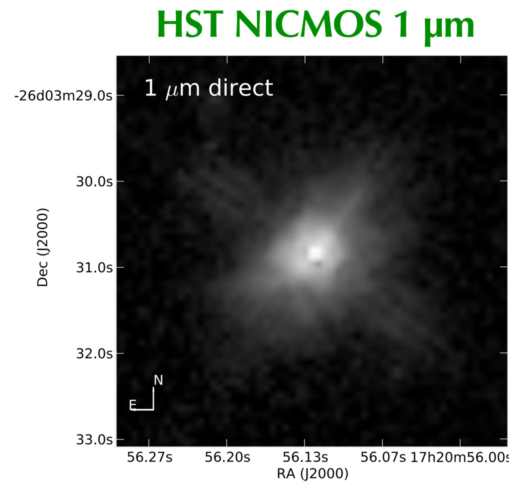
We present the first images of a protoplanetary disk around PDS 453, a young F2e star. Our high-contrast imaging reveals a highly inclined disk ($i \sim 80°$) with a radius of ~220 AU assuming a distance of 140 pc, and a sharp outer edge potentially due to truncation by a nearby candidate companion. As one of only three resolved disks around F-type stars, PDS 453 will be an important link between disk properties observed around T Tauri and Herbig Ae stars.

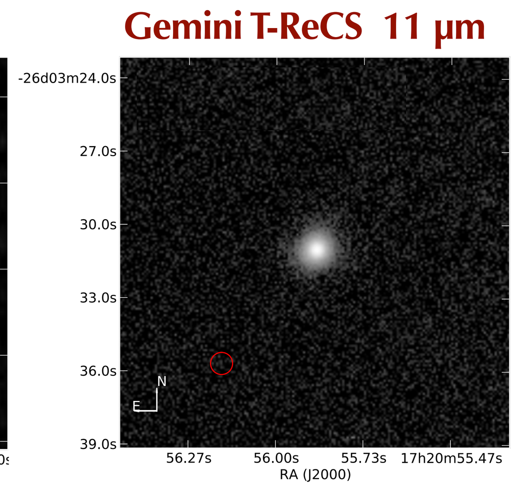
Lick AO + IRCAL 1.6 μm imaging & polarimetry



HST NICMOS 1 μm



Gemini T-ReCS 11 μm

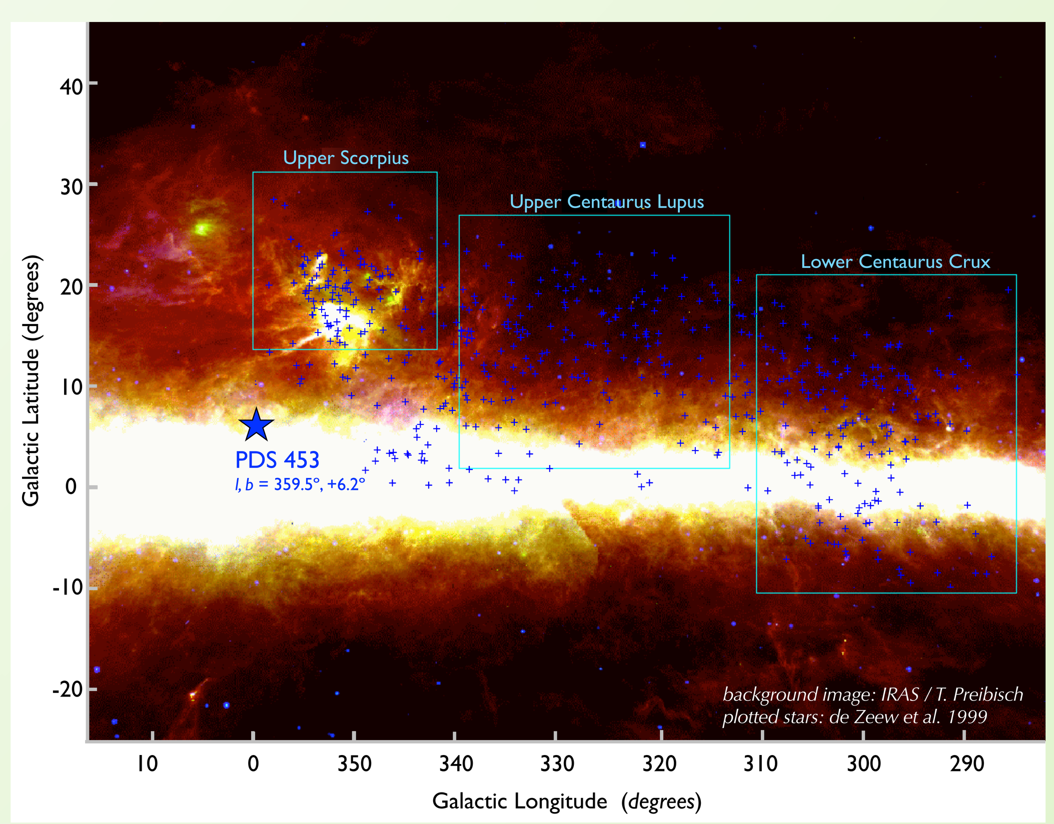


- Identified as F2e YSO in the Pico dos Dias Survey (PDS; Vieira et al. 2003)
- Disk first imaged using **Lick AO + IRCAL** polarimeter (Perrin 2006, 2008) revealing an elongated "butterfly" nebula in polarized light **(above left)** indicative of a nearly-edge-on disk.
- Re-observed at 1 & 2 μm with **HST NICMOS** in 2008. The disk is bright enough relative to the star to be visible in *direct, non-coronagraphic* images **(above center)**, with about 25% of the 1 μm flux in the extended component. See at right for deep coronagraphic images from NICMOS, including the new coronagraphic polarimetry mode (Schneider & Hines 2007).
- Observations at 8 & 11 μm with **Gemini South T-ReCS** in 2009 were unable to resolve the disk (due to poor seeing in Band 3 conditions), but confirm that essentially all of the flux at 12 μm detected by IRAS in this area is due to PDS 453 **(above right)**.
- There is a potential companion 5" southeast, but physical association remains unclear. This star, 2MASS 17205641-2603354, shows no evidence for excess infrared emission from dust, being 2 mag fainter than PDS 453 at *H*, but >12 mag fainter at 11 μm (and undetected).
- PDS 453's disk shows a sharp outer edge, perhaps due to interaction with this companion? Intriguingly, that star's relative position angle is precisely aligned with the disk's major axis, suggesting possible coplanarity of the orbit and disk planes, if it is indeed bound.

Location & Age

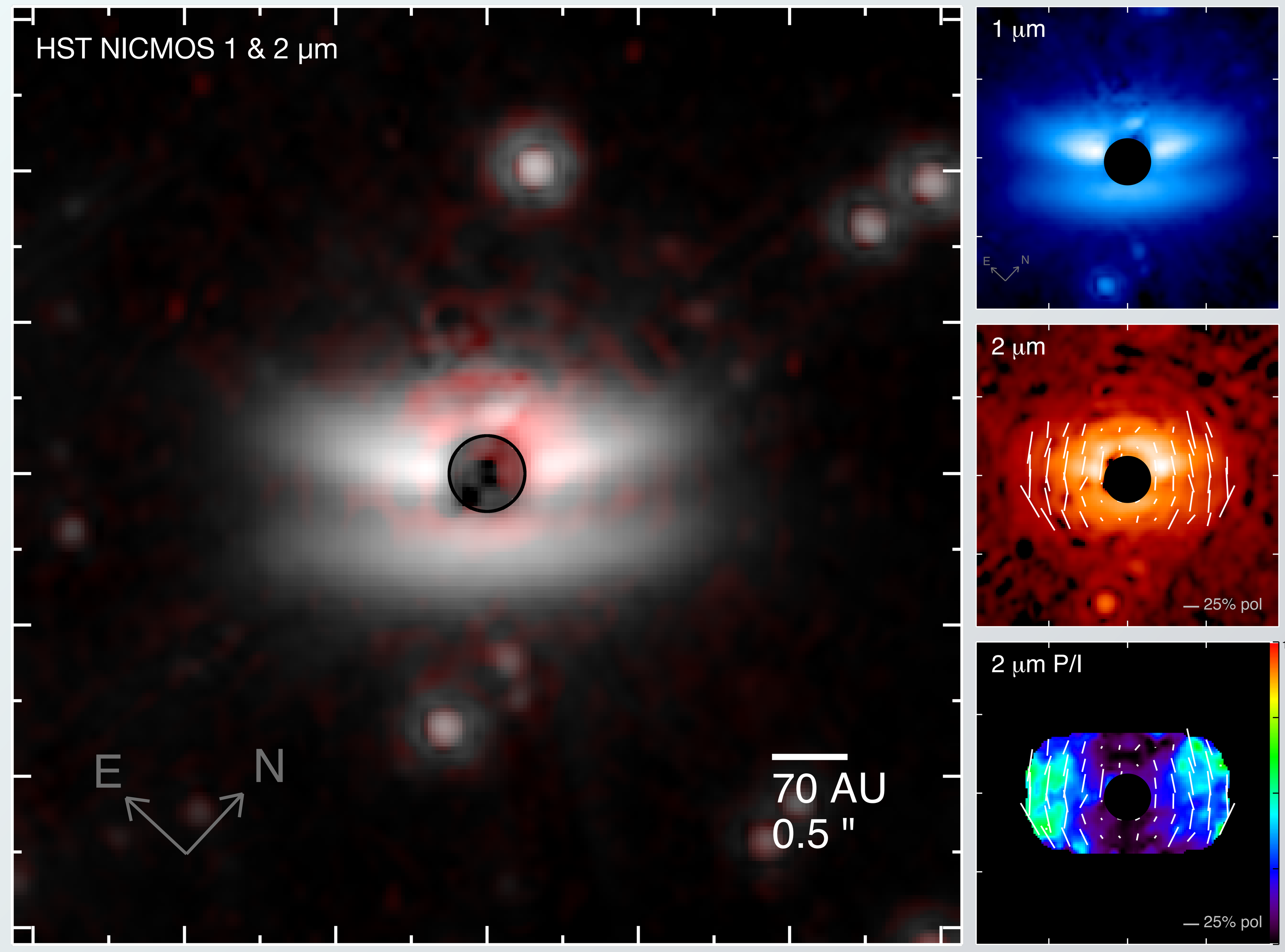
PDS 453 is located near the edge of the galactic plane at almost precisely $l=0°$. This places it apparently on the outskirts of the Sco-Cen OB association, though in fact it is close enough to the galactic plane that almost any distance is plausible.

For now we adopt Sco-Cens' 140 pc distance as our best estimate; SED modeling (at right) shows this appears consistent with the data, but uncertainties remain quite large.



Above: PDS 453's apparent position shown in a wide-field IRAS mosaic. The three sub-regions of Sco-Cen are indicated following Preibisch & Mamajek, with blue crosses indicating probable member OB stars from Hipparcos (de Zeeuw et al. 1999).

PDS 453 appears closest to the Upper Sco subgroup with age ~ 5 Myr (see Preibisch & Mamajek 2008). Optically thick disks are still commonly seen around many stars at that age, while very few disks are seen at the 16-17 Myr ages characteristic of the UCL and LCC subgroups. We therefore consider it most probable that PDS 453 is associated with USco and is approximately 5 Myr in age. Its formation may have been triggered by SN shock waves from UCL, as is suspected to be the case for the main USco population.



Above: NICMOS coronagraphic imaging and polarimetry of PDS 453 allows us to detect the disk from 0.15" - 1.6". The disk is nearly edge-on, with the northeast face the closer and brighter to us. Assuming a distance of 140 pc, the observed disk outer radius is ~ 220 AU. The disk appears smooth and lacks obvious perturbations, though it is slightly brighter on the SE side than the NW.

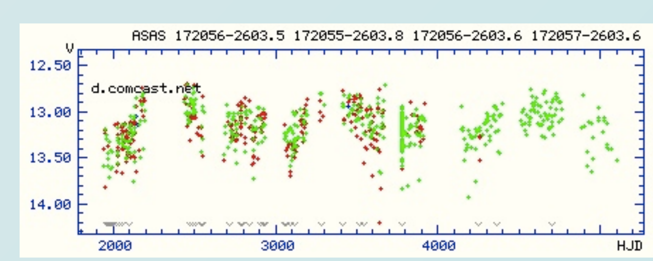
At 2 μm there are more PSF residuals than at 1 μm, due to optimization of the NICMOS coronagraph for shorter wavelengths, but the disk is still clearly detected in both total and polarized light. Based on preliminary measurements, the disk's color is bluer than the star, suggesting scattering by small (submicron) particles. Polarization at 2 μm increases with distance from the star, rising from 5-10% along the minor axis to ~ 60% near the outer edge of the disk.

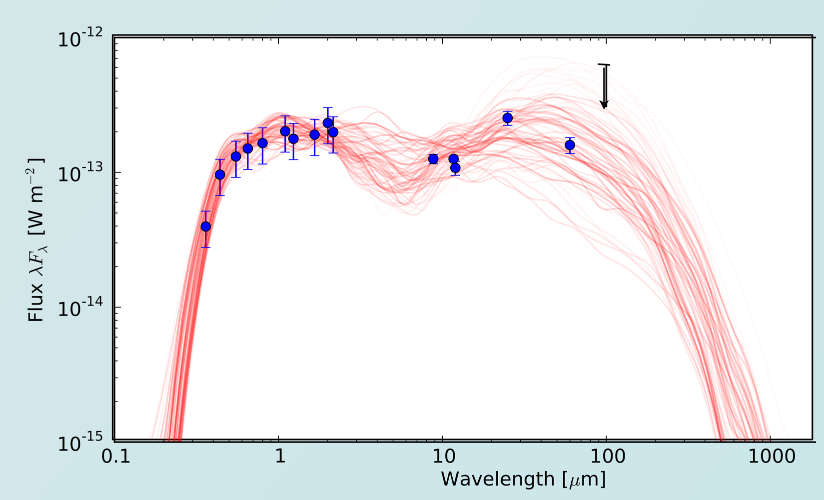
Spectral Energy Distribution

We assembled the SED for PDS 453 using fluxes from Vieira et al. 2003, the USNO-B1, 2MASS and IRAS surveys, and our own observations with IRCAL, HST, and Gemini GMOS. The SED is essentially flat from 0.5-60 μm.

PDS 453 shows evidence for ~1 mag variability at all wavelengths <2.5 μm; the error bars on the plot at left indicate the observed flux ranges. Variability is confirmed by time series photometry from ASAS3. We hypothesize this variability may result from time-dependent shadowing and opacity variations due to the line of sight grazing along the top edge of the disk.

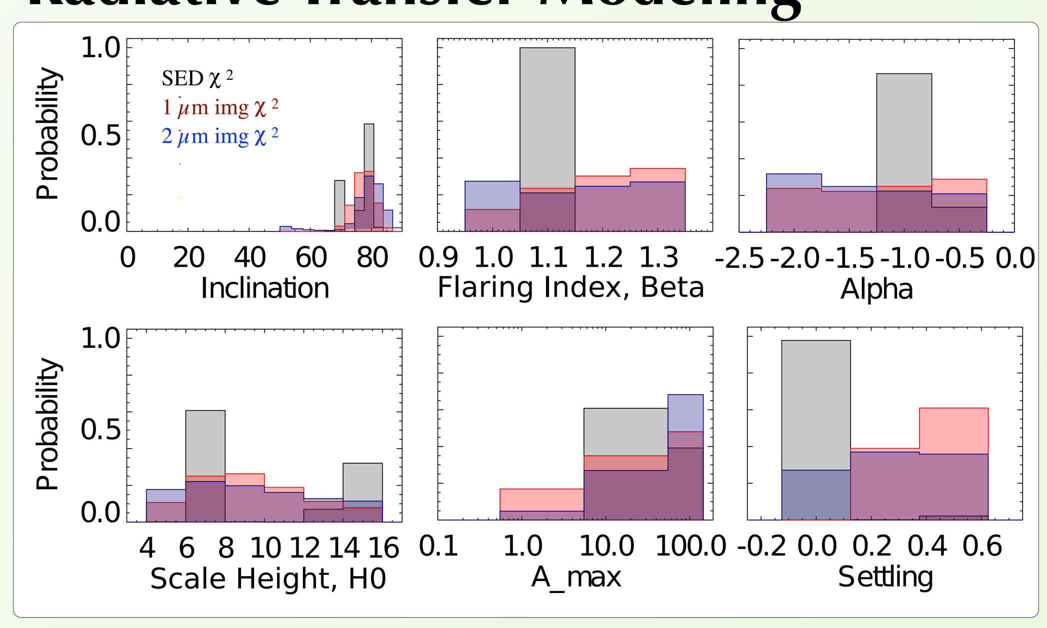
Additional photometry and spectra from 3-10 μm and >100 μm are needed to better constrain models.

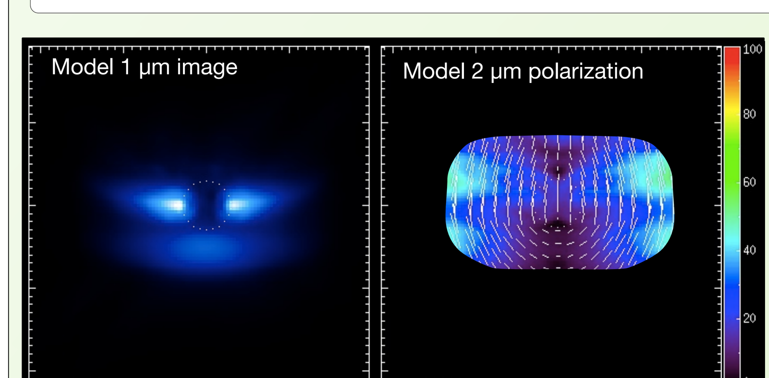




Above: SED for PDS 435, along with model SEDs computed for the best-fitting 100 models in our grid (below). While there is still much room for improvement, particularly at long wavelengths, these models demonstrate that the observations are consistent with an F2 star at 140 pc with about 0.5-2 mag. extinction. **Left:** Light curve from the ASAS3 survey (Pojmanski 2002) showing > 1 mag variability of PDS 453 in V band, with no clear period.

Radiative Transfer Modeling





Model Grid Parameter Values

Inclination	52-89° in 12 steps
Dust Mass	10^{-5} to 10^{-3} M_{sun} in 5 steps
Flaring index (beta)	1.0, 1.1, 1.2, 1.3
Surface Density index (alpha)	-2, -1.5, -1, -0.5
Settling index	0, 0.25, 0.5
Grain A_max	1, 10, 100 μm
Scale height H0 (at 100 AU)	5, 7, 9, 11, 13, 15 AU

We computed model SEDs and 1 & 2 μm images using the MCFOST radiative transfer code (Pinte et al. 2006), for 50,000 model parameter sets as listed below. We calculated χ^2 values for each model based on the SEDs and images, and derived marginal probability distributions for the free parameters using Bayesian statistics, as described in Pinte et al. 2008.

Broadly speaking, our best fit models can reproduce fairly well the SED (shown above), and image morphology and polarization levels (left).

The SED and image calculations all yield consistent best-fit inclinations, 79° ± 3°. While the image fits do not constrain the disk flaring or radial power-law indices, fitting the SED requires beta ~ 1.1 and alpha ~ -1.

The SED fits find two distinct families of solutions, one with scale height ~ 7 AU at r=100 AU and maximum grain size 10 μm, and another with twice the scale height using a dust population with maximum grain size 100 μm (thus lower specific opacity). The distinct families of solutions are likely an artifact of the discrete sampling chosen for A_{max}. At present, the SED is fit best using no dust settling (i.e. dust and gas are well mixed); the image fits suggest some settling but further analysis is needed to confirm this.

Further modeling and analysis is ongoing, along with additional observations. Stay tuned!

Acknowledgements

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