Constraining brightness asymmetries with MATISSE/VLTI in protoplanetary disks at solar system scales

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Introduction

Several scenarios for the formation and evolution of planets are discussed in the literature. For jovian planets, the two competing, most commonly used theories are known as the 'cold' and 'hot start' scenarios, corresponding to the formation and evolution via core accretion and gravitational instability, respectively. The luminosity of forming, embedded planets can be used to approximate their entropy, which has a diagnostic character for the two formation processes. Therefore, the detection and analysis of protoplanets is essential to verify selected stages of the theoretically predicted planet formation scenarios.

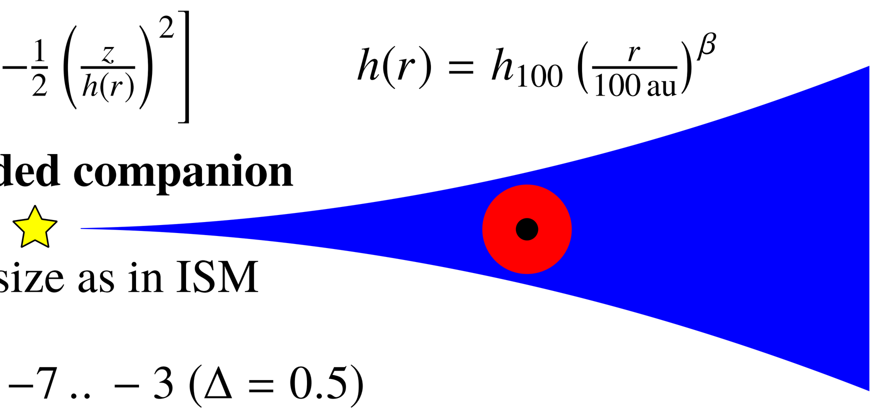
We study the feasibility to detect disk asymmetries potentially caused by embedded protoplanets at solar-system scales using MATISSE/VLTI.

Model

Disk geometry Symmetric density distribution (Shakura and Sunyaev, 1973)

$$\varrho(r,z) = \varrho_0 \left(\frac{r}{R_0}\right)^{-\alpha} \exp\left[-\frac{1}{2}\left(\frac{z}{h(r)}\right)^2\right] \qquad h(r) = h_{100}\left(\frac{r}{100\,\mathrm{au}}\right)^{\beta}$$

Heating sources T Tauri star and **embedded companion**



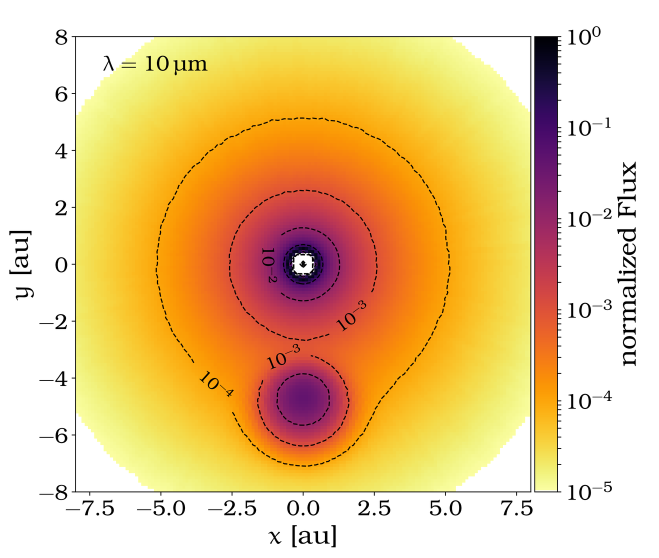
Dust properties Composition and grain size as in ISM

Parameter space
Dust mass $\log M_{\mathrm{dust}}/M_{\odot} = -7 \,..\, -3$ ($\Delta = 0.5$)
Distance star–companion r = 1, 2, 5 and 10 au
Temperature T_C and luminosity L_C of companion (see table below)

	T_c [K]	L_c [$L_{\odot}$]		T_c [K]	L_c [$L_{\odot}$]		T_c [K]	L_c [$L_{\odot}$]
$\mathcal{A}$	4400	1.0	$\mathcal{F}$	2500	$2.9\cdot10^{-2}$	$\mathcal{K}$	1500	$3.0\cdot10^{-4}$
$\mathcal{B}$	4000	$4.0\cdot10^{-1}$	$\mathcal{G}$	2500	$1.4\cdot10^{-3}$	$\mathcal{L}$	1500	$7.7\cdot10^{-5}$
$\mathcal{C}$	3500	$1.5\cdot10^{-1}$	$\mathcal{H}$	2120	$2.8\cdot10^{-2}$	$\mathcal{M}$	1000	$1.0\cdot10^{-4}$
$\mathcal{D}$	3000	$5.0\cdot10^{-2}$	$\mathcal{I}$	2000	$9.1\cdot10^{-4}$	$\mathcal{N}$	1000	$1.8\cdot10^{-5}$
$\mathcal{E}$	3000	$4.5\cdot10^{-3}$	$\mathcal{J}$	2000	$3.0\cdot10^{-4}$	$\mathcal{O}$	500	$5.0\cdot10^{-6}$

- Companions: From evolutionary tracks of planets and brown dwarfs (Burrows et al., 1993, 1997)
- L_C: Sum of intrinsic, accretion, shock, and circumplanetary disk luminosity

Model comparison with PDS 70b



Examplary simulated brightness distribution for companion $\mathcal{B}$ at $\lambda = 10\,\mu$m

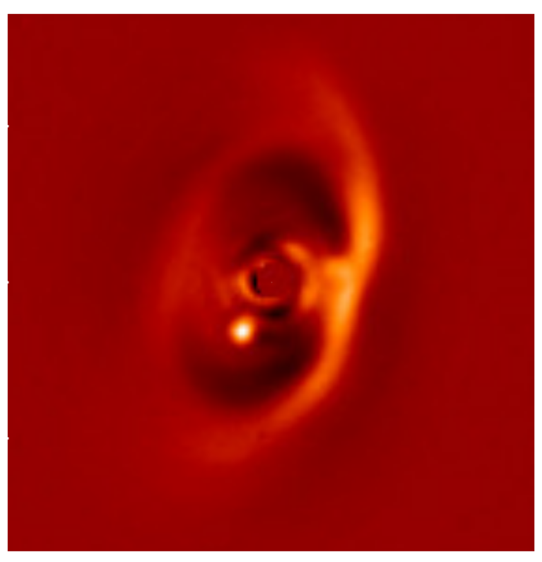
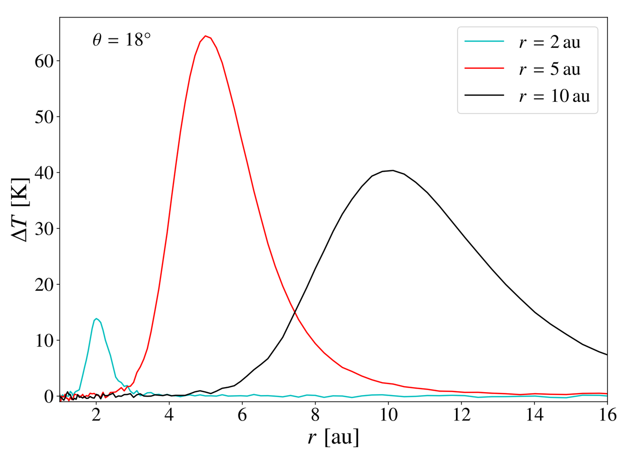
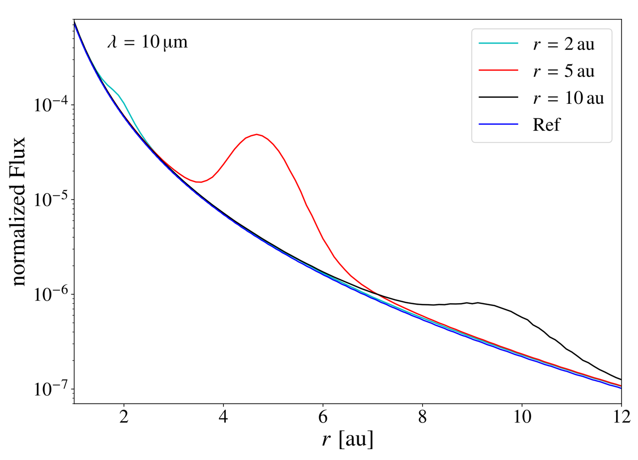


Image of the first approved embedded protoplanet PDS 70b (Müller et al., 2018)

Temperature and intensity profile



Temperature offset due to companion $\mathcal{F}$ at the $\tau_{10\,\mu\mathrm{m}}$ = 1-layer (as seen from the observer)

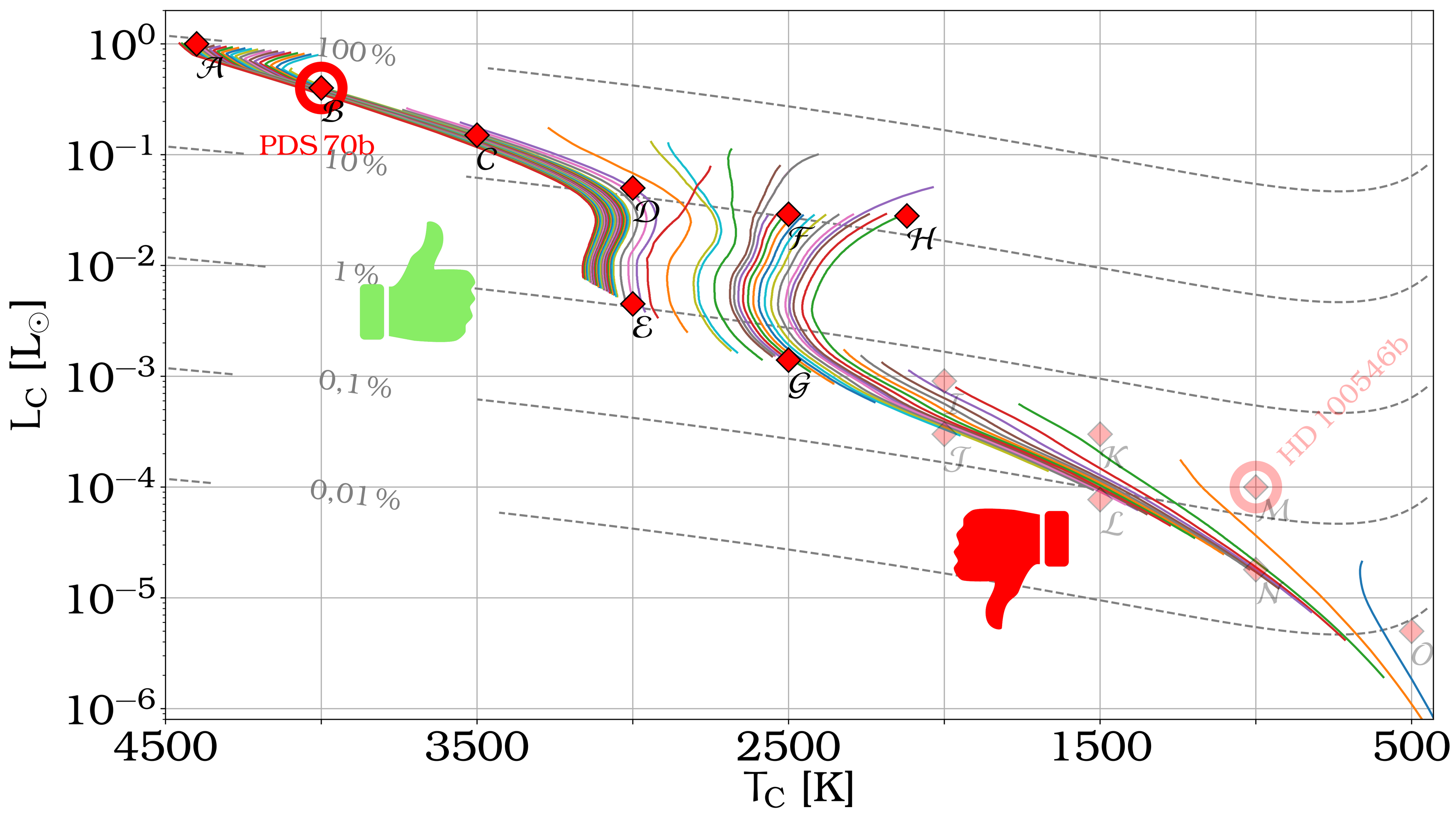


Radial flux profile for different stellar separations of the companion $\mathcal{F}$

Procedure

I Disk model with embedded companion
II Dust temperature, intensity maps via 3D radiative transfer with `Mol3D` (Ober et al., 2015)
III 2D Fast Fourier Transform of intensity maps
IV Evaluation at baselines given by the VLTI UT configuration
V Comparison of visibility and closure phase of disturbed and undisturbed disks

Results



- 8 out of 15 companions detectable
- Minimum flux ratio $F_{\star}/F_{\mathrm{companion}} = 0.5$ % → mid- to high-mass jovian planets
- PDS 70b: Detectable with MATISSE
  HD 100546b: No detection possible

Highest propability to detect companions:

- $r \approx 2$–5 au
- $M_{\mathrm{dust}} \lesssim 1\cdot10^{-4}\,M_{\odot}$
- Closure phase: Higher SNR than visibilities

Conclusion

- MATISSE: Feasibility to directly detect embedded protoplanets and circumplanetary disks
- High spatial resolution: Significant orbital changes after few months
- Combination with ALMA: High-resolution, multi-wavelength description of forming planets and its physical properties, eg. luminosity and temperature
- Combination with high-contrast imagers, eg. SPHERE: High-quality investigation of planet-disk interactions to estimate planetary masses and disk viscosity

Ideal to verify planet formation theories

References

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Questions? I am somewhere close by, **feel free to ask!**