Planet Formation from 100 AU to protoplanet surfaces

ESO Expanding Horizons White Paper

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Introduction

Beyond the 2040s, the ELT's first decade of operation will transform our understanding of planet formation, just as the commissioning of ALMA did in the 2015s. Yet, fundamental physical processes will likely remain difficult to reach, even in the ELT era, namely 1) Planet migration processes 2) Rocky planet formation 3) Resolved planet accretion and circumplanetary environments. Time-domain photometry or spectroscopy surveys will not be able to address the fundamental questions in planet formation, as those techniques do not provide spatially resolved observations. For all those processes, the key factors are angular resolution and observations, infrared wavelengths which traces the scattered light and thermal emission of the disk and the thermal emission of protoplanets, and collecting area which drives sensitivity.

From 100 AU to from Young Planets formation at 1AU

The recent years have shown that planet formation is an extremely dynamic process. On larger scale, multiplicity, large gas streamers, and even fly-bys probably play an important role in the disk formation and evolution (Cuello et al. 2023). Current instruments (VLT/I, ALMA) start constraining the dynamical interaction between the disk and the companion and benchmark our theoretical models (Price et al. 2018). In the mid-term, with the detection of new protoplanets in the GRAVITY+ and ELT era, it will be possible to study the interplay between giant planets and the disk substructures, which we know are ubiquitous in disks (Benisty et al. 2023).

Beyond the 2040s, the next advances will come from:

- High-Contrast capability: increased sensitivity to protoplanets closer-in $< 1\mathrm{AU}$, to increase our sample of protoplanets
- High-precision astrometry down $1\mu\mathrm{as}$ to study dynamical effects, disk-planet interaction and planet migration. We note that those new observations will be very complimentary to the ELT observations which will be able to observe the low-brightness, extended structures of the disk where those planets evolve and with which they interact.

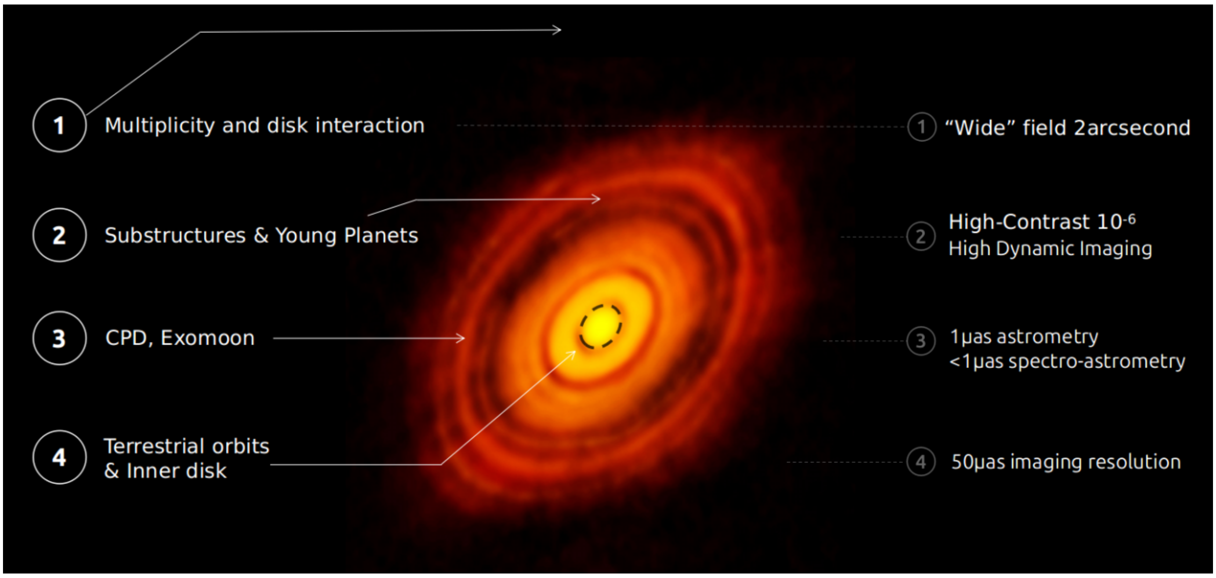

Figure 1: Planet formation studies with a Kilometer Baseline Interferometer, corresponding requirements are indicated on the right.

From Planetary Architecture to rocky planet formation down to 0.05AU

Current VLT and ALMA observations reveal for the first time the disk structures and the first directly image protoplanets in disks - e.g. HL Tau (ALMA Partnership 2015), PDS 70 (Keppler et al. 2018). However, those observations are essentially limited to the outer disk, which are not typical of the scales where our Solar Sytem formed. The ELT instruments will be able to probe the first inner AUs of protoplanetary disks, at typical scales where giant planets are located (at the distance of common star forming regions, 140pc). Yet, the bulk of the mass of currently detected planets by Kepler/TESS (transits) is enclosed below 1AU. In 2040, it will be necessary to gain more than an order of magnitude compared to ELT/MICADO and ELT/METIS in order to fully resolve and image the regions where the bulk of rocky planet forms.

Therefore, the next advances in order to understand rocky planet formation will come from:

- Imaging capability with $100\mu\mathrm{as}$ angular resolution
- High-dynamical range imaging, in the infrared where the emission of the disk peaks.

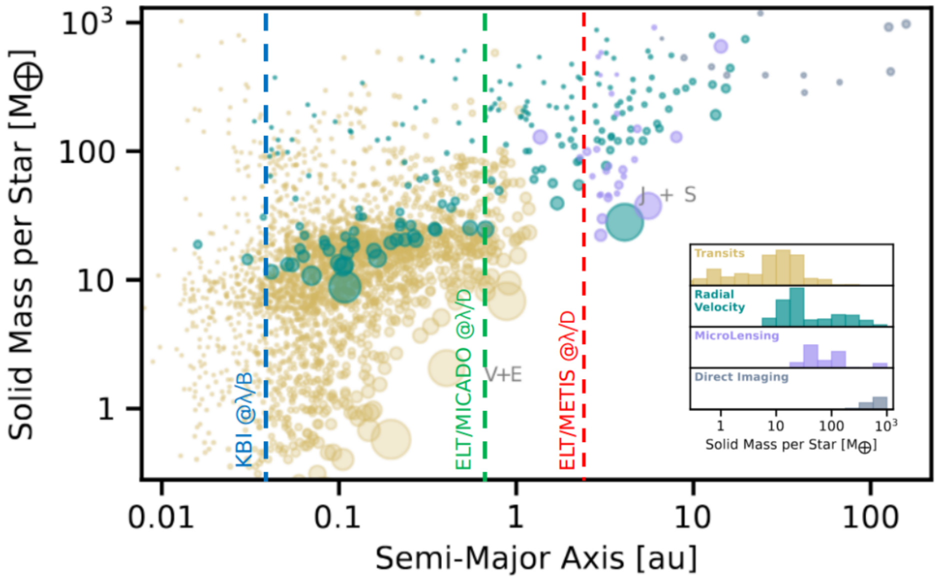

Figure 2: adapted from Drazkowska et al. 2023 (PPVII), solid mass of exoplanets around sun-like stars from different detection methods. The bulk of currently detected planets is located beyond the resolution of ELT instruments (assuming a d=140pc).

From 0.05AU to circumplanetary disk and planet accretion

The final stage of planet formation, after the accretion of pebbles in a core, is the accretion of material by the planet from the surrounding protoplanetary disk. Currently, both observations and numerical models support the existence of a Circumplanetary Disk (CPD) where the planet accretion takes place (Marleau et al. 2025), although little is known about the accretion processes at play in those structures. Spectroscopic monitoring are good tracers of the accretion processes at play (Demars et al. 2023), however the definitive proof of the existence of CPD was obtained with spatially resolved observations with ALMA (Benisty et al. 2021). In the 2040s, with the increased sample of protoplanets with the ELT, it will be possible to focus studies from currently on giant planets - PDS 70-like - to lower mass, potentially $< 1\ \mathrm{M_j}$ planet.

The next improvement beyond the ELT will be:

- Spectro-astrometry with $1\,\mu$as accuracy on Jupiter-size protoplanets, allowing to obtain spatially resolved of the accretion tracers onto the planet itself (e.g. Br-γ, Br-α, see Figure 3) .

Beyond ELT: a Kilometer Baseline Interferometry array

Kilometer Baseline Interferometry (KBI) will provide a transformative improvement for the study of planet formation beyond the ELT. Sub-millimeter observations are not sensitive to the thermal emission of the planet itself, and cannot possibly reach the sub-milliarcsecond angular resolution and astrometry accuracy required here, hence favoring the infrared wavelength coverage. By providing $100\,\mu$as imaging resolution, $1\,\mu$as astrometry accuracy and $< 1\,\mu$as spectro-astrometry capability, KBI will address fundamental questions on planet formation in the 2040s, on planet migration, rocky planet formation and planet accretion. At the same time, combination of KBI and ELT will provide powerful synergies, as ELT instruments will be able to provide detection of protoplanets and deep imaging of low-surface brightness structures in the disk by then.

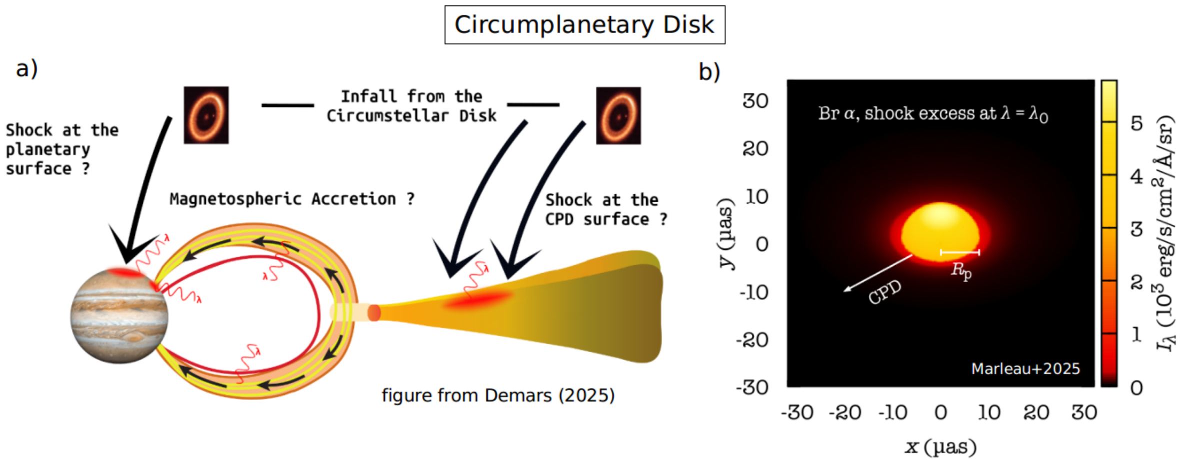

Figure 3: a) accretion process on planet, from Demars (2025), adapted from Hartmann et al (2016). Planet accretion shares similarities with magnetospheric accretion on young stars ; b) from Marleau (2025): Intensity of the emission in Br-alpha for a PDS 70b-like system. The total flux is dominated by the central region $r \approx 4\,\mathrm{R_{jup}}$.

References

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