Signatures of Planets and of their Formation Process in Circumstellar Disks

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Planet Formation in a Nutshell

Star Formation Process → Circumstellar Disks → Planets

Core Accretion – Gas Capture

- Brownian Motion, Sedimentation, Drift
- Inelastic Collision → Coagulation

- Agglomeration;
  Fragmentation

- Gravitational Interaction: Oligarchic Growth

- Gas Accretion

Alternativ: Gravitational Instability → Giant Planet
**Size Scales**

**Solar System**

Angular diameter of the orbit of solar system planets in a distance of the Taurus star-forming region (140pc):

- Neptune: 0.43"
- Jupiter: 0.074"
- Earth: 0.014"

**What is feasible?**

- AMBER / VLTI: ~ few mas [near-IR]
- MIDI / VLTI: ~ 10 – 20 mas [N band]
- SMA: ~ 0.3” (goal: 0.1”) [~submm]
[Wolf et al., subm.]

constraints on radial + vertical disk structure in the potential planet-forming region (r~80-120AU)
Dust Evolution – The Planet Forming Region

Van Boekel et al. (2004): HAe/Be stars
Schegerer et al. (subm.): T Tauri Stars
Vortices – Precursors of Protoplanets?

Klahr & Bodenheimer (2002)

Global baroclinic instability

Turbulence

Long-lived high-pressure overdense anticyclones

Reemission Images (900GHz / 333µm)

[ Wolf & Klahr 2002 ]
Vortices – Precursors of Protoplanets?

Simulation: ALMA
Baseline: 13km, 64 antennas
900GHz,
Integration time 2hrs
Disk survey possible

[ Wolf & Klahr 2002 ]
Finding Protoplanets - In Disks?

Additional Problems
(Dust!)

UV – (N)IR

IR – mm

Young disks

Scattering

Thermal Reemission

Extinction
(inclination-dependent)

= f (dust properties, \( \rho(r, \theta, \phi) \), \( T(r, \theta, \phi) \))

Solution: High-resolution Imaging
Jupiter in a 0.05 $M_{\text{sun}}$ disk around a solar-mass star as seen with ALMA

$d=140\text{pc}$

Baseline: 10km

$\lambda=700\mu\text{m}, t_{\text{int}}=4\text{h}$

[ Wolf et al. 2002 ]
Close-up view: Planetary Region

\[ \frac{M_{\text{planet}}}{M_{\text{star}}} = \frac{1M_{\text{Jup}}}{0.5M_{\text{sun}}} \]

Orbital radius: 5 AU

Disk mass as in the circumstellar disk as around the Butterfly Star in Taurus

Maximum baseline: 10km, 900GHz, \( t_{\text{int}} = 8h \)

Random pointing error during the observation: (max. 0.6")
Amplitude error, “Anomalous” refraction;
Continuous observations centered on the meridian transit;
Zenith (opacity: 0.15); 30° phase noise;
Bandwidth: 8 GHz

See Poster #7: A. Hales & R. Reid
Strong spiral shocks near the planet are able to decouple the larger particles (>0.1 mm) from the gas.

Formation of an annular gap in the dust, even if there is no gap in the gas density.

MHD simulations - Magnetorotational instability
- gaps are shallower and asymmetrically wider
- rate of gap formation is slowed

Observations of gaps will allow to constrain the physical conditions in circumstellar disks.
Complementary Observations: Mid-IR

10$\mu$m surface brightness profile of a T Tauri disk with an embedded planet (inner 40AUx40AU, distance: 140pc)

[ Wolf & Klahr, in prep. ]
High Resolution!

[Graph showing the relationship between wavelength (m), frequency (Hz), and angular resolution (arcsec). The graph includes various labels indicating different observing facilities, such as VLA, ALMA, VLT, NGST, and HST, with a dashed line indicating a requirement.]
**2nd Generation VLTI Instrument**

- **PI**: Lopez (OCA, Nice)
- **Co-PI+Proj.Scient.**: Wolf (MPIA, HD)

**Specifications:**

- **L, M, N, Q band**: ~ 2.7 – 25 µm
- **Spectral resolutions**: 30 / 100-300 / 500-1000
- **Simultaneous observations in 2 spectral bands**

**What’s new?**

- Image reconstruction on size scales of **3 / 6 mas** (L band) **10 / 20mas** (N band) using **ATs / UTs**
- Multi-wavelength approach in the mid-infrared
  - 3 new mid-IR observing windows for interferometry (L, M, Q)
- Improved Spectroscopic Capabilities
**High-Resolution Multi-Band Image Reconstruction**  
+ Spectroscopy in the Mid-IR

Successor of **MIDI**:
Imaging capability in the L, M, N bands

Successor + Extension of **AMBER**:
Extension down to 2.7 µm  
+ General use of closure phases

Complement to **ALMA + TMT/ELT**

Ground Precursor of **DARWIN**  
Wavelength range 6-18 µm
Surface Structure

**K band scattered light image (Jupiter/Sun + Disk)**

*Wolf & Klahr, in prep.*

**AB Aurigae** - Spiral arm structure

(Herbig Ae star; H band; Fukagawa, 2004)

K band scattered light image (Jupiter/Sun + Disk)

[ Wolf & Klahr, in prep. ]
Shadow – Astrometry

Conditions for the occurrence of a significantly large / strong shadow still have to be investigated

[ Wolf & Klahr, in prep.]

Space Interferometry Mission (SIM)

Wavelength range
0.4-0.9 µm

Baseline: 10m

Narrow Angle Field: 1°

Narrow Angle Astrometry
1 µas mission accuracy

Strategy
Center of Light Wobble

[ G. Bryden, priv. comm.]
What disks to study?

Clearly identified disks, well studied, but ... potentially "planet-building sites" well hidden...

Etc. ...

Preparatory studies, concentrating on face-on disks

Useful techniques:
Coronography;
Differential polarimetric imaging;
hires mm maps

AB Aurigae  HD 100546

=> optical, nearIR, midIR;

(Grady 2001 / 2003)
Young circumstellar disks around T Tauri / HAe/Be stars

Debris disks

- optically thick
- optically thin

Density structure dominated by Gravitation +

Gas dynamics

Radiation Pressure

Poynting-Robertson effect
Giant Planets in Debris Disks

Asymmetric resonant dust belt with one or more clumps, intermittent with one or a few off-center cavities

Central cavity void of dust.

- Resonance Structures: Indicators of Planets
  1. Location
  2. Major orbital parameters
  3. Mass of the planet

- Decreased Mid-Infrared SED
Some Problems with SEDs

[ Kim, …, Wolf, et al. 2005 ]
Example: Debris Disks around Vega

Dust reemission \( \rightarrow \) SOFIA, JWST

(Holland et al. 1998, Wilner et al. 2002)

- No clumpy structure
- Inner disk radius: 11”\(+/-2”
- Extrapolated 850\(\mu\)m flux \(<\) observed
- Explanation: Grains of different sizes traced by Spitzer/SCUBA

(Su et al. 2005)
Some Problems with SEDs

Many of the debris disks observed with the Spitzer ST, show no or only very weak emission at wavelengths < 20…30µm (e.g. Kim et al. 2005)

⇒ No / weak constraints on the chemical composition of the dust

Debris disks: Difficult to observe

• Low Surface Brightness

• Optically thin: Only constraints on radial structure can be derived: SED = f ( T(R) )

  but even here degeneracies are difficult to resolve (e.g., planet mass, orbit, grain size)

• Azimuthal (and vertical) disk structure cannot be traced via SED observations / modelling

Imaging is required!
Planet-disk interaction: Signatures in circumstellar disks

- Usually much larger in size than the planet more easily detectable
- Specific structure depends on the evolutionary stage of the disk

High-resolution imaging

- performed with observational facilities which are already available or will become available in the near future will allow to trace these signatures.

⇒ Insight into specific phases of the formation and early evolution of planets in circumstellar disks.
Acknowledgements

German Research Foundation

Emmy Noether Group
“The Evolution of Circumstellar Dust Disks to Planetary Systems”

Research Group FOR 759/1
“The Formation of Planets: The Critical First Growth Phase”

Max Planck Institute for Astronomy
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