Detecting Protoplanets with ALMA

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“Evolution of Circumstellar Dust Disks to Planetary Systems”
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Gravitational Interaction: Oligarchic Growth
Agglomeration; Fragmentation
Brownian Motion, Sedimentation, Drift
Inelastic Collision  =>  Coagulation

Star Formation Process  →  Circumstellar Disks  →  Planets

(sub)μm particles
↓
cm/dm grains
↓
Planetesimals
↓
Planets (cores)

• Gravitational Interaction: Oligarchic Growth

• Gas Accretion

Alternativ: Gravitational Instability  →  Giant Planet
The “Butterfly Star” in Taurus

submm-sized grains in the disk midplane,
instellar-like grain size in the circumstellar envelope

IRAS 04302+2247
**Solar System**

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

- Neptune: 429 mas
- Jupiter: 74 mas
- Earth: 14 mas

**What is feasible?**

- MIDI / VLTI: 10 – 20 mas (N band)
- SMA: ~ 0.3” (goal: 0.1”) [~submm]
Global baroclinic instability

\[ \downarrow \]

Turbulence

\[ \downarrow \]

Long-lived high-pressure overdense anticyclones

\[ 900\text{GHz} / 333\text{\(\mu\)m} \]

Vortices

Precursors of Protoplanets?

Klahr & Bodenheimer (2002)

Wolf & Klahr (2002)
Wolf & Klahr (2002)

Simulation: ALMA
Baseline: 13km, 64 antennas
900GHz, Integration time 2hr

Vortices
Precursors of Protoplanets?

Distance

Disk inclination
Finding Planets – In Disks?!

Additional Problems (Dust...)

UV – (N)IR
IR – mm
Young disks

Scattering
Thermal Reemission
Extinction (Inclination-dependent)

\[ = f \left( \text{dust properties}, \ T(r, \theta, \phi), \ \rho(r, \theta, \phi) \right) \]

Solution: High-resolution Imaging
Response of a gaseous, viscous protoplanetary disk to an embedded planet

Disk surface densities for planets with masses 1, 0.1, and 0.01$M_J$ orbiting a 1$M_{\text{sun}}$ star (Bate et al. 2003)

[see also Bryden et al. 1999, Kley et al. 2001, Lubow et al. 1999, Ogilvie & Lubow 2002, D’Angelo et al. 2003, Winters et al. 2003]
Figure 2. The final azimuthally averaged disc surface density for planets with masses of 1 (long-dashed), 0.3 (dot-dashed), 0.1 (dotted), 0.03 (short-dashed) and 0.01 (thin solid) $M_J$. Only planets with masses $M_p \gtrsim 0.1 M_J$ ($M_p \gtrsim 30 M_{\oplus}$) produce significant perturbations. The thick solid line gives the result for a 1-$M_J$ planet from the two-dimensional calculations of Lubow et al. (1999).
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)
Density distribution in the midplan of the circumstellar disk with an embedded massive planet.

Can we map young giant planets?

Small-scale spirals encircling the planet (detached from the global spiral) → Circumplanetary "Disk"

D’Angelo et al. (2002)
Wolf & D’Angelo (2005)
Planetary region

$M_{\text{planet}} / M_{\text{star}} = 1M_{\text{Jup}} / 0.5 M_{\text{sun}}$

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

Wolf & D’Angelo (2005)
2. The resolution of the images to be obtained with ALMA will allow detection of the warm dust in the vicinity of the planet only if the object is at a distance of not more than about 100 pc. For larger distances, the contrast between the planetary region and the adjacent disk in all of the considered planet/star/disk configurations will be too low to be detectable.

4. Even at a distance of 50 pc, a sufficient resolution to allow a study of the circumplanetary region can be obtained only for those configurations with the planet on a Jupiter-like orbit but not when it is as close as 1 AU to the central star.

6. The observation of the emission from the dust in the vicinity of the planet will be possible only in the case of the most massive, young circumstellar disks we analyzed.
Strong spiral shocks near the planet are able to decouple the larger particles (>0.1mm) from the gas.

=>

formation of an annular gap in the dust, even if there is no gap in the gas density (example: gap in 1mm grains opened by a 0.05M_Jup planet)

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**Fig. 3.** Logarithm of flux densities at 1 mm, normalized by the maximum and convolved with a Gaussian of FWHM 2.5 AU, corresponding to a resolution of 12 mas at 140 pc. Left panel: all particles follow the gas exactly (static dust evolution). Middle panel: particles larger than the critical size decouple from the gas (dynamic dust evolution). Right panel: the corresponding radial flux densities.
**MHD simulations:**

Internal Stress arises self-consistently from turbulence generated by magnetorotational instability (‘MHD turbulence‘)

>>> gaps are shallower and asymmetrically wider

>>> rate of gap formation is slowed

ALMA observations of gaps will allow to constrain the physical conditions in circumstellar disks

Fig. 1. The log density in hydrodynamic simulations after 100 planet orbits for the small-mass planet, $q = 2 \times 10^{-4}$ (top left), the medium-mass planet, $q = 1 \times 10^{-3}$ (top right), and the large-mass planet, $q = 5 \times 10^{-3}$ (bottom). The color map runs from blue to red in log($\rho$) from $\rho = 0.01$ to 1.0. Note the density enhancements inside the gap at the trailing and leading Lagrange points, L4 and L5.

(Winters et al. 2003; see also Nelson & Papaloizou 2003)
Planetary radiation significantly affects the dust reemission SED only in the near to mid-infrared wavelength range.

This spectral region is influenced also by the warm upper layers of the disk and the inner disk structure, the planetary contribution.

=>

The presence of a planet + the temperature / luminosity of the planet cannot be derived from the SED alone.

Planetary Contribution / Disk reemission (inner 12 AU) < 0.4%

(depending on the particular model)
Complementary Observations

Precursor of Darwin in terms of image reconstruction; Experience (MIDI + AMBER)
Complementary Observations
In the Mid-Infrared

Hot Accretion Region around the Planet

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

[Wolf & Klahr, in prep.]

Science Case Study for T-OWL:
Thermal Infrared Camera for OWL (Lenzen et al. 2005)
Justification of the Observability in the Mid-IR for nearby objects (d<100pc)
Wolf, Klahr, Egner, et al. 2005 in Lenzen et al. 2005

T-OWL
Thermal Infrared Camera for OWL
Proposed 2nd Generation VLTI Instrument

Specifications:

- \( L, M, N, Q \) band: \( \sim 2.7 - 25 \mu m \)
- 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 / 20 mas (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
Surface Structure

K band scattered light image (Jupiter/Sun + Disk) [Wolf & Klahr]

AB Aurigae - Spiral arm structure
(Herbig Ae star; H band; Fukagawa, 2004)
Center-of-Light-Wobble

(G. Bryden, priv. comm.)
Further selected gap detection studies:

- Varniere et al. (2006)
  Illumination of the outer gap wall

- Wilner et al. (2004)
  Observations of the inner disk structure with the Square Kilometer Array (Science Case Study)

- Steinacker & Henning (2003)
  Analysis of the spectral appearance of gaps
Protoplanetary Disks evolve ...

• **Near-infrared photometric studies:** sensitive to the inner ~ 0.1 AU around solar-type stars:
  
  • Excess rate decreases from ~80% at an age of ~1 Myr to about 50% by an age of ~3 Myr (Haisch et al.~2001)
  
  • By ages of ~10-15 Myr, the inner disk has diminished to nearly zero (Mamajek et al.2002).

• **Far-infrared / millimeter continuum observations** probe the colder dust and thus the global dust content in disks:
  
  • Beckwith et al. (1990): no evidence of temporal evolution in the mass of cold, small (<1mm) dust particles between ages of 0.1 and 10Myr
  
  • By an age of 300 Myr the dust masses were found to by decreased by at least 2 orders of magnitude (Zuckerman & Becklin 1993).
  
  • Based on studies with the Infrared Space Observatory (ISO), the disk fraction amounts to much less than 10% for stars with ages > 1 Gyr (e.g., Spangler et al. 2001; Habing et al. 2001; Greaves et al. 2004; Dominik & Decin 2003).
... but still the disk may outshine the planet.

- **The exozodiacal dust disk around a target star**, even at solar level, will likely be the dominant signal originating from the extrasolar system:
  - Solar system twin: overall flux over the first 5 AU is about 400 times larger than the emission of the Earth at 10µm

- **Zodiacal light of our own solar system**:
  - potential serious impact on the ability of space-born observations (e.g. DARWIN)
  - attributed to the scattering of sunlight in the UV to near-IR, and the thermal dust reemission in the mid to far-IR
  - > 1micron: signal from the zodiacal light is a major contributor to the diffuse sky brightness and dominates the mid-IR sky in nearly all directions, except for very low galactic latitudes (Gurfil et al. 2002).
Young disks / Debris disks

Planet ⇔ Disk interaction

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

Scattered light images (optical)
A planet, via resonances and gravitational scattering produces

[1] An asymmetric resonant dust belt with one or more clumps, intermittent with one or a few off-center cavities, and

[2] A central cavity void of dust.

Resonant structures can serve as indicators of a planet in a circumstellar disk

[1] Location

→ [2] Major orbital parameters

[3] Mass of the planet

Scattered Light Image

10^7 particles

[Wolf & Rodmann]

Relative brightness distribution of individual clumps in optical to near-infrared scattered light images may sensitively depend on the disk inclination.

Beware: Since dust is produced through planetesimal collisions, debris disks will always have a more or less clumpy structure initially.
Dust reemission

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

Debris disk around Vega

Dust reemission

(Wilner et al. 2002)

(SOFIA, JWST)
Su et al. (2005):
- No clumpy structure
- Inner disk radius: 11" +/- 2"
- Extrapolated 850µm flux << than observed
- Explanation:
  Dust grains of different sizes are traced by Spitzer/SCUBA
Giant Planets in Debris Disks

Characteristic Asymmetric Density Patterns

Decreased Mid-Infrared Spectral Energy Distribution

(but dust grain evolution makes detailed SED analysis difficult)

Wolf & Hillenbrand (2003, 2005)

[ aida28.mpia.de/~swolf/dds ]
The Young Solar System @ 50pc

Moro-Martin, Wolf, & Malhotra (2004)

$M_{\text{dust}} = 10^{-10}M_{\odot}$

with planets

without planets

Moro-Martin, Wolf, & Malhotra (2004)
Some problems with SEDs...

Kim 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…30 micron (e.g. Kim et al. 2005)

=> No / weak constraints on the chemical composition of the dust

Debris disks: Optically thin

- azimuthal and vertical disk structure can not be traced via SED observations / modelling;
- 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)

Problem: Low Surface Brightness
Concluding Remarks

1. SED: (sub)mm slope
2. Shape of 10µm silicate feature
3. Scattered light polarization
4. Multi-wavelength imaging
5. Vertical Disk Structure
Concluding Remarks

Vortices

=> Local Density Enhancements

=> enhanced grain growth

(e.g., Wolf & Klahr 2003, Klahr & Bodenheimer 2006)
Concluding Remarks

1. Gaps
2. Global Spiral Structures
3. Planetary Accretion Region
4. Center-of-light-wobble
5. Inner holes
Concluding Remarks

1. Characteristic Asymmetric Patterns
2. Shape of the mid-infrared SED
3. Warps (β Pic)
Theoretical investigations show that the planet-disk interaction causes structures in circumstellar disks, which are usually much larger in size than the planet itself and thus more easily detectable. The specific result of the planet-disk interaction depends on the evolutionary stage of the disk.

Numerical simulations convincingly demonstrate that 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 of planets.

These observations will provide a deep insight into specific phases of the formation and early evolution of planets in circumstellar disks.