Detection of Extrasolar Planets in Circumstellar Disks

Contribution to to ExoPlanet Task Force Call for White Papers

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Abstract

Motivation 1 Although the currently applied planet detection techniques cause strong selection effects (e.g., the sample of planets found with the radial velocity technique is biased towards massive, short-period planets), it is now obvious, that the solar system planets cover a small region in the parameter space of possible planetary characteristics only. This statement concerns fundamental properties such as orbital parameters, the planetary mass range, and even the classification of planets: In addition to the clearly distinguished classes of terrestrial and Jovian planets in the solar system, so-called "Hot Jupiters" have been discovered.

If one wants to understand the observed diversity of planets, one has to go back into the history of the planetary systems – studying their formation and evolution. Triggered and supported by the rapidly growing field of the search for extrasolar planets and the already collected observational material, our theoretical understanding about the planet formation process has been improved significantly at the same time. Nevertheless, the link between theoretical models and observations is still rather weak. What is missing to a large extent are predictions for observational quantities which will allow to verify existing planet formation theories.

Motivation 2 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 "fingerprints" of planets in protoplanetary and debris disks. These observations will provide a deep insight into specific phases of the formation and early evolution of planets in circumstellar disks.

A number of new instruments and ground and space-based observatories, which are optimized for the observation of planet-forming/harboring disks, is now in operation, such as the Spitzer Space Telescope operating in the mid- to far-infrared wavelength range, long-baseline infrared interferometers such as MIDI and AMBER, cameras such as NACO and VISIR, and submillimeter observatories, such as APEX and the SMA. In the near future even more powerful observatories will provide excellent means to study the process of planet formation (e.g., the LBT, SOFIA, and ALMA). The combination of these facilities will allow to investigate the planet-forming region and to trace various physical processes through multi-wavelength observations.

Young Planets in Gas-rich Disks

Numerical simulations have shown that sufficiently massive planets may cause characteristic large-scale signatures in the disk density distribution. In young circumstellar disks, with a structure dominated by gas dynamics, the most important of these signatures are gaps and spiral density waves (e.g., Bryden et al. 1999, Kley 1999, Bate et al. 2003, Papaloizou et al. 2006). The importance of investigating these signatures lies in the possibility to use them in the search for embedded young planets. Therefore, these disk features can provide constraints on the processes and timescales of planet formation.

ALMA: Gaps + Accreting Planets The only observatory which will provide the required spatial resolution and sensitivity to investigate the potential planet forming regions at (sub)millimeter wavelengths within the next decade will be ALMA. While it was shown before, that ALMA will indeed allow to map the gap caused by a massive planet in such disks (Wolf et al. 2002), more detailed simulations are required in order to investigate whether the planet itself and/or its surrounding environment, heated by the planet and through accretion onto it, could be detected. The detection of a gap would already represent a strong indication of the existence of a planet, thus providing information about the planetary mass, viscosity, and pressure scale-height of the disk. However, the detection / non-detection of warm dust close to the planet would additionally give valuable constraints on the temperature and luminosity of the planet, the accretion process onto the planet, and the density structure of the surrounding medium.

Based on these simulations (Wolf & D'Angelo 2005, see Fig. 1) we make the following predictions about the observability of giant (proto-)planets in young circumstellar disks: [**1**] 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 $\sim$50-100 pc. For larger distances, the contrast between the planetary region and the adjacent disk will be too low to be detectable. [**2**] Even at a distance of 50 pc a resolution being high enough to allow a study of the circumplanetary region can be obtained only for those configurations with the planet on a Jupiter-like orbit but not when it is as close as 1 AU to the central star. This is mainly due to the size of the synthesized beam ($\sim 0.02''$ for the considered ALMA configuration). [**3**] 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 and thus young circumstellar disks.

Furthermore, the signal of the radiation from the planet / circumplanetary material will be best distinguishable if a high planet-to-star mass ratio is targeted. In contrast to the most successful planet detection technique so far, based on radial velocity measurements, the likelihood of detection does not increase with decreasing distance of the planet to the star in the considered range of orbital radii ($r_{\rm P} = 1\,$AU and 5 AU, respectively).

Contribution to the SED The planet's contribution to the net flux at 900 GHz (by direct or scattered radiation and reemission of the heated dust in its vicinity) does not exceed 0.4%

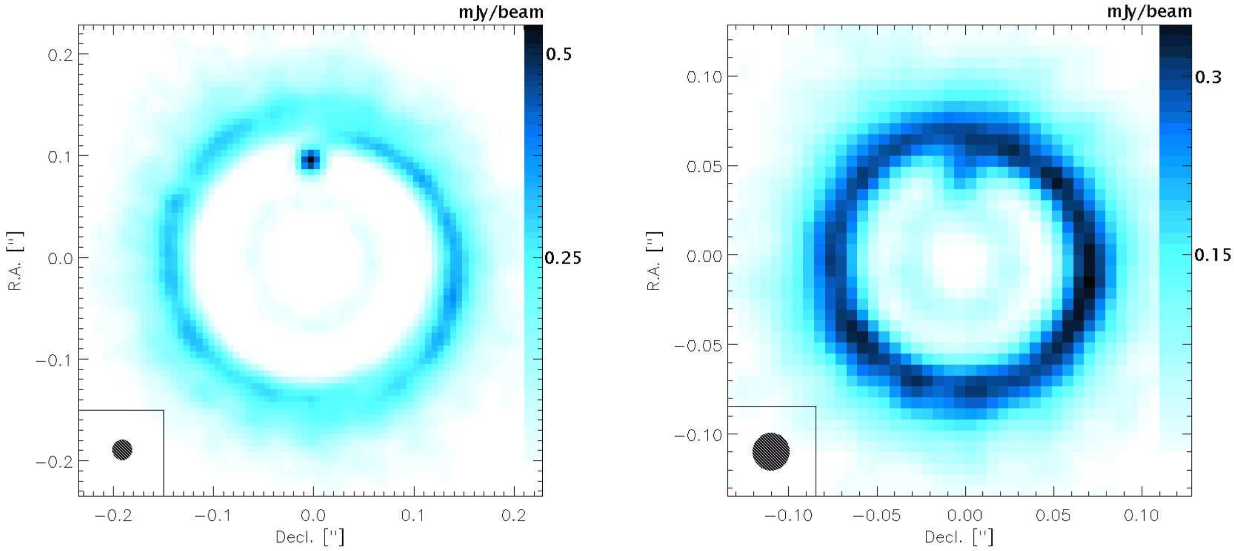


Figure 1: Simulation of ALMA 900 GHz observations of a circumstellar disk with an embedded planet of $1\,M_J$ around a $0.5\,M_\odot$ star (orbital radius: 5 AU, disk mass $1.0 \times 10^{-2}\,M_\odot$). The assumed distance is 50 pc (left) / 100 pc (right). The size of the synthesized beam is symbolized in the lower left edge of each image. Note the reproduced shape of the spiral wave near the planet and the slightly shadowed region behind the planet in the left image. *[from Wolf & D'Angelo 2005]*

of the contribution of the small region of the disk in any of the configurations considered. Furthermore, the planetary radiation significantly affects the dust reemission SED only in the near- to mid-infrared wavelength range. Since this spectral region is strongly influenced also by the warm upper layers of the disk and the inner disk structure, the planetary contribution and thus the temperature / luminosity of the planet cannot be derived from the SED.

Inner Cavities/Gaps Apparent inner cavities in disks – inner holes with radii which are much larger than the sublimation radius of interstellar medium-like grains – have been deduced from observed mid-infrared SEDs of selected disks around T Tauri and debris-type disks. Examples among T Tauri disks are GM Aurigae (Rice et al. 2003) and TW Hydrae (Calvet et al. 2002). These cavities might be due to the influence of a giant planet on the circumstellar disk (e.g., Lin & Papaloizou 1979a/1979b). Furthermore, viscous accretion and photoevaporation by stellar radiation are assumed to clear the inner region of cirumstellar disks (e.g., Goto et al. 2006). However, an alternative explanation could be the consequence of the dust evolution (mainly grain growth) resulting in a depletion of small grains in the inner region. High-resolution interferometric observations at mid-infrared to millimeter wavelengths, tracing larger grains, are best-suited to confirm or rule out the second versus the first scenario (Fig. 2).

Hotspots The planetary accretion region is significantly warmer than the surrounding disk material. As illustrated in Fig. 3, the planetary environment will therefore appear as a "hotspot" in mid-infrared images of the planet-forming region of circumstellar disks. Mid-

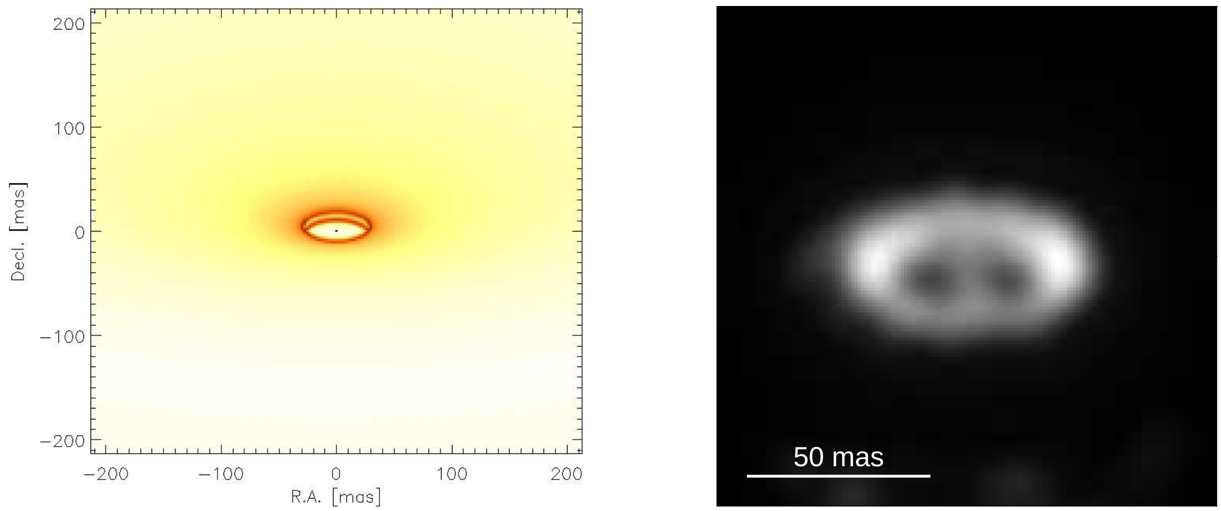


Figure 2: Simulated 10 μm image of the inner region of a T Tauri circumstellar disk with a cleared inner region (inner disk radius: 4 AU; inclination: 60°; assumed distance: 140 pc). *Left:* Original image. *Right:* Image reconstructed from a simulated data set of the planned mid-infrared interferometer MATISSE with 5% noise of the squared visibilities (10% for the simulated closure phases). *[from Wolf et al. 2007 / Hofmann et al. 2006]*

infrared interferometers such as MATISSE[1] will allow to image reconstruction as the basis of the analysis of these complex structures (Wolf et al. 2006a).

Surface Structures and Shadows In the optical to near-infrared the orbit and constraints on the mass of the planet can be derived from the surface structure of the disk which can be traced in this wavelength range (see Fig. 4[left]). Furthermore, numerical simulations indicate that the disk scale height in the planetary accretion region is significantly increased locally, casting a long ($\sim$ few AU) shadow over the outer disk region (see Fig. 4[right]).

Planets in Debris Disks

Debris disks are solar system-sized dust disks produced as by-products of collisions between asteroid-like bodies and the activity of comets left over from the planet formation process. In contrast to optically thick young circumstellar disks around Herbig Ae/Be and T Tauri stars with spatial structures dominated by gas dynamics, the much lower optical depth and lower gas-to-dust mass ratio in debris disks (e.g., Zuckerman et al. 1995, Liseau & Artymowicz 1998, Lecavelier et al. 2001) let the stellar radiation in addition to gravity be responsible for the disk structure. Besides, fragmentation becomes a typical outcome of particle collisions, because relative velocities of grains are no longer damped by gas. Thus, the Poynting-Robertson effect, radiation pressure, collisions, and gravitational stirring by

[1]MATISSE– the *M*ulti *A*per*T*ure Mid-*I*nfrared *S*pectro*S*copic *E*xperiment (Wolf et al. 2006a/2006b, Lopez et al. 2006) is foreseen as a mid-infrared spectro-interferometer combining the beams of up to 4 UTs/ATs of the VLTI.

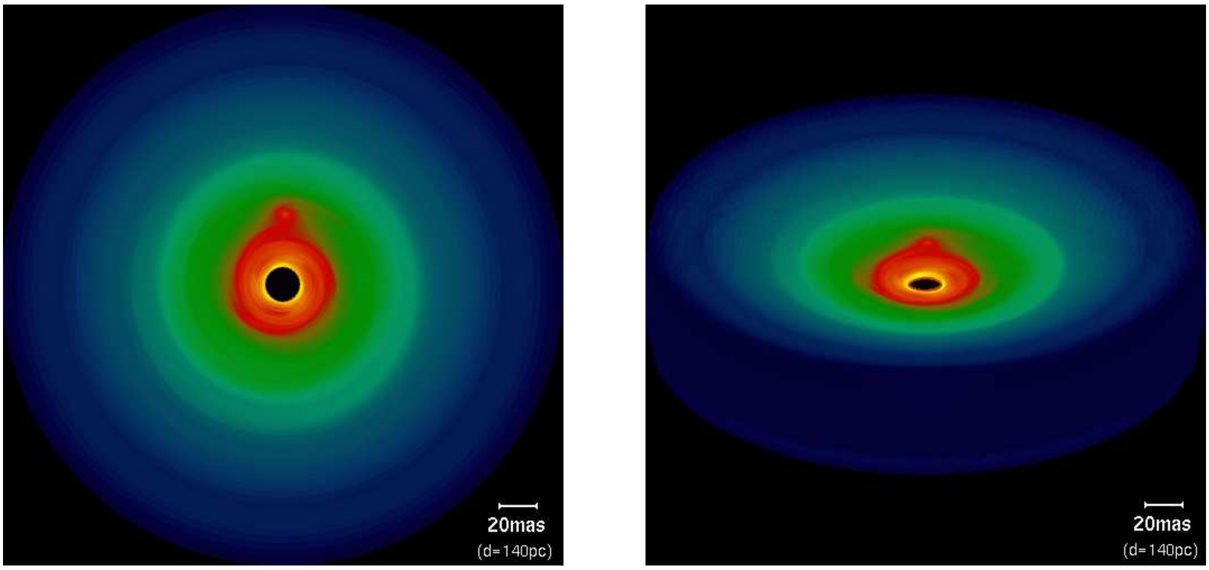
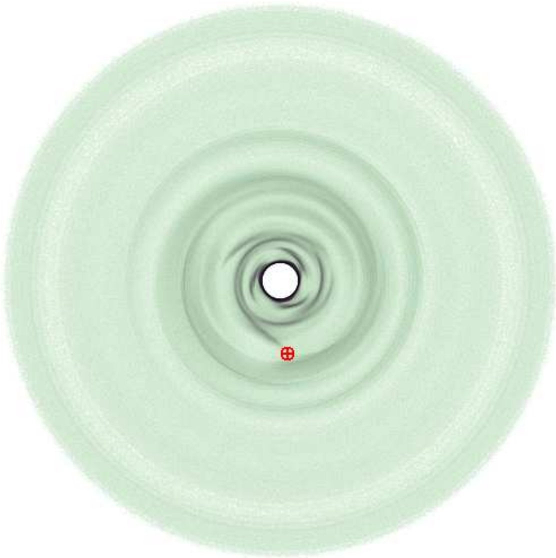


Figure 3: Simulated 10 μm images of the inner region of a circumstellar T Tauri disk, with an embedded Jupiter-mass planet at a distance of 5.2 AU from the central 0.5 $M_\odot$ T Tauri star. The left / right image shows the disk under an inclination of 0°/60°. The hot region around the planet above the center of the disk, indicated as a bright area in these reemission images, is clearly visible. *[from Wolf et al. 2006a/2006b]*

embedded planets are all important in determining the disk structure.

Resonant Structures High-resolution images of debris disks in scattered light in the optical/near-infrared and in thermal emission at mid-infrared to millimeter wavelengths show complex structures, such as rings, gaps, arcs, warps, offset asymmetries and clumps of dust (e.g., Greaves et al. 1998, Schneider et al. 1999, Koerner et al. 2001, Wilner et al. 2002, Holland et al. 1998/2003). In evolved, optically thin debris disks some of these features are likely to be the result of gravitational perturbations by one or more massive planets on the dust disk. The resulting characteristic density patterns are expected to provide the strongest indirect hints on the existence of planets embedded in these disks (e.g., Liou & Zook 1999, Wyatt et al. 1999, Ozernoy et al. 2000, Moro-Martín & Malhotra 2002/2003/2005, Wilner et al. 2002, Quillen & Thorndike 2002).

Inner Cavities Beside resonant structures, inner cavities have been found in several prominent debris disks: β Pic (20 AU), HR 4796A (30-50 AU), ϵ Eri (50 AU), Vega (80 AU), and Fomalhaut (125 AU) – e.g., Dent et al. (2000), Greaves et al. (2000), Wilner et al. (2002), Holland et al. (2003). The analysis of the mid-infrared SED of the debris disks recently discovered with SPITZER shows that the occurence of inner regions with strong dust depletion is a frequent phenomenon in these systems (e.g., Quillen et al. 2004, Kim et al. 2005, Hines et al. 2006, Silverstone et al. 2006). These cavities may be created by gravitational scattering with an inner planet: Dust grains drifting inwards due to the Poynting-Robertson effect are likely to be scattered into larger orbits resulting in a lower dust number density



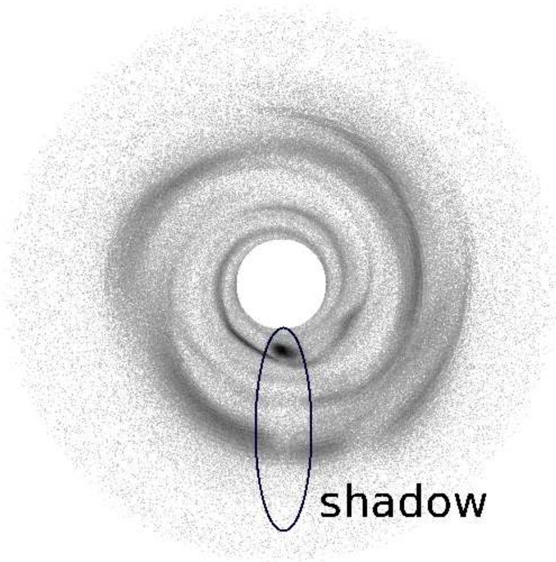


Figure 4: **[Left]** Simulated K band image of the inner region (radius 19.7 AU) of a young circumstellar disk with an embedded Jupiter-mass planet at a distance of 5.2 AU. The spiral density pattern is clearly visible, in contrast to the gap which is less pronounced in this wavelength range. The "$\oplus$" symbol marks the position of the planet. *[from Wolf 2005]* **[Right]** Under certain conditions the local disk scale height in the planetary accretion region becomes sufficiently high to cast a long shadow over the outer regions of the disk *[Wolf & Klahr, in prep.; Bryden, priv. comm.]*.

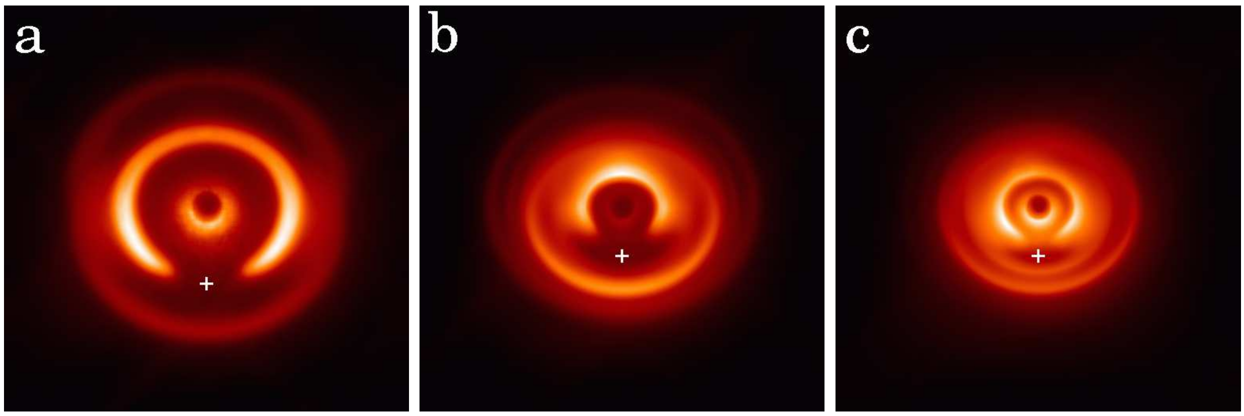


Figure 5: Simulated scattered light images of debris disks (radius 200 AU) with an embedded planet. The position of the planet is marked by the white cross. *[from Wolf & Rodmann, in prep.; see also Rodmann 2006 for details]*

within the planet's orbit.

Vertical Disk Structure / Warps Another mechanism for the possible influence of a planet on the disk structure has been discussed in the case of the β Pictoris disk, seen nearly edge-on and extending to a distance of at least 1000 AU from the central star (Zuckerman &

Becklin 1993, Pantin et al. 1997, Holland et al. 1998, Dent et al. 2000). The Northeast and Southwest extensions of the dust disk have been found to be asymmetric in scattered light as well as in thermal emission. This warp is assumed to be caused by a giant planet on an inclined orbit that gravitationally perturbs the dust disk (Augereau et al. 2001).

Signatures of planets in spatially unresolved debris disks The mid-infrared continuum will allow to conclude if an inner hole / depletion of small dust grains - due to the presence of at least one embedded planet - exists (e.g., Wolf & Hillenbrand 2003). Thus, beside high-resolution imaging of debris disks, multi-wavelength photometry and (low-resolution) spectroscopy aimed at deriving the mid-infrared SED of debris disks are valuable tools to deduce the existence of an inner gap, since the deficiency of hot dust in the stellar vicinity causes a decrease of the mid-infrared flux compared to an undisturbed disk. With increasing gap size the emission spectrum is shifted toward longer wavelengths and the mid-infrared flux is reduced. However, our studies also reveal the degeneracy of disk models, based on the SED alone, e.g. in planet location and the chemical composition of the dust (e.g., Moro-Martín, Wolf, & Malhotra 2005). Thus, it is necessary to obtain spatially resolved images in order to unambigously constrain the location of the planet, using the characteristic large-scale disk density pattern.

Direct planet detection in debris disks? Although debris disks represent a rich source of information about the formation and evolution of planetary systems, they also impose problems on the observations of exoplanetary systems. First, the zodiacal light of our own solar system has a potential serious impact on the ability of space-borne observations to detect and study their targets. It is attributed to the scattering of sunlight in the ultraviolett to near-infrared, and – important for mid-infrared missions such as DARWIN – the thermal dust reemission in the mid- to far-infrared. At infrared wavelengths from approximatelly $1\,\mu$m, the signal from the zodiacal light is a major contributor to the diffuse sky brightness and dominates the mid-infrared sky in nearly all directions, except for very low galactic latitudes (Gurfil et al. 2002). Second, the exozodiacal dust disk around a target star, even at solar level, will likely be the dominant signal originating from the extrasolar system. In the case of a solar system twin, its overall flux over the first 5 AU is about 400 times larger than the emission of the Earth at 10μm. Although the factor reduces to a few tens after partial rejection by usage of a nulling interferometer, one still has to make sure that the exozodiacal signature will not mimic planetary signals such as would be the case if the disk is significantly clumpy. If the origin of this clumpiness is in perturbations of planets, then detecting clumps can help to pinpoint those planets. However, one has to be aware that collisionally regenerated debris disks are also intrinsically clumpy because dust created by collisions between large planetesimals starts out in a clumpy dust distribution.

References

a) Wolf, S., Moro-Martin, A., D'Angelo, G., 2007, "Signatures of Planets in Protoplanetary and Debris Disks", Planetary and Space Science, 55, 569
b) Wolf, S., 2007, Habilitation Thesis, University of Heidelberg