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ORIGINAL ARTICLE

Detecting protoplanets with ALMA

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Abstract Theoretical investigations show that planet-disk interactions cause structures in circumstellar disks, which are usually much larger in size than the planet itself and thus more easily detectable. The specific result of planet-disk interactions depends on the evolutionary stage of the disk. Exemplary signatures of planets embedded in disks are gaps and spiral density waves in the case of young, gas-rich protoplanetary disks and characteristic asymmetric density patterns in debris disks. 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.

In this context, the Atacama Large Millimeter Array (ALMA) will play a crucial role by allowing to trace features in disks which are indicative for various stages of the formation and early evolution of planets in circumstellar disks.

Keywords Infrared excess · Debris disks · Protoplanetary disks · Exo-zodiacal dust · Extrasolar planetary systems

1 Introduction

The detection of extrasolar planets and planetary systems has enormously stimulated and invigorated the studies of planet formation during the last decade. In particular, a detailed picture of the evolution of circumstellar/protoplanetary disks, which provide the material and environment from and in which planets are expected to form, has been developed. However, the planet formation process itself is in major parts still under discussion. In order to improve our understanding of planet formation and to refine existing hypotheses for the various phases of this process, adequate observational constraints are required.

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2 Young planets in protoplanetary disks

Both, the initial conditions of the dust phase in the circumstellar environment, i.e., the distribution of submicron-sized dust grains, and the early stages of the planet formation process (particle growth via coagulation to $\sim$ mm size) can be observed directly in the optical to millimeter wavelength range. In contrast to this, even larger bodies can hardly be traced directly. However, bodies in this size regime are predicted to undergo collision events (Weidenschilling 1997), creating fragments which may allow to trace the location, abundance, and chemical composition of the centimeter to $\sim$ few kilometer-sized parent bodies. Beyond this, 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 (Bryden et al. 1999). 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.

Disk structures caused by the planet-disk interaction may be traced by high spatial resolution mapping of the thermal dust reemission. We performed simulations with the goal 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. In order to achieve these goals, we tested different environments of a planet located in a circumstellar disk for the resulting temperature structure, which, in combination with the density distribution, mainly determines the likelihood of detecting any of the features characterizing the embedded planet. A detailed description of all considered model configurations is given in Wolf and D'Angelo (2005). Based on these simulations we make the following predictions about the observability of giant protoplanets 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 ∼50–100 pc (see Fig. 1). For larger distances, the contrast between the planetary region and the adjacent disk in any of the considered planet/star/disk configurations 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. (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. (4) The planetary radiation significantly affects the dust reemission spectral energy distribution (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 alone.

For completeness, it is important to emphasize that further studies have demonstrated that larger-scale features induced by the planet's interaction with the disk are expected to be observable much easier. One example is the gap, which can be observed also for objects at larger distances, such as in nearby rich star-forming region; e.g., in Taurus (Wolf et al. 2002). Another example are apparent inner cavities in disks—inner holes with radii which are much larger than the sublimation radius of interstellar medium-like submicron-sized grains. 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., Kley 1999). Furthermore, viscous accretion and photoevaporation by stellar radiation are assumed to clear the inner region of circumstellar disks (e.g., Goto et al. 2006). However, an alternative explanation could be the consequence of the dust evo-

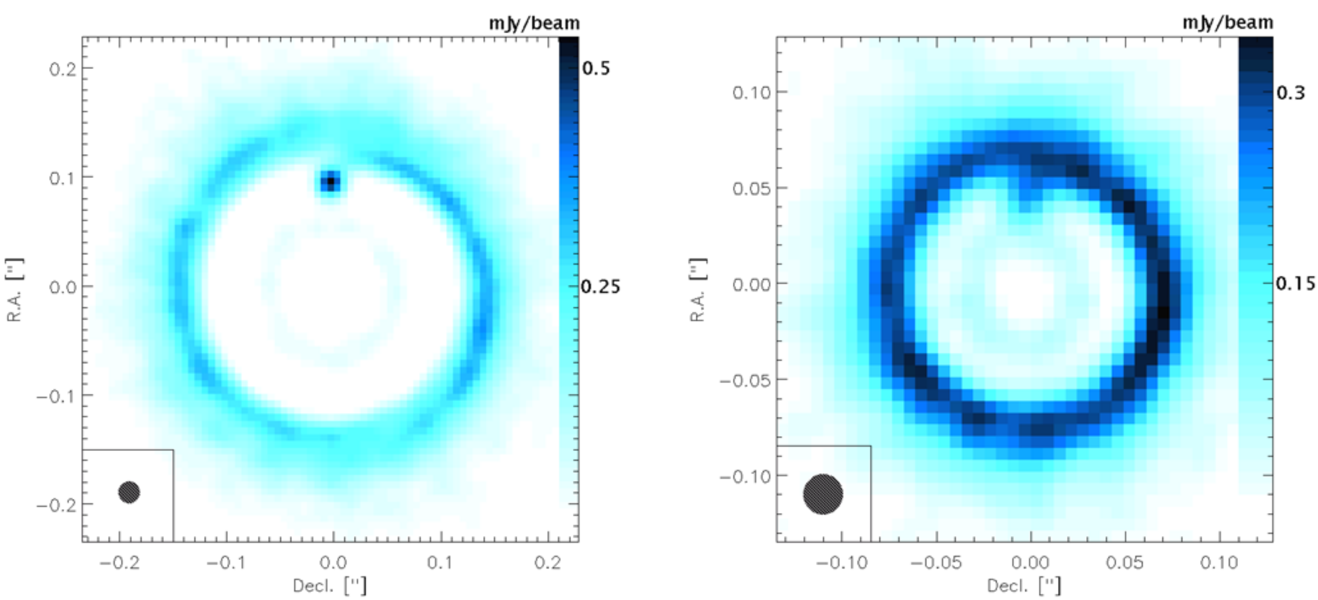

Fig. 1 Simulation of ALMA 900 GHz observations of a circumstellar disk with an embedded planet of 1 M_J around a 0.5 $M_\odot$ star (orbital radius: 5 AU). The assumed distance is 50 pc (*left*)/100 pc (*right*). The disk mass amounts to $M_{disk} = 1.0 \times 10^{-2}$ $M_\odot$. Only structures above the 2σ-level are shown. 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 and D'Angelo 2005)

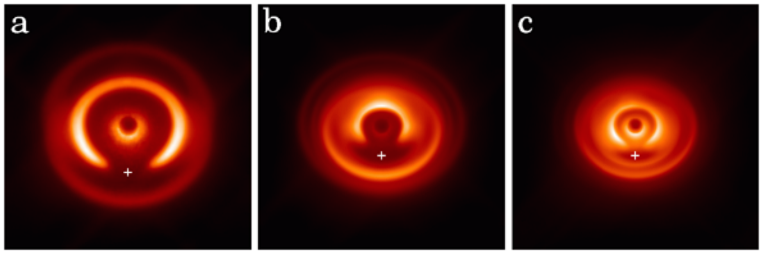

Fig. 2 Simulated scattered light images of debris disks with an embedded planet at a wavelength of 1.1 μm. The position of the planet is marked by the *white cross*. In order to emphasize faint structures, the intensity has been scaled as the cubic root of the flux density. Furthermore, the images were convolved with the corresponding HST/NICMOS F110W filter point spread function. (Selected simulation parameters: Size of the displayed region: 400 AU × 400 AU. Disk: Density distribution based on a dynamical model taking into account the gravitational perturbations by the planet, photon radiation pressure, and dissipative drag force due to the Poynting–Robertson effect and stellar wind. Disk inclination = 31.7°; with the upper part facing towards the observer. Planet: Mass = 3.0 M_J (**a**, **b**)/0.3 M_J (**c**); Orbit radius: 86.3 AU (**a**)/54.4 AU (**b**, **c**). Dust: radius = 14 μm, composition: astronomical silicate (Weingartner and Draine 2001)) (from Wolf 2007; see also Rodmann 2006)

lution, resulting in a depletion of small grains in the inner region. Complementary 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.

3 Planets in debris disks

Planetary debris disks are assumed to represent the almost final stage of the circumstellar disk evolution, i.e., they are the evolutionary products of ongoing or completed planet formation. More specifically, 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, the much lower optical depth and lower gas-to-dust mass ratio in debris disks let the stellar radiation—in addition to gravity—be responsible for the disk structure (e.g., Zuckerman et al. 1995). 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 embedded planets are all important in determining the dust population and disk structure (e.g., Liou and Zook 1999).

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; Holland et al. 1998, 2003; Koerner et al. 2001; Schneider et al. 1999; Wilner et al. 2002). 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, i.e. characteristic density patterns are expected to provide the strongest indirect hints on the existence of planets embedded in these disks. The dominance of any of these structures mainly depends on the mass of the planet and the eccentricity of its orbit (see Fig. 2 for illustration).

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. 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 10 μm. Besides, one 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 the outlined 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 (Wyatt and Dent 2002).

Beside resonant structures, inner cavities have been found in several prominent debris disks: β Pic (inner radius: 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; Holland et al. 2003; Wilner et al. 2002). The analysis of the mid-infrared SED of further debris disks discovered recently with the Spitzer Space Telescope shows that the occurrence of inner cavities, i.e. inner regions with strong dust depletion, is a frequent phenomenon in these systems (e.g., Hines et al. 2006; Kim et al. 2005; Quillen et al. 2004; 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 within the planet's orbit.

Another mechanism for the possible influence of a planet on the disk structure has been discussed in the case of the β Pictoris disk. 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).

A detailed study of the influence of planets on the SED of debris disks has been performed by Wolf and Hillenbrand (2003) and Moro-Martín et al. (2005). The authors find that there exist degeneracies that can complicate the interpretation of the SED in terms of determining the location of embedded planets. For example, the mid-infrared SED of a dust disk dominated by weakly absorbing grains (e.g., Fe-poor silicates) has its minimum at wavelengths longer than those of a disk dominated by strongly absorbing grains (e.g., carbonaceous and Fe-rich silicate). Because the minimum of the mid-infrared SED also shifts to longer wavelengths when the gap radius increases, there might be a degeneracy between the chemical composition of the dust and the semi-major axis of the planet clearing the gap. The degeneracy in the SED analysis illustrates the importance of obtaining high-resolution images, allowing to spatially resolve the debris disk structure, in addition to spectroscopic observations constraining the chemical composition of the dust. High resolution imaging with ALMA will therefore be essential to resolve these degeneracies.

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References

Augereau, J.C., Nelson, R.P., Lagrange, A.M., Papaloizou, J.C.B., Mouillet, D.: Dynamical modeling of large scale asymmetries in the beta Pictoris dust disk. Astron. Astrophys. **370**, 447–455 (2001)

Bryden, G., Chen, X., Lin, D.N.C., Nelson, R.P., Papaloizou, J.C.B.: Tidally induced gap formation in protostellar disks: gap clearing and suppression of protoplanetary growth. Astrophys. J. **514**, 344–367 (1999)

Calvet, N., D'Alessio, P., Hartmann, L., Wilner, D., Walsh, A., Sitko, M.: Evidence for a developing gap in a 10 Myr old protoplanetary disk. Astrophys. J. **568**, 1008–1016 (2002)

Dent, W.R.F., Walker, H.J., Holland, W.S., Greaves, J.S.: Models of the dust structures around Vega-excess stars. Mon. Not. R. Astron. Soc. **314**, 702–712 (2000)

Goto, M., Usuda, T., Dullemond, C.P., Henning, T., Linz, H., et al.: Inner rim of a molecular disk spatially resolved in infrared CO emission lines. Astrophys. J. **652**, 758–762 (2006)

Greaves, J.S., Holland, W.S., Moriarty-Schieven, G., Jenness, T., Dent, W.R.F., et al.: A dust ring around epsilon Eridani: analog to the young solar system. Astrophys. J. **506**, L133–L137 (1998)

Greaves, J.S., Mannings, V., Holland, W.S.: The dust and gas content of a disk around the young star HR 4796A. Icarus **143**, 155–158 (2000)

Hines, D.C., Backman, D.E., Bouwman, J., Hillenbrand, L.A., Carpenter, J.M., et al.: The formation and evolution of planetary systems (FEPS): discovery of an unusual debris system associated with HD 12039. Astrophys. J. **638**, 1070–1079 (2006)

Holland, W.S., Greaves, J.S., Zuckerman, B., Webb, R.A., McCarthy, C., et al.: Submillimetre images of dusty debris around nearby stars. Nature **392**, 788–790 (1998)

Holland, W.S., Greaves, J.S., Dent, W.R.F., Wyatt, M.C., Zuckerman, B., et al.: Submillimeter observations of an asymmetric dust disk around Fomalhaut. Astrophys. J. **582**, 1141–1146 (2003)

Kim, J.S., Hines, D.C., Backman, D.E., Hillenbrand, L.A., Meyer, M.R., et al.: Formation and evolution of planetary systems: cold outer disks associated with Sun-like stars. Astrophys. J. **632**, 659–669 (2005)

Kley, W.: Mass flow and accretion through gaps in accretion discs. Mon. Not. R. Astron. Soc. **303**, 696–710 (1999)

Koerner, D.W., Sargent, A.I., Ostroff, N.A.: Millimeter-wave aperture synthesis imaging of Vega: evidence for a ring arc at 95 AU. Astrophys. J. **560**, L181–L184 (2001)

Liou, J.-C., Zook, H.A.: Signatures of the giant planets imprinted on the Edgeworth–Kuiper Belt dust disk. Astron. J. **118**, 580–590 (1999)

Moro-Martín, A., Wolf, S., Malhotra, R.: Signatures of planets in spatially unresolved debris disks. Astrophys. J. **621**, 1079–1097 (2005)

Quillen, A.C., Blackman, E.G., Frank, A., Varnière, P.: On the planet and the disk of COKU TAURI/4. Astrophys. J. **612**, L137–L140 (2004)

Rice, W.K.M., Wood, K., Armitage, P.J., Whitney, B.A., Bjorkman, J.E.: Constraints on a planetary origin for the gap in the protoplanetary disc of GM Aurigae. Mon. Not. R. Astron. Soc. **342**, 79–85 (2003)

Rodmann, J.: Dust in circumstellar disks. Ph.D. Thesis, University of Heidelberg (2006)

Schneider, G., Smith, B.A., Becklin, E.E., Koerner, D.W., Meier, R., et al.: NICMOS imaging of the HR 4796A circumstellar disk. Astrophys. J. **513**, L127–L130 (1999)

Silverstone, M.D., Meyer, M.R., Mamajek, E.E., Hines, D.C., Hillenbrand, L.A., et al.: Formation and evolution of planetary systems (FEPS): primordial warm dust evolution from 3 to 30 Myr around Sun-like stars. Astrophys. J. **639**, 1138–1146 (2006)

Weidenschilling, S.J.: The origin of comets in the solar nebula: a unified model. Icarus **127**, 290–306 (1997)

Weingartner, J.C., Draine, B.T.: Dust grain-size distributions and extinction in the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud. Astrophys. J. **548**, 296–309 (2001)

Wilner, D.J., Holman, M.J., Kuchner, M.J., Ho, P.T.P.: Structure in the dusty debris around Vega. Astrophys. J. **569**, L115–L119 (2002)

Wolf, S.: Signatures of planets and of their formation process in circumstellar disks. Habilitation Thesis, University of Heidelberg (2007)

Wolf, S., D'Angelo, G.: On the observability of giant protoplanets in circumstellar disks. Astrophys. J. **619**, 1114–1122 (2005)

Wolf, S., Hillenbrand, L.A.: Model spectral energy distributions of circumstellar debris disks. I. Analytic disk density distributions. Astrophys. J. **596**, 603–620 (2003)

Wolf, S., Gueth, F., Henning, T., Kley, W.: Detecting planets in protoplanetary disks: a prospective study. Astrophys. J. **566**, L97–L99 (2002)

Wyatt, M.C., Dent, W.R.F.: Collisional processes in extrasolar planetesimal discs—dust clumps in Fomalhaut's debris disc. Mon. Not. R. Astron. Soc. **334**, 589–607 (2002)

Zuckerman, B., Forveille, T., Kastner, J.H.: Inhibition of giant planet formation by rapid gas depletion around young stars. Nature **373**, 494 (1995)