Interferometric Detection of Planets/Gaps in Protoplanetary Disks

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Abstract. We investigate the possibility to find evidence for planets in circumstellar disks by infrared and submillimeter interferometry. Hydrodynamical simulations of a circumstellar disk around a solar-type star with an embedded planet of 1 Jupiter mass are presented. On the basis of 3D radiative transfer simulations, images of this system are calculated. These intensity maps provide the basis for the simulation of the interferometers VLTI (equipped with the mid-infrared instrument MIDI) and ALMA. While ALMA will provide the necessary basis for a direct gap and therefore indirect planet detection, MIDI/VLTI will provide the possibility to distinguish between disks with or without accretion on the central star on the basis of visibility measurements.

1. Introduction

Hydrodynamical simulations concerning the evolution of protoplanets in protoplanetary disks have shown that giant protoplanets may open a gap and cause spiral density waves in the disk (see, e.g., Kley 1999, Kley et al. 2001, D’Angelo et al. 2002). Depending on the hydrodynamical properties of the planet and the disk, the gap may extend up to several AU in width. We investigate the possibility to find such a gap as an indicator for the presence of a protoplanet with present-day or near-future techniques. For this reason, we use hydrodynamical simulations of a protoplanetary disk with an embedded planet and compute the expected brightness distributions. We show that ALMA will provide the neces-
Figure 1. Images of the inner region of the circumstellar disk with an embedded planet of 1 Jupiter mass at a wavelength of $\lambda = 700 \mu m$ and inclinations $i = 0^o$ (face-on), $30^o$, and $60^o$. [taken from Wolf et al. 2002]

2. The disk model

The density structure of the protoplanetary disk results from hydrodynamical simulations in which the disk is assumed to be flat and non-self-gravitating. The mutual gravitational interaction between the planet and the central star, and the gravitational torques of the disk acting on planet and star are included. The 3D density structure is Gaussian in the vertical direction where for the scale height $H(r)$ we assume a constant ratio $H/r=0.05$. The mass of the star is assumed to be $1 M_\odot$. The planet with a mass of 1 Jupiter mass is located at a distance of 5.2 AU from the star. The disk has a mass of $0.05 M_\odot$ and a diameter of 104 AU. The structure of the spirals and the gap reaches an equilibrium after about 150 orbits ($\approx 1800$ yrs).

The dust reemission is simulated with the Monte-Carlo radiative transfer code MC3D (Wolf, Henning, & Stecklum 1999; Wolf & Henning 2000; Wolf 2002). The radiative transfer is simulated self-consistently, taking into account both the initial temperature of the dust due to viscous heating and the additional energy input of the central star (effective temperature $T_{\text{eff}} = 5500$ K, luminosity $L = 1 L_\odot$). The dust grains are assumed to consist of “astronomical” silicates (optical data from Draine & Lee 1984; radius 0.12 $\mu m$; dust-to-gas mass ratio = 1:100). In Figure 1, images of the inner region (diameter 28 AU) of the disk, seen under different inclination angles $i$ at a wavelength of $\lambda=700 \mu m$, are shown.

3. Simulations of observations with MIDI (VLTI) and ALMA

The goal of the following simulations is to check whether MIDI/VLTI or ALMA can be used to detect gaps discussed in the previous sections.

MIDI: This MID-infrared two-beam Interferometric instrument is designed for operation at the Very Large Telescope Interferometer (VLTI) at ESO.
Figure 2. **Left:** Normalized visibilities at $\lambda=10\,\mu m$ for a disk with an inclination of $i=60^\circ$ (assumed distance: 140 pc) for a disk with/without a gap and with/without accretion. The visibilities marked by the thick and the thin line are oriented perpendicular to each other in the u-v plane (parallel to the major/minor axis of the ellipse resulting from the projection of the disk onto the plane of the sky).

**Right:** Reconstructed image of the disk seen face-on resulting from a simulation of ALMA (assumed distance: 140 pc). The gap at an angular distance of 37 mas (5.2 AU) from the star is clearly visible. Wavelength: 700 $\mu m$ (428 GHz); bandwidth: 8 GHz; total integration time: 4 h; system temperature: 500 K; phase noise: 30$^\circ$; max. baseline: 10 km. [taken from Wolf et al. 2002]

(Leinert et al. 2000). In Figure 2, simulated visibility curves at $\lambda=10\,\mu m$ are shown for different disk scenarios. Comparing the results for a disk with/without a gap we find that the visibilities at a given baseline differ by less than 5% since the innermost region – which dominates the $10\,\mu m$ flux – is only negligibly affected by the presence of the planet at a distance of 5.2 AU. Taking into account uncertainties of “real” measurements a distinction between different disk models (with/without gap) based on significant differences between the visibility profiles is not possible even by a beam combination of the most distant telescopes of the VLTI. However, MIDI will be able to trace the presence of accretion onto the central star. The different density profiles of the innermost region of the disk cause a steeper visibility profile compared to the visibilities simulated for a disk without accretion. Thus, one could clearly distinguish a disk with accretion from a disk without.

**ALMA:** The Atacama Large Millimeter Array is a planned array of 64 12m-antennas with an aspired maximum baseline of 12 to 14 km. It will cover the submillimeter/millimeter wavelength range ($\lambda=0.3$-10 mm). Due to the large number of receivers and the resulting broad distribution of baselines, a sufficient u-v plane coverage can be achieved after a few hours of observation and image reconstruction will be possible. In contrast to the first instruments at the VLTI, the visibility phase can be easily measured in the millimeter wavelength range.
In Figure 2, a reconstructed image of the disk based on a simulation of ALMA observations is shown. Even under consideration of the thermal noise caused by a system temperature of $T_{\text{sys}}=500$ K, the gap is clearly visible.

4. Conclusions

We studied the possibility of the indirect planet detection by observation of the resulting gap in a protoplanetary disk. Based on hydrodynamical simulations and subsequent 3D continuum radiative transfer calculations we generated images of a circumstellar disk with an embedded Jupiter mass planet surrounding a solar-type star.

We found that the gap can be seen very clearly in the simulated images but an extremely high angular resolution is required ($\approx 10$ mas). Furthermore, because of the extreme brightness contrast in the innermost region of the disk in the near to mid-infrared, the gap can hardly be detected in this wavelength range with imaging/interferometric observations. However, we found that it will be possible to distinguish between a disk with or without accretion onto the central star with MIDI. In contrast to this, the (sub)millimeter interferometer ALMA will provide the basis for the reconstruction of an image of a gap. Thus, the search for massive protoplanets in circumstellar disks can be based on the indication of a gap.

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