Simulations of Warped Dust Disks

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Abstract. There is a possible connection between structure in circumstellar dust clouds and the presence of planets, our own zodiacal cloud being the prime example. Asymmetries in such a cloud could be diagnostic of planets which would be otherwise undetectable. The warp in the plane of symmetry of a circumstellar dust disk is caused by the variation of the forced inclinations of the dust particles with respect to their astrocentric distances. SIRTF has the potential to detect a warp in large disks (r $\sim$ 300 AU) at $\sim$ 1 pc in MIPS super-resolution mode.

1. Introduction

There is a possible connection between structure in circumstellar dust clouds and the presence of planets, our own zodiacal cloud being the prime example. Asymmetries in such a cloud could be diagnostic of planets which would be otherwise undetectable. At least three different types of asymmetries can serve to indicate bodies orbiting a star in a disk: (1) a warp in the plane of symmetry of the disk (due to variation of the forced inclinations with respect to astrocentric distance of the particles), (2) an offset in the center of symmetry of the disk with respect to the central star (due to forced eccentricities of the dust particles), and (3) density anomalies in the plane of the disk due to resonant trapping of dust particles.

In either disk component, the orbit of a particle can be described by a set of five osculating elements: the semi-major axis (a), eccentricity (e), inclination (I), longitude of ascending node (Ω), and the longitude of pericenter ($\tilde{\omega}$). In low order secular perturbation theory, osculating elements are decomposed into proper and forced elements. The proper elements are dependent on initial conditions while the forced elements are imposed on the particle's orbit by the gravitational perturbations of the planets. This decomposition is still applicable in the presence of drag forces. Hence, the orbits of dust particles in a circumstellar cloud are directly affected by the planets therein. It is possible to extend the preceding argument to other evolved solar systems and theorize that there is a connection between evolved circumstellar disks and the presence of planets and/or planetesimals in the system (Backman and Paresce 1993).

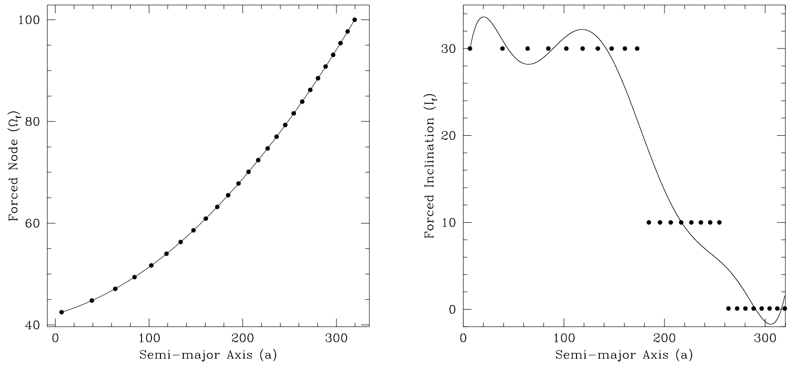

Figure 1. (a) left: The variation of Ω_{forced}, the forced longitude of ascending node and the corresponding Chebychev polynomial fit. (b) right: The variation of I_{forced}, the forced inclination and the corresponding Chebychev polynomial fit. There is a steep step functional decrease in forced inclination with respect to semi-major axis. The range of I_{forced} shown here is very large. These curves are heuristic variations, though they demonstrate how a warp would be generated in a real system.

2. Warp in the Zodiacal Cloud

The warp in the plane of symmetry of the zodiacal cloud is caused by the variation of the forced inclinations of the dust particles with respect to their heliocentric distances. A dust particle orbiting in the asteroid belt has a forced inclination which is determined by the perturbing effects of the major planets. When a particle leaves the asteroid belt to spiral in towards the Sun, its forced inclination changes due to the effect of Poynting Robertson light drag (PR drag), causing the warp. This warp can be identified by comparing the positions of the ascending and descending nodes as observed by COBE at the North and South (N and S) ecliptic poles (at 1 AU) with the positions of the nodes as observed near the ecliptic in the directions leading and trailing (L and T) the Earth in its orbit, i.e., external to 1 AU (Dermott *et al.* 1996). The ascending node at the poles is found to be $70.7° \pm 0.4$ while the node external to 1 AU is observed to be $58.40° \pm 2.3$. If the cloud had only one plane of symmetry, the ascending node observed at the ecliptic poles would be the same as the ascending node observed in the leading and trailing directions. The difference between these two longitudes is a measure of the warp of the cloud (Dermott *et al.* 1998).

3. The Exozodiacal Cloud Model

We build dynamical models of dust clouds from asteroidal particles which include radiation pressure and PR drag. The particles are $9\mu m$ in diameter and assumed to be spheres composed of astronomical silicate. The radial extent of the cloud

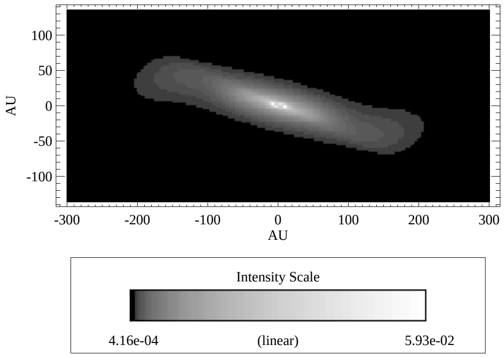

Figure 2. The model viewed at 1.35 pc as it would appear in the 70 μm wave band assuming a SIRTF sensitivity limit of 610 μJy.

is 7.0 AU (an arbitrary cutoff) to 300.0 AU and the particles populate the inner solar system according to a $1/r$ distribution (PR drag). The effects of forced elements are included in the model. Specifically, heuristic ranges of both I_{forced} and Ω_{forced} are included while e_{forced} and $\tilde{\omega}_{forced}$ are set to zero. The particles' orbits are then distributed through a 3D array of cells and a Line of Sight Integrator allows a model to be viewed as it would appear to an Earth-based observer. The face on optical depth of the cloud is $\tau \approx$ 1.2e-8. The optical depth for the zodiacal cloud is $\tau \sim$ 1e-7, so the model cloud is quite diffuse.

The function for I_{forced} for the model is a steep step functional decrease in I_{forced} ranging from $\sim 30°$ to $0°$ with respect to increasing a. The range of I_{forced} shown here is very large. For comparison, in our own solar system I_{mutual} for Jupiter and Saturn is $\approx 1.18°$. A smaller difference in mutual inclination of the perturbers produces a correspondingly smaller variation in I_{forced} and hence a smaller warp. However, for demonstration purposes, we have chosen to model a disk with a large warp (Figure 1a). An image of the model cloud as viewed edge on by an external observer at 1.35 pc, assuming a SIRTF Multiband Imaging Photometer (MIPS) slow scan mapping sensitivity of 610 μJy (Rieke 1998), in the 70 μm wave band is presented in Figure 2.

4. Implications for SIRTF

Listed in the SIRTF Science Requirements Document are several candidate stars with possible debris disks. The closest candidates are α Cen A and α Cen B at 1.35 pc. We therefore scale the brightness of our model to the MIPS sensitivity requirements for the 70 μm wave band at this distance. We then filter the model with a gaussian of width 7 ($\sim \lambda$/D) to simulate convolving the model with a stellar PSF. Lastly, we convert the pixels in our model to represent the 5 " pixel width of MIPS in super-resolution mode. A warp in the cloud is clearly evident (see Figure 3). Thus, SIRTF has the potential to detect a significant warp in large disks very close to our solar system. In addition, models of warped

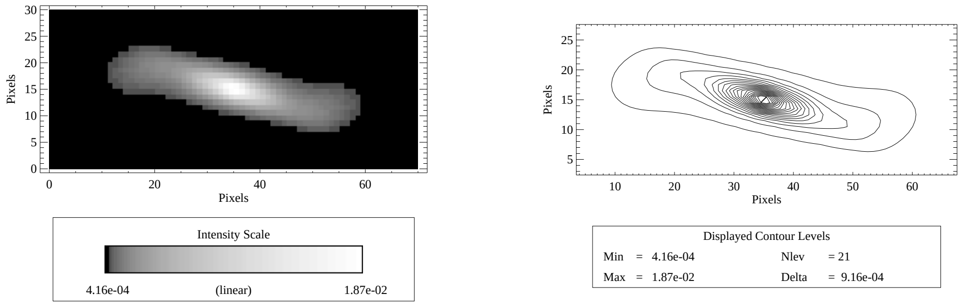

Figure 3. (a) left: The model viewed at 1.35 pc as it would appear to SIRTF in the MIPS 70 μm wave band using the sensitivity limit of 610 μJy and the super-resolution pixel size of 5 ". 1 SIRTF pixel in super-resolution model is equivalent to 3 pixels in the original model. (b) right: A contour plot of the model in (a), clearly showing the warp.

clouds were run with radii out to 3.0 AU (representing a zodiacal disk) and 40.0 AU (representing a solar system type Kuiper disk). However, the extent of these disks in SIRTF pixels were too small to determine the structure of any asymmetries when viewed at 1.35 pc. It may only be possible for SIRTF to map asymmetries in large nearby disks having significant warps. The techniques presented in this paper can be used to better model such future observations.

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