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The circumstellar environment of terrestrial planets II. Simulation of high resolution imaging of the protoplanetary disk inner region disturbed by a passing planet

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Abstract: We propose a new, simple and effective method for simulation of pictures of flux coming from gaseous-dusty disk structures caused by an embedded planet. We combine output of hydro-dynamical simulation with temperature dependent Planck function for each mass cell and integrate flux to derive pictures of protoplanetary disk with planet. We present and discuss simulated images of Earth, 1 and 1.5 Jupiter mass planets. Such images points out current needs in development of high resolution imaging technology and may serve as templates to generate visibility patterns for forthcoming interferometers.

1 Introduction

Presently available facilities do not resolve inner parts of protoplanetary disks. This region is of particular interest of many studies as it is a cradle of borning terrestrial planets and may serve as a habitat for embryos which migrate outward and become gaseous giants later. Significant fraction of known giant exoplanets (Schneider 2004), unlike those we have in our home system, is located very close to its host star. It seems to be quite common phenomena in nature and its possible explanation is a wandering of accreting giants across their courtyard under the influence of surrounding gas and dust.

High resolution imaging is still not able to precisely image inner regions of early stages of structures around pre-main sequence stars (PMSS). These structures are suspected to origin in known phenomena like migration of giant planets and their interaction with gas, dust and remaining disk solids. Growing number of ideas for significant improvements in observational techniques, realized mostly by interferometers, as well as complex process of data processing

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for such technics require to model flux distribution coming from this environment (Absil 2001, 2003). A number of packages is currently available to achieve this goal. Some fast and efficient codes, like ZODIPIC (Kuchner 2001) or DISKPIC (Absil 2003) provide effective tools for image generation although they are not able to handle more complex structures like gaps or spiral density waves generated by planets embedded in disk.

We propose a method to make observational patterns of a narrow inner regions of young planetary systems composed of planet and gas. Although simple our approach offers a tool reliable to understand what conditions are required to image such environment and structures with future facilities. This a task for post-VLTI instruments being currently designed.

2 How to make a picture?

The prescription for an artificial image generation is following: we need to set an observer at one point of universe and point him towards an investigated object somewhere on the sky. Next we need to integrate along the light of side towards an observer the flux coming from a mass distribution inside the object. Performing this in the entire field of view we have got a picture of flux coming towards all pixels of observer detector. This process is described better by a formulae:

$$I(x,y) \simeq \frac{\triangle x \triangle y}{d^2} \int_z^z B_\nu(T(x,y,z))\Sigma(x,y,z) \quad (1)$$

where $\triangle x$ and $\triangle y$ is pixel size in x, y direction, respectively, d is a distance to the center of object from observer, z_1 and z_2 is a range of object at the line of side, $B_\nu(T(x,y,z))$ is Planck function for given temperature as a function of local object coordinates, and $\Sigma(x,y,z)$ is object's matter density as a function of its local coordinates. The object can by oriented on the sky in any way when seen by observer thus it is necessary to transform its coordinates into observer reference frame which is usually sky coordinates system. The flaring index of disk is set to 1.0 what yields linear scaling of disk height with radius. The temperature profile is determined by sound speed profile in hydro simulation with sublimation temperature set to 1500K. To render image we choose 10μ as it is well placed in the middle of N band.

A crucial point in imaging of gaps and density waves is to know the distribution of disk matter. To derive it we evolve the disk with a planet. This may be done by solving hydrodynamics equations for a disk model.

3 Disk model

We have prepared a disk model in the most standard configuration composed of flat surface density profile, with total mass of around 0.01 of central star mass which is assumed to be solar. We set sound speed, $c_s = 0.05$ and put a planet at 1 AU on circular orbit. The masses of planet differs for different runs. To solve hydro equations we applied Piecewise Parabolic Method (PPM) implemented in VH1-like package called Stockholm-Virginia Hydrodynamics which copyrights are held by Pawel Artymowicz. This code, although not the newest, has some marvellous properties like no need for viscosity tensor, fast execution and simplicity. Running our models for several tens of planet periods we obtained several density patterns adapted for further imaging. There are some significant approximations made like not solving real time radiative transfer, uniform matter density and opacity, no planetesimals and solids inside the disk, no division between gas and dust which both are treated as the same not mutually interacting fluid, point size planet and vertically averaged 2D disk model. The latter is a reasonable assumption as recent 3D results show qualitative agreement between 2D and 3D simulation revealing some minor (as for the purpose of this study) differences.

The disk covers a region of 4.0 AU with outer boundary, set for proper simulation, at radius of 2.0 AU. The main function of the region out of the boundary is damping of spiral waves and any other disk density perturbation.

Simulation of evolution of our models generated well developed 2D density patterns with gaps and spiral density waves. For migrator of order of Jupiter mass the planet has changed its location along semimajor axis even by 50% traversing towards the star. Such rapid migration is already confirmed by theory (Masset & Papaloizou 2003) to take place in typical disks.

As the observer usually looks at 3D structure even in the case of thin disk we extended our 2D density distribution obtained from simulation to full 3D objects assuming its gaussian vertical profile and averaging all quantities over their vertical dimension. Such procedure changes a little the shape of a gap or density wave from its real 3D structure although we believe it is negligible for the purpose of our investigation.

4 Results

All rendered images are shown on figures. The images are composed of 400 pixels in each direction and cover the inner region with radius of 2.0 AU. The object was placed at 10pc then each pixel has 1 mas.

For Earth size planets, figure 1, there is no visible distortion of flux coming from the disk, either in face on or inclined position. Density perturbation is much less than 1% and is hardly noticeable. Planet of this size is not able to open a gap due to its linear interaction with surrounding. However, in PMSS stage and soon after such environment is overcrowded by planetesimals and perhaps protoplanets which all generate some turbulence in disk structure.

Increasing the mass of perturber, as seen in figure 2, the interaction of planet and disk becomes nonlinear and develop a gap. For a large mass, here 1.5 that of Jupiter, there is also launching of spiral density waves, clearly seen on the picture. The gap is under formation.

Figures 3 & 4 present visualization of different time steps of hydrodynamic simulation and corresponding flux distribution for generated images. The density and hence the flux coming from the region out of 2.0 AU is artificially damped to uniform value. Bottom row exhibits the disk with deep and evolved gap after around 50 planet periods. The planet is also shifted towards its host star. Linear scale of flux distribution shows only some tiny regular patterns in the disk structure inside the gap. However, the gas accreted by planet and higher density region around the planet resulting as a cumulation of gas streamlines form a blob, which is clearly noticeable and may be treated as a signature of a giant. Logarithmic scale reveals the structure of gap and the spiral pattern across the entire region. The same signatures are visible in the case of inclined disk image, especially in logarithmic scale.

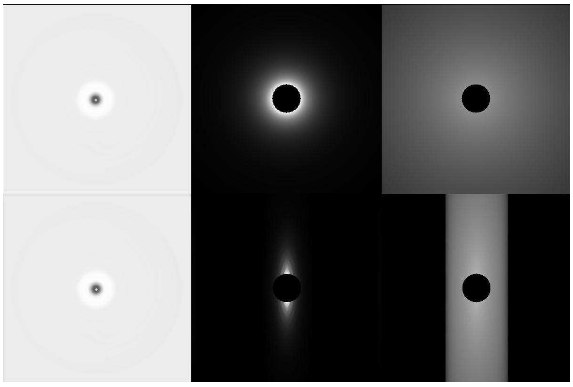

Figure 1: Earth size planet at 1 AU embedded in gaseous-dusty disk. Left column - surface density distribution from 2D disk simulation, up and bottom the same. Middle column - flux distribution for face on (upper) and highly inclined (bottom) disk. Right column, respectively, logarithmic scaled flux distribution.

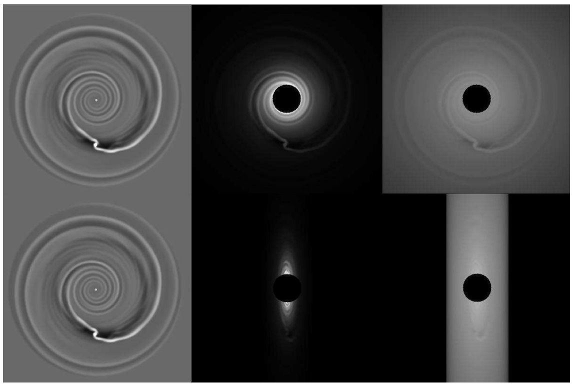

Figure 2: 1.5 of Jupiter mass planet migrating inward from 1 AU embedded in gaseous-dusty disk driving spiral density waves after gap opening. Left column - surface density distribution from 2D disk simulation, up and bottom the same. Middle column - flux distribution for face on (upper) and highly inclined (bottom) disk. Right column, respectively, logarithmic scaled flux distribution.

5 Discussion

Current facilities allow to resolve, as in the case of AU Mic (Liu M. 2004), details of 0.4 AU size at 10pc what significantly exceeds the region simulated through this study. According to present technological advancement N band is particularly useful for ground based observations of protoplanetary disk and their structures. In the case of space facilities like near future interferometers we are not restricted only to atmospheric windows but 10μ still remains attractive wavelength as it quarantees very efficient ratio of star and planet, or planet blob flux, facilitating detection of the latter.

Another possible application of such simulation of imaging method is preparation of templates for interferometers. This techniques requires complex data analysis and generation of visibility patterns to fit it to real data. It may also be helpful in design of observing strategy which is necessary for sufficient and successful covering of u-v plane.

We have proposed a simple method and "toy" models to simulate imaging of inner structure of disk with planet. Although this analysis is rough and neglects many important features it still provides a good recognition of possible outputs of nearest future high resolution imaging according to the state-of-the-art-theory of objects of interest.

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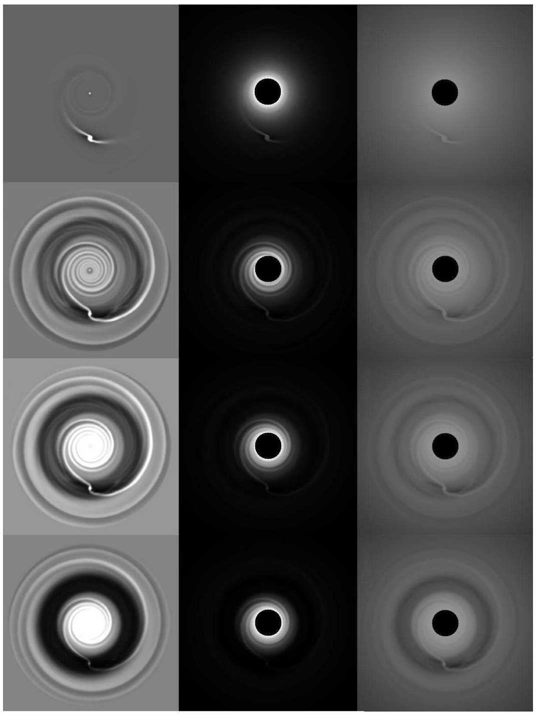

Figure 3: A Jupiter mass planet migrating inward from 1 AU embedded in gaseous-dusty disk driving spiral density waves during and after gap opening. Left column - surface density distribution from 2D disk simulation. Middle column - flux distribution for face on disk. Right column - logarithmic scaled flux distribution. From up to bottom following time shots separated by several orbital periods.

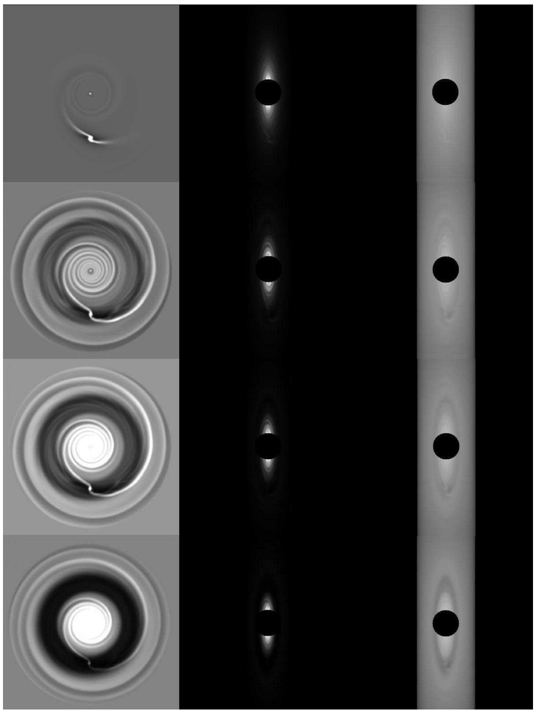

Figure 4: A Jupiter mass planet migrating inward from 1 AU embedded in gaseous-dusty disk driving spiral density waves during and after gap opening. Left column - surface density distribution from 2D disk simulation. Middle column - flux distribution for highly inclined (75 degrees) disk. Right column - logarithmic scaled flux distribution. From up to bottom following time shots separated by several orbital periods.

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