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Outermost planets of Beta Pictoris, Vega and Epsilon Eridani: goals for direct imaging

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Abstract. We discuss our numerical approach to the high-resolution modeling of the 3D structure and infrared emission of circumstellar dust disks. We examine the resonant structures of a dusty disk induced by the presence of giant planet, that outermost from a star. These features can serve as indicators of outermost planets embedded in the circumstellar dust disk and, moreover, can be used to determine its position, major orbital parameters and even the mass of the planet. Such planets are attractive goals for direct imaging. Our simulations indicate that Vega may have a massive planet ∼2 Jupiter mass at a distance >50 AU, and other giant planet(s) at a smaller distance, and Epsilon Eri may have a less massive planet ∼0.2 Jovian mass at a distance of 55–60 AU. Theoretical models and non-direct observations show that Beta Pictoris system can be a multiplanetary system with set of giant planets. Our dynamical model of the origin of the warping of the Beta Pictoris disk includes the gravitational influence of a planet with a mass of about 10 masses of Earth, at a distance of 70 AU, and a small inclination (2.5 deg) of the planetary orbit to the main dust disk. The direct signatures of this planet were discovered on 2002 by Keck observations.

Keywords. Beta Pictoris, Vega, Epsilon Eridani, exoplanets, resonant structures.

1. Introduction

Basic elements of planetary systems are: inner and outer planets; cometary-asteroidal belts; dust disk and Jackson-Zook resonant rings. Origin of planets is the result of fast accretion in dense areas of a planetary system. Outer cometary-asteroidal belt (TNO in the Solar system) is a common element of planetary systems as the result of low peripheral surface density and large period of orbital revolution. These two factors lead to time of accretion larger than life time of planetary system. Origin of inner asteroidal belt (as Main Asteroidal Belt in the Solar system) is the result of interaction between next dynamical mechanisms: 1. Collisions between asteroids and large dust particles lead to origin of micron-size dust. 2. Solar radiation pressure push of small particles to Jupiter zone. 3. 50% of small dust escape in interstellar space by scattering on Jupiter gravitional field (Gorkavyi *et al.*, 2000). As result of this efficient mechanism, asteroidal belt lost most of initial mass and accretion time drastically increased. Additional factor of growing of accretion time is reasonant influence of the Jupiter to relative velocities of asteroids. Dust disk and Jackson-Zook rings are the result of re-distribution and resonant accumulation of dust from asteroids and comets. Any planetary system can demonstrate complex dynamical interaction between all basic components: planets, minor bodies, dust and gas on early stage. Important that dust is the most visible part of planetary

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systems. Link between dust disk features, JZ-rings and invisible planets can be important for search and direct imaging of planets.

2. The multiplanetary systems

Outermost (∼50 AU) giant (∼10–1000 M_{Earth}, where M_{Earth} is the mass of the Earth) planets are attractive goals for direct imaging. ¿From our point of view, planetary systems of Vega, Beta Pictoris and Epsilon Eridani is good sample of multiplanetary systems with outer giants. The results of our study reveal a remarkable similarity of theoretical models with various types of highly asymmetric circumstellar disks around Beta Pictoris, Epsilon Eridani and Vega (Gorkavyi *et al.* 2000, 2004).

According our modeling, Epsilon Eridani may have outermost giant planet with ∼0.2 Jovian mass at a distance of 55–60 AU. Inner panet of Epsilon Eridani (3.4 AU, $\sim 1 M_J$, e∼0.6, M_J is the mass of Jupiter) was discovered by Doppler effect (Hatzes etal, 2000) and we can decide from general theoretical arguments, that Epsilon Eridani can have another massive $\sim 0.1–1 M_J$ planets between 5–50 AU.

Beta Pictoris is the planetary system with specific spectral activity (Lagrange 1995), that is the clear signature of inner giant planets, for example, in (Gorkavyi and Taidakova 1995) was considered system from two planets at radii 3.2 and 5.9 AU with masses 0.0019 and 0.00095 of mass of star. Our dynamical model of the origin of the warping of the Beta Pictoris disk (Gorkavyi *et al.* 2004) includes the gravitational influence of a planet with a mass of about 10 masses of Earth, at a distance of 70 AU, and a small inclination (2.5 deg) of the planetary orbit to the main dust disk. Jackson-Zook ring with similar radii and inclination were discovered on 2002 by Keck observations (Wahhaj *et al.* 2002) and we can consider this JZ-ring as the direct signatures of outermost theoretically predicted planet. Totally four JZ rings was discovered by (Wahhaj *et al.* 2002) with radii of 14, 28, 52 and 82 AU and we believe that Beta Pictoris is a multiplanetary system with at least 5–6 giant planets between 3 and 80 AU. Our simulations indicate that Vega may have a massive planet ∼2 Jupiter mass at a distance >50 AU, and other giant planet(s) at a smaller distance. This planetary system will be considered below in more details.

3. The planetary system around Vega

We applied our numerical method (Taidakova and Gorkavyi 1999) to compute the thermal emission of a dusty resonant structure around Vega (Ozernoi *et al.* 2000, Gorkavyi and Taidakova 2002). Both the Poynting–Robertson and stellar wind drags tend to induce cometary dust inflow toward the star. The modeling has shown that a planet produces an asymmetric resonant dust belt via resonances and gravitational scattering. Our simulations have three main steps:

1. simulation of distribution of cometary population;
2. calculation of distribution of cometary dust (see Fig. 1);
3. determination of thermal emission of dust (see Fig. 2).

Our high resolution (2–3 AU) simulation is in good agreement with the new observation for a ring arc at 95 AU near Vega (Koerner *et al.* 2001). Our modeling indicate that Vega may have a outermost planet at a distance of 90–100 AU with coordinates near 18 35’16.25″ (on image from (Koerner *et al.* 2001), right ascension, B1950) and 38 44’15″ (declination). Another symmetrical position, 18 35’14.75″ and 38 44’32.5″, of the planet is also possible. We can decide between these two positions after measuring the revolution direction of the resonant pattern, which must have an angular velocity of 0.6 deg/yr. Radii of clumps (and planet’s orbital radius) may be smaller: 60–75 AU (according to

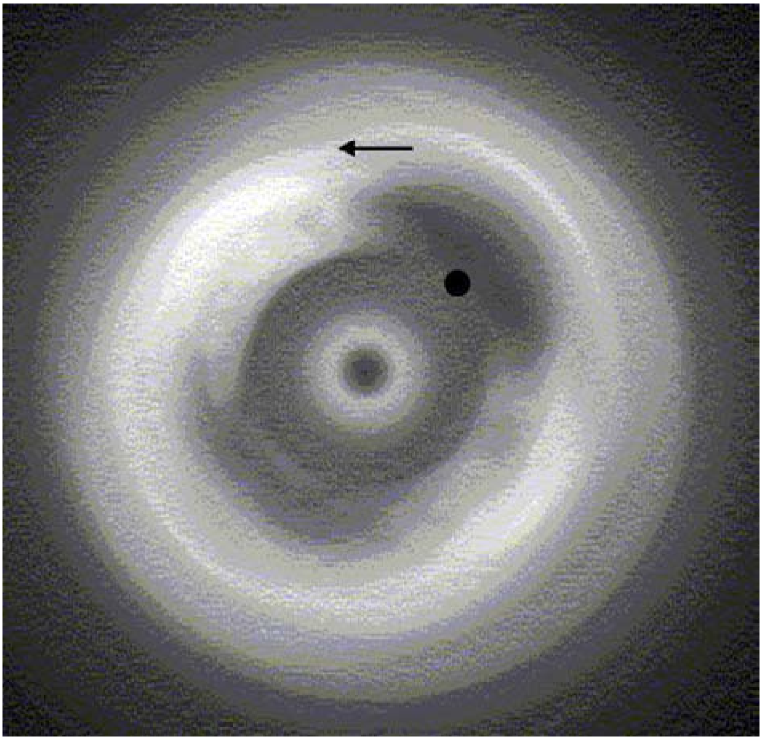

Figure 1. Simulated surface density of circumstellar dust disk with one Jupiter-like planet (dark circle in right top area inside the cavity). Orbital radius is 30 pixels of image (1 pixel = 2.5–3 AU for the Vega). Counterclockwise rotation of disk.

Wilner *et al.* 2002). In this case the planet stay approximately on the line between the two possible points marked above and the angular velocities of the planet and dust pattern will be up to 1.2 deg/year. Preliminary considerations give the mass of outer planet less than ∼2 Jupiter masses. Our simulations in the one planet approximation show that it must have bright emission from inner quasisymmetrical dust disk with radius <30–40 AU. Observations by Koerner *et al.* (2001) don't show emission from such inner dust disk and we can predict existence of giant planet(s) at distance <50–60 AU, which destroyed inner circumstellar dust disk by gravitational scattering. If weak dusty inner clumps (Koerner *et al.* 2001) have resonant link to inner planets, they must revolve around Vega much faster than the outermost arcs.

An example of the results that are obtained from our method is given in Fig. 1 for a surface density. Fig. 2 shows emission for this surface density.

4. Conclusions

1. Predicted in 2000 the outermost (∼70 AU) planet in the Beta Pictoris system at inclined (2.5 deg) orbit was confirmed by observation in 2002 (Wahhaj *et al.* 2002).

2. Our modeling indicates that the Vega has a multiplanetary system. Orbital radius of the outermost planet is approximately the same as the orbital radius of dust clumps (90–100 AU from observation by Koerner *et al.* (2001) or 60–75 AU from observation by Wilner *et al.* (2002).

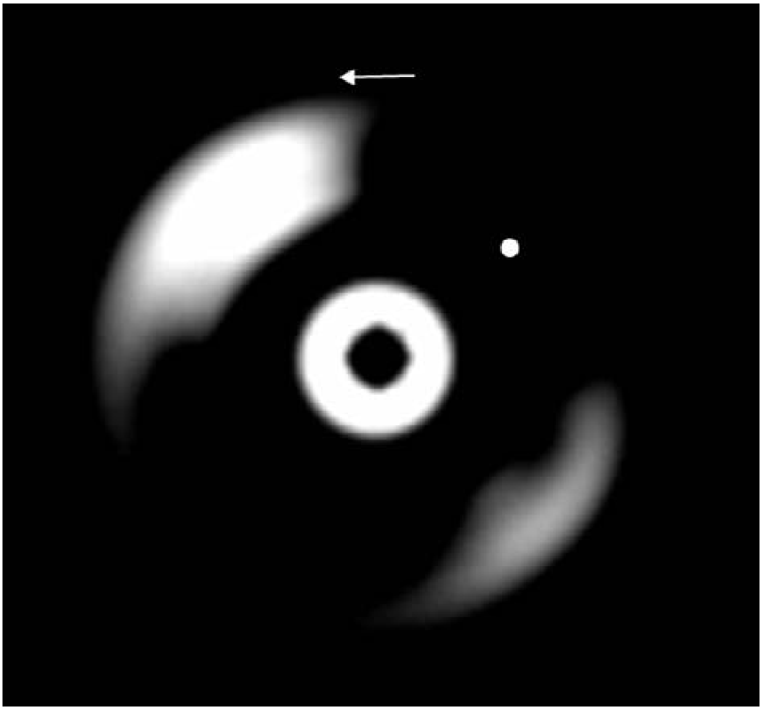

Figure 2. Thermal emission from circumstellar disk (model from Fig. 1). 5 pixel' averaging was used for comparison of our simulation with observation by Koerner *et al.* 2001.

3. Dust clumps near Vega are made of resonant particles (2:1; 3:1 etc); they rotate around Vega exactly with the planet's orbital speed (precession is very small): 0.6–1.2 deg/year depending on orbital radius of parent planet (see point 2).

4. The most dense clump is ahead of the planet in the direction of the orbital motion.

5. The planet stays in the empty area between the clumps.

6. The orbit of the planet may be circular or with small eccentricity.

7. Mass of the outermost Vega's planet is near or less than 2 Jupiter masses.

8. An outer cometary belt (like TNO' belt) there exists beyond the outermost planet.

9. Transparency of the inner part of Vega's planetary system is a signature of inner giant planet(s) with orbital radii <50–60 AU.

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