Orbital Motion of Resonant Clumps in Dusty Circumstellar Disks as a Signature of an Embedded Planet

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Abstract. We have applied a powerful numerical approach to compute, with a high resolution, the structure of dusty circumstellar disks with embedded planets. We emphasize some testable implications of our simulations which would verify the presence of a planet via thermal emission of one or more dusty clumps which are in mean motion resonances with the planet. In particular, our simulations indicate that Vega may have a massive planet of \( m \sim 2 \ m_J \) (\( m_J \) being Jupiter’s mass) at a distance of 50–60 AU, and Epsilon Eri may have a less massive planet of \( m \sim 0.2 \ m_J \) at a similar distance of 55–65 AU. This conclusion is testable: Each resonant feature is stationary in the reference frame co-rotating with the planet, but it is not so for the observer at Earth. Therefore, if our interpretation of asymmetric clumps in circumstellar disks as dynamical resonant structures is correct, the above pattern revolves around the star with an angular velocity of \((1.2 - 1.6)^\circ/yr\) (Vega) and \((0.6 - 0.8)^\circ/yr\) (\( \epsilon \) Eri) – a prediction that can be tested on a timescale of several years.

1. INTRODUCTION

Dusty disks around stars are a very common cosmic phenomenon. These disks, with scales of tens to hundreds (up to a thousand) of astronomical units, demonstrate a great variety in structure; sometimes they have a central ‘hole’ void of gas and dust, and often are highly asymmetric. The dusty circumstellar disks are thought to accompany planetary systems and, at the same time, to hide them from the observer. Knowledge of dust characteristics is of prime importance for future NASA space missions, such as the NGST (Next Generation...
Space Telescope) and the Terrestrial Planet Finder. It is generally expected that a significant limitation to unambiguous planet detection and study will be contaminating thermal emission from dust in the target systems. We propose to turn this hazard into an advantage for detecting and characterizing planetary systems. Both the stellar radiation drag and stellar wind drag as well as residual gas in the disk tend to induce dust inflow toward the star. As dust particles pass by the planets in their infall, they interact with them by accumulating in planetary resonances, which are observable as clumps or belts in the dust disk.

2. NUMERICAL SIMULATIONS

We focus on the conditions favorable to formation of resonant rings near the orbit of just one planet orbiting the parent star. Recently, we have elaborated a novel, very efficient approach to numerical modeling of distributions of test particles in an external gravitational field (Ozernoy, Gorkavyi, & Taidakova 2000; Gorkavyi et al. 1999; Taidakova & Gorkavyi 1999). Our approach removes the major obstacle to reliable numerical simulations – the particle-number limitation. In brief, our approach (which has a number of common elements with the ‘particle-in-cell’ computational method) is as follows: Let us consider, for simplicity, a stationary particle distribution in the frame co-rotating with the planet. The locus of the given dust particle’s positions (taken, say, as $10^4$ positions every revolution about the star) are recorded and considered as the positions of many other particles produced by the same source of dust but at a different time. After this particle ‘dies’ (as a result of collisions, infall, or ejection from the system by a planet-perturber), its recorded positions sampled over its lifetime form a stationary distribution as if it were produced by many particles. Typically, each run includes $10^5$ revolutions, i.e. $\sim 10^7$ positions of a dust particle, which is equivalent, for a stationary distribution, to $10^7$ particles. Allowing for 1000 sources of dust, we deal, after 1000 runs, with $\sim 10^{10}$ particle positions as if they were real particles. In the present paper, we immediately sort this information into $\sim 10^7$ spatial cells (each cell containing $10^3 - 10^4$ particles), thereby forming a 3D grid that models the dust cloud around the star. We have computed about 300 model disks exploring the effects of various resonances given the location of dust sources and adopting as parameters the mass of the planet, initial orbital characteristics of dust particles, and particle radius $r$ (in $\mu$m) coupled with stellar luminosity $L_*$ and mass $M_*$ (in solar units), as described by the parameter $\beta \approx 0.3 \ L_*/(M_* r)$.

The modelling has shown that a planet, via resonances and gravitational scattering, produces an asymmetric resonant dust belt with one or more clumps plus one or more cavities as well as a central region devoid of dust. These features can serve as indicators of a planet embedded in the circumstellar dust disk and, moreover, can be used to determine the mass of the planet and even some of its orbital parameters. Our simulations in more detail, as well as related work, are described by Ozernoy et al. (2000).
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Figure 1. Thermal emission ($\lambda = 850 \mu m$) from simulated circumstellar disks with the resonant structures vs. observations. The star’s location is (0,0). The unit of length = $\frac{1}{30}$ of the planet’s radius. The planet (shown in a, b as a square) revolves, like the disk, counterclockwise. In c, d, a square indicates the expected planet’s location. To compare our simulations with observations, averaging with the beam size (50 units of length in a and 20 units of length in b is applied to the simulations. – a) The simulation reminiscent of the disk of Vega: $M_\star = 2.5 M_\odot$; $m_{pl} = 2 m_J$; $\beta = 0.3$; the lifetime of dust particles $\tau = 2 \times 10^4$ planet’s revolutions; the number of dust sources (comets) is 486, and the number of particle positions is $3 \times 10^{10}$. The adopted size of the central cavity is 10 units of length. For a version of this simulation with the beam size of 40 and the central cavity size of 12 units of length, see Ozernoy et al. (2000). – b) The simulation reminiscent of the disk of ε Eridani: $M_\star = 0.8 M_\odot$; $m_{pl} = 0.2 m_J$; the resonances 2:1 and 3:2 (populated in ca. equal proportions); $\beta = 0.002$; $\tau = 10^2$ planet’s revolutions; the number of dust sources (kuiperoids) is 2910 (of them, 1250 sources form the upper branch and 1660 sources form the lower branch of the pattern), and the number of particle positions is $2 \times 10^9$. – c) Circumstellar disk of Vega (Holland et al. 1998). – d) Circumstellar disk of ε Eridani (Greaves et al. 1998).
The results of this study reveal a remarkable similarity with various types of highly asymmetric circumstellar disks observed at submillimeter wavelengths around \( \epsilon \) Eri and Vega. Fig. 1a,b show the thermal emission from simulated disks (seen face-on) with an embedded planet, which are to be compared with the available observational data on Vega and \( \epsilon \) Eri shown in Fig. 1c,d (the parent stars are seen almost pole-on). The sources of dust are assumed to be alike (gravitationally scattered) comets in the \( \epsilon \) Eri's disk and alike (resonant) kuiperoids in the \( \epsilon \) Eri disk. A planet as massive as 2 Jupiter masses \((m_J)\) (or somewhat less if the role of resonant comets is appreciable) produces, from the cometary dust, two clumps (Fig. 1a), which is reminiscent of the observed asymmetric clumps near Vega shown in Fig. 1c. A smaller mass \(\sim 0.2 \ m_J\) induces, from the kuiperoidal dust, two asymmetric arcs, with four clumps at its edges (Fig. 1b). A similar asymmetric structure has been revealed in sub-mm imagery of the \( \epsilon \) Eri disk shown in Fig. 1d.

Given the particular resonant pattern as the site for the captured dust, the appearance of the resonant structure in a dusty disk depends on the beam size and the presence/absence of a central cavity in the dust distribution. The latter can be produced as a result of gravitational scattering of the dust by a massive planet in the inner part of the planetary system, although the emission of dust from inner comets may mask its presence.

The above modeling indicating that Vega may have a planet of mass \(\sim 2 \ m_J\) at a distance of 50 – 60 AU, and \( \epsilon \) Eri may have a less massive planet of \( m \approx 0.2 \ m_J \) at a similar distance of 55 – 65 AU, is testable: Each resonant feature is stationary in the reference frame co-rotating with the planet, but it is not so for the observer at Earth. Therefore, if the proposed interpretation of asymmetric clumps as dynamical resonant structures is correct, the above asymmetric feature revolves around the star with an angular velocity of \((1.2 - 1.6) ^\circ / \text{yr} \) (Vega) and \((0.6 - 0.8) ^\circ / \text{yr} \) (\( \epsilon \) Eri) – a prediction that can be tested within several years. By the middle of 2000, one could expect the resonant features to be shifted, compared to their original positions in 1997-1998, by 4 – 5\(^\circ\) in the Vega's disk and by \(\sim 2^\circ\) in the \( \epsilon \) Eri disk. In practical terms, an azimuthal brightness distribution at \( R = 50 – 60 \) AU in the disk is to be measured and cross-correlated on a timescale of a few years. This could make it possible to reveal the revolution of the resonant pattern, to determine its direction, and evaluate the rate of motion.

If confirmed, the proposed interpretation of the structure in Vega- and \( \epsilon \) Eri-like circumstellar disks seen face-on would make it possible not just to reveal the embedded planet and determine its semimajor axis, but also to constrain its other basic parameters, such as the planet’s mass and even to pinpoint the position of the planet. Our work suggests important observational tasks as follows:

A. to determine the direction of orbital revolution for dusty clumps;
B. to estimate the angular velocity of those clumps;
C. to reveal a faint peripheral structure external to the clumps.

As our modeling indicates, an answer to task A would enable as to eliminate an uncertainty in the position of the predicted planet; its mass could be estimated more accurately as well. Task B would be important to determine
the planet’s orbital radius. Finally, task C would enable us to determine which particular resonances are the strongest and to pinpoint the position of the cavity in which the planet is located.

So far the most successful method of detecting extrasolar planets, such as the precision Doppler measurements, is biased toward comparatively small distances from the star. Our novel method offers a complementary approach for revealing invisible outer planets in circumstellar disks and determination of planetary parameters using the visible morphology of the outer part of the disk.

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