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Simulations of the dynamics of the debris disks in the systems
Kepler-16, Kepler-34, and Kepler-35

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Abstract

The long-term dynamics of planetesimals in debris discs in models with parameters of binary star systems Kepler-16, Kepler-34 and Kepler-35 with planets is investigated. Our calculations have shown the formation of a stable coorbital with the planet ring is possible for Kepler-16 and Kepler-35 systems. In Kepler-34 system, significant eccentricities of the orbits of the binary and planets can to prevent the formation of such a structure. Detection circumbinary annular structures in observations of systems binary stars can be evidence of the existence of planets, retaining coorbital rings from dust and planetesimals.

Keywords: planetesimals, debris disk, binary star, Kepler-16, Kepler-34, Kepler-35

1 Introduction

Modern scenarios for the formation of planets predict their formation in a gas-rich protoplanetary disk (see, e.g., Zhou et al. 2012). However, the formation of planets in binary star systems involves a number of difficulties. The theory and numerical experiments show that gravitational perturbations in binary star systems cause the eccentricities of planetesimals to increase periodically. This increase, in turn, prevents their mutual accretion, because it leads to their destruction in high-velocity collisions (Moriwaki & Nakagawa 2004; Meschiari 2012a,b; Paardekooper et al. 2012). The scenario for the formation of a planet far from the central instability region and its subsequent radial migration inward, toward the central binary seems probable in that case. In the systems Kepler-16, Kepler-34, and Kepler-35, in order to the planet to occupy its current orbital position in the system, during its migration it would have to cross several zones of chaos attributable to the orbital resonances with the central binary (Popova & Shevchenko 2013).

The formation of circumbinary planets is most likely in the case of close binary systems, while wide star pairs are suitable for planets orbiting around one of the binary components (Holman & Wiegert 1999; Mugrauer et al. 2007). Most of the discovered circumbinary planets belong to binary stars with a separation of less than 1 AU (Doyle et al. 2011; Welsh et al. 2012; Orosz et al. 2012).

With time, the gas component is depleted and the protoplanetary disk passes to the planetesimal stage. If protoplanets have already been formed by this epoch, then their presence can be detected by the interaction with the planetesimal disk. Observations have shown that the planetesimal disks of both single and binary stars have nonsymmetric and ring-like structures, which may suggest the presence of unresolved companions in the disk, for example, giant planets or low-mass stars (Greaves et al. 1998; Augereau 2004; Thalmann et al. 2011; Krist et al. 2012; MacGregor et al. 2013; Fedele et al. 2017). This idea has stimulated the studies aimed at searching for the connection of such structures with characteristics of the invisible companion, primarily its mass and orbital parameters. For example, Ozernov et al. (2000) studied the clumps in the planetesimal disk of a single star caused by the influence of a planet: planetary perturbations were shown to produce an asymmetric resonant dust belt with one or more clumps, intermittent with cavities. Demidova & Shevchenko (2016) investigated a similar problem for the case of a circumbinary planetary system; evidence that the ring-like structure coorbital with the planet is more massive and stable if the central star is a binary rather than a single one was obtained.

The populations of small bodies coorbital with Solar System planets are well known. Jupiter’s Trojans are a well-known example of the motion of small bodies in 1:1 resonance (see, e.g. Murray & Dermott 1999). Nesvorný & Dones (2002) presented their simulations of the dynamics of Saturnian, Uranian, and Neptunian Trojans on time scales comparable to the age of the Solar System. Their calculations showed that the coorbital populations of asteroids are rapidly scattered in the case of Saturn and Uranus, but Neptune can retain 50% of its original population of Trojans. Several Trojans were discovered near Mars (Bowell et al. 1990) and Neptune (Sheppard & Trujillo 2005), one near the Earth (Connors et al. 2011), and
and structures in the Solar System suggests that they can also be revealed in other planetary systems.

Since, as has been noted above, the coorbital rings for circumbinary planets are more stable and long-lived than for planets of single stars, the ring-like structures of dust and small bodies can be revealed near the orbits of discovered circumbinary planets. In this paper we consider the systems Kepler-16, Kepler-34, and Kepler-35. Based on our numerical experiments, we describe the characteristics of hypothetical coorbital rings.

Note that the planetesimals in our models gravitate passively, i.e., their masses, sizes, and self-gravity are disregarded. The masses for the observed debris disks vary from $\sim 3$ to $\sim 20$ Earth masses (Wyatt & Dent 2002; Chiang et al. 2009). Beust et al. (2014) and Pearce & Wyatt (2014) showed that the influence of a massive planet dominates over the mutual gravitational interaction (self-gravity) of planetesimals if the planet’s mass exceeds the disk mass by an order of magnitude or more. In all our models the ratio of the planet’s mass and the disk mass is $\sim 100$. The simulation data on the dynamics of planetesimal disks with and without self-gravity were compared by Lines et al. (2013). They showed that in the systems Kepler-16 and Kepler-34 the contribution of self-gravity affects the distribution of matter in the disk (and the eccentricities of planetesimals) only slightly.

Under conditions of flat planetesimal disks of stars, whose gravity dominates in the disk dynamics, the standard theory of Chandrasekhar (1942), as Hasegawa et al. (1988) showed, gives not the characteristic pair gravitational relaxation time itself but its lower limit. According to Hasegawa et al. (1988), the lower limit for the relaxation time is estimated as $\sim 0.005 v_1^3 / G^2 n_p \rho n_2^2$, where $G$ is the gravitational constant, $m_p$ is the characteristic mass of a gravitating particle, $n_p$ is the space density of interacting particles, and $v_p$ are their characteristic relative velocities. The characteristic relative velocities of planetesimals in circumbinary disks determined by the perturbations from the central binary are $\sim 1000 \, \text{m} \, \text{s}^{-1}$ (Moriwaki & Nakagawa 2004; Marzari et al. 2013). For planetesimals with a particle space density $n \sim 10^{-24} \, \text{cm}^{-3}$ and a diameter of 10 km and a density of 2 g cm$^{-3}$ in a disk with a particle space density $n_p \sim 10^{-24} \, \text{cm}^{-3}$ we have $\sim 10^7 \, \text{yr}$ for the lower limit of the relaxation time in our model, which is much longer than our integration time intervals but is comparable to the lifetimes of the disks under consideration. Thus, self-gravity can be an important effect, especially regarding the long-term evolution of coorbital structures. We leave this question for future further studies. The Toomre parameter (Toomre 1964) for the disks under consideration is $Q \gg 1$ due to their low masses. Therefore, we assume that the disk self-gravity in our models is negligible.

Paardekooper et al. (2012) and Meschiari (2012a) investigated the collisional dynamics of planetesimals in circumbinary disks. According to their calculations, the collisions of planetesimals at high velocities in the system Kepler-16 are intensive in the ring between 1.75 and 4 AU. They obtained similar data for the systems Kepler-34 and Kepler-35 as well. Near the planets themselves the collisions of planetesimals most likely do not lead to significant destructions of planetesimals. Therefore, in all likelihood, collisions do not affect the dynamics of the coorbital ring. However, fine dust can be produced in the planetesimal disk due to collisions. Its presence will allow various structures in disks to be revealed through infrared observations.

Mutter et al. (2017b) considered the influence of self-gravity on the evolution and structure of gas-rich circumbinary disks using the early epochs of evolution of Kepler-16, Kepler-34, and Kepler-35 as an example. According to their results, if the disk is sufficiently light, then self-gravity does not affect significantly the structure of the disks in Kepler-16 and Kepler-35 with low binary eccentricities, but the differences can be significant in the case of Kepler-34. If the gas disk is sufficiently massive, then the disk self-gravity can affect strongly the disk structure, in particular, the size and shape of the inner cavity. The migration of the forming planet can also be affected, because the inward-migrating planet stops near the inner disk boundary (the cavity edge: Pierens & Nelson 2008). The observed positions of the planets and the numerically calculated sizes of the inner cavity were compared by Mutter et al. (2017b). They showed that there is no need to take into account the disk self-gravity to explain the current position of the planet in Kepler-16, while for Kepler-34 good agreement is achieved with self-gravity. No agreement was achieved in any of the models for Kepler-35.

Note also that the possibility of the planet’s migration in the protoplanetary disk of the binary system is disregarded in our calculations. In principle, the radial migration of the planet in the disk can prevent the formation of a ring-like structure coorbital with the planet.

The migration of planets in a circumbinary disk takes place mainly at the stage of their formation when the disk is still gas-rich. Pierens & Nelson (2007) showed that bodies with a mass up to 20 Earth masses migrate in a gas-dust circumbinary disk inward (toward the binary). Their motion is stopped near the inner
Table 1: The model parameters

| Model | 1 | 2 (K-16) | 3 | 4 (K-34) | 5 (K-35) |
|-------|---|---------|---|---------|---------|
| $M_1$ [$M_\odot$] | 0.690 | 0.690 | 0.893 | 1.048 | 0.888 |
| $M_2$ [$M_\odot$] | 0.203 | 0.203 | - | 1.021 | 0.809 |
| $a_b$ [AU] | 0.224 | 0.224 | - | 0.229 | 0.176 |
| $e_b$ | 0.159 | 0.159 | - | 0.521 | 0.142 |
| $m_p$ [$10^{-4}M_\odot$] | - | 3 | 3 | 2.1 | 1.2 |
| $a_p$ [AU] | - | 0.705 | 0.705 | 1.09 | 0.603 |
| $e_p$ | - | 0.007 | 0.007 | 0.182 | 0.042 |
| $\gamma$ [$^\circ$] | - | 69.39 | 69.39 | 176.96 | 24.14 |

The migration is relatively insignificant at the stage of a gas-free planetesimal disk. As Pearce & Wyatt (2014) showed, the migration velocity of a planet due to the scattering of planetesimals is determined mainly by the ratio of the masses of the planet and the debris disk. There is virtually no migration if this ratio exceeds $\sim 10$. Therefore, there is reason to believe that in our models, where this ratio is $\sim 100$, this effect may also be disregarded.

The possibility of the migration of a planet to an orbit far from the binary was discussed by Pierens & Nelson (2008) and Rodet et al. (2017). Under such migration the formation of a long-lived coorbital ring can probably be complicated. On the whole, the problem of the influence of the migration of planets on the survival of their coorbital structures requires additional studies.

2 The model

We consider a model of a binary star system with component masses $M_1$ and $M_2$ with a semimajor axis $a_b$ and eccentricity $e_b$. The binary is embedded in a planetesimal disk with a radius of 4 AU. The model parameters are given in Table 1. They correspond to Kepler-16 (model 2), Kepler-34 (model 4), and Kepler-35 (model 5) (see Doyle et al. 2011; Welsh et al. 2012). For comparison, we consider a model of a binary star system with the parameters of Kepler-16 without a planet (model 1) and a system with a planet around a single star with a mass equal to the sum of the masses of the Kepler-16 stars (model 3). We investigate the dynamics of negligible-mass planetesimals in the gravitational field of a binary star and a circumbinary planet. The planet has mass $m_p$, orbital semimajor axis $a_p$, and eccentricity $e_p$. The initial angle between the directions to the pericenters of the binary and planet orbits is denoted by $\gamma$. Twenty thousand planetesimals initially placed in circular orbits with Keplerian velocities are simulated. The radial distribution of planetesimals is specified by the law $a^{-1}$ ($a$ is the orbital radius).

The equations of planetesimal motion in the barycentric coordinate system are written as

$$\frac{d\vec{v}}{dt} = \nabla \Phi_1 + \nabla \Phi_2 + \nabla \Phi_p,$$  

where $\Phi_1$, $\Phi_2$, and $\Phi_p$ are the gravitational potentials of the stars and the planet, respectively. The orbits of the binary star and the planet are computed in terms of the restricted three-body problem (i.e., we assume that the planet does not affect the dynamics of the binary star).
A symplectic algorithm (Verlet 1967) was used to integrate Eqs. (1). The accuracy of this method is proportional to $O(\Delta t^4)$, where $\Delta t$ is the time step. The choice of a sufficiently small step $\Delta t$ allowed the disk dynamics to be simulated on a time interval of $5 \times 10^4$ yr. To check the accuracy of our calculations, we performed selective integration of the constructed orbits backward in time, which showed good agreement with the initial data.

### 3 Coorbital Dynamics

Demidova & Shevchenko (2015) showed that a one-armed spiral density wave could be formed in the circumbinary planetesimal disk of a close binary star. Our simulations of the motion of planetesimals around a binary with the parameters of Kepler-16 in model 1 also demonstrate the formation of a spiral structure described by Eq. (6) from Demidova & Shevchenko (2015) (Fig. 1). The propagation time of the spiral density wave for Kepler-16 over a disk with a radius of 30 AU is $T_s = 1.1 \times 10^7$ yr. The formation of a matter-free central cavity is clearly seen in Fig. 1. Its size is consistent with the numerical-experiment dependences and the theory (Dvorak 1986; Holman & Wiegert 1999; Valtonen et al. 2008; Shevchenko 2015).

The introduction of a planet that could be formed by the time of gas disk depletion into the model destroys the spiral structure near the planet’s orbit, but the spiral structure is retained on the extended-disk periphery. The formation of a dense ring coorbital with the planet from the planetesimal-disk matter can be seen in Fig. 2. Recall that a similar ring also emerges in the models with a single central star (Ozernov et al. 2000). The capture of particles into librational horse-shoe orbits near the Lagrangian points $L_4$ and $L_5$ (on horse-shoe orbits, see, e.g., Murray & Dermott 1999) is responsible for the formation of the structure coorbital with the planet.

To estimate the characteristics of the ring coorbital with the planet, we constructed the azimuthally averaged radial surface density profiles (Fig. 3). The planetesimal disk is binned along the radius into rings with a step of 0.002 AU. The number of planetesimals within the rings was counted and then divided by the ring area. In addition, these profiles were averaged in time over a period from $10^4$ to $5 \times 10^4$ yr. Our simulations showed that the coorbital ring structure changes little in this time interval. The distances from the radial position of the planet at which the surface density changes by 1% of that at the center of the coorbital ring were taken as the outer and inner boundaries of the coorbital structure. Analysis of the results showed that this approach allows the attainment of a plateau by the surface density profile to be revealed. This makes it possible to determine the radial extent of the coorbital ring with confidence.

Within the revealed boundaries of the coorbital ring the number of particles was calculated with a time step of 10 yr. In agreement with the results from Demidova & Shevchenko (2016), our simulations show...
Figure 2: Distribution of particles at $t = 10^4$ yr in models 2 (a) and 3 (b).

Figure 3: Azimuthally averaged radial barycentric surface density profiles in units [number of planetesimals/AU$^{-2}$] measured from the radial position of the planet. The blue, green, black, and red lines correspond to models 2, 3, 4, and 5, respectively; $N_p/(\text{AU})^2$ is the number of planetesimals per astronomical unit squared.
that the number of planetesimals in the coorbital ring in the single star system decreases more rapidly than it does in the binary system. 95.9% of the matter is retained in the coorbital ring for a time from $10^4$ to $5 \times 10^4$ yr in model 2, while 71.5% is retained in model 3. In models 4 and 5, 77.9 and 87.0%, respectively, is retained.

The enhanced stability in the circumbinary case probably stems from the fact that the presence of a second star in the system causes a relatively fast orbital precession of the planet and planetesimals. As a result, the splitting of mean-motion resonances into subresonances is significant, they essentially do not overlap, and the chaoticity of the motion near the resonances is reduced sharply (for examples of the action of such a mechanism, see El Moutamid et al. [2014]).

The coorbital ring-like structure in model 2 (the blue line in Fig. 3) model 2 corresponds to Kepler-16) has a greater extent along the disk radius than does the analogous structure in model 3 (the green line in Fig. 3). The amount of matter within the boundaries of the coorbital ring at the end of our simulations is 1.19 and 0.93% of the total amount of matter in the disk in models 2 and 3, respectively. However, $\sim 50\%$ of the particles in the ring-like structure in model 2 are concentrated near the planet, while in model 3 this does not occur. A similar effect also takes place in model 4 but is absent in model 5, which is probably attributable to the small mass of the planet in model 5.

In model 4 (with the parameters of the binary Kepler-34; the black line in Fig. 3) the surface density maximum is shifted toward the barycenter of the binary orbit. In addition, the amount of matter retained at the end of our simulations in the coorbital structure under consideration is small, being 0.49% of its total amount in the disk, while the surface density is lower than that in other models by a factor of $2 - 3$. This system is peculiar in that the initial orbit of the planet is not close to a circular one, as in the remaining systems under consideration; its initial eccentricity is $e_p = 0.182$. The central binary also has a significant eccentricity, $e_b = 0.521$. In all likelihood, these two facts prevent the formation of a stable coorbital structure.

The coorbital structure in model 5 (Kepler-35) is noticeably narrower than that in the remaining models, with the maximum surface density being higher than that in models 2 and 3 by a factor of 1.5. The maximum of the radial distribution of matter is slightly shifted relative to the radial position of the planet. The compactness of the ring-like structure is apparently attributable here to the small ratio of the planet’s mass to the sum of the binary component masses $\mu_p = m_p/(M_1 + M_2) = 0.71 \times 10^{-4}$ (while for Kepler-16b $\mu_p = 3.34 \times 10^{-4}$). In addition, in all likelihood, an approximate equality of the binary mass components also stimulates the radial compactness of the ring and an enhanced surface density in it. The amount of matter contained in the coorbital ring-like structure is 0.53% of the total amount of matter in the disk.

## 4 Conclusion

Our study of the dynamics of planetesimals in the debris disks of the circumbinary systems Kepler-16, Kepler-34, and Kepler-35 has shown that the characteristics of the structures coorbital with the planets in the disk depend significantly on the orbital parameters of the binary system and the planet. For Kepler-34 as an example, it can be seen that a significant eccentricity of the binary star ($e_b \sim 0.5$) in combination with an appreciably noncircular orbit of the planet ($e_p \sim 0.2$) does not allow a stable long-lived coorbital ring to be formed. In contrast, low or moderate eccentricities of the binary and the planet facilitate the formation of a stable coorbital structure. In all likelihood, the enhanced stabilization of the coorbital ring in Kepler-35 is attributable to an approximate equality of the binary component masses. Our simulations show that the formation of a noticeable coorbital structure begins after $\sim 500$ orbital revolutions of the planet (which corresponds to a time interval of $\sim 300$ yr for Kepler-16b).

Thus, the observational detection of planetesimal rings coorbital with the planets in Kepler-16 and Kepler-35 as well as in other systems with similar orbital parameters is quite probable. The observational detection of such ring-like structures in circumbinary disks without resolved planets would suggest the real existence of planets generating these structures. The spiral density wave described theoretically by Demidova & Shevchenko (2013) is destroyed near the planet’s orbit but can be noticeable on the disk periphery.

The stability of the ring-like coorbital structures in circumbinary systems is much higher than that of the coorbital rings for planets of single stars. Therefore, the observational detection probability of such structures is also higher in the case of binary star systems.

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