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Resonant multi-lane patterns in circumbinary young debris disks

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Abstract. Formation of resonant multi-lane patterns in circumbinary young debris disks with planets is considered in a set of representative massively simulated models. We find that the long term-stable resonant patterns are generically formed, shepherded by embedded planets. The patterns are multi-lane, i.e., they consist of several concentric rings. Statistical dependences of their parameters on the planetary parameters are recovered. Relevant additional massive simulations of planetesimal disks in systems with parameters of Kepler-16, 34, and 35 are accomplished and described. We find that co-orbital patterns generically form in systems with moderate orbital eccentricities of the binary's and planetary orbits (like in Kepler-16 and 35 cases).

Keywords. Methods: n-body simulations, planetary systems: protoplanetary disks.

A massive planet, if present in a planetesimal disk of a single or a binary star, induces the formation of various resonant large-scale patterns in the disk (see, e.g., Demidova & Shevchenko 2016; Tabeshian & Wiegert 2016; and references therein). The most prominent co-orbital pattern is more long-term stable for the systems with central binary stars than for the systems with central single stars (Demidova & Shevchenko 2016, 2018; Demidova 2018). To analyze the properties of the co-orbital patterns, we simulate a grid of models of circumbinary disks and planets in binary star systems. In the models, a planet in a circular orbit is embedded in a debris disk of passively gravitating planetesimals, initially also in circular orbits (co-planar with the planetary orbit) around the host star. The number of the planetesimals is 20000. The time length of each simulation is 10^5 orbital periods of the binary.

Formation of a ring-shaped pattern, co-orbital with the planet, in the debris disk, is a well-known phenomenon. The pattern consists of planetesimals moving in the "tadpole" and "horse-shoe" orbits. For circumbinary systems, its properties were studied in Demidova & Shevchenko (2018) and Demidova (2018). To characterize the pattern, we compute the average surface density along the radius from the barycenter, using a numerical procedure proposed in Demidova & Shevchenko (2018). The local surface density as a function of the orbital period always has a pronounced maximum at the 1:1 mean-motion resonance and pronounced minima at the 2:1 and 1:2 mean-motion resonances with the planet (Fig. 1). The co-orbital ring pattern corresponds to the 1:1 resonance.

Let a_p denote the planet's orbital radius, and μ_p denote the ratio of the planet's mass and the sum of masses of the central binary and the planet. Using a numerical procedure of Morrison & Malhotra (2015), we estimate the interior and exterior borders of the cleared zone as $\Delta a_\mathrm{cl,in} \approx 2.08\mu_\mathrm{p}^{0.35} a_\mathrm{p}$ and $\Delta a_\mathrm{cl,ext} \approx 1.71\mu_\mathrm{p}^{0.33} a_\mathrm{p}$. The clearing time turns out to be given by $T_\mathrm{cl} \approx 0.0088\mu_\mathrm{p}^{-1.56}$, in units of the orbital period of the central binary. The derived formulas for $\Delta a_\mathrm{cl,ext}$ and T_cl are quite similar to those given in Morrison & Malhotra (2015), and the formula $\Delta a_\mathrm{cl,in}$ has somewhat greater values of the power-law index and the pre-function coefficient.

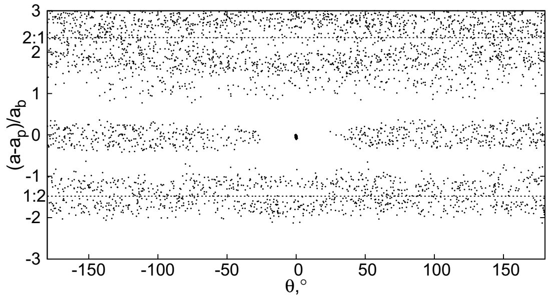

Figure 1. An evolved orbital distribution of planetesimals near the planetary orbit. Here stellar masses are $M_1 = M_2 = M_\odot$, and the planet mass is $m_\mathrm{p} = 3M_\mathrm{J}$, where $M_\odot$ and M_J are the Solar and Jovian masses. The locations of the 2:1 and 1:2 mean-motion resonances with the planet are dashed. a_b is the size of the binary, a_p is the radius of the planetary orbit, and a are the current radial positions of the planetesimals; θ are the current relative angular positions of the planetesimals, as viewed from the barycenter.

Our numerical simulations in models with the parameters of the Kepler-16, 34, and 35 systems (as given in Doyle *et al.* 2011 and Welsh *et al.* 2012) show that the formation of a stable ring co-orbital with the planet is plausible for the Kepler-16 and 35 systems. Concerning Kepler-34, the large orbital eccentricities of the stellar binary and the planet are able to prevent the formation of the pattern. In Morrison & Malhotra (2015), the clearing time of the co-orbital chaotic zone is estimated as $T_\mathrm{cl} \approx 0.024\mu^{-3/2}$, in units of the planetary period. For Kepler-34, in our simulations we find $T_\mathrm{cl} \approx 10^4$, in accord with this formula.

Observations of stellar debris disks often reveal rather sharp contrast edges of the resonant ring structures; see, e.g., Carrasco-González *et al.* (2016). We note that in planetary rings, quite analogously, the edges of annular patterns are often revealed to be extremely contrast (Borderies *et al.* 1982; Fridman & Gorkavyi 1999; Shepelyansky *et al.* 2009), and this can be explained by synchronization processes in the presence of resonant shepherding bodies (Shepelyansky *et al.* 2009). Other contrast-boosting mechanisms can also be active (see Shepelyansky *et al.* 2009 and references therein). The processes that may boost the contrast of pattern borders should be taken into account in simulations of disk structures; we leave it for a future work.

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