Long-term planetesimal dynamics in planetary chaotic zones

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1 Abstract

We perform massive numerical experiments revealing the long-term dynamics of debris disks in planetary systems of single and binary stars. We concentrate on determining the mass parameter dependences of the radial sizes of coorbital particle swarms and planetary chaotic zones. The obtained massive numerical results are discussed and interpreted in the light of the existing analytical theories, based on resonance overlap criteria, as well as in comparison with previous numerical approaches to the problem.

2 Simulations

We perform numerical simulations of the dynamics of a planetesimal disk of a binary or single star with a planet. The mass of the central object is set equal to the Solar mass $M_{\odot}$, while the mass parameter $\mu = m_2/(m_1 + m_2)$ (where m_1 and m_2 are the stellar and planetary masses, respectively) are varied within the limits from $\log_{10}\mu = -1.5$ to -3 with step 0.05 and from $\log_{10}\mu = -3$ to -5.5 with step 0.1. The planet's orbit is circular with period $P_{\rm pl} = 1$ yr. The planet is embedded in the debris disk consisting of 10^4 passively gravitating planetesimals distributed evenly within the radial limits $[a_p(1 - 3\mu^{2/7}), a_p(1 + 3\mu^{2/7})]$. The computation time is 10^4 yr. The equations of motion are numerically integrated by the Bulirsch–Stoer method [1].

3 The chaotic zone structure

Figure 1 shows the evolved (in 10^4 yr) distribution of planetesimals. On decreasing the planet mass, the clearing rate of the chaotic zone decreases, and the co-orbital swarms around the Lagrange points L4 and L5 elongate. In case of a single star, the swarm becomes ring-like at $\log_{10}\mu < -3.1$. In case of a binary star, the co-orbital swarm is ring-like at all values of μ. The radial width of the swarm decreases with decreasing the planet mass [2].

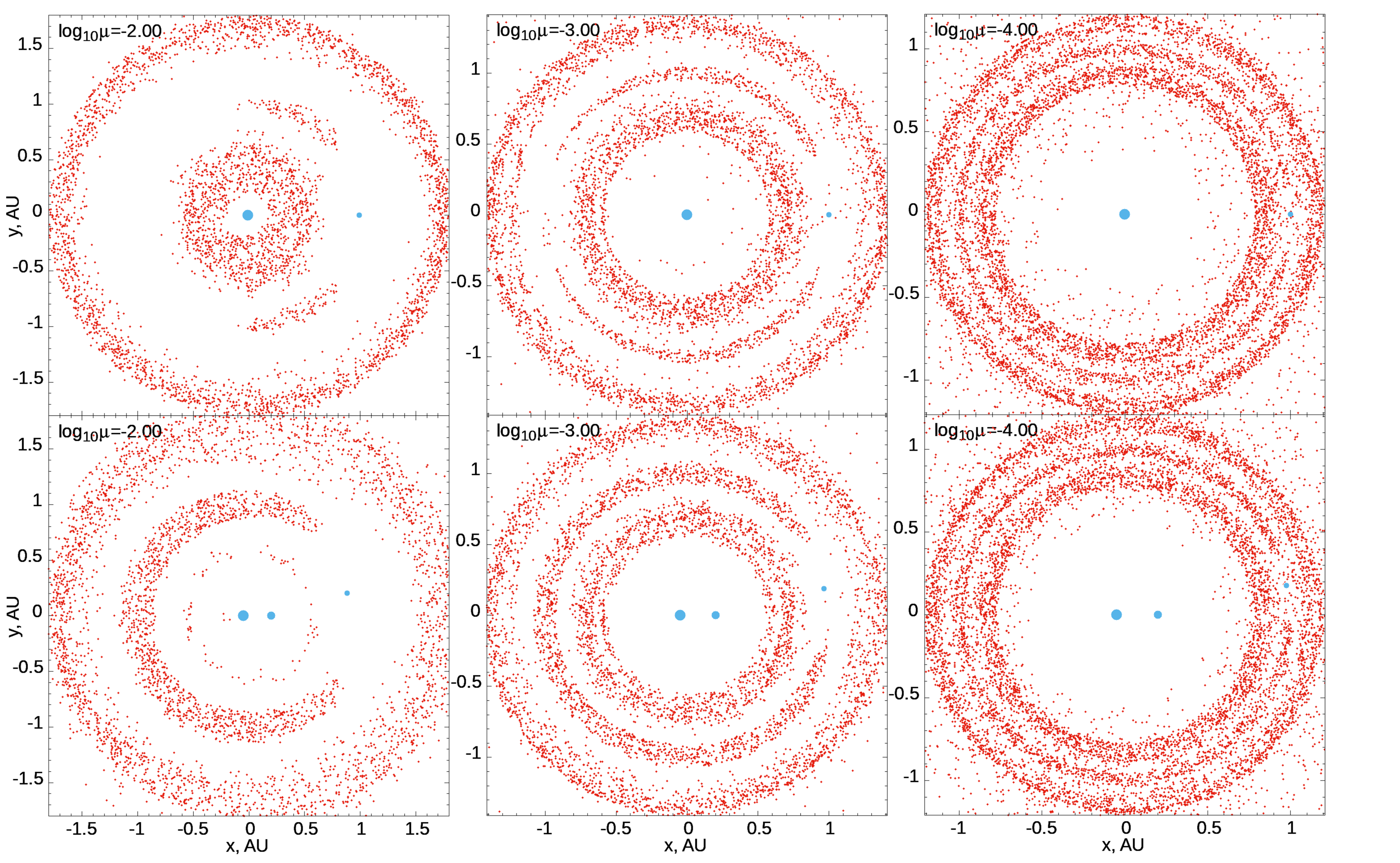

Figure 1: The evolved planetesimal distribution for a single star (upper panel) and a binary star (lower panel). The mass parameter value is indicated at each panel.

To reveal the dynamical behaviour of the particles near the chaotic zone, the disk matter is divided into 100 rings with the same radial steps. The number of particles N_i in each ring, averaged over the azimuthal angle ϕ, is calculated in ratio to its initial value N_0 (see Fig. 2, left panel).

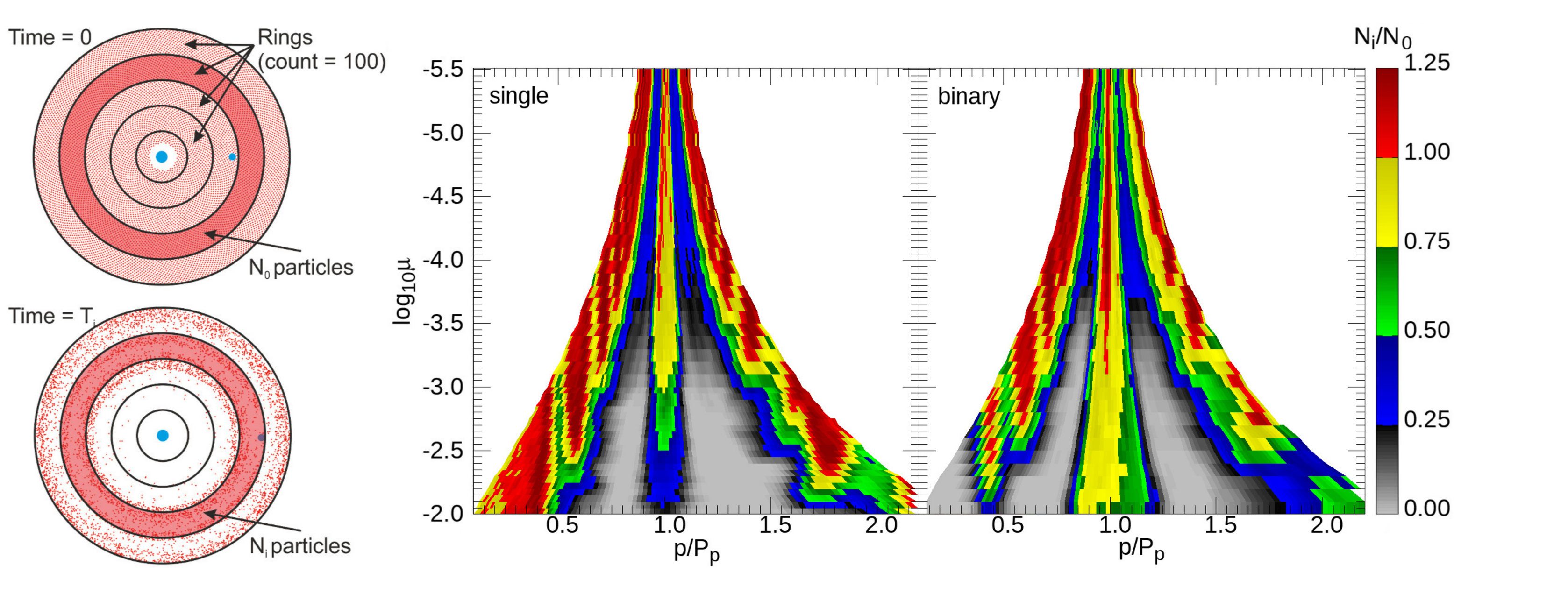

Figure 2: Left panel: averaging the number of particles in the rings. Right panel: the particle population fraction surviving in the disk (in color grades) in 10^4 yr, depending on the particle-planet period ratio (x axis) and the mass parameter logarithm (y axis), for a single star (left) and a binary star (right).

In Fig. 2, one may see that the radial extent of the chaotic zone inner to the planet's orbit is noticeably less than that outer to the planet's orbit, in the single star case. The co-orbital swarm starts to form at $\log_{10}\mu \lesssim -2$, and the relative amount of matter stored in it increases with decreasing μ. In the binary star case, the inner and outer parts of the chaotic zone have similar widths. The co-orbital swarm becomes asymmetric, its inner part is populated more than the outer one.

In the both cases, the width of the chaotic zone changes in abrupt steps (stepwise) with decreasing μ. This is due to separating of resonances from the main chaotic layer: resonance $2:1$ (at $\log_{10}\mu = -2.2 - -2.25$) and resonance $1:2$ (at $\log_{10}\mu = -2.1 - -2.15$), $3:2$ and $2:3$ (both at $\log_{10}\mu = -2.95 - -3$), $4:3$ and $3:4$ (both at $\log_{10}\mu = -3.4 - -3.5$).

4 The role of eccentricity

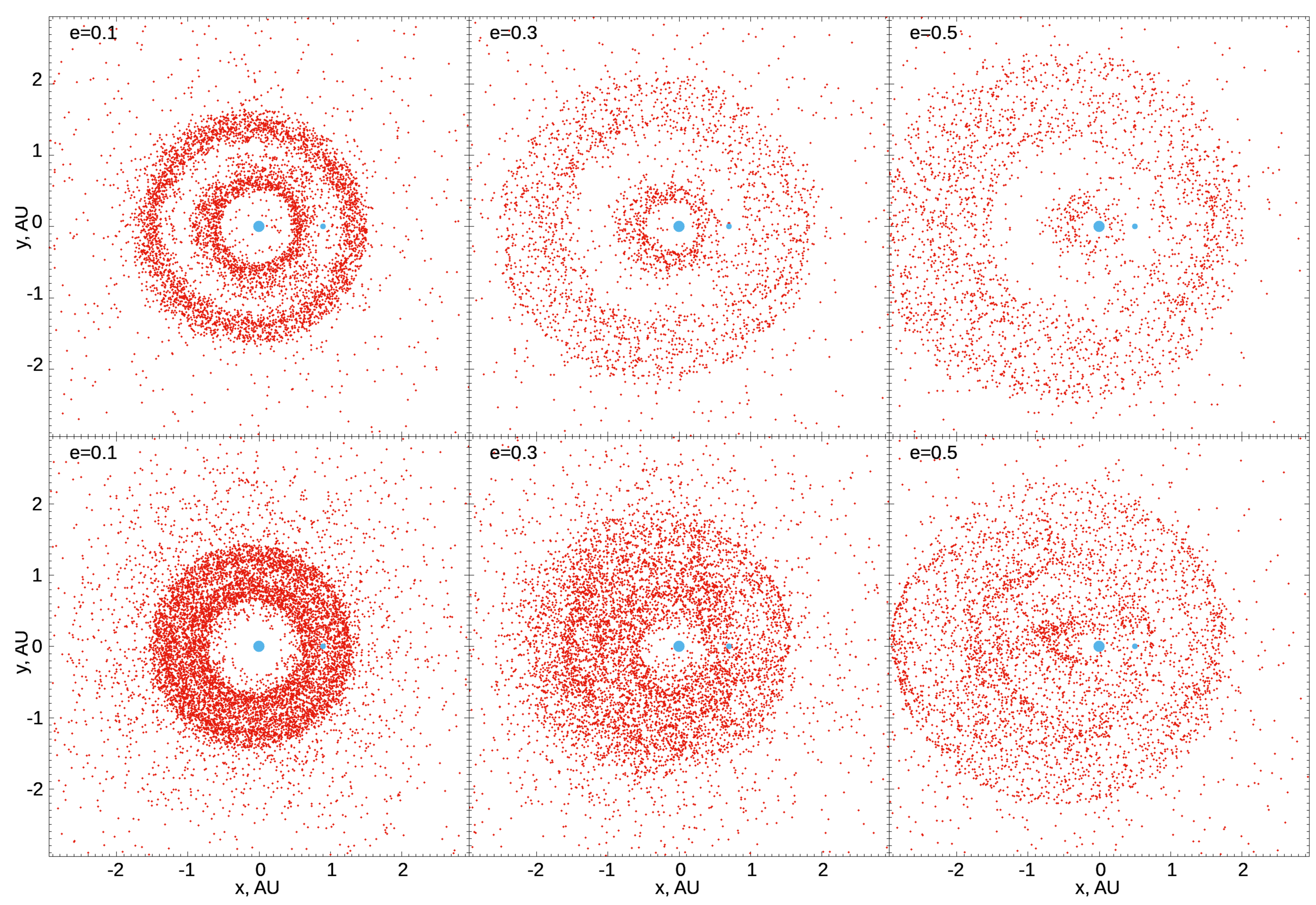

Figure 3: The evolved planetesimal distribution for models of a single star with $\log_{10}\mu = -3$ (upper panel) and $\log_{10}\mu = -4$ (lower panel). Planet's eccentricity is indicated at each panel.

The simulations show that at small eccentricities ($e < 0.1$) the chaotic zone shape is not affected significantly. However, as e increases, the chaotic zone becomes elliptical, and, in the single star case, the co-orbital swarm does not emerge (see Fig. 3). However, in the binary star case, a moderate eccentricity does not prevent the co-orbital swarm to emerge [3].

5 Conclusions

We find that resonances $2:1$, $1:2$ and $3:2$, $2:3$ separate from the main chaotic zone at different values of μ. These values can be used as criteria to determine masses of planets undetected directly. Eccentricity of planetary orbit deforms the chaotic zone. The co-orbital swarm is destroyed if $e > 0.1$.

The co-orbital swarm is more stable and broad in case of the binary star, especially at $\log_{10}\mu > -3$. Therefore, stellar binaries with planets may have prominent dust and planetesimal swarms co-orbital with the planet. Detection of circumbinary ring-like patterns in binary star systems may provide evidence for presence of planets maintaining the patterns.

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References

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