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Migration of planetesimals in the TRAPPIST-1 exoplanetary system

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Abstract. The calculations of the motion of planetesimals at the late stages of accumulation of planets in the TRAPPIST-1 system were made. In each calculation variant, initial orbits of planetesimals were near one of the planets. The number of collisions of planetesimals with the planets were calculated. The calculations has shown that the outer layers of neighboring exoplanets in the TRAPPIST-1 system can include similar material if there were a lot of planetesimals near their orbits at the late stages of the accumulation of the exoplanets.

Keywords: gravitation; methods: numerical; celestial mechanics; planets and satellites: formation

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1 Introduction and initial data

The aim of the calculations presented below was to study the mixing of planetesimals at the late gasless stages of accumulation of planets in the TRAPPIST-1 system. The TRAPPIST-1 exoplanet system consists of a star with a mass equal to 0.09 solar masses and seven planets (from b to h depending on the distance from the star) with masses from 0.33 to 1.37 Earth masses. The semimajor axes of the orbits of these planets range from 0.012 to 0.062 AU. The orbital elements and masses of the planets are presented in Table 1. The motion of planetesimals under the gravitational influence of the star and the seven planets of TRAPPIST-1 was studied. In each variant of the calculations, the initial values of the semimajor axes of the orbits of $N_\mathrm{p} = 250$ or $N_\mathrm{p} = 1000$ planetesimals varied from a_min to a_max around the semimajor axis of the orbit of one of the planets, the initial eccentricities of their orbits were equal to $e_\mathrm{o} = 0.02$ or $e_\mathrm{o} = 0.15$, and their initial inclinations were equal to $e_\mathrm{o}/2$ rad. The values of a_min and a_max are presented in Table 1. Calculations were also carried out at $a_\mathrm{min} = 0.07$ AU. In these calculations, $a_\mathrm{max} = 0.1$ AU at $N_\mathrm{p} = 250$ and $a_\mathrm{max} = 0.09$ AU at $N_\mathrm{p} = 1000$. Greater eccentricities could be caused by the previous mutual gravitational influence of planetesimals. To integrate the equations of motion, the symplectic algorithm RMVS3 from the SWIFT package of Levison & Duncan (1994) was used. Calculations with an integration step t_s equal to 0.01, 0.02, 0.04, or 0.1 Earth days gave similar results. In each variant, the calculations were made for the same disk and for fixed values of e_o and t_s. The planetesimals that collided with planets or the star or were ejected into hyperbolic orbits (reaching 50 AU from the star) were excluded from the integration. The considered model of mixing bodies in the zone of the TRAPPIST-1 planets can also characterize the migration of the bodies ejected from some planets after collisions of these planets with some planetesimals or other bodies. Earlier, the migration of planetesimals in our Solar System was studied, e.g., by Ipatov (1993, 2019); Marov & Ipatov (2023), and the migration of planetesimals in the Proxima Centauri exoplanetary system was studied by Ipatov (2023a,b,c).

2 Results of calculations

The calculation results showed that no more than 3% of planetesimals were thrown into hyperbolic orbits. There were no collisions of planetesimals with the parent star in the considered calculation options. More than a half of the planetesimals from the disks originally located near the orbits of planets b to g collided with the planets in less than 1000 years, and from disks b to d even in 250 years. The planetesimals with dynamic lifetimes of more than 100 thousand years were usually

Table 1. Orbital elements, masses m (in Earth masses $m_{\rm E}$) of exoplanets in the TRAPPIST-1 system, and the values of $a_{\rm min}$ and $a_{\rm max}$ for the considered disks near planets b, c, d, e, f, g, and h.

Planets	$m/m_{\rm E}$	a, AU	e	$a_{\rm min}$, AU	$a_{\rm max}$, AU
b	1.37	0.0115	0.0062	0.0094	0.0137
c	1.31	0.0158	0.0065	0.0137	0.0190
d	0.39	0.0223	0.0084	0.0190	0.0258
e	0.69	0.0292	0.0051	0.0258	0.0339
f	1.04	0.0385	0.0101	0.0339	0.0427
g	1.32	0.0468	0.0021	0.0427	0.0544
h	0.33	0.0619	0.0057	0.0544	0.0694

ejected into hyperbolic orbits or collided with planet h. The times of evolution of disks for planets b–h varied from 12 thousand to more than 60 million years. In the variants with a large time of the evolution of a disk, most of the total time could be due to the last planetesimal, which often was ejected into a hyperbolic orbit.

The fraction of planetesimals that collided with a host planet (compared to collisions with all planets) generally decreased with increasing time intervals. This fraction was usually smaller for the disks located farther from the star. At $N_{\rm p}$ = 1000 for disks c–h, the fraction f_1 of planetesimals that collided with the host planet was between 0.37 and 0.63 at $e_{\rm o}$ = 0.02 and between 0.27 and 0.53 at $e_{\rm o}$ = 0.15. The second and third values (f_2 and f_3) of the fraction of planetesimals (among all initial planetesimals) that collided with a neighboring planet were in the ranges of 0.17–0.28 and 0.11–0.17 at $e_{\rm o}$ = 0.02 and 0.2–0.32 and 0.08–0.19 at $e_{\rm o}$ = 0.15. For disk b and $e_{\rm o}$ = 0.02, the fractions f_1, f_2, and f_3 were 0.78–0.8, 0.18–0.2, and 0.01–0.012, respectively, (the range is for calculations with a step t_s equal to 0.01 and 0.02). For disk b and $e_{\rm o}$=0.15, the fractions f_1, f_2, and f_3 were 0.74, 0.22–0.23, and 0.015–0.021. The fraction of planetesimals collided with the host planet (compared to collisions with all planets) typically decreased within the considered time interval. In each calculation variant, there was at least one planet for which the number of collided planetesimals was greater than 25% of the number of collisions of planetesimals with the host planet. The total number of collisions of all planetesimals with planets c–h was greater than that for 100 kyr (the numbers for 100 kyr were presented in Ipatov (2022)) by not more than 4%. However, last collisions of planetesimals with planets could be after a few million years. For the initial disk near the orbit of planet h (with a mass $m_{\rm h}$ = 0.33 $m_{\rm E}$, where $m_{\rm E}$ is the mass of Earth), the number of collisions of planetesimals with planet g (with a mass $m_{\rm g}$ = 1.32 $m_{\rm E}$) was approximately the same as with planet h. The planetesimals migrating from distances greater than 0.7 AU could collide with any of the planets, but the majority of their collisions ($\geq$ 70%)

were with planets g and h, and the proportion of collisions was greater for the planets farther from the star.

3 Summary

The outer layers of neighboring exoplanets in the TRAPPIST-1 system can include similar material if there were a lot of planetesimals near their orbits at the late stages of the accumulation of the exoplanets.

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