

## MIGRATION OF PLANETESIMALS IN THE TRAPPIST-1 EXOPLANETARY SYSTEM.

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**Introduction:** The exoplanetary system TRAPPIST-1 includes a star with a mass of 0.0898 of the mass of the Sun and 7 planets (from *b* to *h*). The orbital elements and masses of the planets are shown in Table 1. The semi-major axes of the planets' orbits are in the range from 0.012 to 0.062 AU, and their masses are from 0.33 to 1.37 Earth's masses. Below I consider migration of planetesimals at the late gas-free stage of formation of almost formed planets in the TRAPPIST-1 system. Probabilities of collisions of planetesimals with different planets were studied for different initial distances of planetesimals from the star. The previous formation of embryos of planets could include their migration from greater distances and pebble accretion when gas presented in the protoplanetary disk. The studies of migration of planetesimals in the TRAPPIST-1 system presented below are similar to my studies of migration of planetesimals during formation of the terrestrial planets. The considered model of mixing of bodies in the zone of the TRAPPIST-1 planets can also characterize the migration of bodies ejected from some planets after collisions of these planets with some planetesimals or other bodies.

**Mixing of planetesimals during formation of the terrestrial planet:** In [1-2] I studied the mixing of planetesimals during gas-free accumulation of the terrestrial planets and estimated fractions of planetesimals, initially located at different distances from the Sun, that collided with planets. It was concluded in [2] that inner layers of the Earth or Venus were formed by accumulation mainly of material from the neighbourhood of the planet's orbit. The amounts of material from different parts of the zone from 0.7 to 1.5 AU from the Sun, which entered into almost formed the Earth and Venus, differed, probably, by no more than 2 or 3 times.

The model considered in [2] (below denoted as "model A") calculated probabilities of collisions of planetesimals with planets based on the arrays of orbital elements of migrated planetesimals. It didn't exclude planetesimals that already collided with a planet and so could not collide with another planet. If the probabilities of collisions with planets were not small, then the model A overestimated the number of collisions with planets. Later I used the model C which calculates moments of collisions of planetesimals with planets and excludes collided planetesimals from integration of the motion of planetesimals. For both models, the code from [3] was used for integration. The

number of collisions of planetesimals with planets was smaller for the model C than for the model A at the same time interval. The conclusions from [2] presented above are true also for the model C. However, accumulation of a half of masses of the Earth and Venus could take more than 5 Myr in the model C (for the model A such time did not exceed 5 Myr).

**The model and initial data used for calculations:** Migration of planetesimals under the gravitational influence of the star and seven TRAPPIST-1 planets (from *b* to *h*) was calculated with the use of the symplectic code from [3]. In each variant of the calculations, the initial values of semi-major axes of orbits of 250 planetesimals varied from  $a_{\min}$  to  $a_{\max}$ , their initial eccentricities were equal to  $e_0$ , and the initial inclinations equaled to  $e_0/2$  rad. The values of  $a_{\min}$  and  $a_{\max}$  are presented in Table 1. The considered disk of planetesimals was located near the orbit of one of the considered planets. The values of  $e_0$  equaled to 0.02 or 0.15. As for the terrestrial planets, the models A and C were used for calculations.

**Results of calculations:** The results of calculations showed that, as the Earth and Venus, some neighbouring planets in the TRAPPIST-1 exoplanetary system accumulated planetesimals initially located at the same distance. Mixing of planetesimals was smaller for the model C than for the model A. Below the estimates based on the C calculations (at which collided planetesimals were excluded from integrations) are discussed. The conclusions are the same for calculations with the step  $\Delta t$  of integration equaled to 0.1 day and 0.01 day. The number of collisions of planetesimals with planets (from *b* to *h*) over 100 Kyr in the TRAPPIST-1 system for different disks (from *b* to *h*) is presented in Table 2.

Less than 2% of planetesimals were ejected into hyperbolic orbits. There was no ejection for disks initially located near orbits of the planets *b* and *c*. There were no collisions of planetesimals with the host star. More than a half of planetesimals from disks near orbits of planets from *b* to *g* collided with planets in less than 1000 yr, and for disks *b* - *d* even in 250 yr. Times of evolution of disks *b*, *c*, *d*, *e*, *f*, *g*, *h* varied from 12 Kyr to more than 10 Myr (see Table 3). Three planetesimals from the initial disk in the vicinity of the planet *h* at  $e_0=0.02$  still moved in elliptic orbits at  $t = 1$  Myr. The fraction of planetesimals collided with the 'host' planet (compared to collisions with all planets) decreased with 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 fraction of collisions of planetesimals with the 'host' planet was usually smaller for disks located farther from the star. For the initial disk near the orbit of the planet *h*, the number of collisions of planetesimals with the planet *g* was about that with the planet *h*. Planetesimals could collide with all planets for disks near orbits of planets from *d* to *h*. Therefore, outer layers of neighbouring planets 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 planets.

**Conclusions:** Outer layers of neighbouring planets 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 planets.

**Acknowledgements:** Studies of the formation of the terrestrial planets were carried out as a part of the state assignments of the Vernadsky Institute of RAS. For studies of migration of planetesimals in the TRAPPIST system the author acknowledges the support of Ministry of Science and Higher Education of the Russian Federation under the grant 075-15-2020-780.

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

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

**Table 2.** The number of collisions of planetesimals with planets (from *b* to *h*) over 100,000 years in the TRAPPIST-1 system for different disks (from *b* to *h*) for the model C, which excludes colliding planetesimals from further calculations. Initial eccentricities of planetesimals equaled to  $e_0$ . There were 250 planetesimals in each initial disk. Variants with a step  $d_s=0.01$  day are marked by bold letters in the left column, for other variants  $d_s=0.1$  day.

	$e_0$	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>	<i>g</i>	<i>h</i>
<i>b</i>	0.02	<b>179</b>	45	2	2	0	0	0
<b><i>b</i></b>	0.02	<b>162</b>	46	2	3	2	1	0
<i>b</i>	0.15	<b>188</b>	55	6	1	0	0	0
<b><i>b</i></b>	0.15	<b>180</b>	63	5	2	0	0	0
<i>c</i>	0.02	49	<b>153</b>	32	9	3	4	0
<b><i>c</i></b>	0.02	56	<b>148</b>	26	11	3	5	0
<i>c</i>	0.15	77	<b>140</b>	13	10	6	2	2
<b><i>c</i></b>	0.15	73	<b>141</b>	23	7	0	5	1
<i>d</i>	0.02	13	42	<b>120</b>	43	18	11	3
<b><i>d</i></b>	0.02	13	47	<b>128</b>	29	16	14	3
<i>d</i>	0.15	28	69	<b>68</b>	45	16	19	3
<b><i>d</i></b>	0.15	30	71	<b>59</b>	43	23	19	4
<i>e</i>	0.02	5	20	31	<b>110</b>	38	39	3
<b><i>e</i></b>	0.02	7	27	24	<b>105</b>	46	34	4
<i>e</i>	0.15	11	37	32	<b>69</b>	53	32	11
<b><i>e</i></b>	0.15	7	29	22	<b>72</b>	57	53	3
<i>f</i>	0.02	6	11	10	37	<b>98</b>	75	10
<b><i>f</i></b>	0.02	4	7	14	42	<b>108</b>	58	14
<i>f</i>	0.15	6	21	26	42	<b>61</b>	77	12
<b><i>f</i></b>	0.15	7	20	23	45	<b>57</b>	80	9
<i>g</i>	0.02	3	12	12	33	45	<b>109</b>	31
<b><i>g</i></b>	0.02	1	11	16	20	48	<b>114</b>	32
<i>g</i>	0.15	2	12	20	36	62	<b>94</b>	17
<b><i>g</i></b>	0.15	5	16	16	25	68	<b>94</b>	19
<i>h</i>	0.02	1	10	7	15	42	79	<b>87</b>
<b><i>h</i></b>	0.02	6	3	6	23	31	69	<b>98</b>
<i>h</i>	0.15	6	9	8	22	47	81	<b>62</b>
<b><i>h</i></b>	0.15	1	6	14	30	50	86	<b>49</b>

**Table 3.** Times of evolution of disks *b*, *c*, *d*, *e*, *f*, *g*, *h* (until collisions of all planetesimals with planets or their ejections into hyperbolic orbits) in Kyr for initial eccentricities of planetesimals equaled to  $e_0$ .

$e_0$	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>	<i>g</i>	<i>h</i>
0.02	1504	12.0	32.4	6446	6282	212	>10000
0.15	20.1	24.5	355	437	128	119	3391