



Migration of bodies in the Proxima Centauri and Trappist 1 planetary systems

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- **Initial data for calculations for Proxima Centauri:** The motion of planetesimals and other bodies in the Solar System was studied in many papers (see e.g. the review in [6]). I studied the motion of planetesimals in the Proxima Centauri planetary system [2-4]. In these calculations, the gravitational influence of the star (with a mass equal to 0.122 of the solar mass) and two planets: b ($a_b=0.04857$ AU, $e_b=0.11$, $m_b=1.17m_E$, m_E is the mass of the Earth) and c ($a_c=1.489$ AU, $e_c=0.04$, $m_c=7m_E$) was taken into account. The planetesimals were excluded from integration when they collided with the star or the planets or reached 1200 AU (the Hill radius of the star) from the star. The symplectic code from [5] was used for integrations. In most calculations, the integration time step t_s equaled to 1 day. The obtained results were about the same for different considered t_s equaled to 0.2 day, or 0.5 day or 2 days. The considered time interval usually exceeded 100 Myr. For some variants it reached 1000 Myr. The late gas-less stage of formation of planets was considered. Migration of planetesimals from the feeding zone of planet c was calculated. In each calculation variant, initial semi-major axes a_o of orbits of $N_o=250$ planetesimals were in the range from $a_{\min}$ to $a_{\min}+0.1$ AU. In different variants, the values of $a_{\min}$ were in the range from 0.9 to 2.2 AU. Initial eccentricities e_o of orbits of planetesimals equaled to 0.02 or 0.15. Initial inclinations of orbits of the planetesimals were equal to $e_o/2$ rad. Not small considered eccentricities of planetesimals could be a result of the previous evolution of the disk of planetesimals.

- **The feeding zone of Proxima Centauri c :** After hundreds of million years, some planetesimals could still move in elliptical orbits inside the feeding zone of planet c that had been mainly cleared from planetesimals. Initial semi-major axes of orbits of the planetesimals that still had elliptical orbits at the end of considered evolution are presented in [2]. The range ($a_{\min}$, $a_{\max}$) of a_o for which planetesimals were mainly ejected into hyperbolic orbits or collided with planets was about $a_{\min}=a_c(1-e_c)-e_o a_{\min}-k_{\min} a_c \cdot \mu^{1/3}$ and $a_{\max}=a_c(1+e_c)+e_o a_{\max}+k_{\max} a_c \cdot \mu^{1/3}$, where $k_{\min}=2.54$ and $k_{\max}=2.40$ at $e_o=0.02$, and $k_{\min}=2.23$ and $k_{\max}=4.3$ at $e_o=0.15$, a_c and $e_c=0.04$ are the semi-major axis and eccentricity of the orbit of planet c , μ is the ratio of the mass of planet c to the star mass [2]. Often left planetesimals could move inside the feeding zone in some resonances with the planet, e.g. in the resonances 1:1 (as Jupiter trojans), 5:4, and 3:4. The number of such left planetesimals was greater at small eccentricities. Examples of time evolution of a semi-major axis a , perihelion and aphelion distances q and Q of an orbit of a planetesimal moving in such resonances are presented in [2]. Some planetesimals moved for a long time in resonances even if before getting in these resonances they moved in nonresonant orbits. For some (typically resonant) subregions of a_o located outside the main feeding zone of planet c , planetesimals could be ejected into hyperbolic orbits or could collide with planets.

- There can be more analogues of the asteroid and trans-Neptunian belts in the planetary system near Proxima Centauri than in the Solar System. The smaller ratio of the mass of planet Proxima Centauri c to the mass of the star than that for Jupiter, the larger ratio of the semi-major axes of the orbits of the planets c and b than that for Jupiter and Mars, and only one large planet in the Proxima Centauri system can be the reasons for such possible differences in the belts and the possible existence of a planet(s) between the orbits of the planets Proxima Centauri b and c .

- **Probabilities of collisions of planetesimals with the exoplanet Proxima Centauri c and their ejection into hyperbolic orbits:** At times T equal to 1, 10 and 100 Myr, the fraction of initial planetesimals that were left in elliptical orbits is presented in [3]. At $T=100$ Myr it was not more than 0.06 at $1.2 \leq a_o \leq 1.7$ AU and $2.0 \leq a_o \leq 2.1$ AU, not more than 0.3 at $1.1 \leq a_o \leq 1.2$ AU, not more than 0.2 at $1.7 \leq a_o \leq 1.9$ AU, and not more than 0.1 at $2.1 \leq a_o \leq 2.2$ AU for $e_o=0.15$. It was not more than 0.25 at $1.2 \leq a_o \leq 1.8$ AU for $e_o=0.02$.

- The results of calculations showed that the probability of a collision of a planetesimal during its dynamical lifetime with planet c was about 0.5 for $e_o=0.02$ and 0.25-0.3 for $e_o=0.15$ if initial orbits of planetesimals were not far from the orbit of the planet c . It was 0.05 at $1.1 \leq a_o \leq 1.2$ AU, 0.4-0.55 at $1.2 \leq a_o \leq 1.7$ AU, 0.3 at $1.7 \leq a_o \leq 1.8$ AU, 0.02 at $1.8 \leq a_o \leq 1.9$ AU for $e_o=0.02$. This probability was about 0.15 at $1.0 \leq a_o \leq 1.1$ AU, 0.3 at $1.1 \leq a_o \leq 1.9$ AU, 0.04-0.05 at $2.0 \leq a_o \leq 2.2$ AU for $e_o=0.15$. Most collisions of planetesimals with planet c took place during the first 10 Myr. If initial orbits of planetesimals were not far from the orbit of the planet c , then the ratio p_{cej} of the number of planetesimals collided with planet c to that ejected into hyperbolic orbits was about 1 for $e_o=0.02$ and about 0.5 for $e_o=0.15$.

- For $e_o=0.02$, the ratio p_{cej} was about 2 at $1.1 \leq a_o \leq 1.2$ AU, 1.2 at $1.2 \leq a_o \leq 1.4$ AU, 0.85-1 at $1.4 \leq a_o \leq 1.6$ AU, 1.3 at $1.6 \leq a_o \leq 1.7$ AU, 0.5 at $1.7 \leq a_o \leq 1.8$ AU, 0.2 at $1.8 \leq a_o \leq 1.9$ AU. For $e_o=0.15$, this ratio was about 0.9 at $1.0 \leq a_o \leq 1.2$ AU, 0.5-0.6 at $1.2 \leq a_o \leq 1.4$ AU, 0.4 at $1.4 \leq a_o \leq 1.8$ AU, 0.05 at $2.0 \leq a_o \leq 2.2$ AU, and 0.02 at $2.2 \leq a_o \leq 2.3$ AU. The ratio of the fraction of planetesimals ejected into hyperbolic orbits to that collided with exoplanets is greater for a greater mass of a planet moving in the orbit of planet c and for greater initial eccentricities of orbits of planetesimals. Based on estimates of the amount of planetesimals ejected into hyperbolic orbits, it is possible to conclude that during the growth of the mass of planet c from $3.5m_E$ to $7m_E$ [3], the semi-major axis of its orbit could decrease by at least a factor of 1.5.

- **Estimates of the total initial mass of planetesimals in the feeding zone of Proxima Centauri c :** Based on the results of calculations, it is possible to conclude [3] that the ratio $p_{cej}=p_c/p_{ej}$ of the probability of a collision of a

planetesimal with planet c to the probability p_{ej} of its ejection into a hyperbolic orbit was about 0.8-1.3 and 0.4-0.6 at $e_o=0.02$ and $e_o=0.15$, respectively. Such ratio was about 1.3-1.5 and 0.5-0.6 at calculations with a mass of planet c equal to a half of its present mass. The mass planet c is $7m_E$. Therefore, the total mass of planetesimals ejected into hyperbolic orbits could be about $(3.5-7)m_E$. The total mass of planetesimals in the feeding zone of planet c could exceed $10m_E$ and $15m_E$ at $e_o=0.2$ and $e_o=0.15$, respectively. Based on the values of p_{ej} and on the integral of energy, it is possible to conclude that the semi-major axis of the orbit of planet c could decrease by a factor not less than 1.5 during accumulation of this planet.

- **Motion of planetesimals to the inner planets Proxima Centauri b and d :** The probability of a collision of a planetesimal initially located in the feeding zone of planet c with planet b was about $2 \cdot 10^{-4}$ and 10^{-3} at e_o equal to 0.02 or 0.15, respectively [3]. Planet d was not included in integrations, but the probability of collisions of planetesimals with planet d was calculated based on the arrays of orbital elements of migrated planetesimals. The above values of the probabilities were greater than the probability of a collision with the Earth of a planetesimal migrated from the zone of the giant planets in the Solar System. The latter probability (per one planetesimal) was typically less than 10^{-5} [6]. A lot of icy material and volatiles could be delivered to planets b and d . The amount of material delivered from the feeding zone of planet c to planet d could be about twice less than that delivered to planet b .

- **Motion of planetesimals in the outer part of the Hill sphere of the star Proxima Centauri:** About 90% of the planetesimals that first reached 500 AU from the star, for the first time reached 1200 AU from the star in less than 1 million years [4]. The inclinations of orbits of 80% of the planetesimals that moved between 500 or 1200 AU from the star did not exceed 10° . The strongly inclined orbits of bodies in the outer part of the Hill's sphere of the star Proxima Centauri can only be mainly due to the bodies that came into the Hill's sphere from outside. The radius of the Hill's sphere of the star Proxima Centauri is by an order of magnitude smaller than the radius of the outer boundary of the Hills cloud in the Solar System and is two orders of magnitude smaller than the Hill radius of the Sun. Therefore, it is difficult to expect the existence of such a massive analogue of the Oort cloud near this star as near the Sun.

- **Probabilities of collisions of planetesimals with planets in the TRAPPIST 1 exoplanetary system:** The exoplanetary system TRAPPIST-1 consists of a star with a mass equal to 0.0898 of the mass of the Sun and 7 planets (from b to h) with masses from 0.33 to 1.37 Earth's masses. The semi-major axes of the planets' orbits are in the range from 0.012 to 0.062 AU. The semi-major axes of orbits of planetesimals were near the semi-major axis of one of the planets. Initial eccentricities of orbits of planetesimals were equal to 0.02 or 0.15. Their initial inclinations equaled to $e_o/2$ rad. The motion 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 [5] similar to my studies of migration of planetesimals in the Proxima Centauri system. Some calculations with $N_o=250$ were discussed in [1]. Below I present the results for $N_o=1000$ and $t_s=0.01$ or $t_s=0.02$ days. Most of collisions of planetesimals with planets took place in less than 10 Kyr. For disks $b-g$ more than a half of collisions were during the first 1 Kyr. However, last collisions of planetesimals with planets could be after a few million years. There were no collisions of planetesimals with the host star. Not more than 3% of planetesimals were ejected into hyperbolic orbits. The fraction of planetesimals collided with the 'host' planet (compared to collisions with all planets) typically decreased with the considered time interval. For disks $c-h$, the fraction f_1 of planetesimals that collided with the host planet was between 0.37 and 0.63 at $e_o=0.02$ and between 0.27 and 0.53 at $e_o=0.15$. The second and third values (f_2 and f_3) of the fraction of planetesimals that collided with a neighbouring planet were in the ranges 0.17-0.28 and 0.11-0.17 at $e_o=0.02$ and were 0.2-0.32 and 0.08-0.19 at $e_o=0.15$. For disk b and $e_o=0.02$, f_1 was 0.78-0.8, f_2 was 0.18-0.2, and f_3 was 0.01-0.012 (the range is for calculations with a step t_s equaled to 0.01 and 0.02). For disk b and $e_o=0.15$, f_1 was 0.74, f_2 was 0.22-0.23, and f_3 was 0.015-0.021. The fraction of collisions of planetesimals with the 'host' planet was usually smaller for disks located farther from the star. In each variant, including the migration from outside of the disk h , collisions were with all planets. Therefore, the outer layers of neighboring planets in the TRAPPIST-1 system can include similar material if there were many planetesimals near their orbits at the late stages of planetary formation.

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- **References:**

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