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Probabilities of collisions of planetesimals with exoplanets in the Proxima Centauri planetary system

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For the Proxima Centauri planetary system, most of planetesimals from the vicinity of the exoplanet *c* with a semi-major axis a_c about 1.5 AU were ejected into hyperbolic orbits in 10 Myr. Some planetesimals could collide with this exoplanet after 20 Myr. Only one of several hundreds of planetesimals from the vicinity of this exoplanet reached the orbit of the exoplanet *b* with a semi-major axis a_b=0.0485 AU, but the probability of a collision of such planetesimal with the exoplanet *b* was relatively high. If averaged over all considered planetesimals, the probability p_b is greater than the probability of a collision with the Earth of a planetesimal from the zone of the giant planets in the Solar System.

Introduction

- Schwarz et al. [1] studied migration of exocomets in the Proxima Centauri system. Besides the exoplanet with a semi-major axis a_b=0.0485 AU located in a habitable zone, they also considered the second exoplanet with a semi-major axis a_c from 0.06 to up to 0.3 AU (for test calculations up to 0.7 AU). Now it is considered [2,3] that the semi-major axis of the second planet equals to 1.489±0.049 AU.

- [1] Schwarz R., Bazso A., Georgakarakos N., et al. Exocomets in the Proxima Centauri system and their importance for water transport // MNRAS, 2018, v. 480, p. 3595-3608.
- [2] Kervella P., Arenou F., Schneider J. Orbital inclination and mass of the exoplanet candidate Proxima c // Astronomy & Astrophysics, 2020, v. 635: L14.
- [3] Benedict G.F., McArthur B.E. A Moving Target—Revising the Mass of Proxima Centauri c // Research Notes of the AAS, 2020, V. 4, N 6, ID 86. doi:10.3847/2515-5172/ab9ca9.

The model and initial data used for calculations

In the first series of calculations, according to [2], I considered a star with a mass equal to 0.122 of the solar mass, and two exoplanets with the following semi-major axes and masses: a_b=0.0485 AU, a_c=1.489 AU, $m_b=1.27m_E$ and $m_c=12m_E$, where m_E is the mass of the Earth. For the exoplanet "b", the initial eccentricity e_b and initial inclination i_b were considered to be equal to 0, and the initial eccentricity e_c of the exoplanet "c" equaled to 0 or 0.1. Initial inclination of the exoplanet "c" was considered to be $i_c=e_c/2=0.05$ rad or $i_c=e_c=0$. For interest, I also considered $i_c=152^o$; such calculations characterize the case when orbits of planetesimals were inclined to the orbit of the exoplanet.

In the second series of calculations, as in [3], I considered a_b=0.04857 AU, e_b=0.11, $m_b=1.17m_E$, a_c=1.489 AU, e_c=0.04, $m_c=7m_E$. I supposed $i_b=i_c=0$.

In both series of calculations, the densities of the exoplanets "b" and "c" were considered to be equal to densities of the Earth and Uranus, respectively.

The model and initial data used for calculations

In different calculation variants, initial semi-major axes a_b of planetesimals were in the range from a_{min} to $a_{max}=a_{min}+0.1$ AU, with a_{min} from 1.2 to 1.7 AU with a step of 0.1 AU. Initial eccentricities e_o of planetesimals equaled to 0 or 0.15 for the first series of calculations, and $e_o=0.02$ or $e_o=0.15$ for the second series. Greater initial eccentricities could be a result of the mutual gravitational influence of planetesimals. Initial inclinations of the planetesimals equaled to $e_o/2$ rad.

250 planetesimals were considered in each calculation variant.

The motion of planetesimals and exoplanets was calculated with the use of the symplectic code from [4].

Based on the obtained arrays of orbital elements of migrated planetesimals and exoplanets stored with a step of 100 yr, I calculated the probabilities of collisions of planetesimals with the exoplanets. The calculations were made similar to those in [5-7], which had been made for the planets of the Solar System, but for different masses and radii of a star and exoplanets. If the probability of a collision with an exoplanet for some planetesimal reached 1 with time (it was obtained for a few planetesimals), then for a later time this planetesimal did not considered for calculation of the mean probability for the calculation variant.

- [4] Levison H.F., Duncan M.J. The long-term dynamical behavior of short-period comets // Icarus, 1994, v. 108, p. 18-36
- [5] Ipatov S.I., Mather J.C. Migration of Jupiter-family comets and resonant asteroids to near-Earth space // Annals of the New York Academy of Sciences, 2004, v. 1017, p. 46-65. http://arXiv.org/format/astro-ph/0308448
- [6] Ipatov S.I., Mather J.C. Comet and asteroid hazard to the terrestrial planets // Advances in Space Research, 2004, v. 33, p. 1524-1533. http://arXiv.org/format/astro-ph/0212177.
- [7] Ipatov S.I., Probabilities of collisions of planetesimals from different regions of the feeding zone of the terrestrial planets with the forming planets and the Moon // Solar System Research, 2019, v. 53, N 5, p. 332-361. http://arxiv.org/abs/2003.11301

Probabilities of collisions of planetesimals with the exoplanets "*b*" and "*d*"

- **For the second series** of calculations, the probability p_b of a collision of one planetesimal, initially located near the orbit of the exoplanet "*c*", with the exoplanet "*b*" was non-zero in 5 among 18 variants at e_o=0.02 and in 3 among 6 variants at e_o=0.15. In one of 24 variants p_b=0.008, in three variants p_b=0.004, and in other four variants p_b was between to 4×10^{-6} and 3×10^{-4}. For all three considered variants of **the first series** at e_c=0.1 and e_o=0.15, the values of p_b were in the range 0.008-0.019. For other calculations of the first series, p_b=0.
- **For the second series**, only one of several hundreds of planetesimals reached the orbit of the exoplanet "*b*", but the probability p_b of a collision of one planetesimal with this exoplanet (averaged over thousands planetesimals) is greater than the probability of a collision with the Earth of a planetesimal from the zone of the giant planets in the Solar System. The latter probability for most calculations with 250 planetesimals was less than 10^{-5} per one planetesimal [8].
- The probability p_d of a collision of a planetesimal from the zone of the orbit of the exoplanet "*c*" with the exoplanet "*d*" (a_d=0.02895 AU, m_d=0.29m_E, e_d=i_d=0) was nonzero only for seven variants (among 24). The mean values of p_b and p_d averaged over 6000 planetesimals equaled to 8.5×10^{-4} and 7.0×10^{-4}. Therefore, a lot of icy material could be delivered to the exoplanets "*b*" and "*d*".

- [8] Ipatov S.I. Migration of planetesimals to the Earth and the Moon from different distances from the Sun // 50th LPSC. 2019. #2594.

Probabilities of collisions of planetesimals with the exoplanet "*c*"

- **For the first series** of calculations at $i_c = e_c = 0$ and $e_o = 0.15$, the values of the probability p_c of a collision of one planetesimal, initially located near the exoplanet "*c*", with this exoplanet were about 0.06-0.1. For $i_c = e_c/2 = 0.05$ and $e_o = 0.15$, p_c was about 0.02-0.04.
- **For the second series** of calculations, p_c was about 0.1-0.3, exclusive for $a_{min} = 1.4$ AU and $e_o = 0.02$ when p_c was about 0.7-0.8 (and the main growth was before T=1 Myr). Usually there was a small growth of p_c after 20 Myr.
- **For both series** of calculations, most of planetesimals were usually ejected into hyperbolic orbits in 10 Myr. The ratio of the number of planetesimals ejected into hyperbolic orbits to the number of planetesimals collided with the exoplanets usually exceeded 1 if the number of planetesimals decreased by a factor of several. For variants of the second series, this ratio was less than 1 only at $a_{min} = 1.4$ AU and $e_o = 0.02$.
- In some calculations a few planetesimals could still move in elliptical orbits after 100 Myr.

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