DELIVERY OF ICY PLANETESIMALS TO INNER PLANETS IN THE PROXIMA CENTAURI SYSTEM

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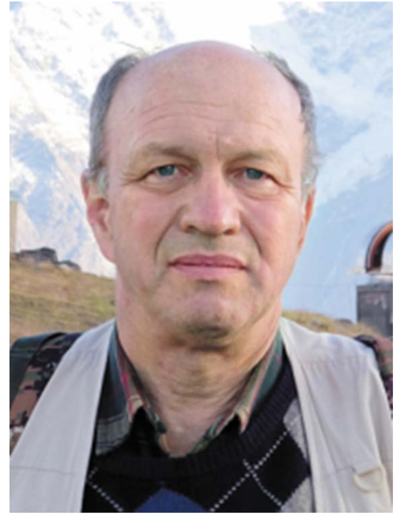

•**The model and initial data used for calculations:** The model of migration of planetsimals initially located in the feeding zone of the exoplanet *c* with a semi-major axis a_c=1.489 AU in the Proxima Centauri system was studied. The aim of these studies is to compare the delivery of icy planetesimals to potentially habitable planets in the Proxima Centauri system and in our Solar System. Integration of the motion of planetesimals and exoplanets was calculated with the use of the symplectic code from [1] for a star with a mass equal to 0.122 of the solar mass and two exoplanets. It was considered that the exoplanet *b* is located in a habitable zone. In the main series *M* of calculations, based on recent observational data, the following initial semi-major axes, eccentricities, inclinations and masses of two exoplanets were 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_b=i_c=0, where m_E is the mass of the Earth. In the series *F* of calculations, based on older observations, it was considered that a_b=0.0485 AU, a_c=1.489 AU, m_b=1.27m_E, m_c=12m_E, e_b=i_b=0, i_c=e_c/2=0.05 rad or i_c=e_c=0. In each calculation variant, initial semi-major axes of orbits of 250 exocomets were in the range from a_{min} to 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 orbits of planetesimals equaled to 0.02 or 0.15 for the *M* series, and equaled to 0 or 0.15 for the *F* series of calculations. Initial inclinations of orbits of the planetesimals equaled to e_o/2 rad. Considered time interval exceeded 50 Myr. 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 probabilities of collisions were calculated also with the unconfirmed exoplanet *d* (a_d=0.02895 AU, m_d=0.29m_E, e_d=i_d=0). The calculations were made similar to those in [2-4].

•**Probabilities of collisions of planetesimals with the exoplanet *c*:** For the *M* series of calculations, the values of the probability p_c of a collision of one planetesimal, initially located near the exoplanet *c*, with this exoplanet were about 0.1-0.3, exclusive for a_{min}=1.4 AU and e_o=0.02 when p_c was about 0.6 (Fig. 1). For the *F* series of calculations at i_c=e_c=0 and e_o=0.15, p_c was 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 both series of calculations, most of planetesimals were usually ejected into hyperbolic orbits in 10 Myr. Usually there was a small growth of p_c after 20 Myr. In some calculations a few planetesimals could still move in elliptical orbits after 100 Myr. The number of planetesimals ejected into hyperbolic orbits was greater by a factor of several than the number of planetesimals collided with exoplanets (Fig. 1). Therefore, a cometary cloud similar to the Oort cloud can exist in the Proxima Centauri system.

Estimates of the probability p_{ex}* of a collision of a planetesimal with exoplanets and the probability p_{ej}* of the ejection of a planetesimal into a hyperbolic orbit vs. a_{min}+0.05 AU are presented in Fig. 2 for two models (*A* and *B*). The values of p_{ex}* are estimated to be in the range between p_{ex}/(1+p_{ex}) and p_{ex}, and the values of p_{ej}* are estimated to be in the range between p_{ej}(1-p_{ex}) and p_{ej}/(1+p_{ex}). The values of p_{ex}=p_b+p_c+p_d and p_{ej} were obtained based on the results of the evolution of considered disks, and p_{ex}≈p_c. At computer simulations, the number of planetesimals decreased only due to their ejections into hyperbolic orbits and due to collisions with the star. Therefore, the above estimates for models *A* and *B* are needed if the probability p_{ex} of collisions with planets is not small. The probability of collisions of a planetesimal with exoplanets can be between 0.19 and 0.27 at e_o=0.02, and it can be between 0.15 and 0.18 at e_o=0.15. The probability of ejection of a planetesimal into a hyperbolic orbit can be between 0.62 and 0.71 at e_o=0.02, and it can be between 0.79 and 0.82 at e_o=0.15 (Fig. 2).

•**Probabilities of collisions of planetesimals with the exoplanets *b* and *d*:** For the *M* 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. At e_o=0.02 for the five variants, p_b equaled to 0.004, 0.004, 1.28×10^{-5}, 0.00032 и 9.88×10^{-5} (see Table). At e_o=0.02 the mean value of p_b for one of 4500 exocomets equaled to 4.7×10^{-4}, but among them there were two planetesimals with p_b≈1. At e_o=0.15 for three variants, p_b equaled to 0.008, 0.004 and 3.6×10^{-6}. The mean value of p_b for one of 1500 planetesimals equaled to 2.0×10^{-3}, but among them there were three planetesimals with p_b≈1. The mean value of the probability p_d of a collision of a planetesimal with the exoplanet *d* equaled to 2.7×10^{-4} and 2.0×10^{-3} at e_o=0.02 and e_o=0.15, respectively. For the *M* series, the mean values of p_b and p_d averaged over 6000 planetesimals equaled to 8.5×10^{-4} and 7.0×10^{-4}. For all three considered variants of the series *F* 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 *F* series, p_b=0. Only one of several hundreds of planetesimals reached the orbits of the exoplanet *b* and *d*, but the probabilities p_b and p_d of a collision of one planetesimal with these exoplanets (averaged over thousands planetesimals) are 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 [5]. Therefore, **a lot of icy material could be delivered to the exoplanets *b* and *d*.**

•An example of orbital evolution of those planetesimals which can have large probabilities with exoplanets *b* and *d* is presented in Fig. 3.

Conclusions: 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. A small fraction of planetesimals could can still move in elliptical orbits after 50 Myr. The number of planetesimals ejected into hyperbolic orbits was greater by a factor of several than the number of planetesimals collided with exoplanets. Only one of several hundreds of planetesimals initially located at the vicinity of the exoplanet *c* reached the orbit of the exoplanet *b* with a semi-major axis a_b=0.0485 AU. However, there were some planetesimals which probability p_b of a collision with the exoplanet *b* can be close to 1, and the probability of such collision averaged over many planetsimals was ~10^{-3}. Similar probabilities were for collisions of planetesimals with the exoplanet *d* with a semi-major axis a_b≈0.029 AU. 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. A lot of icy material could be delivered to the exoplanets *b* and *d*.

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•**References:** [1] Levison H.F., Duncan M.J. (1994) *Icarus* 108:18-36. [2] Ipatov S.I., Mather J.C. (2004) *Annals of the NYAS* 1017:46-65. http://arXiv.org/format/astro-ph/0308448. [3] Ipatov S.I., Mather J.C. (2004) *Advances in Space Research* 33: 1524-1533. http://arXiv.org/format/astro-ph/0212177. [4] Ipatov S.I. (2019) *Solar System Research* 53: 332-361. http://arxiv.org/abs/2003.11301. [5] Ipatov S.I. (2020) *EPSC2020-71*, https://doi.org/10.5194/epsc2020-71.

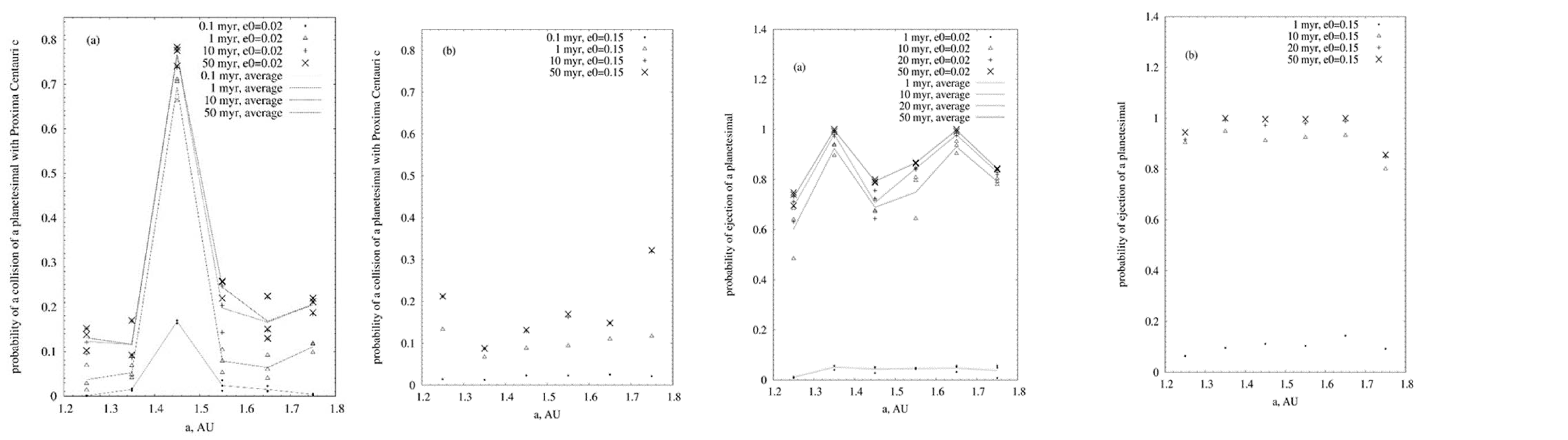

Fig. 1. Two left plots: **Probability p_c of a collision of a planetesimal with the exoplanet *c*** vs. a_{min}+0.05 AU. Initial semi-major axes of planetesimals were between a_{min} and a_{min}+0.1 AU and initial eccentricities e_o were equal to 0.02 (a) or 0.15 (b). The probabilities p_c were calculated based on the arrays of orbital elements of planetesimals obtained at the *M* series of calculations. Each point on the figure corresponds to mean values for 250 planetesimals. Each point of a line corresponds to the mean value for 750 planetesimals.
Two right plots: **Probability p_{ej} of an ejection of a planetesimal into a hyperbolic orbit** vs. a_{min}+0.05 AU.

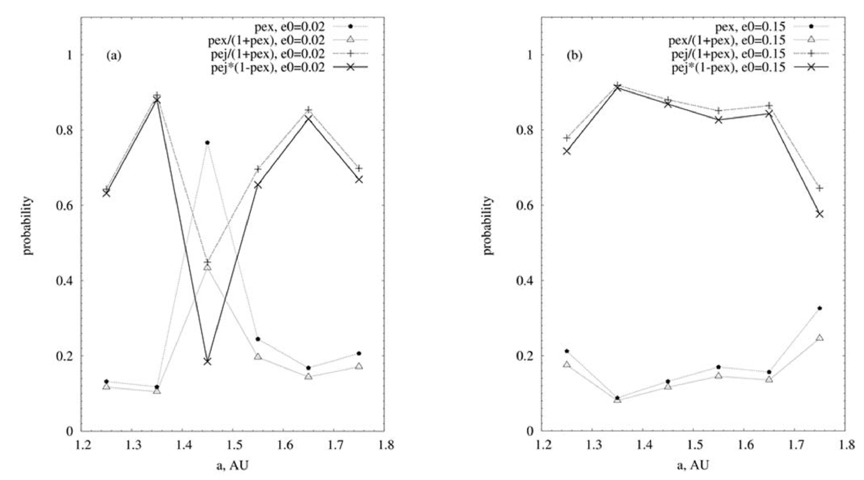

Fig. 2. **Estimates of the probability p_{ex}* of a collision of a planetesimal with exoplanets and the probability p_{ej}* of the ejection of a planetesimal into a hyperbolic orbit for two models** (*A* and *B*) vs. a_{min}+0.05 AU. Every point on the figures corresponds to studies of the evolution of 750 (a, e_o=0.02) or 250 (b, e_o=0.15) planetesimals with initial semi-major axes between a_{min} and a_{min}+0.1 AU. The values of p_{ex}* are estimated to be in the range between p_{ex}/(1+p_{ex}) and p_{ex}, and the values of p_{ej}* are estimated to be in the range between p_{ej}(1-p_{ex}) and p_{ej}/(1+p_{ex}). The values of p_{ex}=p_b+p_c+p_d≈p_c and p_{ej} were obtained based on the results of the evolution of considered discs.

a_{min}	e_o	p_b	p_d	p_{b0}	$p_{\Sigma b}/p_{\Sigma d}$	$p_{\Sigma b0}/p_{\Sigma b}$	N_b	N_d
1.2	0.02	0.004	0.004	0.004	0.42	2.15	1	1
1.3	0.02	0.00403	0.000683	0.00402	5.9	0.45	3	3
1.4	0.02	0.000320	0.000143	0.000423	2.24	1.32	1	1
1.5	0.02	$1.28\cdot10^{-5}$	0	$1.78\cdot10^{-5}$	-	1.39	2	0
1.6	0.02	$9.88\cdot10^{-5}$	$3.02\cdot10^{-5}$	0.000119	3.27	1.2	1	1
1.4	0.15	$3.64\cdot10^{-6}$	$2.58\cdot10^{-6}$	$6.22\cdot10^{-6}$	1.41	1.71	1	1
1.6	0.15	0.008	0.008	0.008	0.11	5.68	2	2
1.7	0.15	0.004	0.004	0.004	0.099	5.01	1	1

Table: **Probabilities p_b and p_d of collisions of a planetesimal with exoplanets Proxima Centauri *b* and *d*** for the *M* series of calculations at *T*=50 Myr. p_{b0} is the probability of a collision of a planetesimal with the exoplanet Proxima Centauri *b* if the eccentricity of the exoplanet is 0. $p_{\Sigma b}/p_{\Sigma d}$ is the ratio of the sums of probabilities of collisions of planetesimals with exoplanets *b* and *d* calculated for all encounters of planetesimals with the exoplanets even if the calculated probability for one planetesimal could exceed 1. $p_{\Sigma b0}/p_{\Sigma b}$ is the ratio of the sums of probabilities of collisions of planetesimals with the exoplanet *b* for its eccentricity equal to 0 and 0.11, calculated for all encounters of planetesimals with the exoplanet even if the calculated probability for one planetesimal could exceed 1. N_b and N_d are the number of planetesimals (among 250) which have non-zero probabilities of collisions with exoplanets *b* and *d*, respectively.

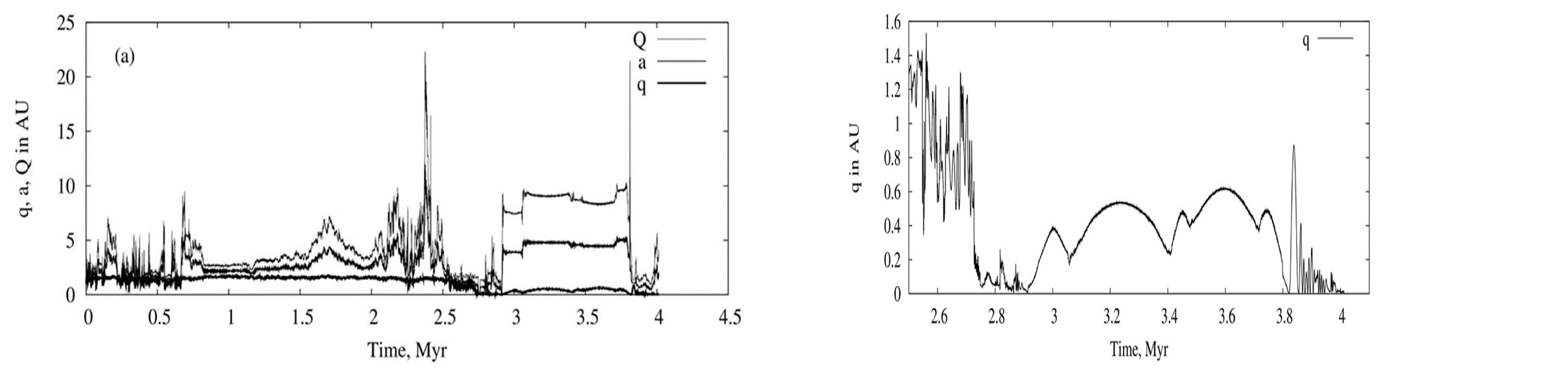

Fig. 3 Time evolution of a semi-major axis *a*, perihelion and aphelion distances *q* and *Q* of a planetesimal for the calculation with a_{min}=1.3 AU and e_o=0.02.