MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Migration of planetesimals and dust particles in the Proxima Centauri exoplanetary system

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Abstract. The motion of the planetesimals and dust particles from the vicinity of the orbit of planet c in the Proxima Centauri exoplanetary system was studied. The computer simulations of planetesimal motion showed that during the growth of the mass of planet c by a factor of 2, the semimajor axis of its orbit could decrease by at least a factor of 1.5. After hundreds of millions of years, some planetesimals could still move in elliptical resonant orbits inside the feeding zone of planet c that had been mainly cleared from planetesimals. The amount of water delivered to the inner planet Proxima Centauri b probably exceeded the mass of water in Earth's oceans. It is difficult to expect the existence of such a massive analogue of the Oort cloud around Proxima Centauri as around the Sun. The probability of the collisions of the dust particles with a diameter of about 100 microns migrated from the feeding zone of planet c with planet b could exceed 0.1, and it could be much greater than for the planetesimals from the same zone. More particles with diameters of the order of 10 and 100 microns can be delivered from the feeding zone of planet c to planet b than to planet c.

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

DOI: 10.26119/VAK2024.134

1 Introduction and initial data

The motion of the planetesimals and dust particles from the vicinity of the orbit of planet c in the Proxima Centauri exoplanetary system was studied in Ipatov (2021, 2023a,b,c,d). The Proxima Centauri planetary system consists of the star (with a mass equal to 0.122 of the solar mass) and of three exoplanets. The calculations of planetesimal motion took into account the gravitational influence of the star and two planets: b (a_b = 0.04857 AU, e_b = 0.11, m_b = 1.17 m_E, where m_E is the mass of the Earth) and c (a_c = 1.489 AU, e_c = 0.04, m_c = 7 m_E). Other values for the mass m_c of planet c (0.7, 3.5, and 12 m_E) were also considered. The late gasless stage of planet formation was studied. Planetesimals were excluded from the integration when they collided with the star or planets or reached 1200 AU from the star (the Hill radius). In each variant of the calculations, the initial values a_o for the semimajor axes of the orbits of N_p = 250 planetesimals or dust particles varied from a_min to $a_\mathrm{max} = a_\mathrm{min}$+0.1 AU. For planetesimals, the considered values of a_min varied from 0.9 to 2.2 AU with a step d_a = 0.1 AU. The initial eccentricities of planetesimal orbits were equal to e_o = 0.02 or e_o = 0.15, and their initial inclinations were equal to $e_\mathrm{o}/2$ rad. Greater eccentricities could be caused by the previous mutual gravitational influence of planetesimals (Ipatov 1993, 2000). For dust particles, a_{min} was equal to 1.4 or 1.5 AU, and e_o = 0.02. Schwarzet al. (2018) studied the motion of exocomets with initial eccentricities between 0.95 and 0.9999 considering the orbit of Proxima Centauri c with a semimajor axis a_c from 0.06 up to 0.3 AU.

To integrate the equations of motion for planetesimals, the symplectic algorithm RMVS3 from the SWIFT integration package of Levison & Duncan (1994) was used. Calculations with an integration step t_s = 0.2, 0.5, 1, or 2 Earth days gave similar results. In most calculations, the integration time step t_s was equal to 1 day. The considered time interval usually exceeded 100 Myr. For some variants it reached 1000 Myr. In each variant, the calculations were made for fixed values of a_min, e_o, and t_s. The planetesimals with planet d (a_d = 0.02895 AU, m_d = 0.29 m_E, $e_\mathrm{d} = i_\mathrm{d} = 0$) were calculated based on the arrays of orbits of migrating planetesimals and planets similar to Ipatov (2000, 2019).

2 Calculation results

2.1 The feeding zone of Proxima Centauri c

The calculations showed that 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. The initial semimajor axes for the planetesimals that still had elliptical orbits at the end of the considered evolution were presented in Ipatov (2023c). The range ($a_{\rm min,e}$, $a_{\rm max,e}$) of the initial semimajor axes $a_{\rm o}$ of the orbits for which planetesimals were mainly ejected into hyperbolic orbits or collided with planets was about $a_{\rm min,e} = a_{\rm c}(1 - e_{\rm c}) - e_{\rm o}a_{\rm min,e} - k_{\rm min}a_{\rm c}\mu^{1/3}$ and $a_{\rm max,e} = a_{\rm c}(1 + e_{\rm c}) + e_{\rm o}a_{\rm max,e} + k_{\rm max}a_{\rm c}\mu^{1/3}$, where $k_{\rm min} = 2.54$ and $k_{\rm max} = 2.40$ at $e_{\rm o} = 0.02$, $k_{\rm min} = 2.23$ and $k_{\rm max} = 4.3$ at $e_{\rm o} = 0.15$, $a_{\rm c}$ and $e_{\rm c} = 0.04$ are the semimajor axis and eccentricity of the planet c orbit, and μ is the ratio of the mass of planet c to the star mass. Often after hundreds of millions of years, the remaining planetesimals could move inside the feeding zone in some resonances with the planet, e.g., in the resonances 1:1 (as the Jupiter trojans), 5:4, and 3:4. The number of such remaining planetesimals was greater at small eccentricities. Examples of the evolution of the semimajor axis, perihelion, and aphelion of the orbit of a planetesimal moving in such resonances are presented in Ipatov (2023c). Some planetesimals had been moving for a long time in resonances even if before getting in these resonances they moved in nonresonant orbits. For some (typically resonant) subregions of $a_{\rm o}$ 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 the planet Proxima Centauri c to the mass of the star than that for Jupiter, the larger ratio of the semimajor axes of the orbits of 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 planets Proxima Centauri b and c.

2.2 Probabilities of the collisions of planetesimals with the exoplanet Proxima Centauri c and of their ejection into hyperbolic orbits

At evolution times $T = 1$, 10, and 100 Myr, the fraction $p_{\rm el}$ of the initial planetesimals remaining in elliptical orbits was presented in Ipatov (2023a). At $T = 100$ Myr, the $p_{\rm el}$ value was not more than 0.06 at $1.2 \le a_{\rm o} \le 1.7$ AU and $2.0 \le a_{\rm o} \le 2.1$ AU, not more than 0.3 at $1.1 \le a_{\rm o} \le 1.2$ AU, not more than 0.2 at $1.7 \le a_{\rm o} \le 1.9$ AU, and not more than 0.1 at $2.1 \le a_{\rm o} \le 2.2$ AU for $e_{\rm o} = 0.15$. It was not more than 0.25 at $1.2 \le a_{\rm o} \le 1.8$ AU for $e_{\rm o} = 0.02$. The calculations showed that the probability $p_{\rm c}$ of a collision of a planetesimal during its dynamical lifetime with planet c was about 0.5 for $e_{\rm o} = 0.02$ and 0.25–0.3 for $e_{\rm o} = 0.15$ if the initial orbits of the planetesimals were not far from the orbit of planet c with a semimajor axis equal to 1.5 AU. The $p_{\rm c}$ value was 0.05 at $1.1 \le a_{\rm o} \le 1.2$ AU, 0.4–0.55 at $1.2 \le a_{\rm o} \le 1.7$ AU, 0.3 at $1.7 \le a_{\rm o} \le 1.8$ AU, and 0.02 at $1.8 \le a_{\rm o} \le 1.9$ AU for $e_{\rm o} = 0.02$. For $e_{\rm o} = 0.15$, this probability p_c was about 0.15 at $1.0 \le a_o \le 1.1$ AU, 0.3 at $1.1 \le a_o \le 1.9$ AU, and 0.04–0.05 at $2.0 \le a_o \le 2.2$ AU. Most collisions of planetesimals with planet c took place during the first 10 Myr.

2.3 Estimates of the total initial mass of planetesimals in the feeding zone of Proxima Centauri c

Based on the results of calculations, Ipatov (2023a) concluded that the ratio $p_{c,ej} = p_c/p_{ej}$ of the probability p_c 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. This ratio was about 1.3–1.5 and 0.5–0.6 in the calculations with the mass of planet c equal to half of its present mass. The mass of planet c is 7 m_E. Therefore, the total mass of the planetesimals ejected into hyperbolic orbits could be about 3.5–7 m_E. The total mass of the planetesimals in the feeding zone of planet c could exceed 10 m_E and 15 m_E at $e_o = 0.2$ and $e_o = 0.15$, respectively. Based on the p_{ej} values and on the integral of energy, it is possible to conclude that the semimajor axis of the orbit of planet c could decrease by a factor not less than 1.5 during the accumulation of this planet.

2.4 Motion of planetesimals to the inner planets Proxima Centauri b and d

Only one of several hundred planetesimals which migrated from the feeding zone of Proxima Centauri c reached the orbits of Proxima Centauri b and d. Ipatov (2023a) showed that 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. The above probability values were greater than the probability of a collision with 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} (Marov & Ipatov 2023). Depending on the initial eccentricities of planetesimals (such variation correspond to the possible mutual gravitational influence of planetesimals), the total mass m_{c-b} of the material delivered from the feeding zone of planet c to planet b was estimated to be in the range from 0.002 m_E to 0.02 m_E. The temperature of planet c is considered to be much below zero, and the feeding zone of planet c was located farther from the star than the snow line. At fraction k_{ice} of the ice in the planetesimals between 0.05 and 0.5, the values of $m_{ice} = k_{ice} m_{c-b}$ are between 10^{-4} m_E and 0.01 m_E. Probably, the amount of water delivered to Proxima Centauri b exceeded the mass of water in Earth's oceans, which is $2 \cdot 10^{-4}$ m_E. Planet d was not included in the integrations, but the probability of the collisions of planetesimals with planet d was calculated based on the arrays of orbital elements of migrated planetesimals. 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. A lot of icy material and volatiles could be delivered to planets b and d.

2.5 Motion of planetesimals in the outer part of the Hill sphere of the star Proxima Centauri

For the present mass of the planet Proxima Centauri c, about 90% of ejected planetesimals moved from 500 to 1200 AU in less than 1 Myr, and not more than 1% of planetesimals had been moving in this region for more than 10 Myr but during less than a few tens of millions of years (Ipatov 2023d). For the mass of the planet embryo equal to half of the mass of planet c, the fraction of planetesimals moved from 500 to 1200 AU in less than 1 Myr was about 70–80%. The inclinations of orbits for 80% of the planetesimals that moved between 500 and 1200 AU from the star did not exceed 10°. The strongly inclined orbits of the bodies in the outer part of the Proxima Centauri Hill sphere can be mainly due to the bodies that came into the Hill sphere from outside. The radius of the Hill 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. The consideration of the gravitational influence of the binary star system α Centauri AB would not change the above conclusions because the motion of planetesimals was considered inside (mainly deep inside) the Hill spere of Proxima Centaury and the ejected planetesimals had very small chances to return into the sphere.

2.6 Migration of dust particles in the Proxima Centauri system

The migration of dust particles in the Proxima Centauri system was studied in Ipatov (2023b) similarly to the calculations for the Solar System (Ipatov 2010). The Bulirsh–Stoer code was used for integrations. The relative error per integration step was taken to be less than 10^{-8}. The gravitational influence of the star and two planets (b and c), the Poynting–Robertson drag, radiation pressure, and star wind drag were taken into account. The particles were excluded from the integration when they collided with the star or the planets or reached 500 AU from the star. Similarly to the Solar System, the ratio of the star wind drag to the Poynting–Robertson drag was considered to be 0.35. In different variants, the ratio β of the radiation pressure force to the gravitational force varied from 0.0002 to 1. For silicate particles in the Solar System, such β values correspond to particle diameters d from 2000 to 0.4 microns; and d is proportional to $1/\beta$. For water ice at a density equal to 1 g/cm^3, d is greater by a factor of 2.4 than for silicate particles. Although the initial orbits of dust particles were close to the orbit of planet c, and planet c is more massive than planet b, at $0.001 \leq \beta \leq 0.1$ more particles collided with the inner planet b than with the larger planet c. In the Solar System, silicate particles with $0.001 \leq \beta \leq 0.1$ correspond to diameters from 4 to 400 microns. At such β values, dust particles effectively deliver matter (including volatiles) to planet b. The probabilities of the collisions of particles with planet b for $e_o = 0.02$ were about 0.15–0.2, 0.1, 0.06–0.08, and 0.016–0.03 at $0.001 \leq \beta \leq 0.004$, $\beta = 0.01$, $\beta = 0.02$, and $0.04 \leq \beta \leq 0.1$, respectively. For $e_o = 0.15$, the probabilities were about 0.07–0.15, 0.04, and 0.01–0.03 for $0.001 \leq \beta \leq 0.01$ (diameters of the particles about 100 microns), $\beta = 0.02$, and $0.04 \leq \beta \leq 0.1$, respectively. The probabilities of the collisions of particles with planet c for $e_o = 0.02$ were about 0.016–0.05, 0.02, and 0.01–0.02 for $0.001 \leq \beta \leq 0.004$, $\beta = 0.01$, and $0.02 \leq \beta \leq 0.1$, respectively. For $e_o = 0.15$, the probabilities did not exceed 0.03 for all considered variants. At $\beta \geq 0.4$, most particles were ejected into hyperbolic orbits. For $0.004 \leq \beta \leq 0.2$, most particles collided with the star with the maximum collision probability at $\beta = 0.04$. The evolution times of the dust disks under consideration were generally shorter for larger β. They were 300 years at β=1 and several million years at $0.004 \leq \beta \leq 0.04$.

Funding

The studies were carried out under the state contract of the Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences.

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