Fragmentation and ablation of the planetesimals in the protoplanetary disks of Jupiter and Saturn

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Abstract. In this study we discuss the capture of bodies into the gaseous disks around young Jupiter and Saturn due to gas drag in the disks. We suppose that solution of the problem will allow estimation of the masses and composition of bodies that fell on the growing icy moons. This would provide explanation of the differences in the mean density and internal structure of giant icy moons of Jupiter and Saturn. The multiparameter problem of braking, fragmentation and ablation of planetesimals (a comet substance) in the gas medium of the circumplanetary disk is solved by a modified approach of the meteor physics. Our research shows that a significant masses of protosatellite material falling on the circumplanetary disks of Jupiter and Saturn are captured in the disks. At the same time the masses captured in the formation region of different moons are very different. The braking and fragmentation of planetesimals can be the main parameter in the mechanism of capture mass of planetesimals by the accretion disks of giant planets. There is a significant difference in the mass of material captured by the aerodynamic braking and ablation in the formation regions of Ganymede, Callisto, and Titan (up to 30-40%). For a material strength of $2 \times 10^4 \text{ Pa} < \sigma < 2 \times 10^5 \text{ Pa}$, a significant difference in the amount of matter captured by the disk in the feeding region of the regular ice satellites of Ganymede, Callisto and Titan is possible. The presence of fragmentation is perhaps one of the reasons for the difference in the internal structure of Ganymede, Callisto and Titan.

1. Introduction

Currently existing models of the Jupiter protodisk can be conditionally divided into two types – massive ones, in which a stationary disk model is assumed, and low massive ones. In a low-mass model, the mass of all Jupiter's satellites ($6 \times 10^{28} \text{ g}$) is approximately equal to the total mass of matter passed through the disk at the stage of satellite formation. In the massive model, the same value is the largest one-time disk mass of matter reached by the end of the stage of accretion onto Jupiter and the disk from the solar nebula. Massive models are characterized by high density (the pressure in the middle plane of the disk varies from $10^{-2}$ to several bar) and high temperature in the disk. Less massive models assume a density close to the background density of the solar disk (pressure in the middle plane of the disk less than $10^{-4}$ bar) and low temperature (less than 200-300 K); i.e. Jupiter's low-mass disk, despite viscous heating, remains rather cold because of its low surface density and optical thickness. Due to such low temperatures, ice becomes stable in orbit of Ganymede, and water-bearing minerals – in orbit of Europa. In low-mass models, at each moment of time, the accretion disk contains only $\sim 10^{-3}$--$10^{-2}$ of the total mass of regular satellites, which indicates an influx of gas, dust particles,
and planetesimals into the accretion disk. In this paper, we consider low-mass models of the accretion disk.

There are two possible types of processes for the entry of solid material into the protoplanetary disk. If solid particles are small enough, they form a single whole with the gas flow and are carried in the protoplanetary disk with the gas flow [1]. The second mechanism is the capture of planetesimals by the accretion disk. Since the size and distribution of solid material in the protosatellite disk affect the accretion time and ice–rock ratio [2, 3], the problem of planetesimal capture by the accretion disk is relevant and has been considered by numerous researchers.

In an early study [4], the authors used a simple semi-analytical model of deceleration and fragmentation of bodies in a gaseous medium of a protostellite disk at an early stage of Jupiter's evolution under the assumption that the density distribution is exponential to the plane of the disk. Sasaki et al. [5] investigated the nature of the difference in structure between the Jupiter and Saturn systems by a semi-analytical method, simulating the growth and orbital migration of proto-satellites in the accretion disk.

In modern studies, the processes of solid matter entering the accretion disk are mainly studied by numerical modeling of the motion of N bodies in a gravitational field, taking into account the interaction of planetesimals with a gaseous medium. The problem of planetesimals passing through a massive disk, their deceleration and ablation was considered in [6] in order to explain the low density of the satellite Iapetus and its probable enrichment in water ice in comparison with the solar abundance. Three-body orbital integrations were used to study the capture of planetesimals from heliocentric orbits into the accretion disk [7]. It was found that the capture rate increases with decreasing size of planetesimals. Tanigawa et al. [8] considered the process of deceleration of solid particles of various sizes. It is shown that the accretion of dust particles at the initial stage of circular orbits is small in the case of a decrease in the surface density as a result of the disk scattering process. In [9], the problem of deceleration, ablation, and destruction of planetesimals in the solar and low-mass proto-Jupiterian disks is solved using a three-dimensional numerical method. The evolution of planetozimals in the gaseous medium of disks and their absorption by growing Jupiter was studied. Strength properties of bodies with initial dimensions of 0.1–100 km corresponded to ice and silicates. The authors take into account almost all the basic physical processes that affect the trajectory and the current mass (size) of planetesimals. The fragmentation of planetesimals under the action of aerodynamic forces was considered. However, the possible collisions of bodies, which also lead to fragmentation of the colliding bodies, were not taken into account. It was found that as a result of the interaction of planetesimals with the gaseous medium, the concentration of bodies with sizes of the order of 1 km and low surface density occurs in the proto-Jupiterian disk. These results can largely be a consequence of the fragmentation and initial size distribution of bodies adopted by the authors, as well as a given dependence of the strength of bodies on dimensions. In [10], the deceleration and orbital evolution of irregular satellites in a waning accretion disk was studied for the capture model with a single interaction with the planet. The formation of satellites in a low-mass disk and the nature of the difference in the structure of the satellite systems of Jupiter and Saturn were investigated using a semi-analytical method [11]. The processes of growth and orbital migration of proto-satellites in the accretion disk were simulated. However, the formation of massive satellites like Ganymede or distant satellites like Callisto is difficult to explain by this model. The capture of planetesimals from heliocentric orbits and their orbital evolution in the protosatellite disk were studied in [12]. The estimates of the ratio of the surface density of dust and captured planetesimals in the protosatellite disk are carried out. It is shown that the current position of regular satellites is mainly due to the capture of planetesimals in the case of a low dispersion of planetesimals’ velocities and the absence of a cavity in the protoplanetary disk.

In this paper, we discuss the problem of interaction with a gaseous medium of a low-mass disk of planetesimals falling on the surface of the accretion disks of Jupiter and Saturn from the zone of gravitational influence of the central planet. Depending on the distance to the central planet and the mass of planetesimals captured by the disk, the conditions for the formation of satellites Ganymede,
Calisto and Saturn's moon Titan in the Jupiter system and, as a consequence, their internal structure can be changed [2, 3]. According to modern data on the mass and moment of inertia of the satellite, it can be assumed that Ganymede has passed the process of complete differentiation into a metallic Fe-FeS core, silicate mantle, and a thick water-ice shell [13]. Callisto has a similar size and mean density. However, the values of the moments of inertia show that the satellite probably consists of an ice shell, undifferentiated rock-ice mantle, and a silicate core [14]. Titan, as shown in [15,16], can also have an undifferentiated rock-ice mantle. Estimates of the size and mass of planetesimals trapped by the disk in the growth zones of regular satellites will probably help to make progress in understanding the reasons for the differences in the internal structure of the icy giant satellites.

Velocities of planetesimals can reach 20 km s\(^{-1}\), and their sizes range from dust particles to 20–100 km in diameter. When a planetesimals enter the gaseous medium of the disk, they are affected by the aerodynamic forces of the interaction of the body with the gaseous medium of the disk [17]. Depending on the size, speed of entry into the disk, density and strength of the planetesimal, distance from the central planet and density of the gaseous medium in the disk, the behavior of planetesimals in the disk will be different. Large planetesimals can pass through the disk without significant deceleration and not return to it, while small bodies will reduce their speed and remain in the disk. The ablation and fragmentation of bodies when interacting with a gaseous medium should also be taken into account. All these processes are described in detail in meteoric physics, where the interaction of high-speed bodies with the atmosphere of planets is considered [17]. The analogy turns out to be quite complete, since the density distribution in the vertical plane of the disk is described in the same way as in the atmospheres of planets – by an exponential relation. Therefore, we have adapted the well-known semi-empirical methods of meteor physics [17-21] to solving the problem of interaction of planetesimals with the gaseous medium of the disk. The solution to the gas-dynamic problem of the motion of a body with hypersonic speeds in the atmosphere of the planets is determined by two dimensionless parameters characterizing the deceleration and ablation of the body in a gaseous medium. A large amount of experimental data in meteoric physics makes it possible to set these coefficients depending on the speed, material of the body and the density of the gas medium. This approach makes it possible to analytically describe the processes of deceleration, ablation, fragmentation of bodies in the gaseous medium of the disk and to obtain estimates of the mass of matter captured by the disk at different distances from the central planet [22].

2. Conditions for gravitational capture of planetesimals by a disk

The average velocity \( V_{1} \) of the fall of planetesimals onto the protosatellite disk in the planetocentric problem of two bodies (i.e., inside the Hill sphere of the planet) is determined from the energy conservation condition

\[
\frac{V_{1}^{2}}{2} - \frac{GM_{p}}{r} = \frac{V_{m}^{2}}{2},
\]

where \( V_{m} \) – the average chaotic velocity of bodies in the circumsolar disk (solar nebula) in the formation zone of the central planet, but outside the sphere of its gravitational influence (Hill's sphere). At the stage when the radius of the planet's embryo becomes greater than \( \sim 1 \times 10^{4} \) km, the growth of chaotic velocities of bodies slows down due to the beginning of the ejection of bodies from the zone of planet formation. In this case, the value of \( V_{m} \) approaches the limiting value \( V_{m} = V_{*} = V_{K}/3 \) [23,24], where \( V_{K} \) is Keplerian circular velocity at a distance a from the Sun. Equation (1) implies that

\[
V_{1}^{2} = V_{e}^{2} + V_{m}^{2},
\]

where \( V_{e} = \sqrt{2GM_{p}/r} \) – the speed of escape from the Hill sphere of the planet (second cosmic velocity) at a distance \( r \) from the center of the planet. During the passage of the disk, planetesimals are decelerated by the gaseous medium and at the exit from the disk acquire velocity \( V_{2}, V_{2} < V_{1} \). If
\( V_2 \geq V_e \), the body will not be captured by the disc. From relation (2) follows the condition on the ratio \( v = V_2/V_1 \) during the capture of a planetesimal by a disk:

\[
\nu_{\text{max}} = \frac{V_e}{V_1}, \quad v \leq \nu_{\text{max}} \tag{3}
\]

For the disk of Jupiter at a distance \( 6R_J \) (Io) \( v_2 \approx 0.97 \), \( 10R_J \) (Europa) \( v_2 \approx 0.95 \), \( 16R_J \) (Ganymede) \( v_2 \approx 0.925 \), \( 26.4 R_J \) (Callisto) \( v_2 \approx 0.885 \). If, when a body passes through the disk, the condition \( V_2/V_1 \leq \nu_{\text{max}} \) is satisfied, then with a high probability the body will transfer to an elliptical orbit and enter the disk.

3. Capturing the mass of planetesimals taking into account ablation processes

The motion of planetesimals in the gaseous medium of the accretion disk will be considered within the framework of the model of a single body, until the pressure on the frontal surface reaches a certain critical value, leading to the fragmentation of the body, after which the motion of each individual fragment is also described within the framework of this model [17, 18, 25, 26]. A model for estimating surface density as a function of distance from the central planet is given in [22].

In the dimensionless form, the equations of mass loss can be written [18, 21]:

\[
\frac{dm}{dy} = -2\alpha \beta \rho_{gn} v^2 s, \tag{4}
\]

where \( c_d, c_h \) – coefficients of strength and heat transfer, \( s \) – midsection area, \( \rho_{gn} \) – gas density, \( \beta \) - mass loss coefficient, \( \alpha \) - parameter defined in the decision process.

The mass loss coefficient \( \beta \) is determined by the ablation coefficient \( \sigma = c_h/c_d H^* \) (\( H^* \) – is the effective heat of failure), the shape factor \( \mu \) and the velocity of falling on the disk \( V_1 \): \( \beta = \sigma (1 - \mu) V_1^2/2 \). If \( V_2 \) after crossing the disk is higher than the second space velocity \( V_e \), planetesimal will leave the disk. In this case, the mass of planetesimals will decrease by the amount of mass of substance lost as a result of ablation. Taking ablation into account for the parameter \( \alpha \), we can obtain the expression:

\[
\alpha = \frac{1}{2} \int_{\nu_{\text{min}}}^{1} \frac{d
u}{\nu} \exp((\beta/3)(1-v^2)) \nu_{\text{min}} = \frac{V_e}{V_1} \tag{5}
\]

According to the parameter \( \alpha \) calculated from (5) under the assumption of the spherical shape of the body, we get the value \( R_{1\text{max}} \) - the maximum radius at the entrance to the disk of the body captured by the disk:

\[
R_{1\text{max}} \approx 0.4 \frac{\Sigma_g}{\rho_m \alpha}, \quad \Sigma_g = \Sigma_{20} \left( \frac{r}{20R_p} \right)^{-3/4}, \tag{6}
\]

where \( R_p \) – radius of the central planet, surface density (\( \Sigma_g \)) at a distance of 20 radii from the planet \( \Sigma_{20}=140 \ \text{g/cm}^2 \) и 60 \( \text{g/cm}^2 \) for Jupiter and Saturn satellites, consequently [27]. In the absence of ablation (i.e. \( \beta = 0 \)) the parameter \( \alpha \) is maximal: \( \alpha_{\text{max}} = 0.5 \ln(V_1/V_e) \). The minimum value of maximum radius of the body captured into the disk, determined by the relation (6) is

\[
R_{1\text{max min}} \approx 0.8 \frac{\Sigma_g}{\rho_m \ln(V_1/V_e)} \tag{7}
\]
The mass of planetesimals at the exit from the disk, taking into account the ablation processes, is estimated from the equation:

$$m_2 = \exp[\beta(v_2^2 - 1)], \quad v_2 = V_i/V_2$$  \hspace{1cm} (8)

The mass of matter lost (evaporated) during ablation and therefore captured in the disk for the body, which, after crossing the disk, left it at a velocity $V_2$ greater than the second cosmic velocity $V_e$: $1 - m_2$.

The ablation coefficient $\sigma$ is a semi-empirical admeasurement and is determined from the numerous observational data of meteorite falls by solving the equations of meteoric physics [19, 20, 21]. In this study, the material of planetesimals is modeled by cometary matter. The ablation coefficient for cometary matter varies over a wide range of values. Comets in accordance with the classification [28] belong to the type IIIA-IIIB with the observed ablation coefficient (reconstructed from the equations of meteoric physics) $0.1-0.2$ s$^2$km$^{-2}$. It should be noted that the observed or "effective" ablation coefficient apparently includes the processes of fragmentation of the surface layers of the meteorite and the drift of particles of small mass. The "proper" ablation coefficient (without the effect of fragmentation processes) is much smaller, almost independent of the types of meteorites, and is in the range of values ($0.004 - 0.008$ s$^2$km$^{-2}$) [19]. The ablation coefficients obtained from the results of observations of falling meteorites in the original work [20], basically have the same order of magnitude, although there are a number of estimations with $\sigma \approx 0.1$ s$^2$km$^{-2}$. Since it is impossible to calculate the density and shape of a meteorite from the results of observations within the framework of the constructed model [20], it is difficult to relate the results to specific types of meteorites. It is shown in [20] that the results of calculations with a variable trajectory mass loss coefficient $\beta$ almost does not differ from calculations with a constant coefficient and, thus, it is possible to set the constant coefficient $\beta$ or $\sigma$ for the total meteorite trajectory. Our numerical modeling also showed a weak effect of the variation of $\sigma$ on the mass loss of planetesimals.

4. Fragmentation of planetesimal by a statistical model

The problem of destruction of planetesimals during the passage of the gaseous medium of the disk will be considered within the framework of the system of destruction of high-speed bodies upon entering the atmosphere. Fragmentation occurs when the value of the dynamic pressure of the flow with the density $\rho_g$ and velocity becomes one of the strongest movements of the body ($\sigma$) [29]:

$$\sigma_t^* = \rho_g V^2.$$  \hspace{1cm} (9)

In this work, it is assumed that planetesimals consist of a material similar in composition and strength to that of comets, since comets can be considered as a compound (rubble piles) of fragments of parent bodies, in our case – planetesimals [30].

According to the statistical theory of strength, large structural defects leading to the destruction of the body are much less common than smaller defects. Therefore, the probability of finding a large defect increases with body size [31]. Effective strength depends on body weight according to the following relation:

$$\sigma_t^* = \sigma^* (m^*/M)^\lambda$$  \hspace{1cm} (10),

where $\sigma^*$ and $m^*$ are the strength and mass of the laboratory sample under study, $\sigma_t^*$ is the effective strength of a body made of the same material of mass $M$, $\lambda$ is the scale factor. Minimum mass of a destroyed body:

$$M_f = m^* \left( \frac{\sigma^*}{\rho_g V^2} \right)^{1/\lambda}$$  \hspace{1cm} (11)
The value of $\lambda$ depends on the properties of the material. A more homogeneous material possesses a lower $\lambda$ value. For concrete $\lambda = 1/3$, for granite - 1/6. According to observations of the processes of destruction of meteorites upon entering the atmosphere, estimates of $\lambda \approx 0.25$ were obtained [32]. Svetsov et al. [33] give estimates $\lambda = 0.2$–-0.68, obtained as a result of processing the results of observations and subsequent modeling of the fall of large meteorites into the atmospheres of planets. The results of impact experiments presented in [34] convincingly show the dependence of the strength of a body on its dimensions with a scale factor $\lambda = 0.2$. Direct measurements of the strength of water ice by Petrovic [35] give $\lambda = 0.2$. Turcotte (1986) considers $\lambda = 0.12$ for ice bodies. In [36], to estimate the scale factors when comparing the matter of comets and the Tunguska meteorite, $\lambda$ was also taken 0.12.

The tensile, shear, and compressive strength of comet matter has been investigated repeatedly in several independent ways, including impact experiments, observations of comet decay, laboratory experiments with imitation of comet matter, and numerical experiments on impact destruction. There is currently no consensus on the strength of cometary material, primarily due to the scale factor. Data from laboratory experiments with analogs of cometary material (a mixture of water ice and dust) give strength values $\sigma^*$ from 20 kPa to 1 MPa [37], which is consistent with experimental data. In [38], the strength of the comet's matter is estimated as $\sigma^* = 10^3$ Pa. According to the estimates [37], the strength on the comet scale is estimated to be $\sigma_1 \approx 100$ Pa. Based on the average size of comets 5–10 km and their average density $0.5$–$0.6$ g / cm$^3$, at $\lambda = 0.12$ for a sample with a mass of $m^* = 1$–$10^3$ g, we obtain the strength estimates $\sigma^* = (4$–$12)$ kPa, which is close to estimates [38]. The comet's strength on a scale of 10 m $^-1$–1km was estimated for comet 67P [39]. The tensile strength of 3–15 Pa (upper limit of 150 Pa) was obtained on the basis of modeling the collapse of canopies, and the shear strength of 4–30 Pa was determined from the estimates of the observed sliding of the slopes. For comparison, snow as shown [40] for a density of 100 kg/m$^3$ strength is 100 Pa.

It follows from [10] that larger planetesimals have a lower effective strength and can be destroyed by the action of a gas flow, while smaller planetesimals remain intact under similar conditions. The smallest radius of a planetesimal not subjected to fragmentation ($R_{\text{f, min}}$) is determined through [11]. For sufficiently large bodies, the planetesimals' self-gravity forces become of the same order of magnitude with the dynamic pressure forces and resist the destruction of the planetesimals [41]. Estimates of the minimum sizes of bodies ($R_{\text{min},G}$) that are not fragmented as a result of self-gravity are given in [9]: $\sim10$ km for ice bodies and $\sim 20$ km for rocky bodies. For matter identical to the cometary one, by analogy, it can be taken $R_{\text{min},G} \sim 10$ km. All planetesimals with radii from $R_{\text{f, min}} < R < R_{\text{min},G}$, when passing through the disk, will be destroyed to fragments with sizes $R \leq R_{\text{f, min}}$. In the simplest fragmentation model, a body with a radius of $1.26 R_{\text{f, min}}$ splits into two parts of the same mass with radii $R_{\text{f, min}}$ reduced to a sphere. Hence it follows that when the condition $1.26 R_{\text{f, min}} \leq R_{\text{f, max}}$ is satisfied, the entire mass of planetesimals in the satellite feeding zone in the size range $0 < R < R_{\text{min},G}$ remains in the disk.

5. Results and discussion
We simulated planetesimals passing through the circumplanetary disks of Jupiter and Saturn and capture of their material into the disks with consideration of combined processes of aerodynamic braking, fragmentation, and ablation of planetesimals in the disk’s gas medium [42]. Below are the results of simulation for the comet material of the planetesimals.

The distribution of bodies by mass is described by a power law (Safronov, 1969):

$$n(M)dM = cM^{-q}dM$$

where $n(M)dM$ is the number of bodies per unit volume with masses in the interval $(M, M+dM)$ [22]. The theoretical results and the distribution of craters in size give the values of $q \approx 1.8$. We estimated maximum planetesimal size (radius $R_{\text{f, max}}$) which the body should have at the entrance to the disk in order to stay in the disk after loosing mass and velocity due to gas drag and ablation. The maximum radius of captured planetesimal $R_{\text{f, max}}$ is obtained as a function of distances from the central planet. We also estimated the ratio $(M' = M/M_\text{f})$ of the mass of solid material, lost by
the falling bodies through ablation and thus captured by the disk \((M_a)\), to the total mass of the falling bodies \((M_t)\) with \(R > R_{1,\text{max}}\) and the parameter \(M_{ac}^*\) (the ratio of the entire captured mass in the range of sizes \(0 < R < R_0\), consisting of the mass of small bodies trapped in a disk with radii \(R < R_{1,\text{max}}\), summed with the mass of the substance evaporated during ablation, and thus captured in a disk to the entire mass of the matter falling on the disk). In the results presented here we basically adopt for the largest body with the radius \(R_0 = 100\) m and 1000 m.

The processes of gas drag and ablation of planetesimals during the passage of the gas medium of the disk and their influence on the mass captured by the disk are discussed. There is a significant dependence on the ablation coefficients of the amount of material captured by the disk. For ablation factors <0.01 s\(^2\) km\(^{-2}\), the contribution of ablation to the captured mass can be ignored, however, for planetesimals from cometary material, ablation can supply 20-30% of the mass of planetesimals in the feeding area of Ganymede and Callisto and 10%-20% in the feeding area of Titan.

The dependence of the \(M_a^*\) and \(M_{ac}^*\) values on the ablation coefficient is shown in Fig 1–3. It is seen from Fig. 1 that the \(M_a^*\) is very small both in disks of Jupiter and Saturn due to small mass loss by ablation \((M_a)\) (at adopted value of ablation coefficient 0.02 s\(^2\) km\(^{-2}\)). At the same time, the parameter \(M_{ac}^*\) (Fig. 1) for \(\sigma = 0.1\) -0.2 s\(^2\) km\(^{-2}\) reaches 0.1–0.3 for planetesimals with maximum radii up to 100–1000 m. The influence of ablation processes on the captured mass increases with decreasing sizes of planetesimals. For planetesimals with \(R_0 = 100\) m, the increase in the captured mass due to ablation can reach 40-50%, Fig. 2. The parameter \(M_{ac}^*\) almost linearly depends on \(\ln R_0\) for \(R_0<1000\) m. Thus, there is a significant difference in the mass of material captured in the formation regions of Ganymede, Callisto, and Titan, Fig 1-3. In the area of Ganymede formation, \(M_{ac}^*\) is 30-40% higher than \(M_{ac}^*\) for the Callisto region, Fig. 3. Note that the presented calculations of values \(M_a\) and \(M_{ac}\) do not take into account the possible fragmentation of planetesimals. The inclusion of fragmentation would increase the captured masses.

**Figure 1.** Dependence of the parameter \(M_a^*\) (the ratio of the mass of the substance evaporated as a result of ablation \((M_a)\) and therefore captured in the disk, to the total mass of bodies \((M_t)\) with radii \(0 < R < R_0\) from the ablation coefficient \(\sigma\). The circle, rhombus, cross - distance from the central planets for Ganymede, Callisto, Titan, respectively, \(R_0 = 100\) m - solid line, \(R_0 = 1000\) m - dashed line.

**Figure 2.** The dependence of the parameter \(M_{ac}^*\) (the ratio of the entire captured mass in the range of sizes \(0 < R < R_0\), consisting of the mass of small bodies trapped in a disk with radii \(R < R_{1,\text{max}}\), summed with the mass of the substance evaporated during ablation, and thus captured in a disk to the entire mass of the matter falling on the disk) from the ablation coefficient \(\sigma\). Circle, rhombus, cross - distances from the central planet for Ganymede, Callisto, Titan, respectively. \(R_0 = 100\) m. - solid line, \(R_0 = 1000\) m - the dashed line.
Simulation of joint processes of aerodynamic braking, fragmentation, and ablation (a comet substance) in the gas environment of the accretion disks of Jupiter and Saturn was carried out. The radii of fragmentation of planetesimals $R_{f_{\text{min}}}$ are determined, depending on the scale factor and strength of the substance at distances of the regular satellites of Jupiter and Saturn (Fig. 5). Dependence between the minimum radius of fragmentation of planetesimals ($R_{f_{\text{min}}}$) in Jupiter systems and Saturn and the distance to the central planet $r$ shows, that for $\sigma^* = 10^4$ Pa radius of fragmentation for planetesimals in the formation zone of Ganymede $R_{f_{\text{min}}} \approx 1$ m, Callisto $R_{f_{\text{min}}} \approx 10$ m and Titan $R_{f_{\text{min}}} \approx 70$ m, Fig 3.

The strengths of weak (IIIB) and strong (IIIA) cometary material, carbonaceous (II) and ordinary (I) chondrites according to the classification [28] are shown in the Fig. 5. It follows from Fig. 5 that the entire mass of planetesimals with radii $R<R_{f_{\text{min}}}^G$ is captured by a disk under the condition: $\sigma^* < 2 \times 10^5$ Pa for Ganymede, $\sigma^* < 2 \times 10^4$ Pa for Callisto and $\sigma^* < 5 \times 10^3$ Pa for Titan. Thus, for a material strength of $2 \times 10^4$ Pa $< \sigma^* < 2 \times 10^5$ Pa, a significant difference in the amount of matter captured by the disk in the feeding region of the regular ice satellites of Ganymede, Callisto and Titan is possible. In this case, in the Ganymede feeding zone, all planetesimals are either decelerated and remain in the accretion disk or are fragmented and then decelerated. In the growth area of Callisto and Titan, there is no fragmentation of bodies in this strength range, and the amount of captured matter is determined only by ablation and deceleration. This could be one of the main reasons for the low differentiation of Callisto and Titan compared to Ganymede.

Summary estimates of the mass captured by the disk as a result of the physical process aerodynamic braking, fragmentation, and ablation are given in Table 1.

**Figure 3.** Dependence of the parameter $M_{ac}^*$ from the radii $R_0$. The circle, rhombus, cross - distance from the central planets for Ganymede, Callisto, Titan, respectively. The ablation coefficient $\sigma = 0.1 \text{ c}^2 \text{km}^{-2}$.
Figure 4. Dependence between the minimum radius of fragmentation of planetesimals (\(R_{\text{fmin}}\)) in Jupiter systems (dot-dashed line) and Saturn (dashed line) and the distance to the central planet \(r\). The circle, the rhombus, the cross - \(r\) at the distances of Ganymede, Callisto, Titan, respectively. The strength of the planetesimal substance is \(\sigma^* = 10^4\) Pa, the scale factor \(\lambda = 0.2\).

Figure 5. Dependence of the minimum radius of fragmentation of planetesimals (\(R_{\text{fmin}}\)) on the strength of planetesimals \(\sigma^*\) at the distances of Ganymede from the central planet (solid line), Callisto (dashed line). The circle, the rhombus, the cross are the points of equality to the values of the maximum radii of capture of the planetesimal disk (\(R_{\text{fmin}} = R_{\text{1max}}\)) at the distances of Ganymede, Callisto, Titan, respectively. In the case of \(R_{\text{fmin}} < R_{\text{1max}}\), all the matter falling on the disk is captured by the disk. The scale factor is \(\lambda = 0.2\). The abscissa axis shows the strength of meteoritic matter in accordance with the classification [28].

Table 1. The \(M_P/M_t\) ratio.

| The physical process P | Ganymede \(M_P/M_t\) | Callisto \(M_P/M_t\) | Titan \(M_P/M_t\) |
|------------------------|----------------------|----------------------|-------------------|
| The braking, \(M_b/M_t\) | 0.85                 | 0.53                 | 0.37              |
| \((R_0 \leq 100\,\text{m})\) |                     |                      |                   |
| The braking, \(M_b/M_t\) | 0.28                 | 0.18                 | 0.12              |
| \((R_0 \leq 1000\,\text{m})\) |                     |                      |                   |
| The ablation, \(M_a/M_t\) | 0.14                 | 0.32                 | 0.2               |
| \((R_0 \leq 100\,\text{m})\) |                     |                      |                   |
| The ablation, \(M_a/M_t\) | 0.28                 | 0.22                 | 0.09              |
| \((R_0 > 100\,\text{m})\) |                     |                      |                   |
| The fragmentation + braking \(\sigma^* < 4\) kPa | 1.0                  | 1.0                  | 1.0               |
| \(R_0\) without restrictions | |                     |                   |
| The fragmentation + braking \(\sigma^* < 4-15\) kPa (комета) | 1.0 \(R_0\) without restrictions | 1.0 \(R_0\) without restrictions | 1.0 \(R_0 > R_{\text{fmin}}\) (120 m) |
| The fragmentation + braking \(\sigma^* < 4-300\) kPa | 1.0 \(R_0\) without restrictions | 1.0 \(R_0 > R_{\text{fmin}}\) (500 m) | 1.0 \(R_0 > R_{\text{fmin}}\) (5000 m) |

Note: \(M_P\) – the mass captured by the disk as a result of the physical process P. \(M_t\) - the total mass of bodies with radii 0<\(R\)<\(R_0\). Scale factor \(\lambda = 0.2\) adopted for material of the comet. In the case of fragmentation all matter falling on the disk is captured by the disk.)
6. Conclusions
Here we discuss the capture of bodies into the gaseous disks around young Jupiter and Saturn due to gas drag in the disks. We consider the deceleration of bodies accompanied by their ablation and fragmentation, which greatly affect the capture. In the present research we use the approach adopted in the meteor physics. Simulation of joint processes of aerodynamic braking, fragmentation, and ablation (a comet substance) in the gas environment of the accretion disks of Jupiter and Saturn was carried out. Our research shows that a significant masses of protosatellite material falling on the circumplanetary disks of Jupiter and Saturn are captured in the disks. At the same time the masses captured in the formation region vary greatly for different moons.

The braking and fragmentation of planetesimals can be the main parameter in the mechanism of capture mass of planetesimals by the accretion disks of giant planets. There is a significant difference in the mass of material captured by the aerodynamic braking and ablation in the formation regions of Ganymede, Callisto, and Titan (up to 30–40%).

For a material strength of $2 \times 10^4 \text{ Pa} < \sigma < 2 \times 10^5 \text{ Pa}$, a significant difference in the amount of matter captured by the disk in the feeding region of the regular ice satellites of Ganymede, Callisto and Titan is possible. The presence of fragmentation is perhaps one of the reasons for the difference in the internal structure of Ganymede, Callisto and Titan.

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