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ҚАЙЫРЫМДЫЛЫҚ ҚОРЫ
HALYK
CHARITY FOUNDATION

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ
«ХАЛЫҚ» ЖҚ

БАЯНДАМАЛАРЫ

ДОКЛАДЫ

РОО «НАЦИОНАЛЬНОЙ
АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН»
ЧФ «ХАЛЫҚ»

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ҚАЙЫРЫМДЫЛЫҚ ҚОРЫ
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ЧФ «ХАЛЫҚ»

В 2016 году для развития и улучшения качества жизни казахстанцев был создан частный Благотворительный фонд «Халык». За годы своей деятельности на реализацию благотворительных проектов в областях образования и науки, социальной защиты, культуры, здравоохранения и спорта, Фонд выделил более 45 миллиардов тенге.

Особое внимание Благотворительный фонд «Халык» уделяет образовательным программам, считая это направление одним из ключевых в своей деятельности. Оказывая поддержку отечественному образованию, Фонд вносит свой посильный вклад в развитие качественного образования в Казахстане. Тем самым способствуя росту числа людей, способных менять жизнь в стране к лучшему – профессионалов в различных сферах, потенциальных лидеров и «великих умов». Одной из значимых инициатив фонда «Халык» в образовательной сфере стал проект Ozgeris powered by Halyk Fund – первый в стране бизнес-инкубатор для учащихся 9-11 классов, который помогает развивать необходимые в современном мире предпринимательские навыки. Так, на содействие малому бизнесу школьников было выделено более 200 грантов. Для поддержки талантливых и мотивированных детей Фонд неоднократно выделял гранты на обучение в Международной школе «Мирас» и в Astana IT University, а также помог казахстанским школьникам принять участие в престижном конкурсе «USTEM Robotics» в США. Авторские работы в рамках проекта «Тәлімгер», которому Фонд оказал поддержку, легли в основу учебной программы, учебников и учебно-методических книг по предмету «Основы предпринимательства и бизнеса», преподаваемого в 10-11 классах казахстанских школ и колледжей.

Помимо помощи школьникам, учащимся колледжей и студентам Фонд считает важным внести свой вклад в повышение квалификации педагогов, совершенствование их знаний и навыков, поскольку именно они являются проводниками знаний будущих поколений казахстанцев. При поддержке Фонда «Халык» в южной столице был организован ежегодный городской конкурс педагогов «Almaty Digital Ustaz.

Важной инициативой стал реализуемый проект по обучению основам финансовой грамотности преподавателей из восьми областей Казахстана, что должно оказать существенное влияние на воспитание финансовой грамотности и предпринимательского мышления у нового поколения граждан страны.

Необходимую помощь Фонд «Халык» оказывает и тем, кто особенно остро в ней нуждается. В рамках социальной защиты населения активно проводится работа по поддержке детей, оставшихся без родителей, детей и взрослых из социально уязвимых слоев населения, людей с ограниченными возможностями, а также обеспечению нуждающихся социальным жильем, строительству социально важных объектов, таких как детские сады, детские площадки и физкультурно-оздоровительные комплексы.

В копилку добрых дел Фонда «Халык» можно добавить оказание помощи детскому спорту, куда относится поддержка в развитии детского футбола и карате в нашей стране. Жизненно важную помощь Благотворительный фонд «Халык» оказал нашим соотечественникам во время недавней пандемии COVID-19. Тогда, в разгар тяжелой борьбы с коронавирусной инфекцией Фонд выделил свыше 11 миллиардов тенге на приобретение необходимого медицинского оборудования и дорогостоящих медицинских препаратов, автомобилей скорой медицинской помощи и средств защиты, адресную материальную помощь социально уязвимым слоям населения и денежные выплаты медицинским работникам.

В 2023 году наряду с другими проектами, нацеленными на повышение благосостояния казахстанских граждан Фонд решил уделить особое внимание науке, поскольку она является частью общественной культуры, а уровень ее развития определяет уровень развития государства.

Поддержка Фондом выпуска журналов Национальной Академии наук Республики Казахстан, которые входят в международные фонды Scopus и Wos и в которых публикуются статьи отечественных ученых, докторантов и магистрантов, а также научных сотрудников высших учебных заведений и научно-исследовательских институтов нашей страны является не менее значимым вкладом Фонда в развитие казахстанского общества.

С уважением,
Благотворительный Фонд «Халык»!

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

БАЯНДАМАЛАРЫ **2024 • 1**

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БЕРСІМБАЕВ Рахметқажы Ескендірұлы, биология ғылымдарының докторы, профессор, ҚР ҰҒА академигі, Еуразия ұлттық университеті. Л.Н. Гумилев (Нұр-Сұлтан, Қазақстан), Н = 12

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КАЛАНДРА Пьетро, PhD (физика), наноқұрылымды материалдарды зерттеу институтының профессоры (Рим, Италия), Н = 26

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БАЙМҰҚАНОВ Дастан Асылбекұлы, ауыл шаруашылығы ғылымдарының докторы, ҚР ҰҒА корреспондент мүшесі, "Мал шаруашылығы және ветеринария ғылыми-өндірістік орталығы" ЖШС мал шаруашылығы және ветеринарлық медицина департаментінің бас ғылыми қызметкері (Нұр-Сұлтан, Қазақстан), Н=1

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ДОКЛАДЫ **2024 • 1**
НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН

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РАМАНКУЛОВ Ерлан Мирхайдарвич, (заместитель главного редактора), профессор, член-корреспондент НАН РК, Ph.D в области биохимии и молекулярной генетики, Генеральный директор Национального центра биотехнологии (Нур-Султан, Казахстан), H = 23

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DESTRUCTION OF COMETS BY THERMAL STRESSES

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Abstract. The problem of comet destruction has not yet been solved. Comets can unexpectedly break down in arbitrary places on their orbits. The mechanisms involved in explaining such phenomena do not provide satisfactory predictions on the possibility of the decay of each individual comet. In addition to existing mechanisms for comet destruction, we propose using the method of thermal stresses inside and on the surface of cometary nuclei as they approach the Sun on elongated orbits. We use a thermal diffusion equation to calculate the compression thermal stress on the surface and the discontinuous stress inside spherical comet nuclei as they move towards the Sun in a parabolic orbit. By comparing the strength limits of the material in the core with the obtained thermal stress, it is possible to predict the cracking of different-sized comet nuclei at different distances from the Sun. Calculations were performed for two different phases of ice: hexagonal crystalline ice (Ih) and amorphous ice. The main conclusions are based on crystal ice data. The observational flare phenomena' data and observed comets' decay were compared with calculation results. From observational cases of comet decay, one can also estimate the composition of the cometary material and its actual strength.

Keywords: comets, thermal stresses, destruction of comets, crystalline and amorphous ice

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КОМЕТАЛАРДЫҢ ТЕРМИЯЛЫҚ КЕРНЕУЛЕРМЕН ЖОЙЫЛУЫ

Аннотация. Кометалардың жойылу мәселесі әлі шешілген жоқ. Кометалар өз орбитасында кездейсоқ жерлерде күтпеген жерден ыдырауға қабілетті. Бұл құбылысты түсіндіру үшін қолданылатын механизмдер әрбір нақты кометаның ыдырау мүмкіндігі туралы қанағаттанарлық болжамды қамтамасыз етпейді. Кометалардың жойылуының қолданыстағы механизмдерінен басқа, біз ұзартылған орбиталарда Күнге жақындаған кезде кометалық ядролардың ішінде және бетінде пайда болатын термиялық кернеулер әдісін қолдануды ұсынамыз. Модельдік есептеулерде біз параболалық орбитада Күнге жақындаған кездегі сфералық кометалық ядролардың ішіндегі бетіндегі қысу термиялық кернеулерін және үзілу кернеулерін есептеу үшін термиялық диффузия теңдеуін қолданамыз. Негізгі материалдың беріктік шегін нәтижесінде пайда болатын термиялық кернеулермен салыстыра отырып, Күннен әртүрлі қашықтықтағы әртүрлі өлшемдегі кометалардың ядроларының жарылуы туралы болжам жасауға болады. Есептеулер мұздың екі түрлі фазалық күйлері үшін жүргізілді: алтыбұрышты кристалды мұз (Ih) және аморфты мұз. Негізгі қорытындылар кристалдық мұз деректерінен жасалған. Есептеулер нәтижелерімен нақты байқалған кометалардың тұтану құбылыстары мен ыдырауы туралы бақылау деректерін салыстыру жүргізілді. Кометалардың ыдырауын бақылау арқылы кометалар материалының құрамын және олардың нақты күшін анықтауға болады.

Түйін сөздер: кометалар, термиялық кернеулер, кометалардың бұзылуы, кристалды және аморфты мұз

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РАЗРУШЕНИЕ КОМЕТ ТЕРМИЧЕСКИМИ НАПРЯЖЕНИЯМИ

Аннотация. Проблема разрушения комет до сих пор не решена. Кометы способны разрушаться неожиданно в произвольных местах орбиты. Механизмы, которые привлекаются для объяснения этого явления, не дают удовлетворительных прогнозов возможности распада каждой конкретной кометы. В дополнение к имеющимся механизмам разрушения комет мы предлагаем использовать метод термических напряжений, возникающих внутри и на поверхности кометных ядер по мере их приближения к Солнцу по вытянутым орбитам. В модельных расчётах мы используем уравнение тепловой диффузии для расчёта компрессионных тепловых напряжений на поверхности и разрывных напряжений внутри кометных ядер шарообразной формы при их приближении к Солнцу по параболической орбите. Из сравнения пределов прочности материала ядра с полученными тепловыми напряжениями можно делать прогнозы о растрескивании кометных ядер разных размеров на различных расстояниях от Солнца. Расчёты проведены для двух различных фазовых состояний льда: гексагонального кристаллического льда (Ih) и аморфного льда. Основные выводы сделаны на основе данных кристаллического льда. Проведено сравнение данных наблюдений вспышечных явлений и распада реально наблюдаемых комет с результатами расчётов. Из наблюдений случаев распада комет можно также судить о составе материала комет и их реальной прочности.

Ключевые слова: кометы, термические напряжения, разрушение комет, кристаллический и аморфный лёд

Introduction

Despite comets being frequently discovered and well-observed, their formation mechanisms and mechanisms for their evolution and disintegration remain unclear. The agglomeration models of comet structure (Greenberg et al., 1995) suggest that these are loose and porous structures with a density of approximately 0.1 g/cm^3, which can easily be destroyed by tidal forces. This model has some inconsistencies due to observations of Halley and Shoemaker-Levy-9 comets showing a density of about 0.6 g/cm^3 (Solem, 1995; Asphaug and Benz, 1996).

There are other mechanisms of comet destruction: disruption by centrifugal forces during rapid rotation, fracture by internal gas pressure during intense evaporation of gases inside the comet as it approaches the Sun and collisions with other small bodies. Despite the abundance of offered mechanisms, the problem is far from solved and requires the involvement of other mechanisms for the destruction of cometary nuclei. There is a list of disintegrated comets, and, according to Sekanina Z. (1997), many of them were destroyed for unknown reasons.

An interesting alternative to the mechanism of destruction by tidal forces may be the destruction of a comet by thermal stresses (Kührt, 1984), which can be calculated both analytically and numerically using the thermal diffusion equation (Kührt, 1984; Shestakova and Tambovtseva, 1997). The values of thermal stresses can be greater than the limits of the mechanical strengths of terrestrial materials and exceed by several orders of magnitude the stresses arising from the action of tidal forces.

The thermal destruction mechanism we are developing is worth considering because it assumes the decay of cometary nuclei at various distances, including large distances from the Sun, and can potentially explain the decay of long-periodic comets in random places of their orbit. In the work of Shestakova and Serebryansky (2023), the mechanism of thermal destruction is proposed as a possible mechanism for forming debris disks at large distances from stars and as a source of material for rings near planets. Thus, applying this mechanism to the decay processes of small bodies may have various interesting consequences.

Our research will focus on analyzing the thermal stress inside and on the surface of comet-like bodies as they approach the Sun on parabolic orbits. By adopting this approach, we can use analytical solutions to the thermal diffusion equation for bodies of various sizes and monitor increases in internal and surface stress as these objects orbit at different distances from the Sun. Once the maximum strength in the nucleus material is reached, comets can be separated and fragmented.

Methods

Theoretical and numerical heat transfer analyses from the surface to the inner layers of a cometary body can be conducted using the heat diffusion equation (hereinafter — HDE). The HDE for a spherical body, according to Kührt (1984), has the form:

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa(T)\frac{\partial T}{\partial x}\right) + \frac{2}{x}\kappa(T)\frac{\partial T}{\partial x}, \tag{1}$$

where T is temperature, *t* is the current time, x is the coordinate, which is calculated from the center of the ball, where x = 0, along the radius of the body up to r, and $c_v(T)$ is heat capacity per unit volume and k(T) is the thermal conductivity of the material.

The above equation can be solved together with the initial condition for $t = 0$ and two boundary conditions: for the center of the body at x = 0 and its surface at $x = r$. The boundary condition for the center of a spherical body is universal because it follows from its symmetry: dT/dx = 0 when x = 0. We choose the initial and boundary conditions on the body's surface based on the physical conditions in which the body is situated. The initial condition is chosen because the whole body is isothermal at a certain starting distance Ro, so $T(x) = T_s$ when t = 0, when T_s stands for equilibrium surface temperature. The main problem is the choice of the boundary condition on the body's surface because the surface temperature changes over time as the body approaches the Sun.

If the parameters k and c_v are constant, then Equation (1) is linear in T. When solving Equation (1), we use parameters $a^2=k/c_v$ [cm^2/sec] and $t_c=(r/\pi a)^2$, where τ_c determines the characteristic heating or cooling time of the body.

If, in the thermal balance of the body, we ignore the loss of sublimation and thermal conductivity towards the center of the body, then we get the surface boundary condition in the form of a blackbody approximation:

$$T_s(t) = \frac{T_{eff}}{\sqrt{2R/R_\odot}}, \qquad (2)$$

where T_{eff} is the temperature of the photosphere and R is the radius of the Sun. The phenomenon of temperature hysteresis, resulting from heat conduction into the core as the body approaches and recedes from perihelion, does not exceed daily fluctuations in the surface temperature (T_s). This T_s is $\sqrt{2}$ times greater than our assumed value at the point closest to the Sun.

The fundamental principle for getting an analytical solution to the HDE is the representation $T_S(t)$ as an explicit function of time. It is only possible for parabolic orbits with a perihelion distance $q \approx 0$. In this case, for parabolic orbits, the transit time from the distance R to the perihelion has the form:

$$\tau(R) = (2/GM_\odot)^{1/2}R^{3/2}/3, \quad (3)$$

where G is the gravitational constant, and $M_\odot$ is the mass of the Sun. As a result, we obtain the boundary condition necessary for solving HDE in the form of an explicit function of time:

$$T_S(t) = \frac{T_o}{(1 - t/\tau_o)^{1/3}}, \qquad (4)$$

where $T_0(t) = \dfrac{T_{eff}}{\sqrt{2R_0/R_\odot}}$, is the body's temperature at the starting distance R_0, $t_o - \tau(R)$ is the current time.

The HDE solution makes it possible to calculate the temperature profile along the radius of a body T(x), moving in a parabolic orbit at any given distance from the Sun and for any materials with known thermal parameters k and c_v.

The only parameter that is directly used in solving the thermal diffusion equation is the ratio of the coefficient of thermal conductivity k to the heat capacity $c_v = c_p\rho$, that is, the coefficient of temperature conductivity: $a^2 = k/(c_p\rho)$.

According to Klinger (1980a), for temperatures above 25 K, the thermal conductivity of crystalline ice can be represented as $k = 567/T$ $Wm^{-1}K^{-1}$. The heat capacity determined from experimental data according to Giauque & Stout (1936) within the temperature range $16.43\ K \le T \le 267.77\ K$ is approximated by the expression (Klinger, 1981): $Cp = 7.49T + 90$ J/kg·K. This Cp value is convenient because it mainly depends on the composition of the material, practically does not depend on the structure of the substance and can be used for both crystalline and amorphous ice. For crystalline ice, we will use the value $a^2 = 0.65$ cm²/sec, which corresponds to T = 30 K. The thermal conductivity of amorphous ice as a function of temperature, obtained from the data by Klinger (1980, 1981), is represented by an approximate formula: $k = 2.34 \times 10^{-3}\ T + 0.028$ W/m K. Substitution of numerical values for a^2 of amorphous ice gives an almost constant value in the temperature range T= [30K – 200K], namely $a^2 = 0.0034$ cm²/s,

Boley and Weiner (1960) got relations for radial and tangential stresses in solid spheres, which can be used to isolate functions with a temperature dimension. The analysis of thermal stresses would be greatly simplified if we used these functions instead of stresses, which only depend on the body's geometry and the temperature distribution within it. By using these temperature functions as analogues of thermal stresses, it is easy to move on to stresses themselves, using a simple form:

$$\sigma_{\varphi\varphi}(x) = \frac{E\alpha}{1-\mu} T_{\varphi\varphi}(x), \quad \sigma_{rr}(x) = \frac{E\alpha}{1-\mu} T_{rr}(x), \quad (1)$$

where the tangential stresses $\sigma_{\varphi\varphi}(x)$ are characterized as the function of $T_{\varphi\varphi}(x)$, and radial stresses $\sigma_{rr}(x)$ are characterized as the function $T_{rr}(x)$. We use the following parameters for the elasticity of bodies: E is Young's module, α is the linear expansion coefficient during the heating, and μ is Poisson's coefficient. The temperature functions obtained from the solution of Boley and Weiner (1960) will have the form:

$$T_{\varphi\varphi}(x) = \frac{2}{r^3}\int_0^r T(y)y^2dy + \frac{1}{x^3}\int_0^x T(y)y^2dy - T(x), \qquad (6)$$

$$T_{rr}(x) = \frac{2}{r^3}\int_0^r T(y)y^2dy - \frac{2}{x^3}\int_0^x T(y)y^2dy, \qquad (7)$$

where *x* is a coordinate along the body's radius, and *T(y)* is the radial temperature profile obtained from the (HDE) solution. A more detailed description of the calculation method is described in the work by Shestakova and Tambovtseva (1997).

The radial and tangential stresses σ_{rr} and $\sigma_{\phi\phi}$, occurring during the heating or cooling of bodies are determined by temperature functions T_{rr} и $T_{\phi\phi}$ and parameters characterizing the elasticity of bodies. If σ_{rr} or $\sigma_{\phi\phi}$, are negative, the material is compressed; when they are positive, the material experiences breaking stresses (Campbell, 1956). The same rule applies to temperature functions: compression stresses, which are characteristic of the surface layers of a body approaching the Sun $T_{\varphi\varphi}(x)$, , have a temperature dimension with a negative sign. Breaking stresses $T_{rr}(x)$ are positive in such case.

In our calculations, we use the value $\sigma_+ = (2-4)MPa$ for the tensile strength of crystalline (hexagonal) ice, based on data from Haynes (1978), where strength values from 0.7 to 3.1 MPa were obtained within the temperature range from 0 to -50C. According to measurements, the tensile strength varies very slightly, and we can consider those values as acceptable for assessing comets' internal destruction. For the value of ice strength under compression stresses, we take the range of values $\sigma_- = (5-30)MPa$ obtained from measurements (Haynes, 1978).

The values of the elastic parameters according to Kűhrt (1984) are the following: $E = 9\times10^3$ *MPa*, $\mu = 0.33$ and $\alpha = 3.8\times10^{-5}\ grad^{-1}$ and the lower value of the crystal ice strength limit is $\sigma_+ = 2\ MPa$. From Equation (5), we obtain the critical values of the temperature functions T_{rr} и $T_{\varphi\varphi}$. Tensile strength for breaking stresses: $T_+ = (4–8)$ K and for compression stresses $T_- = (10–60)$K. It should be noted that the strength of materials increases with decreasing temperature, especially for compression stresses (Haynes, 1978). The starting distance for calculating the motion of a body in a parabolic orbit is assumed to be R_0 = 86.3 AU, which corresponds to the surface temperature T_0 = 30K in the blackbody approximation. Calculations of temperature **and stress profiles along the radii of bodies were carried out for a number of intermediate positions of bodies in orbit corresponding to blackbody temperatures from 40K to 200K.**

Results

After calculating the temperature profiles inside cometary bodies of different sizes from r = 10 m to r = 10 km from the solution of Equation (1), we obtained the behavior of the rate of internal heating of these bodies during their approach to the Sun in a parabolic orbit. Figure 1 shows the temperature dependence near the center of the bodies at the profile point x/r = 0.1 at a distance of about 1.94 AU, corresponding to a surface temperature of T = 200 K. The calculation data is given for crystalline and amorphous ice. Figure 1 shows that large bodies made of crystalline ice maintain a starting temperature of approximately 30K at their centers if their radii exceed 1 km, and those made of amorphous material at r > 0.1 km. On the other hand, smaller bodies with a radius between 1 and 10 meters, rotating in orbit, are strongly heated toward the center to temperatures close to their surface temperatures.

Figure 2 shows the compression stresses that arise on the surface of crystalline ice bodies. For ease of understanding, we have changed the sign of negative compression stress to positive in Figure 2. The straight lines represent a range of compression stresses, T_- = (10 – 60)K, which are limits of strength according to Haynes (1978). When these stresses are reached, the destruction of the surface layer and the formation of craters, as well as flash phenomena, are possible. Stress limits are reached for larger bodies with $T_{ff}(r) = T_s – T_0$, where T_s is the surface temperature, and T_0 (equal to 30° in our case) is the initial temperature of the entire body. The limiting stress is reached on the surfaces of bodies with a radius of 5 and 10 kilometers. Their curves merge in Figure 2.

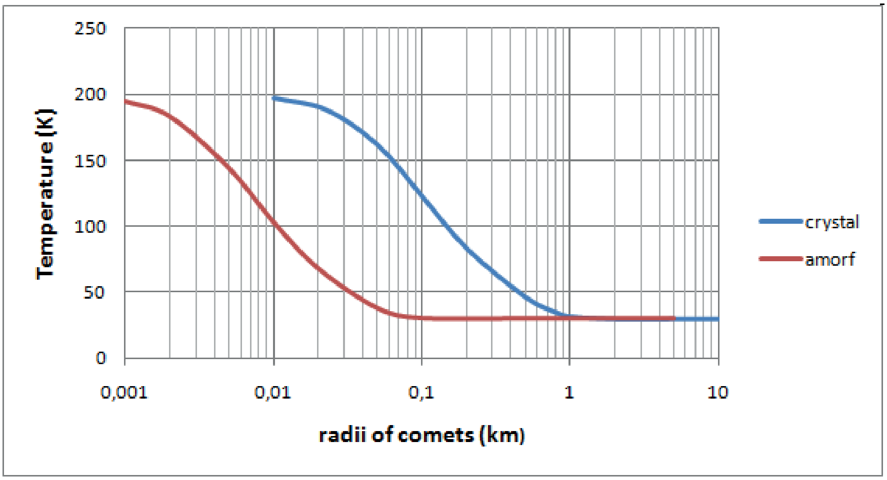

Figure 1. Temperature near the center of cometary bodies (x/r = 0.1) at a distance of 1.94 AU, where the blackbody surface temperature is T = 200K. The calculation results are given for crystalline and amorphous ice.

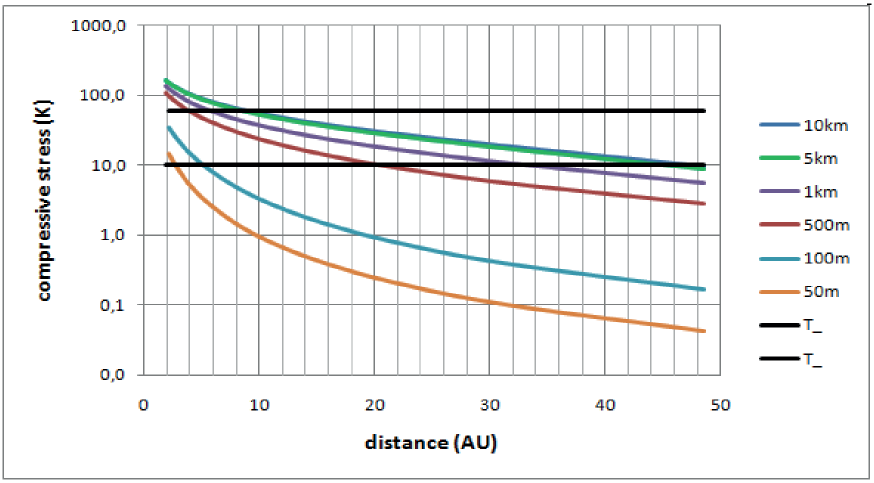

Figure 2. Compression stresses ($-T_{ff}$) on the surface of cometary bodies made of crystalline ice, depending on the distance, arising during the approach to the Sun in parabolic orbits.

Figures 3 and 4 show the increase in tensile stress inside comet bodies as they approach the Sun. These figures clearly demonstrate differences in the increasing behavior of tensile stress depending on the distance.

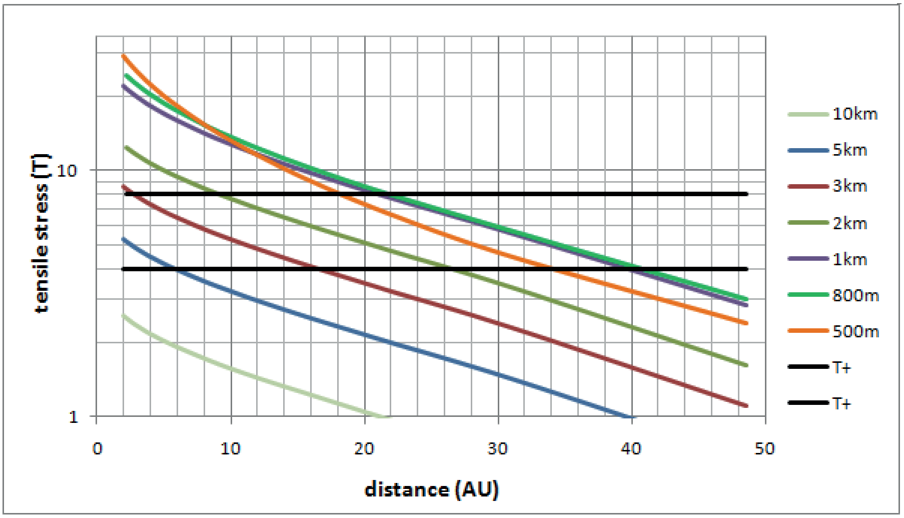

Figure 3. Radial (breaking) stresses near the center of large cometary bodies with radii from 500 m to 10 km, depending on the distance.

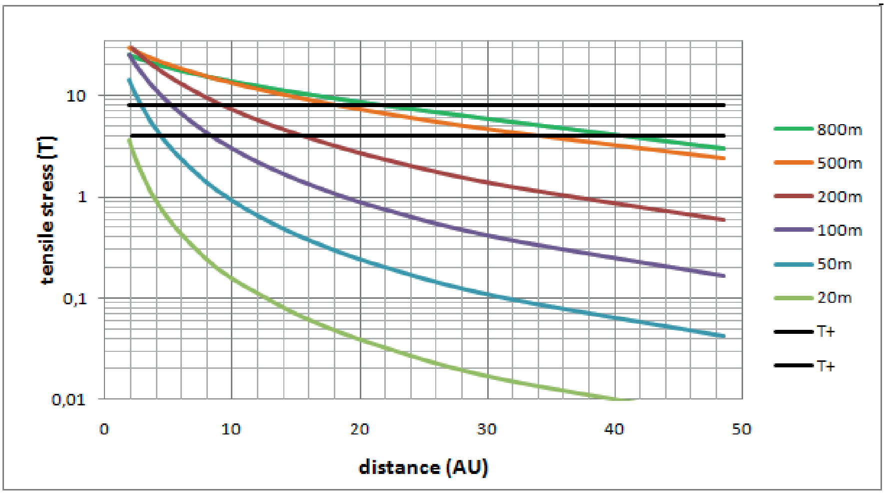

Figure 4. Radial (breaking) stresses near the center of small cometary bodies with radii from 20m to 800m, depending on the distance.

In Figure 3, the largest body with a radius of 10 km shows a slight increase in stresses. These stresses do not reach the lower tensile strength even at a closest distance of about 2 AU. A body with a radius of 5 km has the probability of collapsing from the inside at a distance of (5 – 6)AU, since the breaking internal stress exceeds the lower tensile limit $T_+ = 4K$, which corresponds to $\sigma_+ = 2$ MPa.

Bodies with radii smaller than 3 km will be subject to complete destruction. At maximum distances from the Sun, internal cracks in bodies with radii less than 800 m – 1 km will occur.

Figure 4 shows the internal stresses depending on the distance for bodies with a 20m to 800m radius. In contrast to Figure 3, the maximum stresses correspond to the largest bodies with radii of 500m and 800m. As the size decreases, the stresses decrease and become inessential for a body with a radius of 20 m.

By comparing the results presented in Figures 3 and 4, we have obtained estimates of the possible distances where crystalline bodies of different sizes can experience internal cracks. Figure 5 shows these results for two values of the tensile strength.

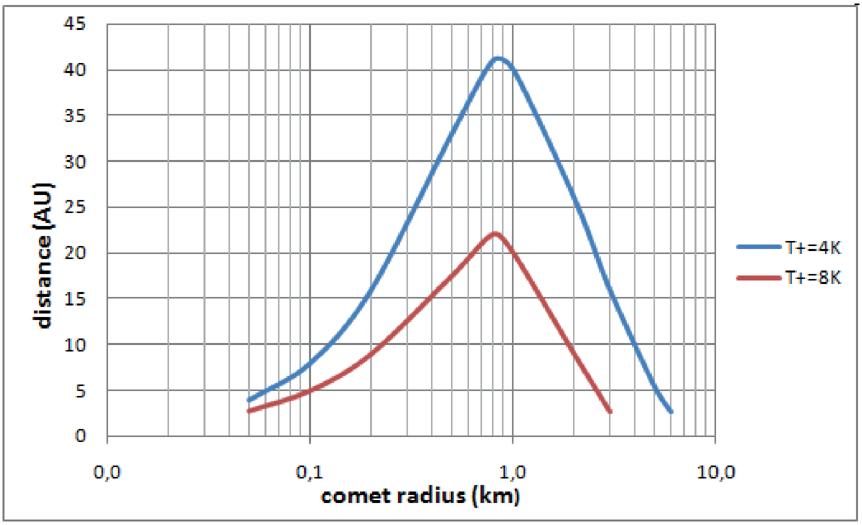

Figure 5. Distances where the internal stresses of crystalline cometary bodies reach two estimated values of tensile strength $T_+ = 4K$ and $T_+ = 8K$.

Bodies in the interval between the curves shown in Figure 5 are at risk of possible destruction due to internal stresses. Cometary bodies of low strength fall into the zone of possible destruction up to distances of about 40 AU, that is, up to the orbit of Neptune. Even denser cometary bodies can collapse near and inside the orbit of Uranus. Inside the orbit of Jupiter, the range of sizes of bodies capable of destruction is maximum. These are bodies with radii from 30m to 6 km.

Figure 6 shows the results of calculations of internal stresses for bodies of crystalline and amorphous ice at a distance of 1.94 AU, corresponding to the blackbody temperature T_{bb} =200K. It can be seen that maximum stresses can be achieved inside bodies of sub-kilometer dimensions, especially bodies with radii (200 – 300) m. Strong stresses occur in bodies with radii less than 100 m for bodies made of amorphous ice, and the maximum stresses correspond to bodies with radii (10 – 30) m. Such bodies are practically inaccessible to observations due to their small size.

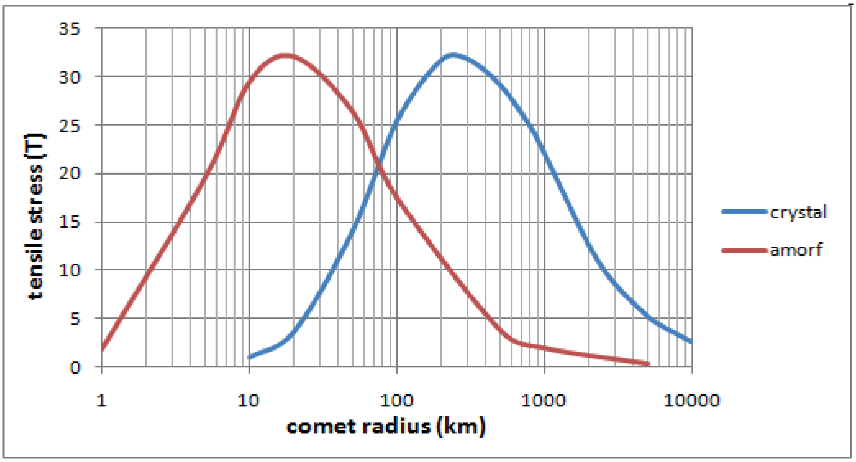

Figure 6. Radial (breaking) stresses near the center of cometary bodies at a distance of 1.94 AU, corresponding to the black body temperature T_{bb} =200K, depending on the radii of the bodies.

Discussion

It is generally believed that comet ice in the Oort cloud is amorphous and contains impurities of volatile gases that can evaporate at low temperatures. In their research (Schmitt et al., 1989) for the ice (H_2O) with impurities ($CO:H_2O$, $CO_2:H_2O$, $CH_4:H_2O$, $CO:CO_2:H_2O$ and $NH_3:H_2O$) has been researched in the temperature range from 10K to 180K. The sequence of evaporation under vacuum conditions is obtained: 25K for CO, 32K for CH_4, 70K for CO_2. At 120K, all molecules leave the ice, and the gas-H_2O ratio becomes less than 0.01 % for CO and CH_4 and less than 0.001 % for CO_2. This evaporation is the trigger for ice crystallization. Finally, pure crystallized H_2O remains. Crystallization from the surface to the interior can be accelerated because this process is exothermic.

Kuiper belt objects are so cold that the estimated time of ice crystallization under these conditions exceeds the lifetime of the Solar System. Despite this, the exploration of satellite spectra in recent years has shown the presence of spectral features from crystalline ice for planetary satellites and Kuiper Belt objects (KBOs). In the research of Prialnik and Jevitt (2022), a deep crystallization simulation was made for the orbital parameters of different comets. The crystallization front inside the satellites of planetary objects in the Kuiper belt has been explored. It has been reported that objects of crystalline ice are present in the IR range at a wavelength of 1.65 microns in many objects. These objects indicate the presence of crystalline ice at temperatures ranging from 48 to 82 K, which is in the area of Uranus and even Neptune.

In the process of approaching the Sun, due to surface heating, an amorphous phase transition to crystalline ice occurs. Specifically, the work by Schmitt B. et al. (1989) states that at T = 125 K, crystallization occurs in 8 days or less than 5 minutes at 150 K. If the object rotates slowly or its axis of rotation is oriented towards the Sun, then the heating at the circumsolar point will be stronger, and the temperature there may exceed the black-body temperature by as much as $\sqrt{2}$ times, greatly increasing the likelihood of ice crystallizing at greater distances from the Sun. In such cases, crystallization could be successful not only near Jupiter, where the blackbody radiation temperature is T_{bb}≈125K, but also at a distance of approximately 10 AU, or in the orbit of Saturn and its moons.

In the process of approaching the Sun, noticeable cometary activity should start to appear after the compressive stresses exceed the material's strength limits. According to our analysis, the surfaces that initiate the formation of comae and flare phenomena first reach critical levels in the largest objects whose radii exceed 5 kilometers. The most distant comets from the Sun should exhibit the most significant cemetery activity. Really, observations of cometary activity at great heliocentric distances have been made in large comets, such as comet C/2014 UN271 Bernstein-Bardinelli (29 AU), comet Hale-Bopp (26 AU), comet C/2010 U3 Boattini (25.8 AU), and comet C/2017 K2 Pan-STARRS (24 AU). These comets were active at heliocentric distances greater than 20 AU (Bernardinelli et al., 2021). Such remote activity can be explained by the release of evaporating gases. Although this does not argue the effect of compression stresses, these processes can be connected. If the ice surface is amorphous at these distances, the compression stress barrier is virtually non-existent, and the evaporation of gases occurs without obstacles in line with the sublimation temperature. As we approach the sun, a phase change gradually occurs, forming a strong crystalline shell. It should be noted that the strength of this crystalline shell that forms on the comet's surface decreases with increasing temperature as it approaches perihelion. In this instance, outbursts of the cryo-volcanic type are possible. These can recur as they approach the sun, like comet 12P/Pons-Brooks, whose perihelion will occur on April 21st, 2024. The first detection of comet 12P/Pons-Brooks was announced by Green Daniel on the Central Bureau for Astronomical Telegrams on July 21st, 2023. The newly growing crystalline crust becomes less resistant after each burst and cannot withstand the increasing internal pressure. We can make an approximate calculation of the strength of the crust during the first outbreak. According to Green Daniel, the first eruption happened at a distance of 3.9 AU, where the black-body temperature is approximately 140 K. If the initial temperature of the comet body is approximately the black-body temperature at the aphelion distance of 33 AU, which is 50 K, then the surface temperature will be approximately 90 K. This means that the material's strength is approximately σ_= 45 MPa. Since estimates of the comet's diameter range from 17 km to 30 km in magnitude, complete disintegration of the body due to burst stresses is not expected.

The most severe destruction of cometary bodies occurs when the internal breaking stresses reach the tensile strength limit and cause the bodies to break into several large fragments. Figures 3 and 4 show how the radial (breaking) stresses inside cometary bodies grow as they approach the Sun, with smaller bodies experiencing a sharp increase in stresses at closer distances. At the same time, the difference in stresses between the far and close distances is much greater for small bodies than for larger ones (Figures 3 and 4). A striking example of how our calculations match observations of real comets is demonstrated by long-periodic comet C/2019 Y4 (ATLAS), which was studied by Hui and Ye in 2020 using Sloan Digital Sky Survey observations between mid-January and early April 2020. Since mid-March 2020, decay has been observed at a distance of around 2 AU, and it was found that the C/2019 core had a radius of over 60 meters before it decayed. During this period, the comet became brighter at the beginning of observation and stopped increasing in brightness about 70 days prior to perihelion in late March 2020. This comet rapidly disintegrated into multiple pieces, suggesting an internal fracture. The results of calculations on breaking stresses based on the distance depicted in Figure 4 demonstrate a close match between the behavior of comet Atlas and a cometary object with a radius of 50 meters. The critical stress level of 8 MPa, corresponding to the tensile strength of crystalline ice, is reached for such an object at a distance of 3 AU. At a range of 2 AU, where the fracture of the comet was observed, the body's surface temperature was approximately 200K. Figure 6 demonstrates that the estimated dimension of the comet closely matches the point of interception of curves in this graph. Thus, no matter if the comet kept its amorphous form or changed structure while moving from the outer parts of the Solar system, it would still break apart because of thermal stresses.

Another long-period comet of a similar size, which disintegrated in May 2019 at a distance of 1.9 AU from the Sun, is comet C/2018 J2 (Palomar), reported by Jewitt and Luu (2019). The authors argue that the comet's disintegration cannot be caused by tidal forces or collisions. Therefore, the disintegration C/2009 J2 is preliminary interpreted in this study as a violation of the core's rotation with a radius of $r \leq 0.1$ km due to the release of gas moments. Actually, the authors provided a possible explanation, which is not obvious. Because the comet disintegrated into many pieces and showed surface activity. Applying the theory of internal discontinuous thermal stresses to this case seems like a more logical explanation for the decay, like in the case of the C/1950 Y4 (ATLAS) comet.

A striking example of the complete disintegration of a long-period comet is comet C/2021 A1 (Leonard) as well. According to Jewitt et al. (2023), a comet with a radius of 0.6 ± 0.2 km did not preserve a single fragment of its nucleus larger than 0.06 km, which corresponds to the complete destruction of the nucleus in mid-December 2021, at a distance of approximately 0.8 AU. The authors argue that models of tidal disruption, collision, sublimation explosions, and pressure explosions provide improbable explanations for disintegration. They acknowledge that the rotational instability caused by released gases has a very short period (approximately 0.1 years) that does not allow for the rapid spin of the comet's nucleus, given its orbit and size. The most probable mechanism for destruction, according to the authors' opinion, is the initial rotational decay accelerated by the impact and intense sublimation of deeply buried volatiles.

Such an assumption is a big stretch, as other possible options have not been considered. One possible explanation for the observed phenomenon may be thermal rupture due to the crystallization of the majority of the volume of the comet. A phase transition from amorphous to crystalline ice could occur on the surface and within the comet, especially if the initial crystalline structure of the object is excluded.

Since comet C/2021 A1 (Leonard) is larger than comets C/2019 Y4 (ATLAS) and C/2019 J2, core cracking could occur at a greater distance from the Sun, and debris dispersion may be initiated by gas flows as it approaches the Sun.

Another interesting case of comet decay is associated with the famous comet 73P/Schwassmann-Wachmann 3, from the Jupiter family. Its initial radius is estimated to be 0.4 km, according to the work of Graykowski and Jewitt (2019). That comet exhibited a beautiful four-stage decay on September 12, 1995, close to the perihelion point at 0.94 AU. It passed through this point on September 22. Graykowski and Jewitt (2019) doubted the previously suggested fragmentation mechanism due to rotational instability. Their argument was that the most likely rotation period of 10.38 ± 0.04 hours (20.76 ± 0.8 hours at double maximum) is much greater than the critical rotation period at any reasonable density or shape of the nucleus, even without considering tensile strength.

It is unknown when the comet was captured by Jupiter, but it is obvious that during its long stay in the Solar System, amorphous ice underwent a phase transition. After this, a comet of this size would start to warm up from the inside, increasing internal stresses and leading to fragmentation into large pieces. This can be expected as a final stage for any comet captured by Jupiter from the Oort cloud. The core would first break up into large fragments and then smaller ones, turning into a meteor shower.

Conclusion

The main conclusions of the research are the following:

1. The proposed mechanism for the thermal destruction of cometary nuclei could be considered a real mechanism for their destruction. Surface compression stresses contribute to the formation of a coma and could trigger flash events at the time of destruction. Internal bursting stresses lead to hierarchical disintegration of the nucleus into several large fragments, which then continue to break down to the stage of a meteor shower.

2. Maximum breaking stresses exceeding the strength limits of crystalline ice lead to the appearance of cracks inside cometary bodies. This process can begin at heliocentric distances (20 – 40 AU) inside nuclei with radii (0.8 – 1.0 km) (see Figure 6). Bodies of both large and smaller sizes will begin to collapse closer to the Sun.

3. Breaking stresses do not have time to develop inside large crystal nuclei with radii of more than 6 km when moving in a parabolic orbit to overcome the

material's ultimate strength. Such bodies are most likely to maintain their integrity during the passage of perihelion at distances of the order of 1 – 2 AU.

It can be concluded that the mechanism of thermal destruction of cometary nuclei should be taken into account when considering new comet passages into the inner Solar System. The available statistics on the destruction of comets at arbitrary points along their orbits, with the phrase "for unknown reasons", may also undergo some changes and clarifications in relation to the proposed mechanism.

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РАКИШЕВ БАЯН РАКИШЕВИЧ
(к 90-летию со дня рождения)

Выдающийся ученый-горняк, действительный член Национальной академии наук Республики Казахстан, заслуженный деятель РК, доктор технических наук, профессор, почетный ректор Казахского национального исследовательского технического университета им. К. И. Сатпаева Баян Ракишевич Ракишев родился 15 марта 1934 года.

После окончания с отличием Казахского горно-металлургического института с 1957 по 1965 годы он работал на Коунрадском руднике Балхашского горно-металлургического комбината в должностях начальника смены, начальника цеха и карьера. В 1964 году без отрыва от производства успешно защитил кандидатскую диссертацию.

Дальнейшая его трудовая деятельность связана с родным вузом. С 1966 по 1987 годы доцент, профессор, заведующий кафедрой теоретической механики, в период с 1988 по 2016 год заведующий кафедрой открытых горных работ, с 1980 по 1993 год научный руководитель проблемной лаборатории новых физических методов разрушения горных пород и отраслевой лаборатории технологии буровзрывных работ КазПТИ им. В.И. Ленина. С 2016 года по настоящее время он профессор кафедры «Горное дело», почетный ректор Казахского национального исследовательского технического университета им. К.И. Сатпаева.

Под руководством Б. Ракишева факультет Автоматики и вычислительной техники занимал передовые позиции в научно-исследовательской, учебно-производственной и общественной деятельности. Факультетский ансамбль «Досмукасан» сформировался, состоялся как творческий самодеятельный коллектив и стал популярным в странах СНГ. О творческой деятельности

«Досмукасан» и роли декана Баяна Ракишева в его становлении рассказывается в кинофильме «Досмукасан», выпущенном Казахфильмом в 2020 году.

В должности ректора он всю свою силу и энергию отдавал расширению связей науки с производством, практической подготовке будущих специалистов. Тогда в КазПТИ впервые в Казахстане были организованы специализированные студенческие отряды для прохождения производственных практик, открылось несколько филиалов кафедр на базе предприятий и НИИ. Активно внедрялись договоры о научно-техническом содружестве и подготовке специалистов по прямым связям с предприятиями. Контингент иностранных студентов из 37 стран в то время составлял внушительную цифру – более 300 человек. Существенно улучшилось состояние материально-технической базы института. КазПТИ им. В.И. Ленина был одним из ведущих высших учебных заведений СССР.

Баян Ракишевич создал стройную теорию разрушения реального массива горных пород действием взрыва ВВ. Разработал аналитические методы определения расположения зарядов ВВ в массиве, гранулометрического состава взорванной горной массы, затрат энергии ВВ на дробление, перемещение и графо-аналитические методы определения размещения разнородных пород в развале, параметров технологий буровзрывных и экскаваторных работ, обеспечивающих наименьшие количественные и качественные потери.

Баяном Ракишевым сформулированы стратегические задачи рационального освоения недр и комплексного использования полезных ископаемых, обоснованы системы их обеспечения, разработаны горно-геологические, геометрические модели сложноструктурных блоков месторождений, математические модели минерального сырья на различных этапах его переработки, позволяющие управлять уровнем извлечения как основных, так и сопутствующих полезных компонентов в концентрат, в металл, что чрезвычайно важно в условиях систематического снижения содержания профильных металлов в руде и увеличения спроса на редкие металлы в связи с развитием высоких технологий.

Разработанные математические модели стабилизации качества многокомпонентной руды для оперативного управления внутрикарьерным усреднением и состоянием минерального сырья на каждом из этапов его переработки способствуют совершенствованию экономически эффективных технологий добычи и переработки полезных ископаемых.

Научными работами, выполненными на высоком теоретическим уровне и оригинальными практическими разработками, получившими признание горной общественности, академик Б.Р. Ракишев внес большой вклад в горную науку и промышленность, создал научную школу в области эффективного разрушения массивов пород и разработки полезных ископаемых в режиме их рационального использования недр, подготовил 9 докторов, 30 кандидатов технических наук, 9 докторов PhD, сотни магистров и инженеров.

Академик НАН РК Б.Р. Ракишев является автором около 800 научных и учебно-методических работ, в том числе 15 монографий, 6 аналитических обзоров, 14 учебников и учебных пособий, 50 авторских свидетельств и патентов на изобретения, более 100 статей в изданиях в базе данных Scopus и Web of Science.

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Поздравляя Баяна Ракишевича с юбилеем, желаем ему здоровья, благополучия и дальнейших творческих успехов.

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