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DESTRUCTION OF SMALL BODIES COMPOSED OF SILICATES BY THERMAL STRESSES. THERMAL EMISSION OF DISRUPTION PRODUCTS

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Abstract. This study investigates the influence of thermal stresses on the destruction of small rocky bodies — meteoroids and asteroids—during their approach to the Sun. Based on an analytical solution of the heat diffusion equation, temperature profiles and thermally induced mechanical stresses are computed for various silicate materials, including basalt, carbonaceous and ordinary chondrites, as well as terrestrial rocks and minerals. It is shown that the degree of heating and the character of thermal stresses depend on the size of the body: meteoroids smaller than 10 cm are heated uniformly, while bodies larger than 10 m experience heating confined to near-surface layers. Calculations are performed for bodies moving from 86 AU (outer Solar System) to 0.03 AU (7 solar radii). Critical disruption distances are determined as follows: basaltic bodies between 0.03 and 2.5 AU (Sun to Main Asteroid Belt), carbonaceous chondrites up to 2 AU (within Mars's orbit), ordinary chondrites up to 1 AU (within Earth's orbit), while rocks and minerals remain stable up to ~1000 K (about 0.17–0.2 AU, between the Sun and Mercury). Small bodies (up to 10 m) may undergo thermal fragmentation between Mars and Mercury, forming dust envelopes. Larger bodies can also become thermally destabilized: carbonaceous chondrites (~40 m) and basalts (~80 m) near Earth's orbit, ordinary chondrites (10–50 m) between Venus and Earth. Very large bodies (over 100 m) disintegrate closer to the Sun, producing dust clouds observable in optical and infrared wavelengths. The primary sources of these bodies are the Main Asteroid Belt and the Kuiper Belt. This work emphasizes the significance of thermal processes in the evolution and observational features of small Solar System bodies.

Keywords: small bodies, asteroids, meteoroids, silicates, thermal stresses, thermal emission

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СИЛИКАТТЫ ҚҰРАМДЫ ШАҒЫН ДЕНЕЛЕРДІҢ ТЕРМИЯЛЫҚ КЕРНЕУЛЕРДЕН БҰЗЫЛУЫ. БӨЛШЕКТЕНУ НӘТИЖЕСІНДЕ ПАЙДА БОЛАТЫН ӨНІМДЕРДІҢ ЖЫЛУЛЫҚ ЭМИССИЯСЫ

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Аннотация. Бұл жұмыста Күнге жақындаған кезде шағын тасты денелердің- метеороидтар мен астероидтардың – термиялық кернеулердің әсерінен бұзылу үдерісі зерттеледі. Жылу диффузиясы теңдеуінің аналитикалық шешімі негізінде түрлі силикатты материалдарда – базальтта, көміртекті және кәдімгі хондриттерде, сондай-ақ тау жыныстары мен минералдарда-температуралық градиенттерден туындайтын температуралық профильдер мен механикалық кернеулер есептелді. Жылыну дәрежесі мен термиялық кернеулердің сипаты дене өлшеміне байланысты екені анықталды: диаметрі 10 см-ден кіші метеороидтар біркелкі жылынады, ал 10 м-ден үлкен денелерде жылу тек беткі қабаттармен шектеледі. Есептеулер Күн жүйесінің сыртқы аймағынан (86 а.б.) Күнге өте жақын арақашықтыққа дейін (0.03 а.б., ($\approx 7R_{\odot}$)) қозғалып келе жатқан денелер үшін жүргізілді. Бұзылу басталатын критикалық қашықтықтар анықталды: базальтты денелер - 0.03–2.5 а.б. аралығында (Күн мен Негізгі астероидтар белдеуі арасында), көміртекті хондриттер - 2 а.б.-ге дейін (Марс орбитасына дейін), кәдімгі хондриттер - 1 а.б.-ге дейін (Жер орбитасына дейін), ал тау жыныстары мен минералдар ~1000 K температураға дейін (шамамен 0.17-0.2 а.б., Күн мен Меркурий арасындағы аймақ) тұрақты болып қалады. Шағын денелер (диаметрі 10 м-ге дейін) Марс пен Меркурий орбиталары арасында бұзылып, шаң қабаттарын түзуі мүмкін. Үлкенірек денелер де термиялық тұрақсыздануға ұшырайды: көміртекті хондриттер (~40 м) мен базальттар (~80 м) Жер орбитасы маңында, кәдімгі хондриттер (10–50 м)-Шолпан мен Жер орбиталары арасында бұзылады. Ал аса ірі денелер (100 м-ден үлкен) Күнге жақын маңда бұзылып, оптикалық және инфрақызыл диапазонда бақыланатын шаңтүзгіш бұлттар түзеді. Бұл денелердің негізгі көздері. Негізгі астероидтар белдеуі мен Койпер белдеуі. Бұл жұмыс Күн жүйесінің шағын денелерінің эволюциясы мен бақылануында термиялық үдерістердің маңыздылығын көрсетеді.

Түйін сөздер: кіші денелер, астероидтер, метеороидтер, силикаттар, жылулық кернеулер,жылу эмиссиясы

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РАЗРУШЕНИЕ МАЛЫХ СИЛИКАТНЫХ ТЕЛ ТЕПЛОВЫМИ НАПРЯЖЕНИЯМИ. ТЕПЛОВАЯ ЭМИССИЯ ПРОДУКТОВ РАЗРУШЕНИЯ

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Аннотация. В работе исследуется влияние тепловых напряжений на разрушение малых каменных тел – метеороидов и астероидов — при их сближении с Солнцем. На основе аналитического решения уравнения тепловой диффузии рассчитаны температурные профили и механические напряжения, возникающие из-за температурных градиентов в различных силикатных материалах: базальте, углеродистых и обычных хондритах, а также горных породах и минералах. Установлено, что степень нагрева и характер термических напряжений зависят от размера тел: метеороиды менее 10 см прогреваются равномерно, а у тел более 10 м нагрев ограничен приповерхностными слоями. Расчёты выполнены для тел, движущихся от расстояния 86 а.е. (внешняя Солнечная система) до 0.03 а.е. (7 радиусов Солнца). Определены критические расстояния разрушения: базальтовые тела – от 0.03 до 2.5 а.е. (Солнце – Главный пояс астероидов), углеродистые хондриты — до 2 а.е. (до орбиты Марса), обычные хондриты — до 1 а.е. (до орбиты Земли), горные породы и минералы устойчивы до температур порядка 1000 K (≈ 0.17–0.2 а.е., между Солнцем и Меркурием). Малые тела (до 10 м) могут разрушаться в зоне между орбитами Марса и Меркурия, образуя пылевые оболочки. Более крупные тела также термически дестабилизируются: углеродистые хондриты (~40 м) и базальты (~80 м) — вблизи орбиты Земли, обычные хондриты (10–50 м) — между орбитами Венеры и Земли. Крупные тела (более 100 м) разрушаются ближе к Солнцу, создавая пылевые облака, которые можно наблюдать в оптическом и инфракрасном диапазонах. Основными источниками тел являются Главный пояс астероидов и пояс Койпера. Работа

подчёркивает значимость термических процессов в эволюции и наблюдаемости малых тел Солнечной системы.

Ключевые слова: малые тела, астероиды, метеороиды, силикаты, тепловые напряжения, тепловая эмиссия

Introduction. To date, the origin regions of most meteorites and kilometer-sized near-Earth objects (NEOs), including some minor classes, have been identified (Brož et al., 2024). The authors of that study examined 38 distinct asteroid families—both young and old—and determined their contributions to the populations of near-Earth objects ranging from meters to kilometers in size using collisional and orbital models. Brož et al. (2024) identified three young asteroid families (Karin, Koronis, Massalia) that serve as the primary sources of ordinary chondrite falls. The origins of various meteorite and NEO classes were established, with a particular focus on different subtypes of carbonaceous chondrites. Some well-known annual meteor showers originate from the fragmentation of comets or active asteroids, such as 3200 Phaethon, which is the parent body of the Geminid meteor shower (Jewitt & Li, 2010). Spectral analysis of Phaethon in the mid-infrared range, conducted using the *Spitzer* Space Telescope, indicated a compositional link to rare carbonaceous chondrites containing olivine, magnesium-rich carbonates, and iron sulfides (MacLennan & Granvik, 2023). These minerals decompose at temperatures around 1000 K, which 3200 Phaethon reaches at perihelion. Regardless of whether small rocky bodies are fragments of comets or asteroids, approaching the Sun at small heliocentric distances leads to the buildup of thermal stresses that may exceed the material's strength. This can result in the formation of fractures or complete fragmentation of the body.

The role of thermal stresses in the physics of small Solar System bodies has been explored by many researchers (Kuehrt, 1984; Tauber & Kuehrt, 1987; Shestakova & Tambovtseva, 1997; Tambovtseva & Shestakova, 1999). According to their estimates, thermal stresses arising during the approach of comets to the Sun can exceed solar tidal stresses by several orders of magnitude. These stresses may surpass material strength thresholds, producing fractures on and beneath the surface of cometary nuclei, which in turn can enhance cometary activity or even lead to complete nucleus disruption. Grinin et al. (1996) also noted that even non-icy planetesimals can be destroyed by thermal stresses near young stars of the UX Orionis type. According to the scenario proposed by Shestakova & Tambovtseva (1997), meteoroids approaching the Sun along highly eccentric orbits gradually heat up internally. The growing temperature gradient between the cold core and the hot surface leads to thermal stresses that can fragment bodies ranging from 10 cm to 10 m in size. In their model, the internal temperature gradient and associated stresses in larger bodies are insufficient to cause full internal disintegration. In such cases, the maximum stresses appear in the surface compression zone, causing material fragmentation at the surface.

In reality, the destruction of small bodies is complicated by additional processes. Surface melting at high temperatures may limit the growth of the temperature gradient between the core and the surface. Sublimation can cool the surface. Another important effect is the formation of a low-conductivity surface layer—similar to a mixture of pebbles and dust—that thermally insulates the interior from large temperature fluctuations and thermal stress accumulation. Large bodies may develop such a protective layer on their surface. Small bodies, however, tend to heat uniformly and become nearly isothermal, effectively suppressing thermal stresses. The problem of calculating thermal stresses was significantly advanced in the work of Čapek and Vokrouhlický (2010), which removed many of the simplifying assumptions of earlier studies. Their model accounted for changes in insolation due to rotation of the body, yielding a more complex but informative picture of the internal thermal field. This approach allows one to determine whether thermal fragmentation conditions arise in the center or subsurface layers. Their model also incorporates the full set of non-radial components of the stress tensor into the temperature field. In the present study, we adopt a simplified analytical method following the approach of Shestakova & Tambovtseva (1997), sacrificing quantitative precision in favor of a qualitative understanding of the fragmentation processes acting on meteoroids. We consider meteoroid materials composed of various silicates: minerals, rocks, basalt, and both ordinary and carbonaceous chondrites. These bodies approach the Sun along near-parabolic orbits. Our objective is to identify the heliocentric distance range where thermal stresses cause material fracturing. Within this region, the total surface area of fragmented material may significantly increase, forming dust clouds and enhancing the probability of detection during astronomical observations in both the visible and infrared spectral ranges.

2. Methods

The method based on the analytical solution of the heat diffusion equation (HDE) is described in detail in the works by Shestakova & Tambovtseva (1997) and Shestakova & Serebryanskiy (2023). The heat diffusion equation (HDE) for spherically shaped bodies takes the following form:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\mathrm{a}^2(T)\frac{\partial T}{\partial x}) + \frac{2}{x}\mathrm{a}^2(T)\frac{\partial T}{\partial x}, \qquad (1)$$

where T is the temperature, t is the current time, and x is the spatial coordinate measured from the center of the sphere (x=0) along the radial direction to the surface (x=r). The parameter $a^2 = \frac{k(T)}{c_v(T)}$, known as the thermal diffusivity, is the key quantity in solving this equation. It depends on the ratio of the thermal conductivity $k(T)$, expressed in $erg * s^{-1}cm^{-1}K^{-1}$, to the specific heat per unit volume $c_v(T)$expressed in erg/(cm³·K). As a result, the thermal diffusivity a^2 has units of cm^2s^{-1}. In the general case, both $c_v(T), k(T)$ are temperature-dependent functions. If $c_v(T), k(T)$are assumed constant, then equation (1) becomes linear with respect to T.

The solution of the heat diffusion equation yields the temperature profile inside the body at a given distance from the star. Boley and Weiner (1960), using this temperature profile, derived expressions for radial (T_{rr}) and tangential ($T_{\varphi\varphi}$) thermal stress functions in solid spheres. The quantities $T_{rr}, T_{\varphi\varphi}$ have the dimensions of temperature. In the study by Shestakova & Tambovtseva (1997), these thermal functions were also obtained analytically.

The analysis of thermal stresses becomes significantly simpler if, instead of dealing with the actual stresses, one works with the corresponding thermal functions $T_{rr}, T_{\varphi\varphi}$, which depend solely on the geometry of the body and the internal temperature distribution.

By using these temperature functions as proxies for thermal stresses, one can easily convert them into actual stress values through a simple relationship:

$$\sigma_{\varphi\varphi}(x) = \frac{E\alpha}{1-\mu} T_{\varphi\varphi}(x), \; \sigma_{rr}(x) = \frac{E\alpha}{1-\mu} T_{rr}(x), \tag{2}$$

where the tangential stresses $\sigma_{\varphi\varphi}$ are characterized by the function $T_{\varphi\varphi}$, and the radial stresses σ_{rr} by the function T_{rr}. The following parameters describing the elastic properties of the material are used: E - Young's modulus, α - linear thermal expansion coefficient, and μ — Poisson's ratio.

2.1 Thermal and Elastic Properties of Silicate Material

Silicate materials exhibit a wide range of properties and may include various rocks and minerals. However, despite this diversity, most oxides, minerals, and rocks demonstrate similar behavior in terms of their thermophysical (c_v, k, a^2) and mechanical (E, α, μ) parameters as temperature varies—often showing even quantitative agreement. Here, c_v denotes the specific heat at constant volume, and k is the thermal conductivity. The parameters that define material strength are also critical:

σ_- is the compressive strength, and σ_+ is the tensile strength. In materials with high thermal conductivity, internal heating occurs more rapidly than in those with low conductivity. The resulting temperature gradients between the body's surface and interior layers induce significant thermal stresses. Among the considered silicate materials, pure fused quartz has the lowest linear thermal expansion coefficient α. All other silicates have α values at least an order of magnitude higher. Since meteorites consist of a heterogeneous mixture of minerals, we considered a broad spectrum of silicate materials. According to Campbell (1956), oxides and silicate materials generally have thermal expansion coefficients of $\alpha = (5-10) * 10^{-6}\, K^{-1}$. We adopted an average value of $\alpha = 7 * 10^{-6}\, K^{-1}$.

While we used unified values for the thermal parameters across the three groups-oxides, minerals, and rocks-for the elastic parameters, such unification is possible only within each group individually. Nevertheless, we accounted for their similar behavior with temperature.

The Young's modulus of refractory oxides decreases by approximately a factor of two upon heating to 1500°C, while their compressive and tensile strengths may drop by more than an order of magnitude. For minerals, we used the Young's modulus of fused quartz, which is 72,000 MPa (Campbell, 1956), as a baseline, noting that other minerals have comparable values. According to the same source, refractory oxides may have significantly higher values, while rocks tend to have lower elastic moduli. A similar trend holds for compressive and tensile strength. Refractory oxides have the highest strength limits, while minerals exhibit lower values. For minerals, we adopted $\sigma_+ =$ (80±30) MPa (Campbell, 1956), and for rocks-being mixtures of minerals-this value is even lower. Common rocks such as granite, basalt, andesite, and others include minerals found in meteorite material, such as olivine, pyroxene, plagioclase, magnetite, quartz, and glassy phases (Krinov, 1955). According to Hütte (1964), these rocks exhibit compressive strengths in the range of σ_-= −(100-380) MPa. This range agrees well with data for andesite, whose average compressive strength is σ_- =−(180±60) MPa. For all cited rock types, the uncertainty does not exceed a factor of two, with the exception of particularly strong basalt. In Hütte (1964), the tensile strength is given by a single relation: $\sigma_+ = \frac{\sigma_-}{7\varepsilon}$. We adopted an upper limit of $\sigma_+ =$ 20 MPa, which is approximately one order of magnitude lower than the average compressive strength for andesite.

We chose to adopt upper-bound values for the critical compressive and tensile stresses so as not to overestimate the likelihood of fragmentation caused by thermal stresses. The Young's modulus for rocks was taken as 26,000 MPa, although this value may vary by a factor of two. The Poisson's ratio was set to $\mu =$ 0.15, for both minerals and rocks. Table 1 summarizes the adopted material parameters and the corresponding thermal stress functions for minerals and rocks. Separately, we include data for a specific type of basalt, taken from educational sources and references therein (Kobanova, 1986; Portsevsky & Katkov, 2009). Despite substantial differences in σ, E values between rocks and minerals, the thermal stress functions T_-, T_+, derived from the relation $T = \frac{\sigma(1-\mu)}{E\alpha}$, turned out to be quite similar. Therefore, we adopted common average values of these functions for both rocks and minerals, with deviations not exceeding 30%.

Table 1 - Physico-Mechanical parameters of silicate meteorites

parameters	a^2	α	μ	E	T_-	σ_-	T_+	σ_+
measurement	$cm^2 s^{-1}$	K^{-1}	-	*MPa*	K	Mpa	K	K
minerals	0.00548	$7.5\cdot 10^{-6}$	0.15	72000	-1300	-800	130	80
rocks	0.00548	$7.5\cdot 10^{-6}$	0.15	26000	-800	-180	90	20
basalt	0.0167	$7.5\cdot 10^{-6}$	0.25	$7\cdot 10^4$	-300	-160	7	4.5
carbonaceous chondrites	0,01178	$7.5\cdot 10^{-6}$	0.25	$7\cdot 10^4$	-86	-60	13	9
ordinary chondrites	0,01178	$7.5\cdot 10^{-6}$	0.25	$7\cdot 10^4$	-214	-150	36	25

As shown in Table 1, the selected basalt rock exhibits relatively lower strength. It is also evident that rocks and minerals possess similar physical parameters, and when these are used in the calculation of thermal stresses via the heat diffusion equation, they yield nearly identical stress values. The only differences arise from the distinct values of their strength limits. The aforementioned authors (Campbell, 1956; Hütte, 1964) also note that, upon heating to high temperatures around 900–1000 K, the strength of materials drops sharply-by approximately a factor of 10 to 20.

The study by Slyuta (2017) provides experimental data for stony meteorites, including compressive strength (σ_-), tensile strength (σ_+), as well as other physico-mechanical properties (E, α, μ) and thermophysical parameters such as c_p, a^2. A detailed analysis of the thermal and elastic properties of stony meteorites is presented in Shestakova & Serebryanskiy (2023). Table 1 also includes the adopted material parameters and the corresponding thermal stress functions for two types of chondrites based on the data from Slyuta (2017), and for basalt, based on Kobanova V.N. (1986) and Portsevsky A.K. (2009). In our study, the values for thermal conductivity and specific heat were taken from Opeil et al. (2012), where the thermal conductivity was measured for seventeen stony meteorites over the temperature range from 5 K to 300 K. The selection of this rock type is motivated by the fact that, for example, the Frankfurt meteorite (howardite) is a representative sample of the surface material of asteroid Vesta. The primary parameter used in solving the heat diffusion equation is the thermal diffusivity, defined as a^2.

To model the thermal fragmentation of bodies composed of ordinary and carbonaceous chondrites, we used the value $a^2 = 0.01178\, cm^2 s^{-1}$ for the Frankfurt sample (Opeil et al., 2012), corresponding to an equilibrium temperature of approximately 150 K, which we adopted as the initial temperature of a uniformly heated body at the starting heliocentric distance of 3.46 AU. The same thermal diffusivity value was applied to basalt, since the values of a^2 are of the same order, and differences in the calculated temperature profiles from the center to the surface only appear in the third decimal place. Moreover, their physico-thermal parameters-such as (E, α, μ) are also similar, making their comparison in Figures 1b, 2, and 4 appropriate and convenient.

3. Results and discussion

Temperature and stress profiles were calculated for various materials, with their parameters listed in Table 1. It is assumed that the bodies are spherical in shape and follow parabolic orbits. The initial heliocentric distance was set at 3.45 AU, where the blackbody temperature is close to 150 K. At this starting distance, the bodies are assumed to be isothermal throughout their volume, and no thermal stresses are present. The radii of the bodies range from r=5 cm to r=300 m. The final distance was set at 0.0345 AU, which corresponds to 7.42 solar radii ($7.42R_*$), where the blackbody temperature reaches approximately 1500 K a temperature at which silicate materials undergo intense sublimation.

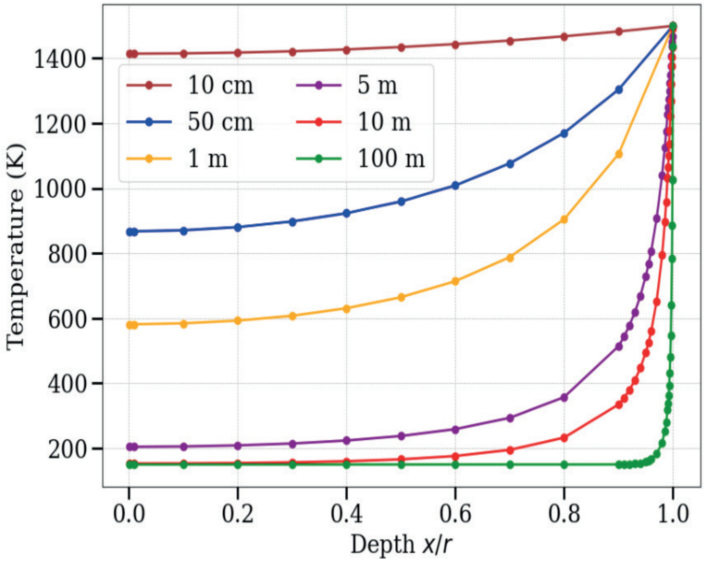

Figure 1a - Temperature profiles from the center (x/r=0) to the surface (x/r=1) inside bodies of different sizes at the final heliocentric distance of 0.0345 AU ($\approx 7.42 R_*$), for rocks and minerals ($a^2 = 0.00548\ cm^2 s^{-1}$).

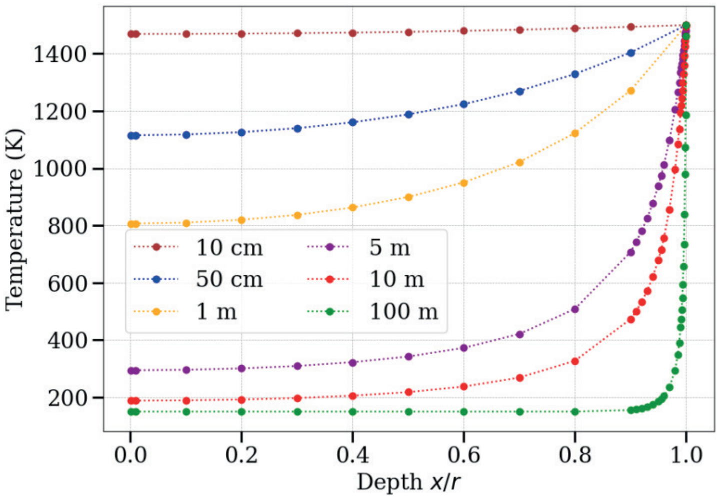

Figure 1b - Temperature profiles from the center (x/r=0) to the surface (x/r=1) inside bodies of different sizes at the final heliocentric distance of 0.0345 AU ($\approx 7.42 R_*$), for basalt and chondrites ($a^2 = 0.0167\ cm^2 s^{-1}$).

As shown in Figure 1, the internal heating of bodies approaching the Sun along a parabolic orbit strongly depends on their size. Large bodies with radii greater than 10 m retain low internal temperatures close to the initial value, with a rapid increase occurring only near the surface. In contrast, small meteoroids with radii less than 10 cm exhibit nearly uniform temperature profiles throughout their volume, close to the surface temperature, as they have sufficient time to become fully heated during their approach.

A comparison between Figures 1a and 1b shows that basaltic and chondritic bodies heat more efficiently than those composed of minerals and rocks.

Figures 2 and 3 present the results of thermal stress calculations inside rocky bodies of different compositions as they approach the Sun along parabolic trajectories. The thermal stresses are evaluated at a distance x=0.1r from the center of the body, where r is the radius.

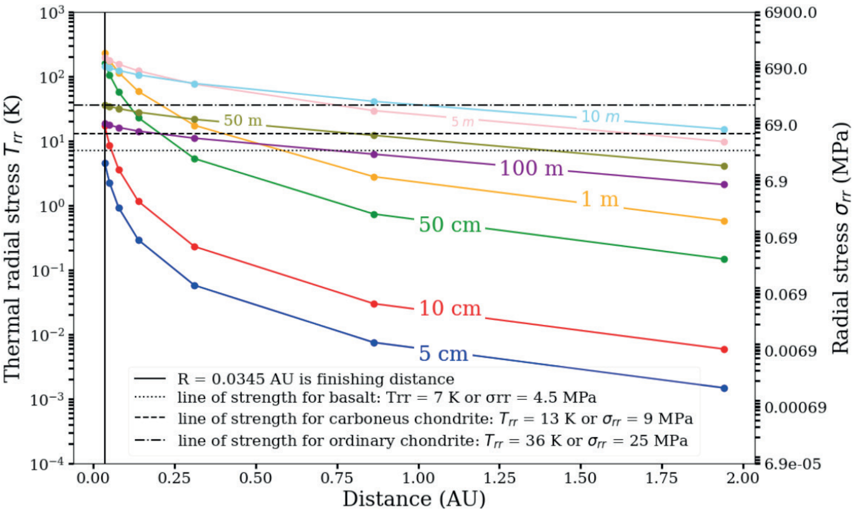

Figure 2 - Dependence of thermal stresses on heliocentric distance for pebbles and rocks of various sizes approaching the Sun along parabolic orbits from an initial distance of 3.45 AU, where their equilibrium temperature is 150 K.

To calculate the radial stresses presented in Figure 2, we used a uniform thermal diffusivity value of $a^2 = 0.0167\ cm^2 s^{-1}$ for all three materials: basalt, carbonaceous chondrites, and ordinary chondrites. The resulting values of the thermal stress function T_{rr} are identical for these materials; however, their strength limits differ. The horizontal lines in the figure indicate the strength thresholds for each of the three materials: basalt has the lowest strength, carbonaceous chondrites represent an intermediate case, and ordinary chondrites have the highest tensile strength.

As shown in Figure 2, basaltic particles with radii starting from approximately 5–7 cm experience stresses near the strength limit at the final heliocentric distance of 0.0345 AU ($\approx 7.42R_*$) and thus are expected to fragment. At the same distance, carbonaceous chondrite stones with minimum radii of 8–9 cm and larger are also subject to destructive stresses. Among the materials shown in Figure 2, ordinary chondrites are the most resistant. Fracturing of these bodies begins at final distance only when their radii exceed ~15 cm. Larger stones easily exceed the tensile strength threshold at heliocentric distances significantly greater than $(\approx 7.42R_*)$.

It should also be noted that even larger bodies, on the scale of decameters (5–

50 m), may begin to crack at distances beyond 1 AU and continue to fragment into smaller pieces as they approach the Sun.

Figure 3 presents results of similar calculations for bodies composed of stronger materials such as typical rocks. These bodies fragment only near the final distance and within a limited size range of approximately 0.5 m to 10 m. The figure also displays two vertical axes: on the left — thermal stresses, and on the right — mechanical stresses for rocky materials. Thermal radial stresses are converted into mechanical stresses $\sigma_{rr} = 0.222 * T_{rr}$ using equation (2) and the values listed in Table 1. The T_{rr} scale is also applicable to minerals, although conversion to mechanical stress values $\sigma_{rr} = 0.615 * T_{rr}$ requires a different relation.

Rocks and minerals exhibit very high strength limits, significantly exceeding those of basalt and chondrites.

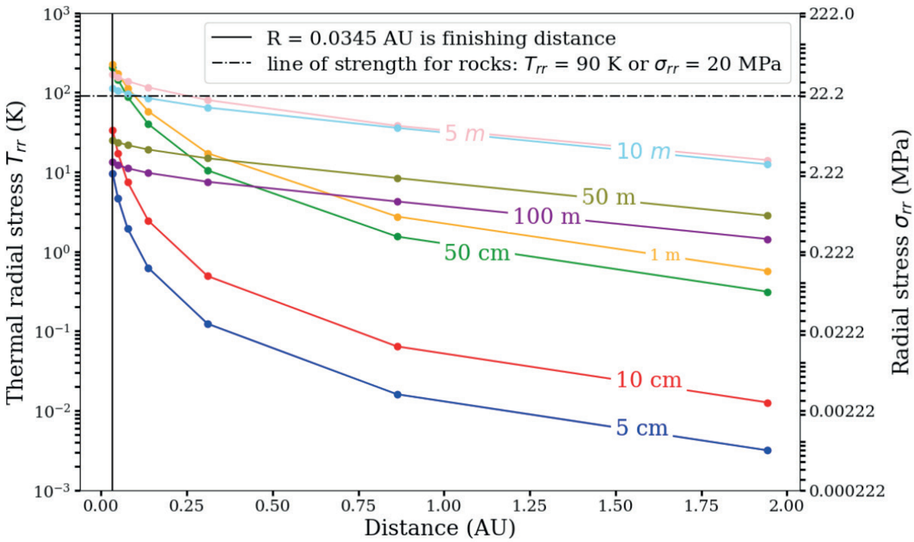

Figure 3 - Dependence of thermal stresses on heliocentric distance for pebbles and rocks of various sizes approaching the Sun along parabolic orbits from an initial distance of 3.45 AU. The composition of the small bodies corresponds to rocky materials.

The final distance adopted in our model, at which centimeter-sized stones undergo fragmentation, corresponds to the melting temperature of silicate particles. Furthermore, once the temperature exceeds 1000 K, the mechanical strength of the material decreases by nearly an order of magnitude, making particles as small as 1 cm susceptible to thermal disruption. Since rapid sublimation of particles is expected near the final distance, a region of enhanced dust density may form at distances of $(7-10)R_*$, which can be detected in the infrared range via its thermal emission.

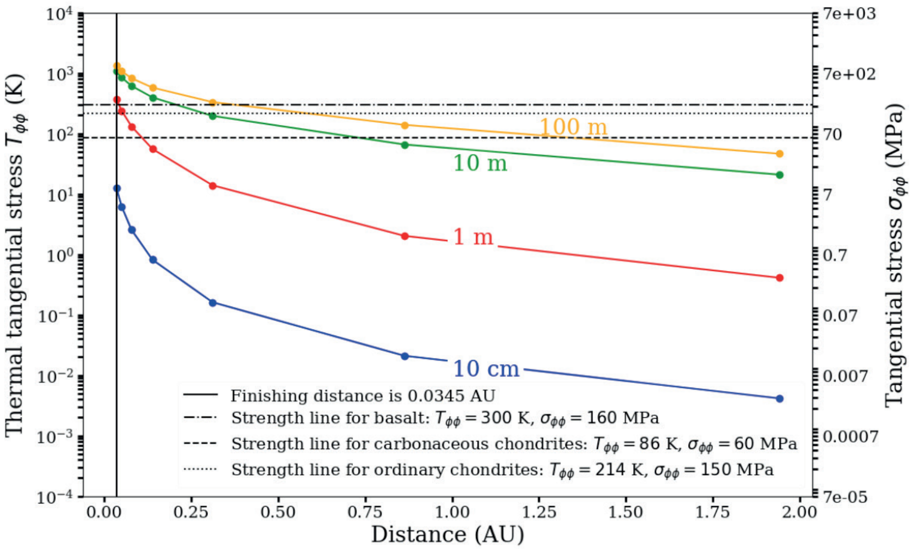

Figure 4 - Dependence of tangential thermal stresses on heliocentric distance for stones composed of basalt and chondrites.

Figure 4 presents the results of calculated tangential thermal stresses for three types of stones composed of basalt and two types of chondrites. The plot includes two vertical axes: the left axis shows the tangential thermal stresses $T_{\varphi\varphi}$ units of kelvin (K), and the right axis shows the corresponding values in mechanical units (MPa). The conversion between these units is performed using equation (2) and the material parameters listed in Table 1. Three strength thresholds are shown in Figure 4. The lowest strength corresponds to carbonaceous chondrites, the intermediate strength to ordinary chondrites, and the highest strength to basalt. According to the results, stones with a radius of 10 cm do not undergo surface fragmentation, whereas bodies with radii of 1 m or more may experience surface compressive failure, leading to dust generation.

Similar calculations for rocky materials indicate that bodies composed of such material can undergo surface stress-induced fragmentation starting from radii of approximately 2 m. Bodies composed of mineral material can potentially remain intact-without dust production-until they reach the sublimation zone boundary or attain surface temperatures close to 1000 K at distances around $16R_*$, where a sharp drop in material strength is expected. For all materials listed in Table 1 and for a wide range of body radii from 5 cm to 300 m, we performed calculations of radial thermal stresses at a distance of 0.1r rom the center of the body.

Figure 5 shows the heliocentric distances at which the radial stress inside parabolically orbiting bodies reaches the material strength limit, initiating mechanical failure. Depending on the material’s strength, fragmentation can begin at different distances from the Sun.

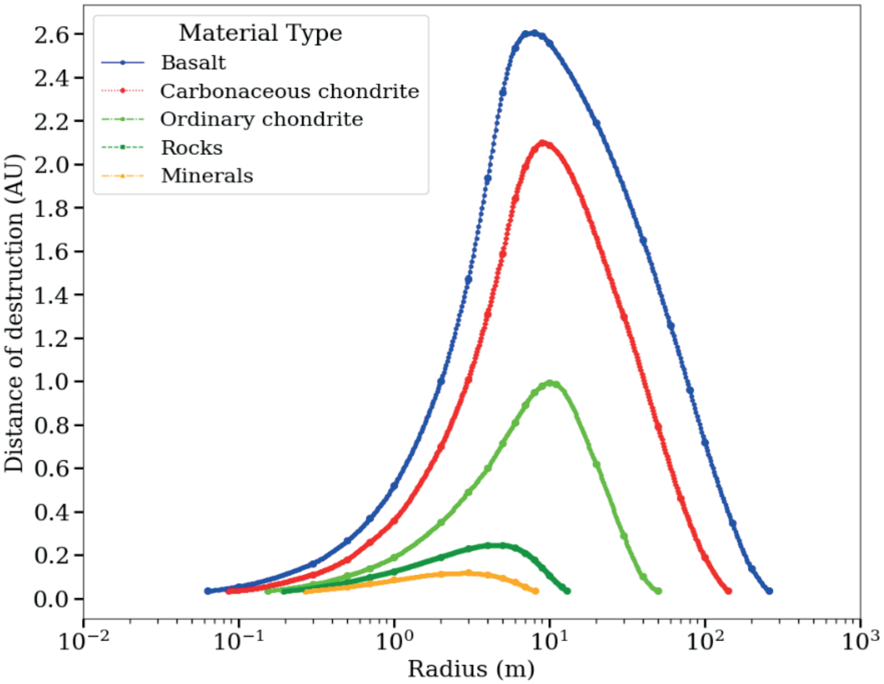

Figure 5 - Heliocentric distances at which bodies of various sizes experience internal thermal stresses equal to the material's strength limit. Onset of internal fracturing.

A characteristic feature of the curves in Figure 5 is the presence of a maximum, which highlights an intermediate size range of bodies whose internal failure may begin at the greatest heliocentric distances. Basaltic bodies with radii of 6–9 m, carbonaceous chondrites of 6–9 m, and ordinary chondrites of 6–9 m reach critical stress levels at distances of approximately 2.5 AU, 2 AU, and 1 AU, respectively. Fragments from such bodies may reach Earth as meteorites. Both smaller and larger bodies attain critical internal stresses closer to the Sun. The broadest size range susceptible to thermal fragmentation is found for basaltic bodies: from 6 cm to 260 m. Carbonaceous and ordinary chondrites are prone to destruction within narrower ranges: 9 cm to 140 m and 15 cm to 50 m, respectively. According to our calculations, rocky bodies fragment within $50R_{\odot}$ for radii ranging from 20 cm to 13 m, and mineral bodies within $50R_{\odot}$ for radii between 30 cm and 8 m. It is evident that as the heliocentric distance approaches ~$50R_{\odot}$, where surface temperatures reach ~1000 K and material strength drops sharply, the fragmentation process may become catastrophic, accompanied by the release of fine fragments and dust.

The curves shown in Figure 6 represent the distances at which bodies of a given size begin to release dust from their surfaces—a phenomenon analogous to a coma in comets. This effect intensifies as the body approaches the Sun. For large bodies with radii exceeding 100 m, thermal stresses stabilize at specific distances characteristic of each material.

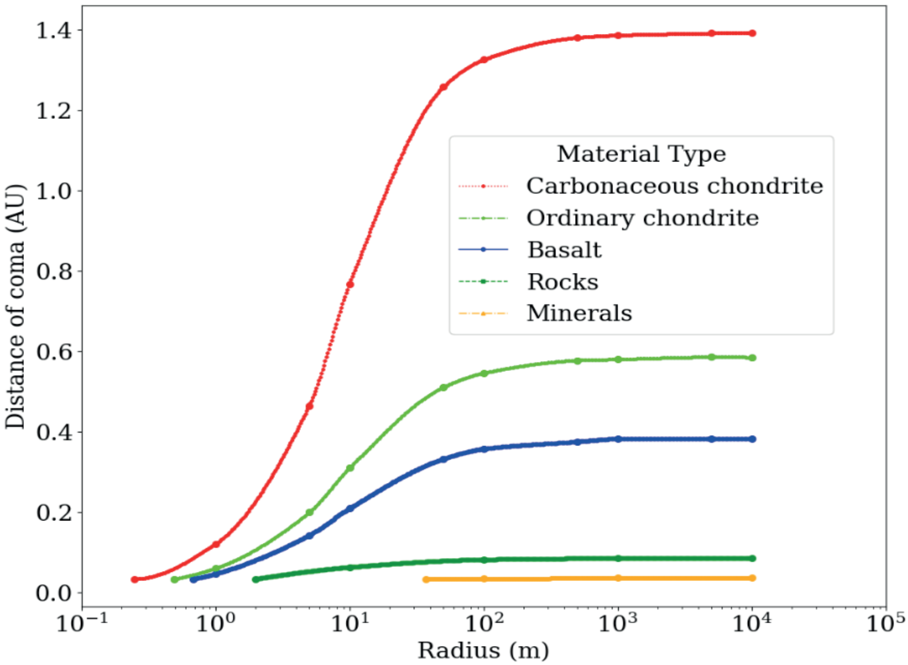

Figure 6 - Heliocentric distances at which bodies of various sizes experience surface thermal stresses equal to the material's strength limit. Onset of surface fragmentation and dust release.

By comparing the curves, one can conclude that bodies composed of chondrites and basalt begin releasing dust at greater heliocentric distances. Carbonaceous chondrites may start shedding dust at distances as far as 1.4 AU, ordinary chondrites at around 0.6 AU, and basalts at approximately 0.4 AU. In contrast, rocks and minerals are capable of releasing dust only near the sublimation zone, where material strength drops sharply due to high temperatures-i.e., near $16R_{*}$

4 Final Remarks

Our calculations have shown that dust production by solid bodies approaching the Sun along highly elongated orbits can occur at various heliocentric distances. Due to surface thermal stresses, dust envelopes may form around solid bodies with radii exceeding 100 m between the orbits of Mars and Mercury. Such bodies could be detected using both ground-based and space-based observational methods.

Destructive internal stresses arise in basaltic, carbonaceous, and ordinary chondritic bodies at the most distant regions from the Sun-approximately 2.5 AU, 2 AU, and 1 AU, respectively. However, as illustrated in Figure 5, these distances correspond to relatively small bodies (up to ~10 m in radius), and their disruption is unlikely to generate dust clouds of sufficient size to be detected in the optical or infrared range-unless the event occurs near Earth. In such cases, ordinary chondrites with radii around 10 m could be observable. Around Earth's orbit, carbonaceous chondrites with radii of ~40 m and basaltic bodies with radii of ~80 m may also undergo fragmentation. The largest bodies tend to disintegrate closer to the Sun, triggering a cascade fragmentation process. The resulting fragments are rapidly broken down into smaller ones, leading to the formation of a dust cloud that approaches the sublimation zone. These clouds could be observable in the optical or infrared spectral ranges.

The primary sources of rocky bodies are believed to be the Main Asteroid Belt and the Kuiper Belt. Infrared observations (1–100 μm) allow researchers to estimate the number of asteroids in the Main Belt. According to Tedesco and Désert (The Infrared Space Observatory Deep Asteroid Search), the Main Asteroid Belt contains between 700,000 and 1.7 million objects with diameters of 1 km or more. In addition, infrared surveys have revealed active asteroids exhibiting signs of dust emission. For example, the WISE telescope detected active asteroids such as 596 Scheila (James M. Bauer, A. K. Mainzer et al.), confirming the presence of dust trails in the Main Belt. In recent years, researchers have increasingly focused on asteroids located on orbits interior to Earth's, as several large objects posing potential threats have been discovered. The Chelyabinsk superbolide is a striking example of how little is known about such objects. Ground-based and low-Earth-orbit telescopes have limited ability to detect objects on the Sun-facing side, highlighting the need for new approaches in identifying potentially hazardous asteroids and associated dust activity.

One promising solution involves the use of high-orbit infrared space telescopes. Within the framework of the program BR24992759 «Development of the concept for the first Kazakhstani orbital cislunar telescope – Phase I», the following observational equipment is proposed:

A telescope with an aperture of 30–40 cm, equipped with a filter tuned to the near-infrared range. Suggested filter passband: λ0=3–6 μm range.

As an alternative, a simpler device can be used: a small photometric camera with a wide field of view (10°–20°), without focusing optics. A 10° field of view corresponds to ~$40R_*$. In front of the objective lens (with a fast f-ratio of f/1 to f/1.5 and an aperture of 4–6 cm), an IR filter fully covering the light beam is installed. A CCD array sensitive to wavelengths λ = 3–6 μm is placed in the focal plane.A key challenge is precise pointing toward the near-Sun region from multiple directions. Ideally, solar occultation should be applied down to ~$4R_* \approx 1$, with a comparison channel using a filter in the λ<2 μm range. The most scientifically valuable region lies between 4 and $(4-24)R_*$(1°–6° from the solar center), which coincides with the sublimation zone for dust of various chemical compositions.

Observations can be restricted to two sectors: west and east of the Sun near the ecliptic plane. If close solar pointing proves difficult, it is possible to monitor more distant regions near the ecliptic plane and toward its poles to detect dust clumps. In terms of instrumentation, the task of detecting dust closely parallels the task of observing small asteroids in the inner Solar System within the broader framework of asteroid-comet hazard identification.

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