GRAVITATIONAL DEFORMATION OF ICY SMALL SOLAR SYSTEM BODIES. E. N. Slyuta[1] and S. A. Voropaev[1], [1]Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, 119991, Kosygin St. 19, Moscow, Russia. slyuta@mail.ru.

Introduction: A typical irregular figure of a small body, as well as the usual debris is approximated by a model triaxial ellipsoid with axes $a>b\geq c$. Shape of small bodies is a product of a long collisional evolution, i.e. mechanical processes such as excavation and crushing. Planetary bodies which belong to another class are characterized by a spherical and equilibrium shape. Small icy bodies are widespread in the Saturn system. The size of small icy bodies varies from 1.5 km (Polydeuces) to 360 km (Hyperion) in the longest axis. Saturn's moon Hyperion is the largest of the small icy bodies of the Solar system (Fig. 1). Saturn's moon Mimas is the next size icy body with a mean radius of 198.2 km [1]. But Mimas, unlike the above small icy bodies, is already characterized by a clearly expressed a spherical equilibrium shape, i.e. belongs to a class of planetary bodies (Fig. 2). Thus, Mimas is the smallest icy planetary body in the Solar system [2]. There is a sharp transition between the small and planetary bodies [3, 4]. Investigation of a transition between the small and planetary icy bodies, as well as the nature of the mechanisms that underlie this transition (creep, heating, or gravitational deformation of a solid elastic body having yield strength) is the main objective of this work.

Physico-mechanical properties: All small Solar system bodies, depending on the composition are characterized by its own individual shape [5]. Mean ratio of the principal semiaxes b/a and c/a of small icy bodies is 0.81 and 0.61, respectively, and - a:b:c=1.64:1.33:1 [6]. All small bodies in the Saturnian system are characterized by a high albedo (0.4 to 1.0) and consist mainly of water ice [7]. Density of small icy bodies ranges from 340 to 857 kg m^{-3} [1], i.e. much less than the density of ice due to high porosity. It should be noted that the high porosity of icy small bodies indicates the absence of any gravitational compression and gravitational deformation by which this porosity would be destroyed [3].

Table 1. Stress deviator (τ_{max}) in small icy bodies*

Small body	Diameter, km	R_m, km	Density, kg m^{-3}	τ_{max}, MPa
Pandora	104.0×81.0×64.0	40.7	490±60	0.019
Prometheus	135.6×79.4×59.4	43.1	480±90	0.012
Epimetheus	129.8×114×106.2	58.1	640±62	0.026
Amalthea	250×146×128	83.5	857±99	0.130
Janus	203.0×185×152.6	89.5	630±30	0.062
Hyperion	360.2×266×205.4	135	544±50	0.135

*Size and density by [1]

Icy Jovian satellite Amalthea is characterized by the highest density (857 kg m^{-3}) [8] among icy small bodies (Table 1). It is the largest irregular satellite in the Jupiter system [9]. Low albedo of a satellite (<0.1) is due to the presence on a surface of dust layer [10].

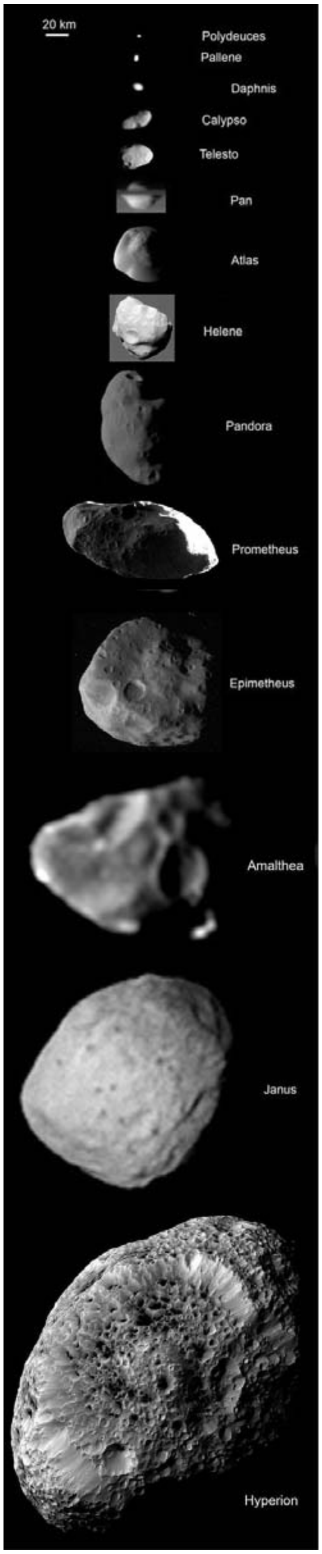

Fig. 1. Small icy bodies shown at the same scale. Photos by “Galileo” and “Cassini” (NASA).

Gravitational deformation: Gravitational loading in small bodies in the form of stress deviator caused by mass and a nonequilibrium figure of bodies, is constant and actually exists from the moment of their formation [3]. There’s no creep in small Solar system bodies [5, 6]. An analysis of mechanical properties of Kuiper Belt objects has been carried out with a model, which uses the elastic theory with ultimate strength for a three-dimensional self-gravity body, and allows the exact solution of differential stresses in a solid elastic body to be received and to carry out their analysis. The value and distribution of stress deviator in small body depends on mass, size, density, figure eccentricity and Poisson coefficient and defined by equation [6]

$$\boldsymbol{\tau_{max}=\sigma_0 F(\varepsilon,\nu)}, \quad (1),$$

where the dimensional factor

$$\sigma_0 = \frac{9}{8\pi}\frac{GM^2}{a^2bc},$$

G - gravitational constant; M – mass ($M=\frac{4}{3}\pi\rho_0 R_m^3$, R_m – mean radius), a, b and

c – main semiaxes, and $F(\varepsilon, v)$ – dimensionless function, which depends on figure eccentricity (ε) and Poisson coefficient (v).

Hyperion has a density equal to 544 kg m^{-3} (Table 1). Poisson's ratio for ice takes equal to 0.31 [11]. Having the largest mass, size and figure eccentricity among icy small bodies, Hyperion is characterized by the highest stress deviator (Table 1). Mimas density is of 1149 kg m^{-3} [1], which is almost in twice higher than the density of porous small icy bodies not subjected to gravitational deformation. Assessing the value of stress deviator in Mimas, we obtain an upper limit of yield stress for the observed transition between the icy small and planetary bodies equal to 0.868 MPa. The lower limit corresponds to the maximum stress deviator of the largest icy small body, i.e. Hyperion, and is estimated as 0.14 MPa (Table 1). Thus, the range of a yield stress for real composition of icy Solar system bodies, consisting mainly of water ice is $0.14<\sigma_p<0.87$ MPa.

The temperature distribution within the Solar System and the probable pressures in the interiors of small bodies (~100 MPa) enable us to deal only with the ice I polymorph [12, 13]. The theoretical value for the yield strength of pure ice I is 0.1E [14, references therein], or approximately ~290 MPa at about 0 K, but this value drops with increasing temperature. Creep observed at temperatures above about 100 K has four major mechanisms, the relative contributions of which depend on stress and temperature. The law of creep is well known:

$$\dot{\gamma} = A\sigma^n e^{-\frac{Q}{kT}}$$

where γ represents the strain rate, σ the applied stress, Q the molecular activation energy, and A and n constants determined by experiment [14]. Experimental data for pure ice define a range of yield strengths at low temperatures of 0.1 MPa$<\sigma_p<$2 MPa; the upper limit was obtained at 203 K, and increased as temperature decreased.

Using in equation (Eq. 1) Hyperion parameters (density and shape eccentricity) (Table 1) and guided by the maximum stress deviator of Mimas (0.87 MPa), we can estimate the maximum size that had a small porous icy body (ProtoMimas) until its gravitational deformation and turning it into Mimas. ProtoMimas radius is estimated as R=465×302 km, and a mean radius is R_m=349 km which almost twice present size of Mimas (Fig. 3). Mimas density is also in twice more than Hyperion density and, accordingly, ProtoMimas density.

Summary: There's no creep in small Solar system bodies. Small icy bodies are solid elastic bodies which are characterized by the yield strength. The yield strength obtained for icy bodies fits well with available experimental data for pure ice and suggests that the observed transition between the icy small and planetary bodies is probably due to gravitational deformation of solid ice, but not by heating and melting ice as a result of, for example, decay of short-lived radioactive nuclides, or energy dissipation of tidal deformation, etc.

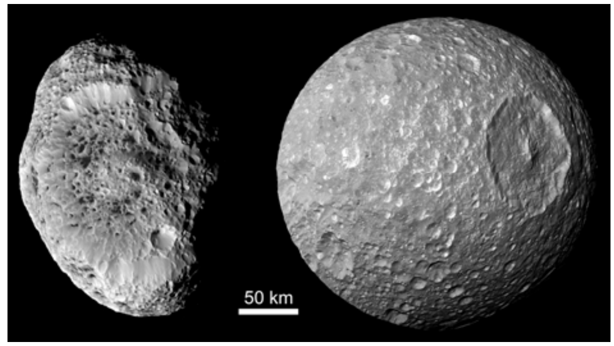

Fig. 2. Icy Saturn's satellites Hyperion (on the left) and Mimas (on the right) are shown at the same scale. Photos by "Cassini" (NASA).

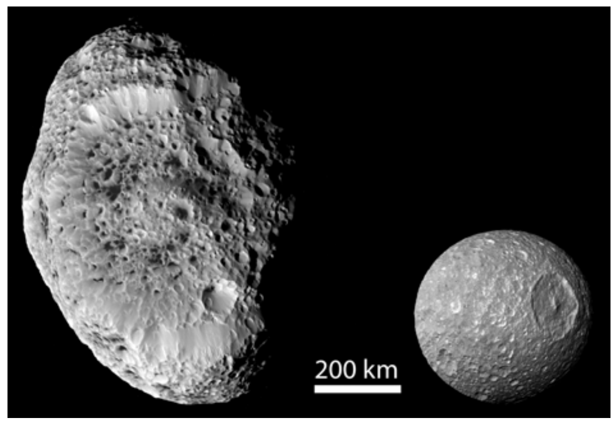

Fig. 3. Hypothetical ProtoMimas (on the left) until to gravitational deformation. To visualize ProtoMimas the image of Saturn's satellite Hyperion was used. Saturn's satellite Mimas (on the right) is shown at the same scale. Photos by "Cassini" (NASA).

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