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

Introduction: All solid bodies in the Solar System may be divided into two major classes on the basis of their shapes. The first class consists of small bodies possessing nonequilibrium irregular shapes. The second class includes planetary bodies (including terrestrial planets, large enough satellites, the largest asteroid Ceres and some of numerous Kuiper Belt and trans-plutonian objects) that are characterized by a sphere-like shape. Therein lies the principal difference between the small and planetary bodies, as the terms are used here [1, 2]. Note that the *c/a* ratios for planetary bodies, as distinct from those for small bodies (0.26-0.85), are, as a rule, between 0.9 and 1.0 [1, 2]. Small bodies have limb roughness of a few percent of the mean radius *(R_m)*, but the roughness of planetary bodies is below $0.01R_m$ [3]. The direct relationship between increasing relief and mean radius of small bodies is given by $h \approx 0.13R_m^{1.1}$ [4]. For planetary bodies, the dependence is inversely proportional. Gravity is the only force that can overcome the ultimate strength of a material and reconstruct an irregular shape of small bodies into an equilibrium ellipsoid of planetary bodies.

Self-gravity and the rheology: Estimation of the gravitational deformation parameters of small bodies with the well known "hydrostatic pressure" equation [5, 6] may be correct only in the case of viscous liquid rheology of strengthless material. It is necessary to take into account also, that hydrostatic pressure alone does not produce plastic deformation. An analysis of the rheological properties of small bodies has been carried out with a rheology 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 [1, 2]. Providing the body mass does not exceed some critical value, the deviatoric stresses caused by gravity and a nonequilibrium figure, are unable to overcome yield strength of this material. "Critical mass" theory (CMT) [1, 2] establishes a connection between the rheological properties of a material, the shape parameters and the body mass and explains an observed dependence of transition parameters on the bodies' composition and as well as explains threshold character of the transition between small and the planetary bodies.

For icy Solar System bodies the transition between the small and planetary bodies is observed between satellites of Saturn Hyperion (a small body) and Mimas (a planetary body) [1, 2]. For rocky bodies this transition is observed between much larger bodies - 2 Pallas and 1 Ceres asteroids [2, 7]. An obtained yield strength for the Hyperion - Mimas (water ice) pair is within $0.38<\sigma_p<1.4$ MPa [2] (Fig.1). Experimental data for pure water ice is $0.1<\sigma_p<2$ MPa at 203°K temperature for the upper limit [2]. For a rocky pair such as Pallas – Ceres, this range is within $30.3<\sigma_p<60.2$ MPa [2, 7] (Fig.1). To reach a threshold value of the stress deviator and to proceed into a category of a planetary body the mass of the asteroid, Vesta should be more observable for a minimum on the order of magnitude [2]. For L-5 ordinary chondrite (Tsarev meteorite) the critical radius is estimated to be 756 km [2]. Experimental data on physical and mechanical properties of Sayh al Uhaymir 001 and Ghubara meteorites (L4/5 ordinary chondrites) [8] allow to estimate the critical radius for ordinary chondrites, undergone much smaller shock metamorphism. Taking a density of 3.40 g cm^{-3}, compressive strength of 97.50 MPa, and a Poisson coefficient of 0.33 for material of Sayh 001 meteorite [8], and using the stress deviator equation (Eq. 10 [2]) we can estimate the critical radius, which is estimated to be 545 km. For Ghubara material with a density of 3.45 g cm^{-3}, compressive strength of 72.22 MPa, and a Poisson coefficient of 0.33 [8] the critical radius is estimated to be 463 km. For comparison, for terrestrial basic and ultrabasic rocks depending on their mechanical properties, the critical radius settles down in a range between $582<R_{cr}<1038$ km [2]. As the yield strength depends not only on structure, but on temperature also, a body's critical radius varies accordingly. For example, the critical radius of a metallic body similar to the Sikhote-Alin iron meteorite, at 200°K temperature (asteroid belt) is estimated to be 259 km, at 77°K (Saturn system) - 337 km and at 4,2°K (deep space) - 389 km [2], i.e. the metallic body critical mass depending on temperature increases more than by a factor of 3. Ceres composition according to the rheologic properties obviously differs from the considered examples and, probably corresponds to the carbonaceous chondrites [2, 7] exhibiting lower strength properties in comparison with other rocky bodies. The last data by [9] confirm that Ceres structure is really characterized by weak mechanical properties and the asteroid, apparently, is a differentiated planetary body. If to take into account the recent data on Ceres's mass (*M*=9.395±0.125×1020 kg), density (2077 kg m^{-3}) and size (476.2 km in mean radius) [9], and if to take a Poisson coefficient of 0.33 [8], in this case the yield strength for Ceres's bulk composition will be limited by value of $\sigma_p \leq 28$ MPa. It is valid too little for rocky bodies and too much for icy bodies and will well be coordinated to the assumption of the mixed structure from rock and ice [10].

Phoebe: If comets are small bodies with an irregular shape, Phoebe is large enough a body to have developed a sphere-like shape. The mean radius of the satellite is 106.6 km [11]. As the satellite has a very low albedo (0.06) it was considered, that Phoebe is a rocky body [12]. But among small rocky bodies Phoebe differed by anomalous shape parameters [2, 13]. With regards to the shape parameters, Phoebe belongs to the planetary bodies [2, 14]. An explanation which followed from the CMT, consider that Phoebe has a composition that differs from rocky and even icy bodies. Phoebe is less than Mimas (icy planetary body), and is less than Hyperion (icy small body). Its volume makes 55% from volume of Hyperion and 17% from volume of Mimas. According to the most recent data, Phoebe's composition is similar to that of Kuiper Belt objects [15, 16]. The orbital properties of Phoebe suggest that it was captured by Saturn's gravitational field. Cometary nuclei are characterized by high porosity and low density [17, 18]. The maximum mean density of a fully packed cometary nucleus would be ≈ 1.65 g cm^{-3} [19]. Phoebe's density is 1.63 g cm^{-3} [11] and corresponds to the above-stated value for a fully packed cometary nucleus. It means that the minimal stress deviator for Phoebe exceeds yield strength of material and gravitational deformation has already taken place. Gravitational deformation is accompanied by gravitational densification and gravitational strengthening of a material at the entire body due to three-dimensional gravitational compression accompanied by two basic mechanisms of plastic deformation [2, 14]. Taking shape parameters of the satellite of *a*=115, *b*=110 km, *c*=105 km [12], and density of 1.63 g cm^{-3} [11], and a Poisson coefficient of 0.31 [20], and using the stress deviator equation (Eq. 10 [2]) we obtain a stress deviator of 0.9 MPa. Hence, the yield strength of a material of Kuiper objects is within the range $0.002<\sigma_p<0.9$ MPa, where the minimum value corresponds to a cometary nucleus tensile strength [21]. It is necessary to note, that if to take a yield strength of 0.9 MPa, the mean radius of a small body not exposed to gravitational deformation (i.e. with a density of about 0.3 g cm^{-3} [17]), would reach 570 km. Hence, among Kuiper Belt objects small bodies with irregular shape which sizes exceed Phoebe's size may be observed. Perhaps, large Kuiper object 1998 $_{SM165}$ may be considered such an example [22]. But it is necessary to take into account that under equal temperature conditions and similar composition the mass of such bodies should be less than critical one, and accordingly, less than mass of Phoebe, due to their high porosity. Thus, Kuiper Belt objects are characterized by the lowest value of yield strength among Solar system bodies, due to their composition. In comparison with water ice (about 30%) the share of exotic ices (CO, CO_2, CH_3OH, CH_4, H_2CO and others) in cometary nuclei is rather small (about 12%) [23]. Obtained data on the rheology of Kuiper Belt objects shows that even subordinated amount of exotic ices can result in the change of rheologic properties of a material. Such dependence of transition parameters on composition can serve as a good indicator of the distinction between the bulk composition of numerous Kuiper and trans-plutonian objects studied by remote sensing. Phoebe can be considered such an example.

Summary: Strength properties of Solar system objects dependent on their composition vary within an extremely broad range – from 0.002 up to 350 MPa (Fig. 1). There are five basic groups of objects dependent on their rheologic properties (Fig. 1). Kuiper Belt objects are characterized by the lowest value of yield strength. Thus, critical or minimal size of sphere-like Kuiper objects belonging to planetary bodies due to their mass and shape parameters, is equal about 100 km (Phoebe's radius). For icy bodies the critical radius is approximately twice more, and is equal about 200 km (Mimas's radius). For the rocky bodies described by low mechanical properties (for example, carbonaceous chondrites, or rock-ice mixture), the critical radius is limited to Ceres's size (less than 450 km in radius). For the rocky bodies consisting of more dense and strong rocks, the critical radius depending on strength properties of material is within the range of $460<R_{cr}<1040$ km. For the metallic bodies (meteoritic iron), which are characterized by high density and strength, the critical radius depending on temperature of environment is within the range of $260<R_{cr}<390$ km.

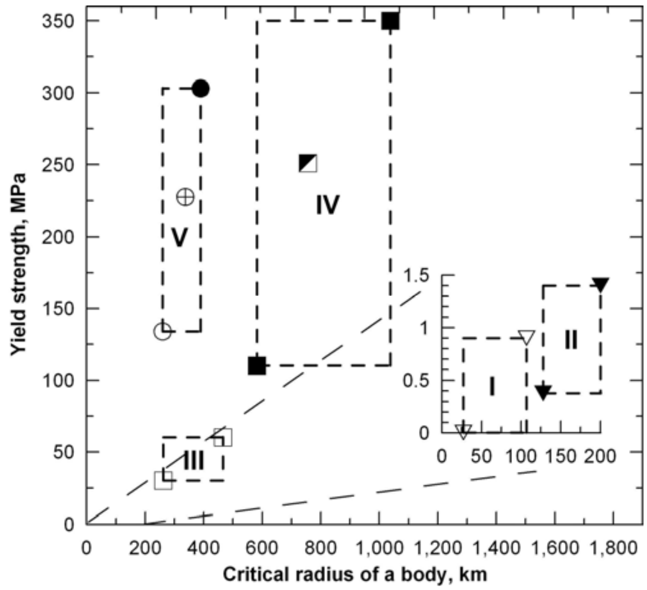

Fig. 1. Dependence of the critical radius of Solar system bodies on yield strength of a material according to the observed, experimental and the rheological model data. ▽ - Kuiper Belt objects; ▼ - Hyperion – Mimas; □ - Pallas – Ceres; ◩ - L-5 ordinary chondrite; ■ - Terrestrial basic and ultrabasic rocks; ○ - Meteoritic iron, 300°K; ⊕ - Meteoritic iron, 77°K; ● - Meteoritic iron, 4.2°K. The first (I) is Kuiper Belt objects which are characterized by the lowest yield strength. Ice bodies' parameters (Hyperion-Mimas) form independent, separate transition field (II) and are not crossed with ones of Kuiper objects. The third group (III) unites rocky bodies which are limited to Ceres parameters. Probably, that is a transition field of carbonaceous chondrites [2, 7] and similar rocks characterized by week mechanical properties, or perhaps, rock-ice mixture [10]. The fourth group (IV) includes L-4/5 ordinary chondrite and material similar to terrestrial basic and ultrabasic rocks [2]. These rocky bodies are characterized by much stronger mechanical properties. Probably, at accumulation of experimental data on mechanical properties of different types of meteorites this extensive field can be divided into some areas. The fifth (V) is a field of the metal bodies (meteoritic iron) at temperatures of 300°K, 77°K and 4.2°K. These objects are differed by a high density and high strength properties [2].

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