FRAGMENTATION OF METEOROIDS IN ATMOSPHERE: MODELS VERSUS OBSERVATIONS.

N. A. Artemieva[1,2,3], [1]Planetary Science Institute, Tucson, USA (artemeva@psi.edu); [2]Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany; [3]Institute for Dynamics of Geospheres, Moscow, Russia

Introduction: There are three fundamental physical processes involved as meteoroids intersect the atmosphere: deceleration, ablation, and fragmentation. The latter is a typical process for meteoroids larger than a few kg. Understanding of this process help to explain light flashes accompanying the entry, strewn fields on the surface, or the paucity of meteorites after powerful airbursts.

Strength and fragmentation criteria: The resistance of small meteorites to compression and tension has been measured in laboratory experiments, revealing that their strength is, on average, ~200 MPa, i.e., quite similar to that of terrestrial rocks [1]. At the same time, the best current estimate of the strength of stony meteoroids is in the range of 0.1-1 MPa, as derived from observations of their fragmentation due to dynamic atmospheric loading upon entry [2]. The most popular explanation of this glaring contradiction is strength degradation with increasing mass, known as Weibull statistics.

Models: There are no simple equations quantifying either the process of fragmentation itself or the motion of the fragmented meteoroid. The pancake model [3-4] treats fragmentation as liquefaction of a solid body with constant density which spreads under hydrodynamic loading in the direction perpendicular to the trajectory. In contrast, the separated fragments model [5-6] assumes that fragmentation divides the body into fragments with a lateral separation velocity which is a small fraction of the total velocity. The most advanced models combine both approaches: some fragments are treated as clouds of dust subjected to pancaking and some as separated fragments [7-8].

These simplified approach describes the trajectories, light flashes, and meteorites distribution on the surface if drag and ablation coefficients are known from more sophisticated models, observations, or experiments. However, this approach does not describe the propagation of atmospheric shock waves created by hypersonic flight, the interaction of shock waves with the surface, and other post-entry events. To address these problems, full-scale hydrodynamic modeling, i.e., solution of the Euler equations for mass, momentum, and energy conservation with radiative transfer must be used [9-11].

Observations: Fragmentation is usually accompanied by a sharp increase of meteoroid luminosity. Meteoroids that are disrupted in the atmosphere give rise to terrestrial strewn fields. For lower-mass objects, the strewn field exists as meteorite fragments, and then (with increasing mass) meteorites plus small impact pits/craters (Chelyabinsk, Agoudal, Morasko, Kamil); craters whose rims overlap (Henbury); and finally, the strewn field merges into a single crater (Meteor Crater). Recently, high-resolution images of Martian surface allow to detect hundreds of small crater clusters on Mars [12].

Tunguska event remained enigmatic for at least 80 years. Much of the observed effects (butterfly shape of the damaged area, absence of meteorites, white nights in Europe) are fully consistent with those of a typical airburst caused by a body 40-100 m in diameter entering Earth's atmosphere at cosmic velocity.

Conclusions: The simplified analytical models are still a more efficient approach to fit the model to observed data for typical meteoroid scenarios. On the contrary, larger Tunguska-like bodies are more suitable for hydrodynamic modeling: The Chelyabinsk event allows us to bridge the gap between two classes of models: while analytical models [7,8] reproduce peculiarities of the observations, hydrodynamic models try to explain physics behind accepted simplifications (such as intense dust production and deficiency of meteorites on the surface, e.g. [13]).

Small impacts recur on a decadal timescale and are difficult to predict; Earth's atmosphere decreases the risk of such impacts, though not to a negligible level. Prior education and adequate and timely information are key to avoiding panic if an impact occurs in a densely populated area.

Acknowledgement: The work was supported by National Science Center (Poland), grant no. 2013/09/B/ST10/01666.

References: [1] Petrovic J.J. 2001. *J. Mater. Sci.* 36:1579-83. [2] Popova O.P. et al. 2011. *Meteoritics & Planetary Science* 46:1525-50. [3] Chyba C.F. et al. 1993. *Nature* 361:40-44. [4] Hills J.G. and Goda M.P. 1993. *Astron. J.* 105:1114-44. [5] Passey Q.R. and Melosh H.J. 1980. *Icarus* 42:211-33. [6] Artemieva N.A. and Shuvalov V.V. 2001. *J. Geophys. Res.* 106(E2):3297-310. [7] Borovička et al. 2007. *Astron. Astrophys.* 473:661-72. [8] Popova O.P. et al. 2013. *Science* 342:1069-73. [9] Svetsov V.V. et al. 1995. *Icarus* 116:131-53. [10] Crawford D.A. et al. 1994. *Shock Waves* 4:47-50 [11] Shuvalov V.V. and Artemieva N.A. 2002. *Planet. Space Sci.* 50:181-92. [12] Ivanov B.A. et al. 2014. Abstract #1812. 45th Lunar & Planetary Science Conference. [13] Artemieva N.A.and Shuvalov V.V. 2016. Abstract #1749. 47th Lunar & Planetary Science Conference.