

CRATER FIELDS ON VENUS, EARTH AND MARS, N. Artemieva¹ and P. A. Bland², ¹Institute for Dynamics of Geospheres, Leninsky pr., 38, bldg.6, 119334, Moscow, Russia, nata_art@mtu-net.ru, ²Department of Earth Science and Engineering, Royal School of Mines, Exhibition Road, Imperial College London, South Kensington Campus, London SW7 2AZ, UK, p.a.bland@imperial.ac.uk

Introduction: Meteoroids that are disrupted and dispersed in the atmosphere may give rise to crater fields at the surface. For lower mass objects fragmentation may produce a strewn field of meteorite fragments, and then (with increasing mass) meteorites plus impact pits; small meter- to tens m-sized well separated craters; craters whose rims overlap; and finally single craters produced by a swarm of poorly separated fragments. The masses that define the transition from one type of fragmented impact to another depend on atmospheric properties and projectile type. The disruption of impactors in the Earth's atmosphere was initially studied by Passey and Melosh [1]. The cross-range spread is probably produced by the interaction of bow shocks after breakup, spreading velocity U (two identical fragments with density \mathbf{r}_b , trajectory velocity V disrupted at the altitude with atmospheric density \mathbf{r}_a) is defined as $U = CV(\mathbf{r}_a/\mathbf{r}_b)^{0.5}$ with $C=0.01-1$ from the analysis of the Earth's strewn fields. The idea is confirmed in 3D modeling of disrupted meteoroid motion [2,3] and the coefficient of repulsion C is defined as 0.45. Similar estimates are known for Venus [4] and Mars [5]. Here we use the model of separated fragments (SF) [2,3] to investigate disruption of impactors in the very different atmospheres of Earth, Venus and Mars.

Model of separated fragments: The model takes into account successive fragmentation and ablation of individual fragments (number of fragments (n) = 1 at the start, n may be as large as a billion of fragments). The meteoroid is subjected to disruption into a pair of fragments if dynamic loading exceeds its strength, which depends on the projectile type and size. The values for fragment mass and direction of repulsion are defined by random choice. Fragments as usual have higher strength than the initial body, but may be disrupted again later into a new pair, etc. The equation of motion [1] is solved for each individual fragment, with an additional equation describing repulsion. In contrast to the more common 'pancake' model [6], which treats the disrupted meteoroid as a deformable (but continuous) liquid, our approximation allows us to define a mass-velocity distribution on the surface for the solid fragments which create craters (in the case of high final velocity) or which may be found as meteorites (fragments with low final velocity). As the random choice procedure is used, the final results

change from run to run, but some common features may be distinguished.

All simulations are at average asteroidal impact velocities (19 km/s for Venus, 18 km/s for Earth, 10 km/s for Mars). Variations of impact angle allow us to reproduce individual crater fields observed on the Earth and Venus. Two types of projectiles are considered: stony bodies with density of 2400 kg/m³, ablation coefficient of 0.014 s²/km² and low tensile strength of $4.4 \cdot 10^7$ dyn/cm² (for 1 kg sample) and iron bodies with density of 7800 kg/m³, ablation coefficient of 0.07 s²/km² and 10 times higher strength.

Venus: The dense atmosphere of Venus (64.8 kg/m³ near the surface) strongly affects crater production: ~98% of the craters between 2 and 35 km in diameter expected on a hypothetical airless Venus are eliminated by the "atmospheric filter" [7,8]. 69 craters observed by Magellan have irregularly shaped floors, and 16 are crater fields [4]. The smallest craters on Venus have anomalously low depth/diameter ratios [9]. 370 "splotches" with diameter in the range of 10-70 km [7] are common on the surface and most probably were produced by the impact of atmospheric shocks produced by catastrophic disruption of impactors in the venusian atmosphere [10].

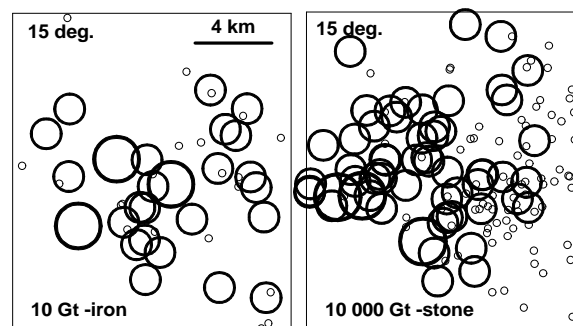
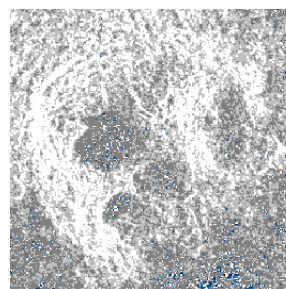


Fig.1 Shallow impacts lead to more intensive dispersion of the fragments. 10^{13} kg iron body (or 10^{16} kg stony) creates a crater field with strong overlapping for 15° impact (upper plates). On the left – irregular crater ~14 km in diameter, it is centered at -21.4° latitude, 335° longitude in the northern Lavinia Region of



Venus.

STREWN FIELDS: N. Artemieva and P. Bland

The 'pancake' model predicts no substantial influence of atmosphere on projectiles larger than 4 km (stony), or 2.5 km (iron) in diameter. The final crater diameter is ~30 km; in a good agreement with venusian craters counts [7]. For smaller projectiles the SF model is applied. Crater fields are typical for iron projectiles with pre-entry mass of 10^{11} - 10^{12} kg, (250-540 m in diameter) with the largest crater less than 3 km and with many small, <100 m diameter craters, which are not resolvable by Magellan. For iron impactors with pre-entry mass up to 10^{13} kg (1 km) the final crater (~10 km) is created by a swarm of fragments and has irregular shape. Similar crater fields may be created by stony projectiles with mass of 10^{15} - 10^{16} kg (7-15 km). Taking into account the size-frequency distribution of incoming projectiles [11], the vast majority of crater fields and irregular craters on Venus were created by iron projectiles.

Earth: The atmosphere of the Earth is 60 times weaker than the venusian one. 17 craters with diameters <1.5 km are associated with an iron impactor-type, and only 1 is a stone. In contrast, 18 craters >10 km have an inferred impactor-type, and 16 are stones. This suggests that in the range $\sim 4 \cdot 10^4$ kg - $3 \cdot 10^8$ kg 95% of impactors reaching the surface with sufficient velocity to form craters are irons, in contrast to the average flux, where the fraction of these bodies is <10%. Of the 22 terrestrial craters <1.5 km in diameter 14 are <0.3 km. 9 of these are multiple craters, whilst none of the 0.3-1.5 km craters are multiples, suggesting disruption of iron impactors with mass < 10^6 kg.

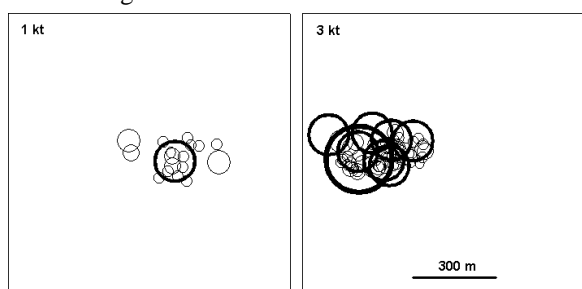
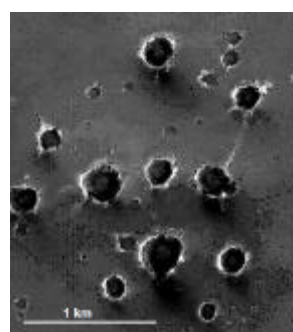


Fig.2 A strewn field on the left and a single (possibly irregular) crater on the right produced by a swarm of iron fragments with initial mass of 1-3 kt (~5m).

SF model simulations show that disruption is typical for stony meteorites with mass >50 kg and for iron meteorites with mass > 10^4 kg. Iron bodies < $2 \cdot 3 \cdot 10^6$ kg (7-8 m) are disrupted at sufficient altitude into rather small pieces so that separated fragments form crater fields. For larger iron bolides the SF model indicates that impact of closely spaced but large fragments will form single simple craters, an idea originally suggested by Melosh [12] and confirmed in

the experiments [13]. As on Venus, stony projectiles may produce similar crater fields and craters, but require 1000 times the iron pre-entry mass.

Mars: Comparing the results for Earth and Venus, we see that strewn fields are created by projectiles with a mass approximately equal to the mass of atmosphere in a "trajectory tube" (a cylinder with length equal to the trajectory length and radius equal to the projectile radius). Extrapolating to modern martian atmosphere we find that iron projectiles with mass as low as 10^3 - 10^4 kg are not disrupted on Mars at all! Stony projectiles with a mass in the range of 10^4 - 10^5 are disrupted and may produce crater fields with weak separation, which may be identified most probably as irregular craters with the size of ~100 m (too small to be recognized in details even by the MOC MGS). Nevertheless this camera revealed a lot of crater fields with typical crater size of 0.2-1 km and separation of ~1 km (**Fig.3**). Assuming atmospheric dispersion nature of these clusters we need high-velocity,



extremely low-density (0.015 g/cm^3) kms-sized bodies, which are unknown in astronomy. The origin of these crater fields is thus not yet known.

Fig. 3 Clusters on Mars - MOC image M0401900.

Discussion. Crater fields and irregular

craters are typical for planets with atmospheres. Their size is defined by atmospheric density and varies from a few meters for Mars to tens km for Venus. Although iron projectiles account for <10% of the total flux, they create the majority of multiple craters. Clusters on Mars may not be of atmospheric dispersion origin.

Acknowledgements. NA thanks RFBR for financial support (project #01-05-64564a). PAB thanks the Royal Society for their support.

References: [1] Passey Q. R. and Melosh H. J. (1980) *Icarus*, 42, 211. [2] Artemieva N. and Shuvalov V. (1996) *Shock waves* 5, 359. [3] Artemieva N. and Shuvalov V. (2001) *JGR* 106, 3297. [4] Herrick R. R. and Phillips R. J. (1994) *Icarus* 112, 253. [5] Vasavada et al (1993) *JGR* 98, 3469. [6] Chyba C. F. et al (1993) *Nature*, 361, 40. [7] Schaber G. G. et al (1992) *LPICo*, 100. [8] Schaber G. G. et al (1999) *LPS* XXX, #1221. [9] Cochrane C. (2002) *Microsymposium in Comparative Planetology 36th*, MS014. [10] Zahnle K. J. (1992) *JGR* 97, 10243. [11] Ivanov B. A et al (2003) *Asteroids III*, 89. [12] Melosh H. J. (1981) *Multi-Ring Basins*, 29. [13] Schultz P. H. and Gault D. E. (1985) *JGR* 90, 3701.