IMPACT PLUME NUMERICAL MODELING. N. Artemieva[1,2] .[1]Institute for Dynamics of Geospheres (Moscow, 119334, Russia, nata_artemeva@rambler.ru), [2]Planetary Science Institute (Tucson, AZ 85719, artemeva@psi.edu).

Introduction: An impact expansion plume is a mixture of vaporized, melted and solid target and projectile material that quickly expands outward from the forming crater from the very early stages of crater formation [1]. The complexity and energy associated with a planetary impact-produced expansion plume cannot be reproduced in low-velocity impact laboratory experiments, with a few exceptions [2]. Attempts to address impact plumes through laser experiments [3-4] are far from the real conditions of natural impact plumes. Numerical simulations are the best approach to investigate the evolution of expansion plumes, but they must be validated by real data.

Specific problems: There are a few serious numerical problems in impact plume modeling: (1) high contrast in densities (from solid material to rarified vapor) and energies (from standard planetary conditions to high-temperature plasma); (2) high expansion velocities; (3) high spatial resolution near a growing crater versus planetary-scaled region to be resolved; (4) a short time of ejection in comparison with a long time of the final ejecta deposition; (5) mixing of vapors versus separation of molten-solid fractions; (6) gas-particles interaction. The plume is a gas-particle mixture, not just a low-density continuum, and should be described using two-phase hydrodynamics [5], which takes into account individual particle characteristics (mass, density, shape) and their collective behavior (momentum and energy exchange with surrounding gas). The plume expansion depends upon both the particle-gas mass ratio and the particle's size frequency distribution (SFD). Solid particles are the product of ejecta fragmentation, molten particles are disrupted melt (tektites) and/or condensates from the vapor (microkrystites). Two-phase SOVA [6] and KFIX-LPL [7-8] are independent models with different particle treatments, but they both describe the physics of phenomena correctly and should produce similar results.

Example 1 - tektites: The modeling approach was satisfactory in the theoretical study of terrestrial tektites - moldavites from the 24-km-diameter Ries crater [9] and Ivory Coast tektites from the Lake Bosumtwi crater [10]. The initial ejection velocities of molten material from the uppermost target layer are high, up to 10 km/s, which is close to the velocity of the expanding plume. As a result, the particles are not subjected to high dynamic pressures that otherwise would disrupt them into a fine dust immediately after ejection. The temperature of the entraining gas is rather high, in the range of 1000-2000 K, so the particles do not cool quickly during the flight, allowing enough time to have them aerodynamically shaped (which is typical for tektites), and to lose volatiles. The total calculated mass of moldavites is near 10 Mt which compares well with the 5 Mt estimated from field observations [11]. An oblique impact (30°-45°) produces a relatively narrow-angle distribution of tektite-type material downrange, in agreement with that observed for the known strewn fields. These asymmetric distributions allow us to speculate about impact angle and impact direction [9-10].

Fig.1 The first 20 s of tektites (in green) ejection from the Ries crater. Gray circle shows the final crater. The projectile strikes along the X-axis.

Example 2 - Chicxulub distal ejecta: In early two-dimensional (2D) hydrocode simulations of impact expansion plumes, the plume expanded vertically as a cylinder above the opening crater: only after reaching the thinner upper atmosphere (well beyond the stratosphere) would it expand horizontally [12]. 2D and 3D simulation of the Chicxulub impact indicate that the expansion plume is initially dominated by water vapor, soon followed by vaporized sedimentary and projectile material, suggesting that much mixing is going on inside the plume during expansion. Recently, we carried out long-term (up to 15 minutes) simulations of the plume expansion created by an oblique impact into a Chicxulub-like target (3 km of sediments, 30 km of crystalline basement, and mantle) [13]. We modeled crater collapse and proximal ejecta deposition, while the high-velocity distal ejecta (i.e., beyond the first 400 km of the atmosphere) was further modeled using a ballistic approach. The simulations covered a range of impact angles (30° to 90°) and projectile size (16 km to 14 km) while keeping the impact velocity at 20 km/s, to maintain a transient cavity size in the range 90-100 km. Results of these simulations indicate that high-velocity, globally distributed ejecta consist exclusively of vaporized/molten projectile material and sediments (Fig. 2). This is in agreement with the understanding that well-known types of high-velocity ejecta (tektites and meteorites from other planets) originate from a very thin surficial layer (probably a few meters for tektites and less than 10%

of the projectile diameter for martian meteorites). Basement ejecta leave the growing crater with velocities well below 4 km/s. Vaporization of ejecta from deep layers is minimal, and does not provide additional ejecta acceleration. Velocity distribution within the plume increases linearly with altitude (in agreement with analytical solutions for plume evolution [14]) with only minor mixing of fast and slow materials at late times (Fig. 2 - right). Large scale (200 km) turbulence does not operate efficiently at the time scale of a few minutes.

The early time mass-velocity distribution from the simulations are in reasonable agreement with observations (a few cm thick layer at distances of 2,000-3,000 km; a few mm world-wide). Molten droplets derived from crystalline basement are deposited within 1,000 km from the crater, consistent with the impact melt found in Haiti and other proximal sites [15]. However, dispersal of basement melt outside this region is unlikely. Even after including non-ballistic transport of very small particles we could not reproduce the massive (850 km^3) worldwide spherule deposits. Shocked quartz grains are a minor fraction of total KT deposits (0.01% of spherules volume –see [13]). They may originate from minor (<1%) contamination of the Upper Cretaceous sediments by sand (or other silica-rich materials) and/or may be transported non-ballistically within a few days after the impact similar to volcanic ash clouds. Deposition of 50 µm spherules through Earth's atmosphere takes a few days (even though ballistic transport occurs within tens of minutes). Current knowledge of the shocked quartz grains size versus distance relationship [16] does not favor any particular hypothesis.

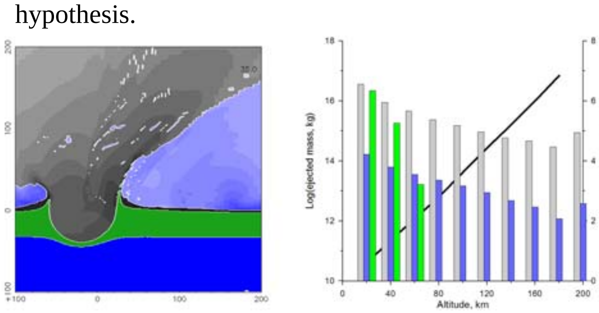

Fig. 2: *Left*: Chicxulub impact plume 35 s after a 45º impact, modeled with SOVA. Gray color shows projectile material and sediments, green - crystalline basement, dark blue - mantle, light blue – atmosphere. *Right*: mass-velocity distribution of different materials with altitude; colors are the same as on the left plate.

Perspectives: A list of plume-ejecta related problems includes: (1) suevite formation and deposition; (2) Australian-Asian tektite strewn field and predictions for the parent crater; (3) rampart craters on Mars; (4) erosion of planetary atmospheres; (5) material exchange between planets; (6) specific chemistry of tektites and KT spinels.

Chemistry: Current approaches allow us to address mainly the "mechanical" component of the complex plume expansion problem; that is, the possibility of non-ballistic transporting particles hundreds and thousands of km away from the parent crater. However, the 3D view of the plume obtained can then be used to model the condensation history of vapor and the recrystallization behavior of melt droplets. If chemical reactions lead to substantial energy re-distribution within the plume, we can take into account this heating (or cooling) in the subsequent set of gas-dynamic iterations. Calculations [17] were not coupled to a realistic dynamic model of plume physics, however, they indicated a highly oxidized plume (due to carbonate and sulfate sediments) that condenses silicate liquid droplets bearing spinel grains of compositions close to those found at the KT boundary.

Bridging the gap: Until recently the results of numerical modeling, based on poorly known initial conditions, could be compared only with old and, hence, not well-preserved geological features. Extension of impact models into volcanology [18] allows us to compare the results of a volcanic direct blast (which is very similar to an impact generated plume in many respects). For example, recorded blast dynamics and fresh geological records at Mt. St-Helens and Bezymianny volcanoes. NASA's Deep Impact experiment [19] opened a new era in impact plume studies, allowing us for the first time to observe an impact plume *in situ* under well-controlled initial conditions.

References: [1] Melosh H.J. (1989) *Impact cratering: A geological Process*, 264 pp. [2] Sugita S. et al. (1998) *JGR 103*, 19427-19441. [3] Mukhin et al. (1989) *Nature 340*, 46-48. [4] Ishibashi K. et al. (2006) *LPS 37*, Abstr. #1721. [5] Valentine G.A. and Wohletz K.H. (1989) *JGR 94*, 1867-1887. [6] Shuvalov V. (1999) *Shock Waves 9*, 381-390. [7] Rivard W.C., Torrey M.D. (1977) *LA-NUREG-6623 NRC-4* [8] Goldin T. J., Melosh H. J. (2007) *LPS 38*, Abstr. #2114. [9] Stöffler D. et al. (2002) *M&PS 37*, 1893-1908. [10] Artemieva et al. (2004) *GGG 5*. [11] Montanari A., Koeberl C.(1999) *Impact stratigraphy: The Italian Record*, 364 pp. [12] Pierazzo E. et al. (1998) *JGR 103*, 28607-28626. [13] Artemieva N. and Morgan J. (2007) *LPS 38*, Abstr. #1543. [14] Zeldovich Y. B. and Raizer Y.P. (1966) *Physics of shock waves and high temperature phenomena.* [15] Smit J. (1999) *Ann. Rev. Earth Planet. Sci. 27*, 75-113. [16] Morgan J. et al. (2006) *EPSL 251*, 264-279. [17] Ebel D.S., Grossman L. (2005) *Geology 33*, 293-296. [18] Artemieva N. (2006) LPS 37, Abstr.#1525. [19] A'Hearn M.F. et al. (2005) *Science 310*, 258-264.