IMPACT EJECTA MECHANICS: ATMOSPHERIC INTERACTION AND FRAGMENT-SIZE DISTRIBUTION FROM NUMERICAL MODELING.
R. Luther[1], M. –H. Zhu[1,2], K. Wünnemann[1] and N. A. Artemieva[3,4], [1]Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science (Invalidenstraße 43, 10115 Berlin, Germany, robert.luther@mfn-berlin.de), [2]Space Science Institute, Macau University of Science and Technology, Taipa, Macau, [3]Planetary Science Institute, Tucson, USA, [4]Institute for Dynamics of Geospheres, RAS, Russia.

Introduction: Impact craters form through the displacement and ejection of material. Most of the debris expelled from a crater is deposited as a more or less continuous ejecta blanket whose characteristics depend on the distance to the point of impact, target properties, and the presence or absence of an atmosphere. Scale and material depending fragmentation will produce particles of various sizes. Trajectories of small particles as dust, spherules or condensation products can deviate from the well understood ballistic trajectory due to the interaction with an atmosphere or an expanding impact plume. Large plumes or atmospheric stratification cannot be produced in laboratory experiments. Therefore, calibrated and validated numerical models are a powerful tool for a systematic study of ejecta distribution as a function of material properties, impact velocity, impactor size, and atmosphere.

For calibration, we use data from the MEMIN (Multidisciplinary Experimental and Numerical Impact Research Network) impact experiments at the Fraunhofer Ernst-Mach Institut: various projectile materials (e.g. aluminium, Campo de Cielo iron meteorite) with a mass of ~100 mg and ~5 g are accelerated up to 5-8 km/s to impact onto geological target materials (e.g. sandstone, marble) at the two light gas gun facilities SLGG and XLLGG, respectively [e.g. 1]. Ambient pressures in the target chambers are ~1 mbar and ~300 mbar, respectively. In the case of the XLLGG, pressure is reduced to ~50 mbar and then increased again by N_2 gas. Ejecta catchers and high-speed cameras are used to analyse ejection velocity, angle, fragment size and launch position [2,3].

The goal of this study is to simulate the fragmentation of the target prior to ejection to quantify the size-frequency distribution (SFD) of ejecta and the flight behaviour of the ejected particles in the atmosphere of the target chamber. In a further step, we plan to use the validated models to investigate the ejecta distribution on natural scale and as a function of different target properties and varying atmospheric conditions (e.g. Moon, Mars, Earth, and Venus) more systematically.

Methods: We use the iSALE shock physics code [4-6]. The strengths of iSALE are: (1) the different available material models (brittle/ductile rheology), (2) the damage model, and (3) the various equations of state that can be combined with a porosity compaction model [6]. For this study, we added to the standard iSALE package the Grady-Kipp fragmentation model that enables to estimate the SFD of matter as a function of tensile failure [7] and a dusty flow model [10] that allows for simulating the interaction of small particles with the gas in the target chamber.

Fragmentation: The Grady-Kipp model assumes that any natural rock contains a system of flaws. Application of the Weibull SFD of these flaws gives the possibility to describe the strain-rate and specimen-size dependencies of the tensile strength (Fig. 1). Following the approach by [8], we calculate the damage D in each time step for each cell according to Eq. 1:

$$\frac{dD^{1/3}}{dt} = \frac{(m+3)}{3}\alpha^{1/3}\varepsilon^{m/3} \quad (1)$$

where ε is the effective strain from principal stress tensor, $\alpha = 8\pi c_g^3 k/((m+1)(m+2)(m+3))$ in which c_g is crack growth velocity, m and k are the Weibull constants that can be estimated from experiments (e.g. for basalt: $k = 10^{33}$ m^{-3}, m = 9.5) [8,9]. The mean fragment size is derived from the total fracture area $A(t)$, which can be derived from:

$$\frac{dA}{dt} = \frac{(m+2)(m+3)}{2c_g}\alpha^{2/3}\varepsilon^{2m/3}D^{1/3} \ . \quad (2)$$

The peak of SFD for each cell is calculated based on the total fracture area at the time when D = 1 (total damaged) is achieved [8,9].

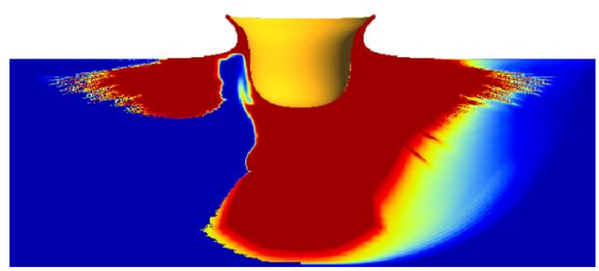

Figure 1: Snapshot of tensile (left panel) and total damage (right panel) for a basalt impactor on a basalt target at a velocity of 6.5 km/s. The blue colour represents intact material, red represents completely damaged material.

Dust: We follow the in-code approach [10-12], and activate representative particles (RP) when material is ejected. RP are characterized by size, shape and their own velocity. They interact with the surrounding gas phase (MEMIN: 300 mbar N_2 atmosphere, perfect gas). In contrast to the flight in vacuum, it is important to take the SFD of ejected fragments into account. Each RP represents a certain size-class of the ejecta SFD that will be obtained from the fragmentation model. However, in a first step, we use empirical particle SFD from the MEMIN experiments [2, 3].

The main forces exerted on the ejected particles are gravity $\boldsymbol{g}$ and drag by a surrounding gaseous medium:

$$m\frac{d\boldsymbol{v}}{dt} = m\boldsymbol{g} + C_D \pi r^2 \rho_g |\boldsymbol{v}_g - \boldsymbol{v}|(\boldsymbol{v}_g - \boldsymbol{v}) + 6\pi r \mu (\boldsymbol{v}_g - \boldsymbol{v}), \quad (3)$$

where C_D is the drag coefficient, m and r the particle mass and radius, ρ_g and μ are gas density and viscosity, and $\boldsymbol{v}$ and $\boldsymbol{v}_g$ are the particle and gas velocity. The second term represents standard high-velocity drag, the third describes Stokes' force. Eq. (3) is coupled with the momentum exchange equation to update particle and gas velocity.

Results: In general, the Grady-Kipp fragmentation model could reproduce the largest size and SFD for the fragments. For tensile damage, the fragmentation zone is strongly related to the damage zone. The largest fragment size depends on the fracture area: the larger the fracture area, the smaller the size of the largest fragment in the cell.

We evaluate the ejection of the fragmented material and describe ejection velocity and angle for the corresponding launch positions (Fig. 2). Using the ejecta scaling fit, we find the values of the parameters μ_{ej}=0.61 and C_1=0.15 for the sandstone:

$$\frac{v}{v_{Imp}} = C_1 \left[\frac{x}{a}\left(\frac{\rho}{\delta}\right)^{\nu_{ej}}\right]^{-\frac{1}{\mu_{ej}}}, \quad (4)$$

where v_{Imp} is the impact velocity, a the projectile radius, ρ and δ the target and projectile densities, respectively, and ν_{ej}=0.4. The average ejection angle is ~49°.

RP are initiated with the given ejection velocity and angle, then they move within a gas according to Eq. (3) and exchange momentum with this gas at each time step. After ejection into the atmosphere, the drag decelerates the RP, which transfer momentum to the gas. In Fig. 3 we show trajectories for two RP that represent 12 and 5520 dust particles with a radius of 0.5 mm and 0.05 m, respectively, in a previously undisturbed atmosphere and one Earth gravity. We assume spherical particles with a C_D of 0.5.

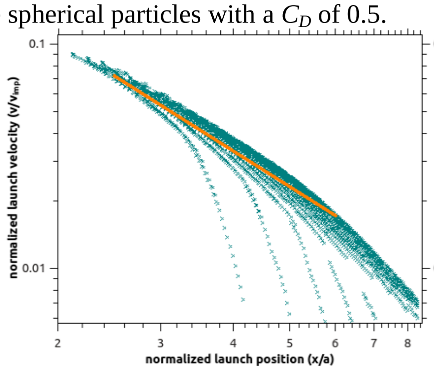

Figure 2: Ejection Velocity at normalized launch position for an impact of iron into sandstone (impact velocity 4.5 km/s). The simulation corresponds to experiment nr. E1 [3]. The orange line shows the scaling fit according to Eq. (4).

Discussion: The models show a slightly smaller damage factor for ejecta originating from the spallation zone than from other areas. This means that the fragment size of ejecta as a consequence of tensile damage is smaller than those fragments that are expelled from the spallation zone. Further work is required to validate the modelled ejecta SFD against experimental data. The SFD of ejecta is a key input parameter for the dust model to study the flight behaviour of the ejected particles in the atmosphere for large-scale impact events. So far, we employed an ejecta SFD measured by Sommer et al. [2] in the MEMIN experiments into our dust model. The resulting trajectories in the case of undisturbed atmosphere overlap for both size classes in the range of the target chamber (<1 m) and thus agree with the experiment, where no sorting by size was observed in the catchers. As a next step, we will also analyse RP in a disturbed atmosphere (e.g. by the projectile entry).

Considering different material properties from layers in the target, we see a possible application of our model for the study of layered ejecta blankets on Mars.

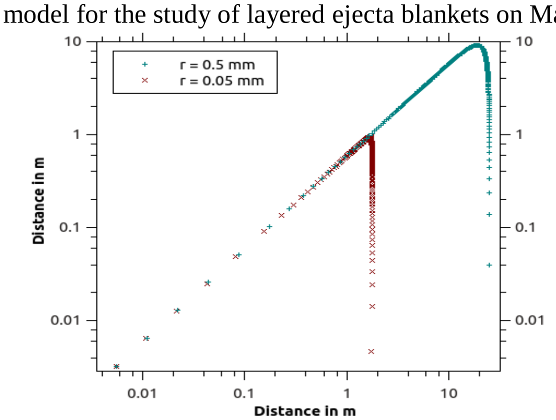

Figure 3: Trajectories of two RP. The cyan trajectory represents 12 dust particles (+ symbol) and the red one 5520 dust particles (x symbol). After horizontal deceleration, the RP show only one velocity component in gravity direction.

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References: [1] Poelchau M.H. et al. (2013) *Meteorit. & Planet. Sci., 48*, 8-22. [2] Sommer F. et al. (2013) *Meteorit. & Planet. Sci., 48*, 33-49. [3] Buhl E. et al. (2014) *Icarus, 237*, 131-142. [4] Amsden A. et al. (1980) *LANL, LA-8095*, 101. [5] Collins G.S. et al. (2004) *Meteorit. & Planet. Sci., 39*, 217-231. [6] Wünnemann K. et al. (2006) *Icarus, 180*, 514-527. [7] Grady D. E. and Kipp M. E. (1978) *Int. J. Rock Mech. Min. Sci. Geomech., 17*, 147 – 157. [8] Melosh H. J. et al. (1992) *JGR, 97*, 14,735-14,759. [9] Ivanov B. A. et al. (1997) *Int. J. Impact Engng., 20*, 411-430. [10] Shuvalov V.V. (1999) *Shock Waves 9*, 381-390. [11] Artemieva N.A. and B. Ivanov (2004) *Icarus, 171*, 84-101. [12] Artemieva N.A. et al. (2013) *Meteorit. & Planet. Sci., 48*, 590-627.