EFFECTS OF ATMOSPHERE ON EJECTA EMPLACEMENT ON EARTH AND MARS. M. C. Carlson[1], B. C. Johnson[1,2] and H. J. Melosh[1,2,†], [1]Purdue University, Department of Physics and Astronomy, West Lafayette, Indiana, USA (Carls113@purdue.edu), [2]Purdue University, Department of Earth, Atmospheric, and Planetary Science, West Lafayette, Indiana, USA. [†]Deceased 09/11/2020

Introduction: During the excavation stage of crater formation, the material excavated from an impact crater forms an ejecta plume. Under vacuum, this material follows a ballistic trajectory in which the leading edge forms an ejecta curtain [1]. The expansion of the ejecta plume under vacuum has been well studied and relationships between the excavated debris' speed and the radius at which it leaves the crater have been developed [2]. However, within even the most tenuous atmosphere the ejecta interacts with the atmospheric gases and deviates from its ballistic path as it loses both energy and momentum. Previous numerical studies on the shape of ejecta curtains have relied on using a simple drag coefficient to model curtain formations in given atmospheric conditions [3,4]. However, such an approach may not account for the energy and momentum transfer from the particulates to the surrounding atmosphere. Through altering the characteristics of both the ejecta and the atmosphere, we can observe patterns in ejecta curtain simulations under different conditions. Our work aims to demonstrate the effects of varying atmospheric conditions (such as those on Earth and Mars) on the formation of ejecta curtains.

Methods: KFIX, an Eulerian hydrocode developed at Los Alamos National Lab in the 1970s, is capable of modeling dual-material and dual-phase flows [5]. By modeling both the ejecta material and the atmosphere as linked, continuum fluids rather than individual particles, we can effectively capture the interactions between the ejecta and the atmosphere while conserving energy and momentum. If one chooses the first phase to be the atmosphere and the other to be the particulates ejected from the crater, the exchanges of energy and momentum between the ejecta curtain and the atmosphere can be accurately modeled by KFIX [6], given suitable equations of state for the gas (we assume an ideal gas with an appropriate mean molecular weight) and solid (we use a stiffened gas equation of state [7] for basalt). We also take into account the fragment size distribution to accurately model the drag [8].

Prior to the first computational time step, the atmosphere is pre-stressed to create a pressure, temperature, and density gradient in the mesh comparable to that near the surface of Mars or the Earth. The impact axis and plane are free slip boundaries, preventing the loss of material from the computational area through the ground. The top and far right edges are outflow boundaries, allowing material to leave the computational area and not rebound. The ejected debris is introduced in the lower left boundary of the mesh through an inflow boundary to model a crater 2 km in diameter.

The excavation flow of ejecta follows the established relationship between the material's radius from the point of impact and the speed at which it is ejected [2]. The material is ejected with an initial angle of 60° at the impact axis which decreases linearly to 30° at the crater rim. The inflow boundary at the lower left of the computational region is partitioned into ten areas of ejecta injection. The flow of this material into the computational region, or atmosphere, is determined by the duration of crater formation in the simulation. At the beginning of the simulations, all these cells immediately start injecting material at a rate determined by Pi-scaling predictions [2]. The cell transition from active to inactive occurs smoothly, with the cells nearer to the point of impact active for less time than the outer cells. This design ensures that the mass injected into the computational area follows the relationship between excavated mass and radius established in Maxwell's Z-model [9]. Material close to the impact point is ejected at high speed and the ejecta nearer the transient crater rim is ejected at a lower velocity. The mass injected per unit time stays constant through excavation for each cell, but the mass injected per unit radius increases for the inflow cells closer to the rim of the transient crater. In this way, we ensure that the simulated ejecta plume's behavior is physically consistent with accepted models.

KFIX accepts a variety of input parameters to modify the event modeled. Those most relevant to ejecta curtain studies include fluid pressure and density, gravity, crater size, and temperature. Through these parameters, we can accurately model crater excavation in a variety of atmospheric environments, including Earth and Mars.

Results: Since the ejecta is modeled as a continuum fluid, we need a way to track the shape of the ejecta cloud. To do this, we inject tracer particles to follow the leading and trailing edges of the ejecta cloud as the simulation progresses. These tracer particles take an average of the velocities of the closest cells each time step to determine their movement that step.

Results of Martian impact. We model an impact cratering event on current-day Mars using typical physical quantities: gravity-3.71 m/s^2, impactor speed-7 km/s, temperature-120 K, surface pressure-610 Pa, molar mass of atmosphere-44 g/mol, ejecta density-3000 kg/m^3. The crater simulated is 1 km in radius.

For the Martian case, we do see some small effects of atmospheric interactions. As the injected material encounters the atmosphere, the tip of the ejecta cloud begins to decelerate, which increases the density of tracer particles at the top of the ejecta cloud. This effect can be seen in Fig. 1, which shows the time evolution of the tracer particles tracking the leading and trailing edges of the ejecta cloud. However, the majority of the mass follows the ballistic trajectory we see in vacuum cases. After 100 seconds of simulation, there is 0.5 million kg of ejecta suspended in the atmosphere (after nearly 7 million kg has been injected into the simulation).

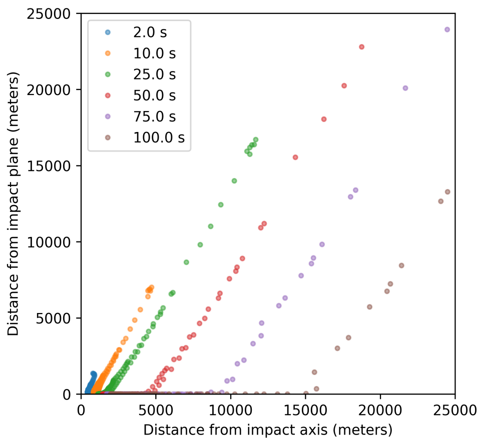

Figure 1 - Ejecta curtains at different times on Mars. The points on this graph are the tracer particles showing the leading and trailing edges of the ejecta cloud. Each color corresponds to a different time in the simulation. The crater and injection cells are in the bottom left corner of the graph.

Results of terrestrial impact. We model an impact cratering event on Earth using typical physical quantities: gravity-9.81 m/s^2, impactor speed-20 km/s, temperature-278 K, surface pressure-10^5 Pa, molar mass of atmosphere-28 g/mol, ejecta density-3000 kg/m^3. The crater simulated is 1 km in radius.

We see strong evidence of atmospheric interactions on Earth. We see the deceleration of the ejecta at the tip of the ejecta cloud, as we did with the Martian case, but we also see that the atmosphere impedes the ejecta cloud's progress, both vertically and radially. This can clearly be seen in Fig. 2. In addition, at the 100s mark, the ejecta has lost so much momentum that it is almost completely entrained by the atmosphere. This causes it to be lofted by vortices created in the atmosphere until it eventually settles and is deposited on the ground.

After 100 seconds of simulation, 1.5 million kg of material is still suspended in the atmosphere, three times as much as the Martian case. In addition, the rate of settling is significantly slower for Earth, leading us to believe that impact ejecta on Earth would continue being suspended in the atmosphere much longer than ejecta on Mars created from a similar impact.

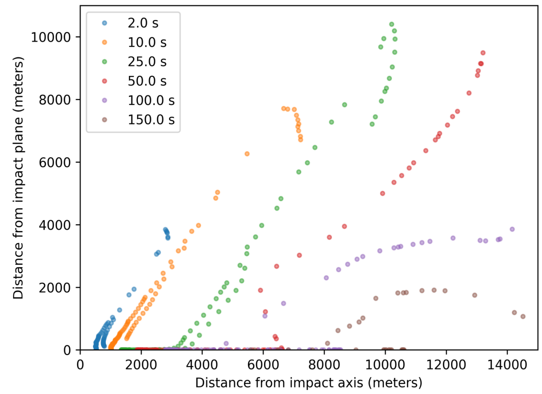

Figure 2 - Ejecta curtains at different times on Earth. The points on this graph are the tracer particles showing the leading and trailing edges of the ejecta cloud. Each color corresponds to a different time in the simulation. The crater and injection cells are in the bottom left corner of the graph. Note that this figure has a different vertical scale as compared with Fig. 1.

Discussion: Ries crater has long been a mystery, owing to the inverted layers of suevite on top of breccia [10]. In terms of ejecta, what this means is that there was a mass of mostly ballistic material that was deposited first and after some time (possibly up to half an hour), melted ejecta was deposited on top. Simulations seem to indicate that the atmosphere plays a large part in this occurrence. Another debated mystery is the multi-layered ejecta blankets seen on Mars. However, atmospheric interactions have significantly less influence in creating the abnormal ejecta blanket morphologies seen on Mars, since the atmosphere is not dense enough to create any meaningful deviations from standard ballistic trajectories. This supports the hypothesis that fluids or icy surface layers are responsible for these morphologies on Mars.

References: [1] Melosh, H. J. (1989), Impact Cratering. [2] Richardson, J. E. et al. (2007), Icarus 191, 176-209. [3] Schultz, P. and Gault, D.E. (1979), JGR 84, 7669-7687. [4] Barnouin-Jha, O. and Schultz, P. (1996), JGR 101, 21,099-21,115. [5] Rivard, W.C. and Torrey, M. D. (1976), LA-NUREG-6623. [6] Harwell, M.L. and Melosh, H. J. LPSC 48, #1964. [7] Lemons, D.S. and Lund, C.M. (1999) Am J. Phys 67, 1105. [8] Melosh, H. J. (2020). LPSC 51 #2587. [9] Maxwell, D.E (1977). Impact and Explosion Cratering, 1003-1008. [10] Osinski, G. et al (2016). Meteoritics & Planetary Science.