INTERACTIONS BETWEEN HYPERVELOCITY IMPACT EJECTA AND PLANETARY ATMOSPHERES: FROM THE EARLY EARTH TO MARS. T. J. Goldin[1] and C. Koeberl[1,2], [1]Department of Lithospheric Research, University of Vienna, A-1090 Vienna, Austria (tamara.goldin@univie.ac.at), [2]Natural History Museum, Burgring 7, A-1010 Vienna, Austria (christian.koeberl@univie.ac.at).

Introduction: Large impacts produce tiny molten droplets, which can travel great distances ballistically at high velocities. On Earth, the resulting deposits are preserved in stratigraphy as impact spherule layers of early Archean to Phanerozoic ages [1]. Fine-grained ejecta deposits have also been observed around craters on Venus and Mars [2]. Differences between distal ejecta deposits on the three planets have been attributed to differences in the formation and transport of particles from the impact event as well as differences between the atmospheres through which the particles must descend [3]. Although it is fairly simple to calculate how a single particle (e.g. a micrometeorite) descends through an atmosphere, the arrival and deceleration of many hypervelocity particles is more complex [4], requiring a numerical treatment of the ejecta-atmosphere mixture.

Previous numerical models [4,5] have examined the interactions between ejecta from large Phanerozoic impact events and the modern Earth's atmosphere. Here we examine the effect of atmospheric structure on ejecta-atmosphere interactions and the implications for ejecta descent through the O_2-poor Archean Earth's atmosphere, the relatively thin atmosphere of Mars, and the relatively thick atmosphere of Venus.

Numerical Modeling: Ejecta descent through a range of atmospheres was modeled using the two-phase fluid flow code, KFIX-LPL [4], which has been modified from KFIX [6] to accommodate ejecta fall through an atmosphere from the free molecular to continuum flow regimes. The ejecta phase is approximated as identical basaltic spheres (250 μm), which reenter the atmosphere at 45 degrees at speeds not exceeding the planet's escape velocity. Assumed to behave as an ideal gas, the initial model atmosphere is isothermal with a pressure gradient that decays exponentially upwards as a function of the atmospheric scale height. For these preliminary investigations, which are not tied to specific impacts, the ejecta reenter the upper atmosphere at a constant flux of 0.005 kg/m²-s, on the order of that expected for distal ejecta from a Chicxulub-sized impact [7]. A range of initial atmospheres are considered, including that of the modern and Archean Earth, as well as the cold, thin Martian and hot, dense Venusian atmospheres.

Results: Ejecta reentry through air was first modeled for a range of scale heights by varying the force of gravitational acceleration and initial atmospheric temperature, but keeping the surface pressure fixed. The particles decelerate through the upper atmosphere, become hot, heat the surrounding gas via friction, and radiate their remaining heat as thermal radiation. The altitude at which the particles reach their fall velocities has a linear dependence on the atmospheric scale height (Fig. 1). The upper atmosphere is heated to ~3200 K and the spherules to 1300 K, regardless of scale height (for this particular spherule flux, velocity, size). This is to be expected because the stopping height is determined by the mass of atmosphere displaced—thus the particles reach their fall velocities at higher altitudes for longer scale heights and since the total mass of air molecules encountered is approximately the same regardless of scale height, the frictional heating is similar.

While the exercise above involves taking the same mass of atmosphere and spreading it out to various distances, atmospheres on different planetary bodies contain different masses. Thus, the stopping altitude is strongly dependent on the surface pressure (Fig. 2). For a given scale height, increasing the surface pressure also increases the particle stopping altitude.

Archean Earth. Despite the weaker luminosity of the early Sun, evidence that liquid water persisted on the Archean Earth suggests surface temperatures above freezing. This paradox has been explained by a higher concentration of atmospheric CO_2 [8], perhaps as high as ~0.2 bars [8], although recent models suggest it may have been much less [9]. The N_2 content is thought to have remained unchanged, thus the total surface pressure in the Archean (~1 bar), assuming the higher CO_2 estimates, is similar to the modern atmosphere and the scale height is only slightly reduced by the increased molar mass of an N_2-CO_2 atmosphere vs. the modern N_2-O_2 atmosphere. For identical reentry scenarios at 5 km/s, the Archean spherules fall ~5 km farther and become ~20 K hotter than modern spherules before reaching their terminal velocities, but overall the models are similar.

Despite the similar atmospheres, Archean impact spherules are, on average, larger (~1 mm [1]) than those in younger terrestrial deposits and models predict maximum spherule temperatures 200 K hotter and enhanced heating of the surrounding atmosphere for particles of this size. Additionally, the spherule densities in Archean deposits, compared to their Phanerozoic counterparts [1], suggest larger impacts with higher reentry fluxes. For purposes of comparison, a constant flux is used in all the simulations, but larger fluxes

result in increased energy deposition and associated heating of the upper atmosphere.

Mars and Venus. A simplified modern Martian atmosphere is modeled as initially isothermal (220 K) CO_2 gas with a surface pressure of 0.6 kPa and gravitational acceleration of 3.7 m/s². The modern Venusian atmosphere is also assumed to be CO_2 gas, but hotter (700 K) and with more Earth-like gravity (8.9 m/s²). For comparison, the spherules enter both atmospheres at 5 km/s, which is approximately the escape velocity of Mars and is also consistent with expected Martian plume expansion velocities (~1/2 the impact velocity [10]). The model ignores Venus' strong zonal winds.

Due to the high surface pressure and hot initial temperatures, particles in the Venusian atmosphere reach their fall velocities at 200 km. In contrast, particles in the (initially) cold Martian atmosphere are able to penetrate to <50 km in altitude. For identical reentry scenarios the atmospheres reach similar temperatures for Earth, Mars, and Venus, although the altitudes affected vary due to the different deceleration distances.

Discussion: The numerical models show that the upper atmospheres of the modern Earth, the Archean Earth, Mars, and Venus all respond to the injection of high speed impact ejecta in the same general way.

The fate of the energy delivered to the atmosphere by high velocity impact ejecta has important astrobiologic implications for the early Earth and other planets with atmospheres. Not only does the heating of the upper atmosphere affect post-impact atmospheric geochemistry on a potentially global scale, but some portion of this energy reaches surface environments as thermal radiation. The preliminary simulations do not currently include gas opacity in the thermal radiation transfer calculation. Greenhouse gases in the modern atmosphere absorb ~50% of the downwards thermal radiation emitted by the decelerating ejecta [4], so an Archean atmosphere with as much as 100-1000× the modern CO_2 partial pressure may shield the surface and early life from deadly doses of radiant heat despite increased heat emission by larger spherules and larger spherule fluxes. Implementation of an equation of state that includes ionization of CO_2 is also needed for more accurate temperature calculations for CO_2-rich atmospheres.

Acknowledgements: This work was supported by the Lise Meitner Program of the Austrian Science Foundation- FWF, project M1179-N13

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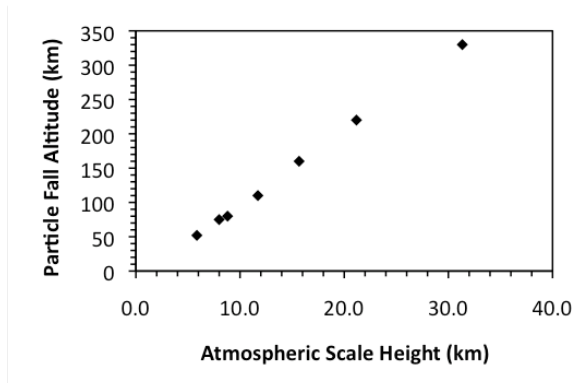

Fig 1. Altitude at which spherules reach their fall velocity as a function of atmospheric scale height. In all simulations, spherules are 0.25 mm in diameter and are injected into standard air at 45 degrees, at 8 km/s, and at a constant flux.

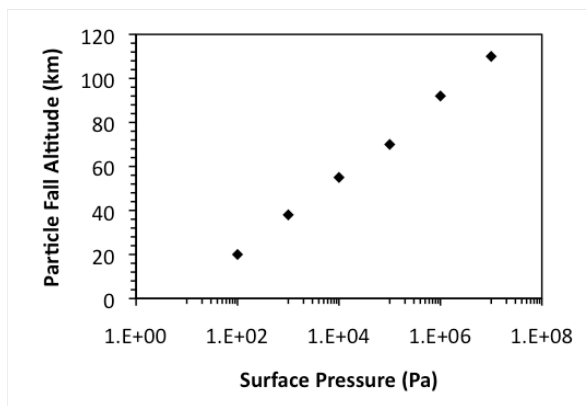

Fig 2. Altitude at which spherules reach their fall velocity as a function of surface pressure for atmospheres an Earth scale height. In all simulations, spherules are 0.25 mm in diameter and are injected into standard air at 45 degrees, at 8 km/s, and at a constant flux.