A NUMERICAL MODEL TO CONSTRAIN THE ORIGIN OF LUNAR IMPACT EJECTA.

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Introduction: Terrestrial planets and moons in the solar system, such as Mercury, the Moon, and Mars, all contain heavily cratered surfaces suggesting an intense amount of bombardment in the early solar system. It has been proposed that these planets experienced an intense bombardment period between ~4.1-3.7 Ga, the so-called Late Heavy Bombardment (LHB) [1], which could have been triggered by planetary migration [e.g., 2]. However, recent studies have cast doubt on this hypothesis for several reasons. First, the shock age dating methods based on $^{40}Ar/^{39}Ar$ have more uncertainties than originally expected [3]. Another key reason is that a large impact, the Imbrium basin in particular, could have produced a large amount of ejecta and contaminated nearby craters. This could have led to the interpretation of the apparent spike in the impact flux during the time period, but the extent of contamination is not well constrained. Given that crater chronology of the solar system is based on the lunar craters, it is important to quantify the effect of contamination.

The ultimate goal of this work is to quantify the effect of contamination on Apollo samples ages due to ejecta from nearby craters. To achieve this goal, we conduct a number of impact simulations to quantify (1) the amount of ejecta produced by impact and their distribution, and (2) pressure-temperature conditions of the ejecta. This information will be used to identify the origin of any Apollo sample.

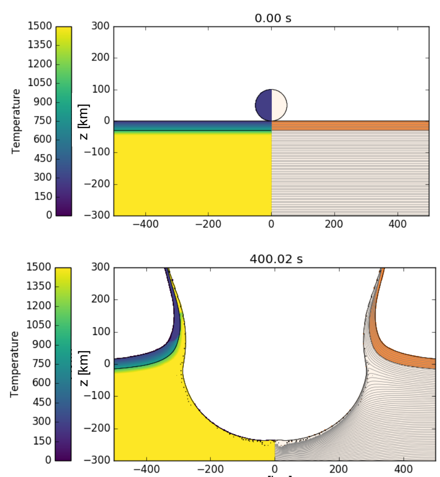

Figure 1. Snapshots of the Imbrium Basin forming impact. The color gradient shows the temperature (left) and the light orange, dark orange, and grey show the impactor, crust, and mantle (right).

Methods: We use the impact code called iSALE, which is a multi-material, multi-rheology shock physics code. Tracers are implemented in each simulation in order to track properties of materials throughout the entire impact event. We explore various impact basins whose sizes range from 100 km to several 1000s of km in diameter. For basins smaller than 1000 km, we use flat target geometry (see Figure 1) [e.g., 4]. We run an array of simulations with varying impact parameters resulting in impact basins spanning this entire range. With known impact parameters, the final basin size is approximated with known scaling laws [5]. We then interpolate the results of this simulation array to create impact data from any impact basin with final diameters in this range.

We take a separate approach to model the South Pole-Atkins basin, which is 2500 km in diameter and the largest basin on the Moon. We run a simulation with a spherical geometry because the curvature of the Moon is important for such a large basin [6].

Ejecta Distribution: We define ejecta as materials that travel above the pre-impact surface [7]. Most ejecta travel farther than the domain of the simulation, and are their landing locations are not recorded directly in the simulations. Moreover, the dynamics of the ejecta may not be accurate in the simulations, and therefore we calculate the landing locations as follows; as soon as ejecta travel above the pre-impact surface, we compute their ballistic trajectories to calculate their final landing locations [6]. We assume a spherical geometry for this part of the calculation regardless of the basin sizes. This is because even though the impact simulations can be run using flat geometry, most ejecta flies 1000s of kilometers outward and upward before landing, and therefore the curvature of the target body, and height differing gravitational potentials must be taken into account. The ejecta landing locations are calculated via central force Lagrangian equations.

Kernel Density Estimates: Using the respective mass or volume of each tracer and their landing location, we generate a kernel density estimate (KDE) (continuous histogram) of the amount of material at given landing location and peak pressure. Figure 2 show the proportions of ejected mass landing at every location. KDE is also utilized to show the abundances of tracers that that experienced each peak pressure during the impact. Figure 3 shows the proportions of ejected mass that experience every peak pressure up to 200 GPa.

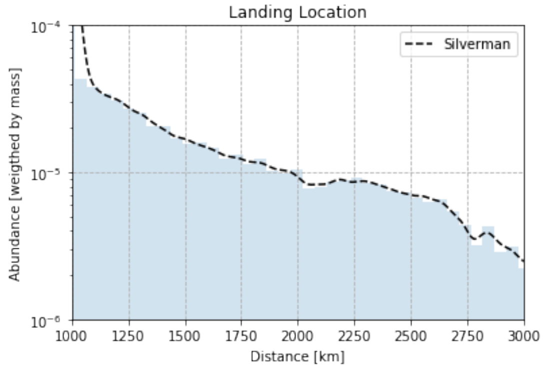

Figure 2. The landing locations of ejecta from Imbrium basin. The KDE is generated by adding up gaussians centered at each data point. The bandwidth and amplitude of every gaussian is determined by Silverman's rule [8].

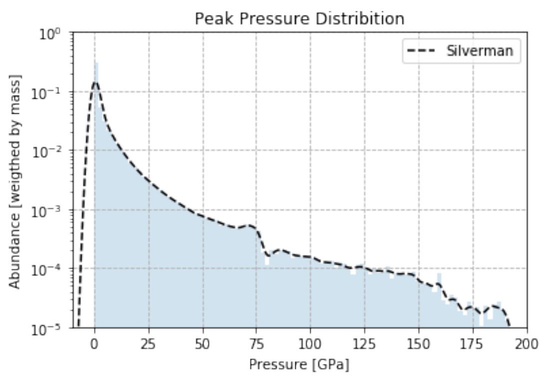

Figure 3. Peak pressures of ejecta from Imbrium basin.

We use 2D KDE to create continuous 2D histograms with peak pressure on one axis, and landing locations of the other axis as shown in Figure 4. This creates a visualization of both variables.

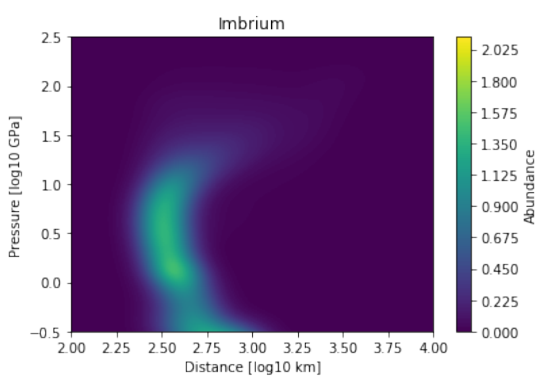

Figure 4. Combining the landing locations and peak pressures creates a 2D array of values that can be used to extract peak pressures at any location of the Moon.

A vertical cross section of this 2D KDE at a given landing location gives the local peak pressure distribution at that distance from the impact. For each simulation, this makes it possible to extract the local pressure distributions at any distance from the center of the impact basins.

Combining Simulations: We now define the locations of all relevant impact basins on the Lunar surface. Given any sample location, it is only a matter of adding up the local peak pressure distributions contributed by each impact basin. An example calculation is shown in Figure 5, which shows the peak pressure profile contributions from Imbrium and Serenitatis basins. Our preliminary result indicates that samples near the Apollo 11 landing site is more likely from the Serenitatis impact than from the Imbrium basin in the peak pressure range of 10^0-10^2 GPa.

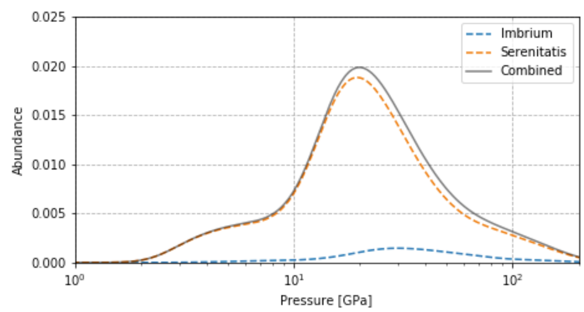

Figure 5. The peak pressure distributions from each impact basin contribute to the total peak pressure distribution at the Apollo 11 Landing Site.

Thus, our model can determine the peak pressure profile of material at any location on the Moon, if the material originated from one of the included impact basins.

References:

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