LCROSS IMPACT PREDICTIONS. D. G. Korycansky[1], C. S. Plesko[1,2], E. Asphaug[1], [1]*CODEP/IGPP Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064*, [2]*Los Alamos National Laboratory, Los Alamos NM 87545.*

The Lunar CRater Observation and Sensing Satellite mission (LCROSS) [1] will use the second stage of the LRO/LCROSS mission launch vehicle as a kinetic impactor to strike the lunar surface at a permanently shaded location yet to be determined. (The current recommended target is the floor of Shoemaker crater near the Moon's south pole.) The second stage will be a Delta IV or Atlas V booster of dimensions ~ 10 m $\times$ 2 m and mass ~ 2000 kg. The impacting stage will be chased by a second shepherding spacecraft (S/SC) that will observe the impact at close range before striking the lunar surface itself. The impact will be monitored by various Lunar-orbital and Earth-based instruments. It is therefore necessary to verify that the impact will pose little risk to instruments in Lunar orbit, and to model the expected results of the impact in order to plan and deploy the most effective observational campaign.

Accurately modeling the EDUS impact and its aftermath is a challenging problem. The impactor is a complicated structure and would require inordinately high resolution for precise description in a hydrocode. Crucial aspects of the target are as yet unknown and difficult to model, such as the depth of regolith at the impact site and its material properties (strength, fragmentation, etc.) For this reason, it is necessary to rely not only (or even primarily) on numerical modeling, but also experimental results and analytical models based on them. All approaches have their uses and contribute information to the task of guiding the design of the LCROSS mission. Given that the present goal is mission design, such a variety of approaches and the corresponding range of results will very likely prove more useful in bracketing the expected outcomes, rather than a highly focused prediction that would undoubtedly miss the mark due to unanticipated factors.

The hydrodynamic codes available to us include RAGE, developed at Los Alamos National Laboratories[2], and ZEUS-MP, a three-dimensional hydrocode developed by M. Norman and others [3]. We also present Monte Carlo models for the ejecta based on analytical models covering the expected range of parameters. In the following sections we describe each modeling effort in turn.

Analytical models of the carter and ejecta curtain

Semi-empirical scaling models for the crater diameter and ejecta are useful for our predictions[4,5]. Pi-scaling estimates for a a solid, spherical aluminum impactor of standard density of 1.15 m diameter and 2.5 km s^{-1} impact velocity predict a crater of diameter $D = 18$ m, depth $d = 4.9$ m, and formation time $t = 1.8$ s. The total ejected mass $M_e = 6.5 \times 10^5$ kg. For a 5 m diameter sphere of bulk density 0.03 gm cm^{-3} (simulating a hollow cylindrical rocket stage), with a total mass of 2000 kg impacting at 2.5 km s^{-1} at 70° from horizontal, into a 401.5 gm cm^{-3} , the crater is smaller ($D = 13$ m, $d = 3.7$ m, $t = 1.5$ s, $M_e = 3.4 \times 10^5$ kg).

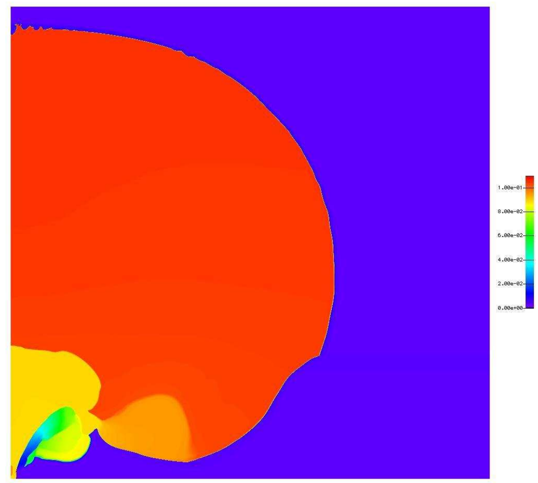

Figure 1: RAGE: Plume temperature at $t = 0.05$ s. The color scale is proportional to temperature from 0 to a maximum temperature of $T = 1230$K.

For the ejecta, we use the simple ballistic-trajectory model based on scaling rules [5]. Ejecta are shot outward and upward at a constant angle $\theta \approx 45°$ from the horizontal, and the ejecta velocity v at radial position x, and volume $V_e(<x)$ of ejecta x, in a crater of radius R are given by

$$\frac{v}{\sqrt{gR}} \propto \left(\frac{x}{R}\right)^{(\alpha-3)/2\alpha}, \quad \frac{V_e(<x)}{R^3} \propto \left(\frac{x}{R}\right)^3. \qquad (1)$$

The cumulative distribution of the amount of ejecta mass m launched with velocity V or greater is

$$m(>V) = M_e \left[\left(\frac{V}{v_{min}}\right)^{6\alpha/(\alpha-3)} - \left(\frac{v_{max}}{v_{min}}\right)^{6\alpha/(\alpha-3)} \right]. \qquad (2)$$

(A normalization factor $1 - (v_{max}/v_{min})^{6\alpha/(\alpha-3)}$ in the denominator is nearly 1 for $v_{max} = v_{esc} \gg v_{min}$ as is the case here.)

Ejecta are assumed tp follow parabolic trajectories, resulting in simple expressions for the maximum height z_{max} reached by the particles, and corresponding expressions for fractional mass that reaches a given height z. The basic parameters in the model are $v_{min} = (gR_{crat})^{1/2}$, α, M_e, and θ.

RAGE: Initial thermal plume modeling

RAGE is a version of the SAIC Adaptive Grid Eulerian hydrocode. It is a compressible Eulerian hydrodynamics code that uses continuous adaptive mesh refinement (AMR) for following discontinuities with a fine grid while treating the bulk of

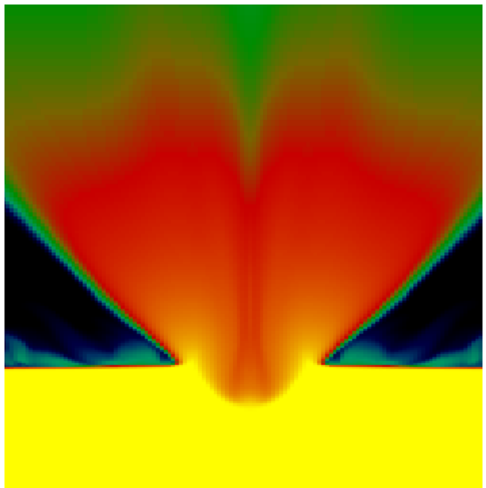

Figure 2: ZEUS-MP: Ejecta curtain and crater at t=4 s. The plots shows a planar slice of density ρ along *xz*-plane with a logarithmic scale $10^{-9} < \rho < 3.0$ gm cm^{-3}.

the simulation more coarsely. RAGE's strength lies in modeling detailed physics at high precision, with detailed equations of state such as SESAME.

For the RAGE calculations we concentrated on the development of the hot plume that will form immediately upon impact and should be observable from the S/SC. We followed the plume to 5 km radius from the impact point, over a period of 0.07 s. It has a maximum temperature of 1230 K, above the low-pressure vaporization points for both basalt (1034 K, 0.089 eV) and aluminum (1160 K, 0.1 eV) predicted by the SESAME equation of state, and contains both materials from the earliest stages of the plume.

ZEUS-MP: Ejecta launch and crater development

ZEUS-MP is a three-dimensional numerical hydrodynamics code that has been extensively modified by Korycansky and collaborators. ZEUS-MP has proven to be a robust and fast code for atmospheric impact calculations, and is currently being used by Korycansky for studies of impact calculations. By comparison with RAGE, its physical models are relatively crude, but it is fast and robust and can model the impact process through crater formation. We modeled the rocket stage as a uniform-density cylinder of 0.03 gm cm^{-3} of mass 2600 kg impacting vertically at 2.5 km s^{-1}. A sample of the results is shown in Fig. 2, where the EDUS impact and crater formation are shown at $t = 4$ s after the impact. Fig. 3 shows the ejecta mass-velocity relation $M_e(> v)$, the amount of ejecta mass moving at velocity v or greater, as found from the ZEUS-MP calculations. The crater diameter at $t = 4$ s is about 70 m, $\sim 4\times$ that predicted by scaling laws. Overall, the mass-velocity distribution is in qualitative agreement with scaling predictions. The total ejecta mass 10 - 30 times larger than predicted from crater and ejecta scaling laws due to the oversized crater the calculation generates. There is a range from $\sim 10-500$ m s^{-1} in which there is an apparent power-law distribution. The cutoff at larger velocities (~ 1 km s^{-1}) and its time-dependence (i.e. the drop in the distribution for the later times) is consistent with material flowing off the edge of the grid.

Monte Carlo models

Due to uncertainties in the modeling and the surface properties mentioned above, it is worthwhile to generate a suite of models that cover the expected range of the parameters R_{crat}, α and M_e, and θ. The ranges of values for R_{crat} and M_e are derived from the estimates by us and other members of the LCROSS science team. For the results given here, $6.5 < R_{crat} < 11$ m, and $2.5 \times 10^5 < M_e < 1 \times 10^6$ kg. (In principle M_e is a function of R_{crat}, but given the wide range of possible properties of crater scaling and regolith, we treated M_e as an independent model parameter.) For α we used the range between momentum and energy scaling ($3/7 < \alpha < 3/4$), and opening an opening angle range $0.2\pi < \theta < 0.3\pi$. We generated a set of 10^4 models with parameter values chosen as just described and evaluated quantities such as the amount of mass that reached given heights z. An example of the results is shown in Fig. 4, where we plot the distribution of numbers of models for which the amount of mass reaching heights heights $z = 2$, 5, 10, and 15 km is plotted. The models are most sensitive to the power-law index α. Perhaps the most important result is the amount of mass $m(z > 2$ km)that reaches 2 km or higher above the surface, as the ejecta must rise high enough to be sunlit, and the crater rim will be approximately this height. We find that the lowest 10% of the model results are $m(z > 2$ km$) < 8.5 \times 10^2$ kg, the median value is $m(z > 2$ km$)\sim 3.8 \times 10^3$ kg, and the highest 10% yield $m(z > 2$ km$)> 3.8 \times 10^4$ kg. Imposing a maximum velocity v_{max} of 300 m s^{-1} reduces those numbers to 7.1×10^2, 2.9×10^3, and 2.8×10^4 kg, respectively. Amounts of mass reaching higher altitudes are far more sensitive to assumptions about α or v_{max}.

References

[1] `http://lcross.arc.nasa.gov` [2] Plesko, C. S, *al*. 2007, LPSC abstract #2115 [3] Norman, M. *Rev. Mex. AA Ser. Conf.*, **9**, 66, Korycansky *et al.* 2006, *Ap J.*, **646**, 652. [4] `http://keith.aa.washington.edu/craterdata/scaling/index` [5] Housen *et al.* 1983, *J. Geophys. Res.*, **88**, 2485-2499

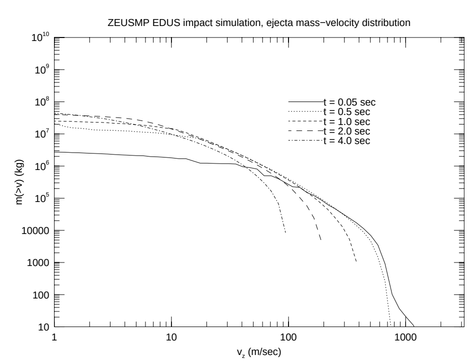

Figure 3: ZEUS-MP: Ejecta-mass/velocity $M_e(> v)$ relation at times 0.05, 0.5, 1, 2, and 4 s.