

**MODELING METEORITE IMPACTS: WHAT WE KNOW AND WHAT WE WOULD LIKE TO KNOW.** H. J. Melosh (Lunar and Planetary Lab, University of Arizona, Tucson AZ 85721. jmelosh@lpl.arizona.edu).

**Meteorite impacts can be studied by computer simulation:** Large meteorite impacts are among those phenomena that are either too large or too dangerous to study experimentally. Although impacts have affected the formation and surfaces of nearly every body in the solar system, we are limited to observing the results of past events. Investigation of impact processes is thus divided into observational studies of the traces of past impacts, small-scale analogue laboratory experiments and, most recently, detailed computer modeling. Computer models offer the possibility of studying craters at all scales, provided we completely understand the physics of the process and possess enough computer power to simulate the features of interest [1].

**But computer models cannot do everything!** One of the most common disappointments of geologists not familiar with modeling is that computer simulations cannot answer all questions we might like to ask. Numerical simulations suffer two major shortcomings: One is that they cannot treat processes that are not included in the computer code. Thus, no computer code presently treats the chemical or isotopic interactions that occur during an impact. This does not mean that such processes are untreatable, just that the appropriate codes that embody the correct physics must be created. In some cases the physics is poorly known and research must be done to improve the basic foundations. The second shortcoming stems from resolution in both space and time. All digital computer simulations depend on dissecting time and space into discrete blocks. The number of such blocks is limited by the amount of time and physical memory available for the computation. These limits can be easily exceeded by even an apparently modest computation. Thus, if an investigator wants to know about the dynamics of meter-size ejecta blocks in a 10 km diameter impact crater, he or she may discover that the required resolution far exceeds the capacity of any existing computer (a 3-D computation must include at least  $10^{12}$  computational cells!). Models to “predict” the effects of the impacts of Shoemaker/Levy 9 fragments with Jupiter [2] were still running at the time of the impacts, more than a year after the comet was discovered! These limitations can be surmounted both by faster computers with more memory as well as by better solution algorithms, such as the recent adoption of SPH codes when both hydrodynamics and self-gravity are important in a simulation [3].

Before beginning any computer simulation it is important to ask whether the numerical computation is capable of answering the desired question. Are all of the relevant processes included in the code to be used? Can the problem be solved in reasonable time on the

available hardware? Too often the answer is “no” and the potential modeler must look elsewhere for enlightenment. But there **are** plenty of open questions that are still ripe for computer solutions.

**The three pillars of impact simulation:** The physics needed to simulate large meteorite impacts lies squarely in the classical domain. The size scale is so large that quantum effects are not important (although quantum mechanics does determine the thermodynamic equation of state) and the velocities are well below the speed of light, so classical Newtonian mechanics, supplemented by classical thermodynamics, provides an adequate framework for modeling impacts. In addition, it has become clear that successful simulation of real impact craters often requires a detailed understanding of the response of real rocks to stress and heat.

Of these three supporting pillars, Newtonian mechanics is probably the least troublesome. All modern “hydrocodes” (a now obsolete term that reflects the historical development of computer codes that, at first, did not contain material strength) incorporate the standard  $F = ma$  foundation of mechanics, although this is often obscured by an impressive amount of bookkeeping to keep track of all the pieces. All codes incorporate some form of gravitational acceleration, although only a few employ self-gravitation (only important in planet-scale impacts). It is notable that there do not appear to be any talks at this conference on this aspect of computer modeling.

The next supporting pillar is thermodynamics, through the equation of state [4]. The equation of state for impact modeling is a little peculiar: Instead of the conventional thermodynamic relation relating pressure  $P$  to density  $\rho$  and temperature  $T$ ,  $P(\rho, T)$ , hydrocodes require a relation between  $P$ ,  $\rho$  and internal energy  $E$ . Equations of state for metals have been vigorously pursued by squadrons of physicists since the end of WWII, mainly to support the design and testing of nuclear weapons. However, few good equations of state exist for geologic materials, such as rock or ice. More research is needed to create these important relations.

Finally, in the late stages of an impact event material strength becomes important. Very little work has been done on good strength models for rock [5]. Porosity is also now recognized to play a key role for some impacts, especially on asteroids, which recent research has shown might be as much as 50% porous. Impact crater collapse and the morphology of large craters are controlled by strength, and observations suggest that a poorly understood mechanism must operate to greatly degrade the strength of rocks surrounding an impact site shortly after an impact event

[6].

**What next?** Our ability to numerically simulate impact events is currently being taxed by a number of difficult problems. We are concerned about the possibility of impacts causing future extinctions, as they did at the K/T boundary. Two and three-dimensional models have already been used to estimate the mass and type of environmentally active gases released by the impact [7], but the ultimate effects of these gases on climate is still largely unknown. Chemical reactions of material in hot vapor plumes may be important for both environmental effects as well as explaining the observed oxidation state and isotopic fractions observed in the ejecta. Several new craters with unusual morphologies such as the Silverpits crater in the North Sea [8] and the Chesapeake Bay crater [9] challenge our understanding of the response of the Earth's surface to large impacts. Crater morphologies on Europa [10] may be indicating the thickness of the ice shell beneath the surface, but we must understand the cratering process better before we can cite a numerical value for the thickness. An active question is whether damaging tsunami result from relatively small impacts in the Earth's ocean. Solving this problem requires a full understanding of interactions near the surface and the physics of wave breaking, a new challenge to existing computer codes.

We currently have a list of urgent needs for making our simulations more realistic. Much work is needed in the near term on equations of state and constitutive models for geologic materials. We will hear more about these needs in subsequent talks. Nevertheless, numerical modeling of impact processes has made important contributions to our understanding of impacts in the past and will surely continue to do so in the future.

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