MAKING AN IMPACT: ADVANCES IN NUMERICAL MODELLING OF IMPACT CRATERING ON ROCKY PLANETARY SURFACES

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Introduction: Numerical simulations have made important contributions to our understanding of impact cratering and its products for more than fifty years. They provide our only means of replicating the impact process in regimes that cannot be accessed in a laboratory and complement and enhance experimental studies in more accessible cratering regimes. Simulations also provide a means of extrapolating between and beyond incomplete geological, geophysical and remote sensing observations. Here, I review advances in our understanding of the impact process driven by recent evolution and application of numerical impact simulations.

Advances: The fundamental methods employed in most impact simulations to solve the differential equations that describe impact dynamics have not changed dramatically in thirty years. Instead, most scientific advances have come from three complementary directions: (1) improvements in material modelling; (2) increases in solution efficiency, resolution and dimensionality; (3) application of numerical modelling to new problems.

Correctly describing the response of complex, heterogeneous geologic materials to the extreme forces of impact cratering continues to be the major challenge in impact modelling. Recent progress has focused on the interplay between deformation, fragmentation, strength and porosity. This has advanced our ability to predict geophysical anomalies [1], fracture patterns [2] and fragment size distributions [3] and the effects of layering [4]. Advances in our understanding of the thermodynamic response of rocks to planet-forming collisions have also been made [e.g., 5, 6], but their influence on the cratering process has yet to be explored.

The inexorable increase in computer power, together with software optimized to exploit it, has allowed simulations with higher fidelity and longer time scales than ever before and allowed three-dimensional simulations of oblique impacts to become more routine. This has revealed new insight into previously inaccessible aspects of the impact process, such as jetting [7, 8] and high-speed ejection in oblique impacts [8], large-scale faulting in multi-ring basins [9] and asymmetric collapse of complex craters [10].

Many recent advances in our knowledge of the impact process, however, have come not from new models or increases in computer power, but simply from the novel application of existing tools to new problems or old problems with new insight. For example, simulations have revealed that shear heating rather than shock heating can be the dominant heating mechanism in low-velocity impacts [11] and that the thermal state of the target can have dramatic influence on the size and structure of large impact basins [12]. Simulations have provided new insight into the timing and orientation of structural deformation [13], the origin of large-scale faulting [9] and the influence of layering on crater morphology [14]. Simulations have also revealed the importance of ejecta-atmosphere interactions for the global transportation and deposition of dust following large impacts on Earth.

Future perspective: Numerical modelling will remain a key pillar of impact research. In the coming years, ever increasing performance and availability of compute resources will make three-dimensional simulations of impact more common-place and allow different scales of deformation, currently studied independently [e.g., 15], to be connected and coupled. Accurate and realistic material models of a wider range of geological materials is desperately needed, especially fully coupled and consistent multi-phase equations of state [5]. I expect a growing focus on the environmental consequences of impact cratering, especially the interaction of ejecta with the atmosphere. Application of machine learning may also lead to a new breed of highly efficient surrogate impact models trained to emulate conventional but costly impact simulations.

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