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Impact Processes in the Solar System: New Understandings through Numerical Modeling

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Imagine two rocky objects circling the sun in space, each roughly the size and mass of a large mountain range. A random component of their orbits moves them towards one another at a velocity many times faster than a supersonic jet. To what degree can we predict the outcome of such a collision?

Rudimentary energy calculations lead us to expect an almost inconceivably violent catastrophe, whose magnitude — about one billion megatons — would greatly exceed all of our thermonuclear stockpiles detonating at once. Extensive melting and vaporization would occur, along with explosive fragmentation, high-velocity ejection of debris in many directions, and an overall change in the orbits. But can we establish this in a more quantitative sense? We must strive to do so, for much of our understanding of the solar system depends on what we know about these kinds of hypervelocity impact processes.

According to our current interpretations of solar system evolution, impacts such as the one above were the basis for planetary growth, or *accretion*. Circling the new sun some 4.6 billion years ago was a cloud of gas and dust which soon condensed into small asteroid-like objects called *planetesimals*. The mechanism for this condensation is not well-understood, but it involved gas drag and collisions. The planetesimals, in turn, impacted with one another on a regular basis until their relative velocities were damped enough for them to gravitationally bind together — leading to the growth of planets. Typical impact velocities in the current asteroid belt are ~ 5 km/s; in the past they were probably a few times greater, and far more frequent. It is an open question whether the asteroids we see today are unaccreted remnants of the planetesimal swarm.

Consider the impact described above, occurring in free space. If the collisional velocity is great enough, fragments will be dispersed: from the two impactors we will get dozens or hundreds or thousands of minor objects flying out at independent trajectories.

Figure 1. (a) The projectile approaching the target at velocity v. (b) The outcome for a velocity much greater than the threshold, with projectile and target fragments dispersing. (c) The outcome for a velocity lower than the threshold, with relatively large fragments gravitationally reaccreting. Intermediate outcomes are also possible.

But at some lower threshold velocity, the disruptive effect of the catastrophe will no longer exceed the mutual gravity, and the material will clump into a single object whose momentum is the sum of the two colliding parents. There will in fact be a range of such outcomes: intermediate velocities, for instance, might expel some fragments but leave a large aggregated body behind. These scenarios are illustrated in Figure 1.

These threshold velocities are clearly dependent on the masses of the impactors. (Equivalently, if we assume a typical encounter velocity of some 5 km/s, then we could talk about a threshold mass.) Tiny dust grains would have virtually no gravitational binding energy, so the threshold velocity would be low. Colliding planets (*c.f.* the "giant impact" scenario for the ejection of the Moon from the proto-Earth), on the other hand, would have to involve much greater velocities to result in dispersion. One early qualitative approach was to characterize impacts by their *Safronov number*, which is essentially the ratio of gravitational binding energy to impact energy. If the Safronov number is large, then the bodies will coalesce; if it is small, dispersion of fragments will occur. But this is hardly the level of quantitative precision we need for the sophisticated models of planetary accretion that are now possible with high-speed computers. These models, to be accurate, require specific outcomes for specific impacts. Given, say, a 100 km projectile impacting a 300 km target at 5 km/s, what will the fragment size distribution look like? What will the velocities of these fragments be? How much mass will escape from the bodies, and how much will be gravitationally re-accreted? To what degree will the material be altered by shock pressurization, melting and vaporization? What direction will the ejected fragments take?

To answer these important questions, our group has developed a *fragmentation hydrocode* to perform dynamical computations of collisional outcomes. Our impact research takes two seemingly unrelated sciences — explosive fragmentation and fluid dynamics — and draws them together into a single application. To model a solid, we input certain material parameters, such as density, elasticity, rigidity, and energies of melting and vaporization. These parameters are well-known for a variety of important materials, such as ice, iron, granite and basalt. Another important parameter is the distribution of initial flaws within the material. These flaws are the locations where fractures can initiate; each flaw has associated with it a yield stress above which it will begin to grow. Flaw distributions are gathered for given materials from laboratory impact experiments.

An impact will fragment the material in a manner determined by the flaw distribution and the timescale and magnitude of the stresses. Once a material is fully damaged, it behaves like a fluid — its structural rigidity is lost. The subsequent fate of the material therefore obeys the laws of fluid dynamics, which are accurately implemented by the code. Furthermore, because our algorithm allows for the complex intermediate states that occur *during* fragmentation, the transition between solid behavior and fluid behavior is not abrupt, but follows the impact stresses through the target.

Figure 2 shows the fragmentation sequence for a typical target — in this case, a 22 km target being hit by a small projectile to model the impact into the Martian satellite Phobos (Figure 3) that created the crater Stickney, which dominates one hemisphere. The projectile hits at the top center. The half-circle represents a small wedge of the target, like a slice of an apple: the experiment takes place with rotational symmetry such that the left-hand straight boundary is the central axis. This sequence illustrates the propagation of the "damage pulse" through the target; undamaged material (farthest from the impact) obeys the physics of a solid, whereas fully damaged material (closest to the impact) is best described as a fluid. The material inbetween is in transition — it is undergoing rubblization by the stress waves of the impact. Free-surface interactions are evident, since without them the pulse would be hemispherical; the final frame shows the undamaged regions remaining in the target. Besides causing extensive damage, the impact accelerates the fragmented material and provides the fragments with velocities that might carry them off.

This code is the first successful, *i.e.* predictive, two-dimensional model of continuum fragmentation that we know of; we have been able to consistently reproduce the results of laboratory fragmentation experiments with high precision. Because the code is based on physical (rather than phenomenological) rules of material behavior, the sizes and velocities that characterize an impact can be varied at will, as long as the physics involved does not change. We do, for instance, incorporate gravity into our models for impactors larger than about 30 km. Our knowledge of collisional outcomes is therefore extended far beyond the range achievable in the laboratory, where ~ 10 cm objects are the largest sizes, and self-gravity is totally untestable.

The collisional event that created the crater Stickney, for instance, can be modeled as easily as a meteoric dust grain hitting an icy ring particle around Saturn, or the ejection of surface material from a major asteroid such as Vesta. Along a different vein, we can simulate cratering impacts into planetary surfaces — such as the one that launched the SNC meteorites from the surface of Mars, sending them into trajectories that brought them to Earth.

In addition to enabling us to extrapolate to large sizes, we can observe the process of fragmentation at arbitrarily small *timescales*. Prior to photographic studies, "collisional outcomes" was synonymous with "fragment size distributions," since all that could be done was to gather and sieve the debris. (A fragment size distribution is a plot of the number of fragments in each size range.) Modern high-speed film analyses give far more complete results, and show the velocities and rotation rates of the fragments. But the *process* is not captured on film: the fastest film rates are still far slower than the timescale of a typical laboratory impact event, some 20 millionths of a second. (And even if we achieved million-frame-per-second film rates, how could we observe what is happening inside of a target?) The fragmentation hydrocode allows us to step through a fragmentation event in arbitrarily small timesteps, viewing the propagation of the stress wave through the target, its interaction with free surfaces, the onset of fragmentation, and the velocities of fragments accelerated by the impact.

This "numerical laboratory" should provide significant insights into the many puzzles of planetary accretion, asteroid regoliths and families, meteorite delivery, and planetary ring genesis and evolution. An understanding of fragmentation, however complete, cannot *alone* provide the answers to these questions; it must, however, play an inseparable role in any satisfactory physical explanation.

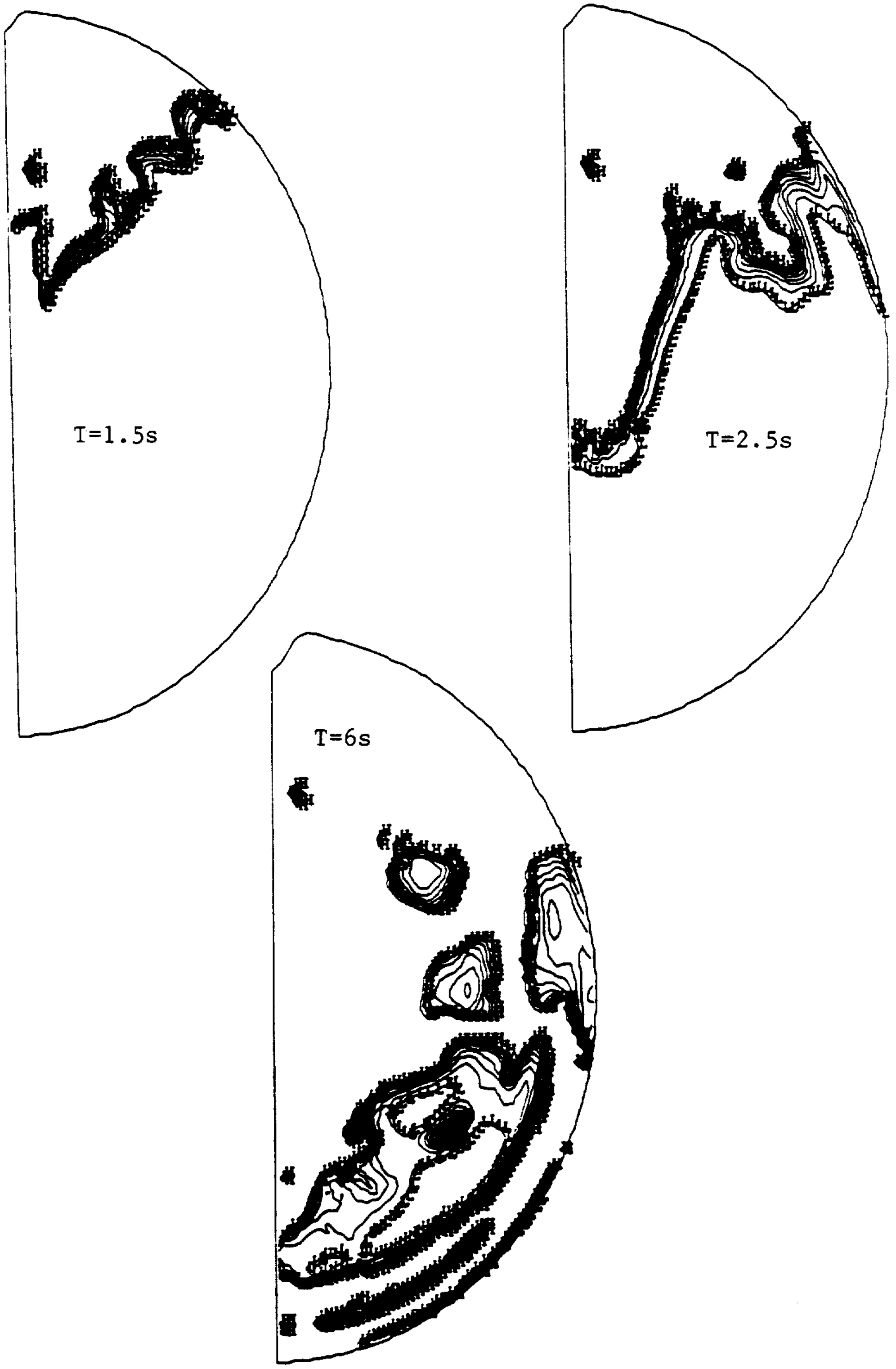

Figure 2. This simulation of the Stickney impact of Phobos illustrates a relatively non-disruptive impact event. Damage levels are contoured, representing the level of disruption of the target. The first two frames show the importance of free-surface interactions in the propagation of the damage front, while the final frame shows the remaining unfragmented regions. A more catastrophic event typically results in far greater distortions as the fragments are accelerated away from the impact.

Figure 3. A photomosaic of the Martian satellite Phobos, as imaged by one of the Viking orbiters. The prominent crater is Stickney, whose diameter (11.3 km) is actually greater than the satellite's mean radius (11.0 km). It is generally accepted that the prominent grooves, such as the ones observable to the lower right, were caused by the impact. Because Phobos may serve as a base for the manned exploration of Mars, it is important to understand what changes were brought about by this impact. Furthermore, Phobos may in fact be a captured asteroid, and could heighten our understanding of this very mysterious and important family of objects.