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# The Impact of Comet Shoemaker-Levy 9 on Jupiter*

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**Abstract.** We have performed computational shock-physics simulations of the hypervelocity (60 km/s) impact of 1-3 km, water-ice spheres entering a hydrogen-helium Jovian atmosphere. These conditions simulate the best current estimates for the collision of fragments of Periodic Comet Shoemaker-Levy 9 with Jupiter in July, 1994. We used the Eulerian shock-physics code CTH, and its parallel version PCTH to perform 2-D analyses of penetration and breakup, and 3-D analyses of the growth of the resulting fireball during the first 100 seconds after fragment entry. We can use our simulations to make specific predictions of the time interval between fragment entry and fireball arrival into line-of-sight from the earth. For a fragment larger than about 1 km, we believe that the time of fireball arrival above Jupiter's limb will be directly observable from earth. Measurements of this time by observers, in conjunction with our simulations, may allow mass of cometary fragments to be determined.

## 1. Introduction.

The collision of periodic comet Shoemaker-Levy 9 with Jupiter in July, 1994 is a challenging problem for analytical and numerical study. On July 8, 1992, the comet broke up during a close encounter with Jupiter and presently consists of a string of about 20 large fragments and associated debris in Jupiter-bound orbits (Fig. 1). Much of the debris will strike the planet over a 2-3 month period centered on July, 1994, with the largest fragments scheduled to collide during July 16-22 (UT). Images obtained from the Hubble Space Telescope place an upper limit of 4 km on the diameter of the fragments (Weaver et al. 1994), but it is more likely that the fragments are smaller (Scotti and Melosh 1993). Unfortunately, the impacts will occur just beyond the limb of Jupiter and will not be directly visible from Earth. The Galileo and Voyager II spacecraft, however, will be positioned for direct view of the impact sites. Even though the impacts will not be spatially resolved by the spacecraft, timing, spectral and luminosity data will be invaluable for

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comparison with analytical and numerical models. Data will also be collected from other spacecraft, earth-based and airborne instruments. Measurements of optical flashes reflected off of Jupiter's moons will be attempted.

While uncertainty remains as to the size and nature of the fragments, the unprecedented amount of energy potentially released during the impacts of the larger cometary fragments presents an unparalleled opportunity for the hypervelocity impact community to assess highly energetic impacts and the ability of the current generation of analytical models and shock physics codes to predict the associated phenomena (Hills and Goda 1993; Sekanina 1993; Vickery 1993; Mac Low and Zahnle 1994; Takata et at. 1994; Zahnle and Mac Low 1994). The numerical simulations that we are presenting here are divided into two parts. The first part is a two dimensional simulation of the entry, deformation and breakup of the cometary fragments as they penetrate the Jovian atmosphere. These simulations are followed in some cases by the much more computationally intensive 3-D simulations of the generation and growth of the resulting fireballs.

## 2. Entry, deformation and breakup of the cometary fragments.

We are using the CTH Eulerian shock-physics code to simulate two- and three-dimensional representations of the impact events. The 2-D computations are of the penetration phase, simulating the entry, deformation and breakup of the impacting comet fragments. The calculations are performed in a "reverse ballistic" sense using a Jovian atmosphere moving upward at 60 km/s impinging upon an initially stationary fragment. The Eulerian mesh extends 100 km radially and 1000 km above and below the comet. The fragment is maintained in a high resolution portion of the mesh (equivalent to 25 computational zones across the projectile radius and extending 10 km vertically and 5 km radially) by Galilean transformations of the entire mesh every 0.1 seconds of simulation time. Zone size gradually increases away from the high resolution portion of the mesh in order to preserve all the materials of the calculation yet maintain computational efficiency.

The comet fragment in the simulation is composed of water ice with initial density and temperature of 0.95 g/cm$^3$ and 100 K, respectively. For the ice, we used a tabularized version of the ANEOS equation-of-state which allows melting and vaporization. We assume a Jovian atmospheric stratigraphy that matches Voyager data at high altitudes and extends adiabatically to lower altitudes (Snell, private communication). The atmosphere is assumed to consist of 89% hydrogen and 11% helium at all altitudes and is modeled with a tabular equation-of-state allowing dissociation and ionization (Kerley, private communication). It is scaled vertically by a factor of 1.41 to account for the 45° entry angle and inserted into the lower portion of the computational mesh. As the calculation proceeds, the atmosphere propagates into the upper portion of the mesh as the comet deforms and explodes in the higher-pressure regions of the lower atmosphere.

The total energy deposited by three hypothetical 1-, 2- and 3-km diameter cometary fragments during their penetration of the Jovian atmosphere is shown in Figure 2. An important conclusion of these calculations is that most of a large fragment's kinetic energy will be deposited beneath Jupiter's outermost visible cloud layer which is about 10-15 km above the reference altitude at 1-bar. This deep energy deposition results in an upwardly growing fireball that entrains atmospheric constituents that are normally hidden at depth. We investigated the importance of body shape by performing simulations using a 2-D axisymmetric sphere, cylinder, short rod and flat disk. There is significant dependence on body shape; however, we find that simulations with spheres are representative of average penetration behavior in this velocity and size regime. For the four shape-dependence simulations performed, the average penetration depth was 300±50 km below the 1-bar level for a body with mass equivalent to a 3 km sphere.

### 3. Fireball simulations

We have performed fireball simulations on the 1840 processor Intel Paragon massively parallel supercomputer at Sandia National Laboratories. Three-dimensional, bilaterally symmetric simulations most accurately render fireball evolution during the early-growth phase (from 10 to 100 seconds after first contact of the fragment with Jupiter's atmosphere). We take the results from the two-dimensional entry, deformation and breakup studies, incline them at 45° and map them into a three-dimensional representation for studies of fireball evolution. Density, temperature, fluid velocity and pressure of the cometary debris and shocked Jovian atmospheric constituents are preserved in a spatially average sense while total energy is conserved. The calculation is started and allowed to evolve for up to 100 seconds. Generally, the simulation results indicate that early-time fireball growth is predominantly directed outward along the incoming bolide trajectory but is redirected, at later time, towards growth dominated by the vertical gradient of the Jovian atmosphere.

Because of the large size of these calculations, adequate resolution is difficult to attain. The simulation of the fireball formed by the impact of a 3-km comet fragment consisted of 6.3 million 5-km cubical zones. Lower energy events, formed by the impact of 1- or 2-km fragments, are modeled with more finely resolved, but less extensive, simulations.

The final result from the 3-km fragment impact and fireball simulations is shown in Figure 3. The fragment deposited more than 95% of its kinetic energy (approximately 6 million megatons) during its 13 second penetration into the Jovian atmosphere (a comparatively small amount remains as kinetic energy of cometary water vapor). At the end of the simulation, 56 seconds later, the fireball depicted in Figure 3 is the result of that tremendous energy deposition. By this time, a detached shock has formed in the Jovian stratosphere and is propagating upward at speeds approaching 30 km/s. Cometary debris (water vapor) and shock-heated atmospheric gases were left in the wake of the entering cometary fragment and have been entrained and uplifted by the fireball to altitudes as high as 800 km above the 1-bar level.

## 4. Prediction of observable phenomena

The principle scientific reason for simulating this event before it happens is to have an opportunity to make predictions that can guide observers. From another perspective, the impact event can be considered a large experiment by which the simulations can be validated on a scale many orders of magnitude beyond that which can be achieved in the laboratory. The simulations are providing insight into the physical mechanisms and instabilities that lead to the breakup of the cometary fragment, transfer of energy and growth of the fireball. Finally, this event is of interest to a wide-ranging community, so it is being analysed by a variety of numerical and analytical technques (Hills and Goda 1993; Sekanina 1993; Vickery 1993; Mac Low and Zahnle 1994; Takata et at. 1994; Zahnle and Mac Low 1994). These solutions can be used to benchmark, or cross-validate one another.

A particularly useful set of observations that will be made by many observers, including the Voyager II and Galileo spacecraft, are the light curves produced by each of the large impact/fireball events as functions of time. As has been noted by many workers, the entry of each cometary fragment into the Jovian atmosphere should produce an intense burst of light before the fragment penetrates below the visible cloud tops and disappears from view. The deposition of the fragment's kinetic energy at depth in the atmosphere leads to the development of a fireball which emerges back into view several tens of seconds later. Our simulations show that the time interval between fragment entry and fireball arrival into line-of-sight from earth is directly related to fragment mass. For a nominal impact occurring 6° beyond Jupiter's limb, minimum altitude of direct earth line-of-sight is about 400 km above the 1-bar level. Our simulation of a 3-km ice body predicts that this time interval is between 45 and 50 seconds. Preliminary results from simulations of smaller-body impacts indicate that the time interval in these cases is substantially increased.

**References**

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**Figure Captions**

Figure 1. Image of Comet Shoemaker-Levy 9 taken in January, 1994 from the just-repaired Hubble Space Telescope (top). For orientation, north is at the bottom, and the tails are streaming off to the northwest. The twenty largest fragments shown above will impact Jupiter during July 16-22, 1994, in order from right to left (NASA Space Telescope Science Institute photo).

Figure 2. Energy deposited by three hypothetical cometary fragments during their penetration of the Jovian atmosphere. The fragments are modeled as 1-, 2- and 3-km diameter spheres of water ice initially traveling at close to escape velocity, 60 km/s. The plots were produced at the end of each numerical simulation by summing the total energy contained within discrete altitude bands (3-25 km thickness) of the computational mesh and normalizing by band thickness. The internal energy contribution of the initial atmosphere has been removed. Most of the comet's kinetic energy will be deposited beneath Jupiter's outermost visible cloud layer.

Figure 3. Fireball formed by the impact of a 3 km fragment of Comet Shoemaker-Levy 9 on Jupiter. The fragment, modeled as water ice, entered Jupiter's atmosphere approximately 69 seconds before this point in the simulation. It deposited most of its kinetic energy (approximately 6 million megatons) into the atmosphere in the first 10 seconds. The fireball shown here is the result of that tremendous energy deposition. At this point in the simulation a detached shock has formed in the Jovian stratosphere and cometary debris (water vapor) and shock-heated atmospheric gases ($H_2$ and He), originally left in the wake of the entering cometary fragment below 100 km altitude, have been entrained and uplifted by the fireball to velocities of 20-30 km/s and an altitude of 800 km above the 1-bar level. This is a cross-sectional view with temperature represented by color.