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Impactful Times

Memories of 60 Years of Shock Wave Research at Sandia National Laboratories

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Fig. 6.10 Sheet metal structure loaded by an explosive blast (Reprinted with permission from Attaway et al. 2011, Sandia National Laboratories)

An additional example of the continuing increase in computing capability, as of 2013, was achieved by Sandia researchers who performed a shock wave calculation using CTH on a massively parallel computer located at LLNL. An announcement was made in the *Sandia Daily News*[8] following this phenomenal success:

> CTH runs one trillion zones on over one million cores: Success! The CTH team announces demonstration of scalability to over one million cores on the LLNL HPC [high performance computer] system Sequoia. The test problem is an interacting blast wave shock physics problem in 3D. The problem consists of one trillion zones, with approximately one million zones per core. CTH is a multi-physics computational tool for simulating multiple materials in high-rate, large deformation and shock physics application[s].

6.10 The Shoemaker–Levy Comet Impact on Jupiter at 60 km/s

As the CTH hydrodynamic code was being developed in the early 1990s, a major event occurred that accelerated its development and resulted in international recognition for modeling hypervelocity phenomena at Sandia. This was the impact of the

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[8] Bob Schmitt, CTH development team, Sandia National Laboratories, September 2013.

Shoemaker–Levy 9 (SL9) comet on Jupiter that occurred in July 1994. Mark Boslough was the first at Sandia to recognize that this event provided a compelling motivation to validate CTH's capabilities for three-dimensional modeling of hypervelocity impact events. Around a year before the expected impact, he advocated for a research effort to use CTH to accomplish this goal and, after receiving approval, formed a team to model the hypervelocity impact event. Within a year, the team was performing 3-D high-fidelity simulations of the SL9 impact that accurately predicted a vapor plume caused by the impact that would be visible from the Earth. In his recollections, Boslough provides an account of the events leading to the 3-D simulations of the SL9 impact on Jupiter. These simulations resulted in significant external recognition for Sandia and for members of the team, while establishing CTH's capabilities as the premier hydrodynamic code for predicting hypervelocity impact phenomena. A brief summary of this story is provided in this section; a more complete perspective is in Boslough's recollections.

About 20 years ago, an announcement in the International Astronomical Union Circular of March 25, 1993, was the first public description of the comet that became known as Shoemaker–Levy 9:

> It is indeed a unique object, different from any cometary form I have yet witnessed. In general, it has the appearance of a string of nuclear fragments spread out along the orbit with tails extending from the entire nuclear train as well as what looks like a sheet of debris spread out in the orbit plane in both directions.[9]

As Boslough remembers this announcement,

> It was a puzzling find and very exciting to planetary scientists because of its unique character. In those pre-World-Wide-Web days,[10] I first read about it in the July 1993 issue of *Sky & Telescope*. Co-discoverer David Levy, a regular columnist, described the serendipitous events on top of Palomar Mountain that led to Carolyn Shoemaker's first identification of the comet on damaged film, polluted with the glare from Jupiter, from an image taken just before clouds covered the sky for the rest of the night. "I don't know *what* this is," she said. "It looks like… like a squashed comet."[11]

Around that time, Boslough was a staff member in the Experimental Impact Physics Department, working with Lalit Chhabildas and others at the STAR facility

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[9] These words, according to the book *Shoemaker by David H. Levy: The Man Who Made an Impact* (Princeton University Press, Princeton, 2000), are those of James Scotti, who was observing at the Spacewatch telescope at Kitt Peak the same night and was contacted by the Shoemakers and Levy to see if he could see the object. Scotti sent an email to Brian Marsden, the Director of the Minor Planet Center in Cambridge, MA, on March 26, 1993. A copy of Scotti's email is in David Levy, *Impact Jupiter: The Crash of Comet Shoemaker-Levy 9* (Basic Books, Cambridge, MA 1995), pp. 27–28.

[10] *Editors' note*: Tim Berners-Lee, a software engineer at CERN (the European Organization for Nuclear Research), invented the World Wide Web in 1989. However, it wasn't until April 1993 that CERN announced the technology would be available to use by anyone on a royalty-free basis. In 1994, the World Wide Web Consortium was formed.

[11] Carolyn S. Shoemaker and Eugene M. Shoemaker, "A Comet Like No Other," in *The Great Comet Crash: The Impact of Comet Shoemaker Levy 9 on Jupiter*, edited by John Robert Spencer (Cambridge University Press, Cambridge, 1995). The full quote is "I don't know what this is, but it looks like a squashed comet."

to test the effectiveness of debris shields against space debris. The goal of these experiments was to validate numerical simulations of impacts and explosions for other departments in the Computing Research Center that were focused on computational shock physics. Boslough had just received approval for an LDRD project to model the impact and seismic consequences of the dinosaur-killing impact event 65 million years ago. By modifying a few milestones, the project was redirected to include the SL9 impact on Jupiter. Furthermore, the new Intel Paragon MPP computer had just become available for hydrodynamic calculations, and its availability for planetary applications was timely.

Boslough and his collaborators developed a comprehensive research plan centered around the newly developed CTH hydrocode to simulate the SL9 impact and sought approval from Mike McGlaun, who managed the CTH development project, and from Ed Barsis, the Director of the Computer Sciences and Mathematics Center. As Boslough remembers,

> Ed Barsis gave us the green light [to proceed with the calculation]. Our goals were to test the machine with a big problem, use our results to make recommendations to astronomers for observations the following summer, and then use the observations as a validation opportunity for our models.

With Barsis' concurrence, Boslough, Dave Crawford, and Tim Trucano began utilizing the CTH code to model the impact, first in two dimensions and then in three. Allen Robinson, who was developing a 3-D version of the code referred to as PCTH for use on MPP computers, also joined the effort with the goal of porting PCTH to the Intel Paragon. This was the fastest computer in the world at the time and promised considerably increased resolution of the impact event.

As the Sandia effort got underway, planetary scientists initially hoped the impact would occur on the side of Jupiter facing the Earth. This was not to be. Boslough states in his recollections, "It wasn't long, however, before orbital dynamicists had enough data to calculate the point of impact. The collision was going to be on Jupiter's *back side*, and not directly visible from Earth, as we had all hoped." This made the job of comparing numerical simulations of the event with actual photographic data much more difficult and motivated high-fidelity computer simulations to identify a signature of the impact that would be useful to astronomers.

Boslough further notes in his recollections:

> A convergence of technologies in 1994 enabled the scientific community to make the most out of this event. It was timed perfectly. First, the Intel Paragon allowed us to model the event with sufficient fidelity to make useful predictions. Second, the Hubble Space Telescope, which had just been repaired, was producing exceptionally sharp images. Third, and more easily forgotten, was the role of the Internet that was just beginning to connect various research institutions, allowing rapid dissemination of information.

Development of CTH proceeded at a fast pace from July onward, and the code was beginning to produce interesting results by fall 1993. Boslough commented on the increased understanding being obtained through the Sandia calculations: "By October 1993 Tim Trucano had completed the first two-dimensional simulations showing how the comet fragments would break up as they entered Jupiter's atmosphere."

Trucano's simulations provided an estimate of the fragment sizes that would impact Jupiter's liquid surface and were crucial to understanding the observable effects of fragments traveling at around 60 km/s and impacting the surface. As Boslough noted in a press release for a meeting of the American Astronomical Society's Division for Planetary Sciences, held in Boulder, CO, October 18, 1993:

> Sandia National Laboratories researchers have performed supercomputer simulations to find out what will happen when Comet Shoemaker-Levy 9 collides with Jupiter next summer. Some astronomers have predicted that the impact will be one of the most spectacular celestial events ever witnessed. Telescopes and spacecraft are being rescheduled to observe the resulting display, but what will they see? To help answer that question, the Sandia scientists have made use of a computer code of the type that was originally developed to understand what happens within nuclear weapons…. The computer simulations show that when the comet enters Jupiter's atmosphere, the pressure increase is gradual. The atmosphere is thin at the top, so for the first second or so, the comet slices through almost unhindered. In the next second, however, the pressure builds up rapidly and deforms the comet until it begins to break up…. After the comet begins to break apart, energy is released very rapidly by mechanisms that are not well understood. The Sandia calculations are concerned mainly with the processes that lead to the breakup. One of the surprising results is that, for a collision like the one expected next summer, the comet is torn apart by the large deformations due to atmospheric drag.

In the fall of 1993, Allen Robinson's team was actively pursuing development of the PCTH code that could be run on the Intel Paragon. This was an important advancement because the enormous increase in computing speed and memory available on the Paragon provided considerably better definition of fragment interaction with Jupiter's atmosphere and helped to clarify how the fragments would break up. This was especially important to determine if the size of the impact-generated plume would be observable from the Earth, since the impact was projected to be in Jupiter's shadow but near the boundary (limb) with the observable surface. Early in 1994, the capability to perform 3-D hydrocode calculations on the Intel Paragon was finally available. Boslough describes the very first 3-D simulations of the comet impact obtained by the planetary community:

> In early 1994, Dave had run 3-D simulations for various assumed fragment sizes on the Paragon, showing that the fireballs would be ejected at much higher speeds and to higher altitudes than the other groups had predicted. We also showed that, for an inclined impact (the fragment entry angle would be 45° from the local horizon), the plume would be ejected along the wake – at the same angle but in the opposite direction. Because we had access to the most powerful computer in the world, we had the advantage of higher resolution and three-dimensionality, both of which were required to make these predictions.

This was an important development and provided hope that the resulting plume would be observable from the Hubble Space Telescope and would allow astronomers to infer information about the impact. Mike McGlaun emphasized this groundbreaking development in his recollections:

> Allen's team got a version of PCTH working that demonstrated excellent parallel speedup and good performance…. Mark Boslough, David Crawford, and Tim Trucano were some of the first users. In 1994, they analyzed the Shoemaker-Levy 9 comet impacts on Jupiter using 3-D calculations on the Intel Paragon. PCTH proved spectacularly successful. Astronomers could not observe the comet impacts because they were on the side of Jupiter

Fig. 6.11 Simulated impact of a 3-km fragment 55 s after impact on Jupiter. The plume debris above the dashed line would be visible from the Earth. Temperature in the plume is represented by color: blue = 100 K, red = 3300 K (Reprinted from Crawford et al. 1994, Fig. 4, with permission of Springer Science + Business Media)

> facing away from Earth. Our calculations indicated an optical signature should be visible over the apparent visual edge (limb) of Jupiter. Astronomers could infer information about the impacts from that optical signature. Mark, Dave, and Tim received a Sandia Quality Award and published several papers on this work. It was a great demonstration of PCTH's capabilities and the power of massively parallel computers.

Rapid progress was made by the Sandia team in developing the code to the point where it could accurately model the impact and the resulting vapor plume, which they predicted to be visible from Earth. The pioneering research performed by this dedicated team of researchers represented the first 3-D calculations of a large and complex impact event and established the standard of performance for future MPP computer applications.

Figure 6.11 shows a CTH simulation of a 3-km fragment of the comet that consists of water ice traveling at 60 km/s that entered Jupiter's atmosphere about 55 s before impact. The calculation indicates that the fragment deposits most of its six megatons of kinetic energy in the atmosphere in the first 10 s. This accounts for the water ice debris cloud and shock-heated hydrogen and helium atmospheric gases entrained in the plume.

Figure 6.12 shows a comparison of the calculated plume size observable from the Earth for several minutes after impact, along with Hubble Space Telescope (HST) images taken on July 16, 1994, at the corresponding times (Hammel et al. 1995; Boslough et al. 1995a, b; Boslough and Crawford 1996, 1997; Crawford et al. 1994, 1995). In the HST images, the string of fragments making up the comet tail was identified alphabetically. The "G" fragment was about 3 km in diameter. Shown in Fig. 6.12a are 3-D CTH calculations for the plume formed by a 3-km fragment at different times after impact with Jupiter. Shading indicates log (density) with a cutoff at 10-12 g/cm^3; times are in minutes after impact (Boslough and Crawford 1997). Since the impact point was not visible from the Earth, the calculated evolution of the fireball was important to astronomers who would be able to view only

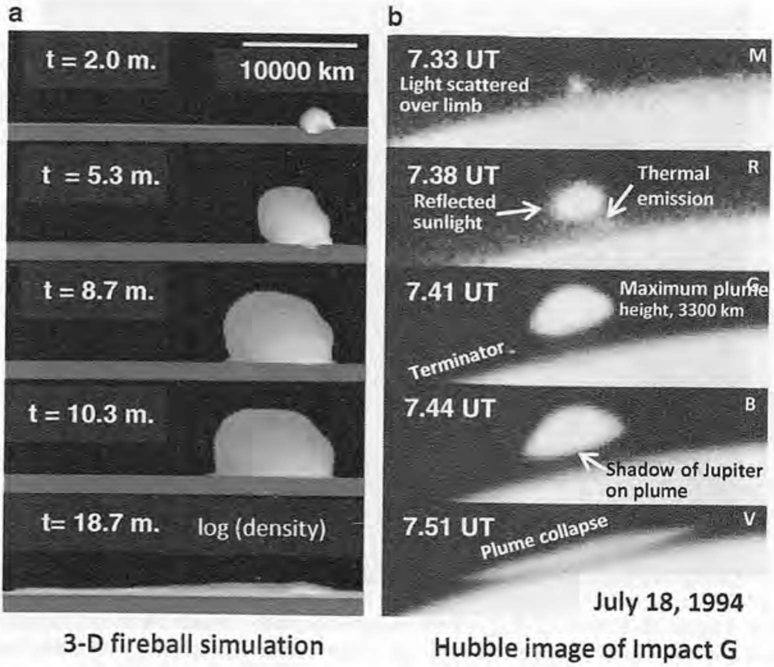

Fig. 6.12 (**a**) Simulations of 3-D fireball/plume evolution after impact of a 3-km-diameter fragment with times shown in minutes. (**b**) HST images obtained at different times after impact for a similarly sized fragment (Reprinted with permission from Boslough and Crawford 1997, Fig. 6, Copyright 2006, John Wiley and Sons. NASA and the Space Telescope Science Institute (STScI) are acknowledged for use of the Hubble image

part of the plume after impact. HST images of the impact are shown at similar times to the CTH calculations in Fig. 6.12b. In his recollections, Boslough captures a comment from one of the astronomers, Heidi Hammel, upon seeing the photographs of the plume for the first time.[12] In an email communication with Mark in January 2015, Heidi recalled, "We subsequently put together a time lapse set of Hubble images showing the G plume's rise and descent. They were so eerily like Sandia's predicted models that I showed them side by side for years afterwards."

The comet impact on Jupiter, starting on July 16, 1994, was one of the most spectacular events that have been observed from Earth. The Sandia team received considerable international recognition for their groundbreaking and inspiring research of the SL9 impact on Jupiter. The fact that it was possible to accurately predict the evolution of the ejected plume with the computing capabilities and codes that were available in the 1990s is truly remarkable and a tribute to the talents, energy, and dedication of the team. Their pioneering results were enabled by the

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[12] Heidi Hammel was a Principal Research Scientist at MIT and a member of the Science Observation Team for the Hubble Space Telescope Jupiter Campaign in charge of the Wide Field and Planetary Camera that was used to photograph the impact plume.

Fig. 6.13 Eugene Shoemaker (sitting) views a replication of the impact event on a virtual reality system at Sandia. Behind him are Jim Asay (*left*), Mark Boslough (*center*), and Craig Peterson (Reprinted with permission of Sandia National Laboratories)

unmatched capabilities of the 3-D PCTH hydrodynamic code and the use of massively parallel computing.

To focus international attention even further on these unique results, Mark organized a special session of the Hypervelocity Impact Symposium (HVIS) that was held after the impact event in Santa Fe, NM, in July 1994. Gene Shoemaker gave the keynote address at the Symposium, which included Carolyn Shoemaker and a large number of international researchers who presented poster board results of their work on the comet impact. The CTH results were especially well received by the computational, planetary science, and shock physics communities. Figure 6.13 shows Gene Shoemaker reviewing the Sandia results a few days before his keynote address at the Hypervelocity Impact Symposium.

6.11 ALEGRA: The Next-Generation Hydrodynamic Code

As the second-level manager of the Solid Dynamics Research Department, Dennis Hayes began an initiative in 1989 to develop a robust 3-D hydrodynamic code that included magnetohydrodynamic (MHD) phenomena. The Pulsed Power Sciences Center had recognized the need for such a code to study the high-temperature plasmas and current flows being produced on the Z accelerator (sometimes called the Z machine, or Z), shown conceptually in Fig. 6.14. At that time, Z was used to

Fig. 6.5 Mark Boslough standing next to the Wide Field and Planetary Camera 2 in 2014 that had been used by the Hubble Space Telescope to take the photos of the Shoemaker-Levy 9 impact shown in Fig. 6.12b. Impact micro-craters on the camera structure have been drilled out, leaving the visible holes (Private collection, M. B. Boslough)

6.4 The DOD/DOE Memorandum of Understanding

In the 1980s, DOD and DOE signed a memorandum of understanding (MOU) concerning jointly funded shock wave research programs at the national security laboratories on materials of common interest. The MOU program was initiated at Sandia in the mid-to-late 1980s under Max Newsom and managed by Bill Tucker and, later, by Tom Hitchcock. The research included studies of geological materials, metals, ceramics, porous materials, energetic materials, and concrete. A wide range of studies was conducted under the auspices of the MOU, including high-pressure equations of state, material strength, fracture, and fragmentation. This highly successful research initiated under an MOU continued for several years. Dennis Grady managed this project since its inception and was initially the project manager at Sandia for experimental studies conducted within the Solid Dynamics Research Department before the shutdown of STAR. As Grady mentions,

> An extensive research program emerged during the late 1980s that entailed a joint effort between the Department of Defense and the national laboratories on issues of mutual concern. Material property studies through impact shock physics methods were undertaken at Sandia. Extensive experimental studies were performed on low density and high strength ceramics that had potential application for military armor needs. From this effort emerged Hugoniot equation of state and dynamic strength properties for a suite of ceramics that remain, to the present day, the basis for computational analysis of ceramic performance in the terminal ballistic environment.