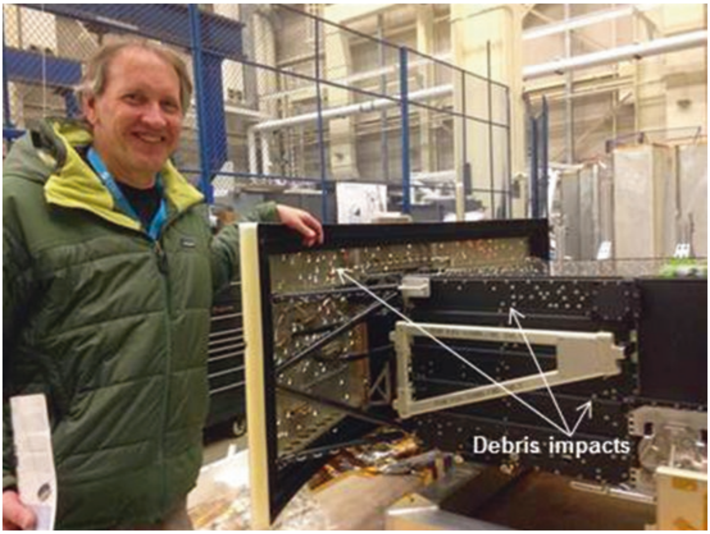

Fig. 6.5 Mark Boslough standing next to the Wide Field and Planetary Camera 2 in 2014 that had been used by the Hubble Space Telescope to take the photos of the Shoemaker-Levy 9 impact shown in Fig. 6.12b. Impact micro-craters on the camera structure have been drilled out, leaving the visible holes (Private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

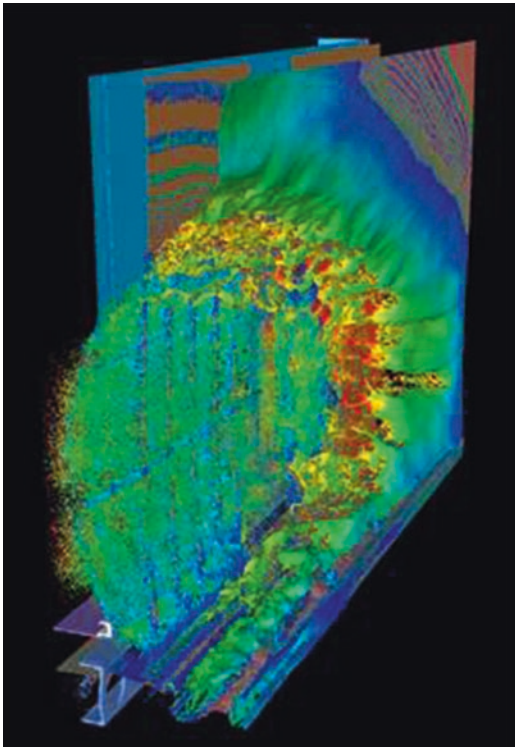

Fig. 6.10 Sheet metal structure loaded by an explosive blast (Reprinted with permission from Attaway et al. 2011, Sandia National Laboratories)

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

[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

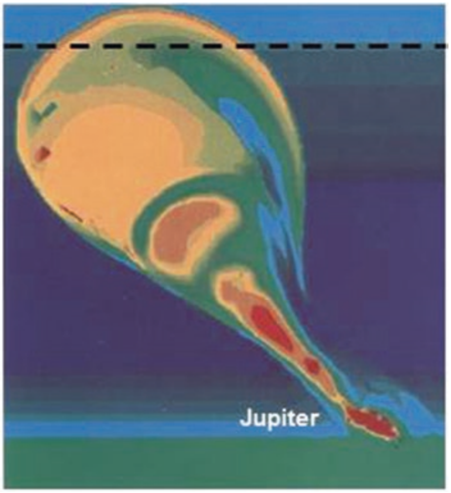

Fig. 6.11 Simulated impact of a 3-km fragment 55 s after impact on Jupiter. The plume debris above the dashed line would be visible from the Earth. Temperature in the plume is represented by color: blue = 100 K, red = 3300 K (Reprinted from Crawford et al. 1994, Fig. 4, with permission of Springer Science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

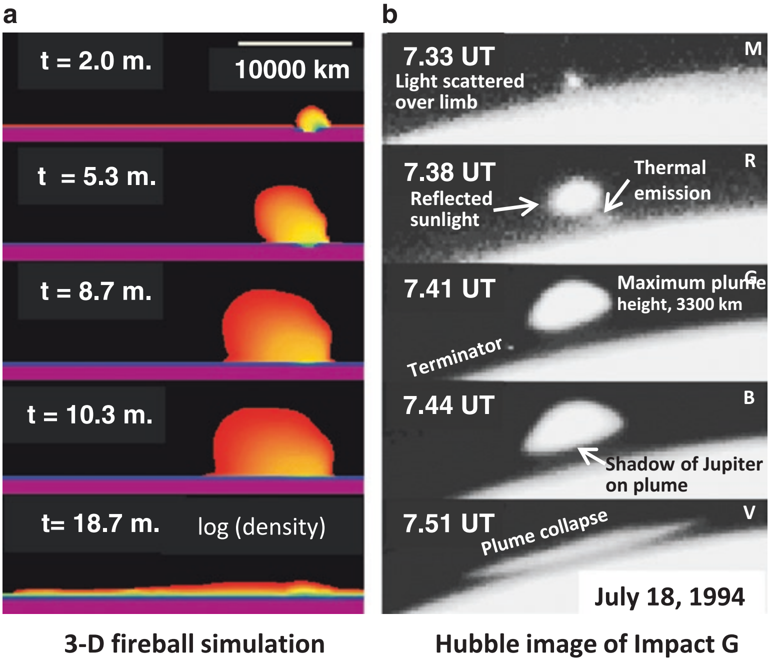

Fig. 6.12 (**a**) Simulations of 3-D fireball/plume evolution after impact of a 3-km-diameter fragment with times shown in minutes. (**b**) HST images obtained at different times after impact for a similarly sized fragment (Reprinted with permission from Boslough and Crawford 1997, Fig. 6, Copyright 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

[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

Mark B. Boslough

(1983–Present[15])

Editors' comments: Mark Boslough graduated in Applied Physics from the Geological and Planetary Sciences Division at the California Institute of Technology (Caltech). He joined the Shock Wave and Explosives Physics Division led by Bruno Morosin. The early part of his career focused on a variety of experimental projects, including a new research effort on shock-induced chemistry initiated by Bob Graham and research on hypervelocity impacts of debris shields with Lalit Chhabildas. In the early 1990s, his research turned to more emphasis on the numerical simulation of hypervelocity impact events and planetary physics. He has become internationally known for his wide-ranging investigations of cometary and asteroid impact events. In his recollections, Mark describes how he became involved in investigating planetary airbursts. He provides a fascinating account of efforts to use the rapidly evolving computing capability at Sandia to model the impact of Comet Shoemaker–Levy 9 on Jupiter.

Opportunity Knocks into Jupiter at 60 km/s!

> 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.[16]

This was the first public description of the comet that came to be known as Shoemaker–Levy 9 (SL9), as the discovery announcement in International Astronomical Union Circular No. 5725 of March 25, 1993. The words were those of James V. Scotti of the Spacewatch program at the University of Arizona, who confirmed the object's existence. It was a puzzling find and very exciting to planetary scientists because of its unique character. In those pre-World Wide Web days,[17] 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

[15] Mark worked in experimental shock wave science until the mid 1990s, followed by a couple of years in simulations of shock wave problems. He was then involved in other activities at Sandia until around 2006 when he became active in planetary applications that continue to the present.

[16] Private communication on March 26, 1993 from James V. Scotti to Brian G. Marsden of the Central Bureau for Astronomical Telegraphs. The description that Scotti sent then appeared in IAU Circular No. 5725 that same day.

[17] 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.

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."[18]

David went on to speculate about how the comet might break apart, and what might happen to it:

> As Comet Shoemaker-Levy continues to evolve, we may see some of the fragments fade to nothing. Maybe a few will last a year or more. Right now, all we can do is wait, watch, and speculate. No matter what the outcome, all of Comet Shoemaker-Levy's offspring will live long in our memories.[19]

He was right about one thing. We have not forgotten. But he underestimated the magnitude of the memories because he didn't know at the time what really would happen to the comet. His article was already in the newsstands when I happened to notice a small, 5-column-inch story in the *Albuquerque Journal* on June 12, 1993: "Jupiter, Comet Could Collide in Huge Crash." New calculations by comet co-discoverer (and Carolyn's husband) Gene Shoemaker showed that the remaining chunks of the comet might collide with Jupiter on July 20, 1994. It was thought that the collision could unleash the energy equivalent to a billion megatons of TNT, more powerful than the one that wiped out the dinosaurs 65 million years ago. One scientist speculated that the impacts would cause Jupiter to flare up to 25 times its normal brightness for a couple minutes.

I had always been interested in planetary impacts and, as a graduate student at Caltech, had taken a course about impact craters from Gene, which included a field trip along with Carolyn to Meteor Crater, Arizona. That was where I first learned how legendary Gene already was to crater *aficionados*. When I told the cashier at the Meteor Crater visitor center that our guide would be Gene Shoemaker, she was thrilled he would be there and exclaimed, "That's like getting a field trip to heaven with God!"

In 1993, I was a staff member in the Experimental Impact Physics Department, making use of the STAR facility to test the ability of bumper shields to protect spacecraft from space debris, among other things. Part of our department's role was to validate numerical simulations of impacts and explosions for our sister departments, which were focused on computational shock physics. What could be better for validation than the ultimate natural impacts and explosions? So I brought the newspaper clipping in to work and showed it to Mike McGlaun, manager of one of the other groups. It didn't take long to get him interested, and he said he'd talk to Ed Barsis, our Center Director.

Fortuitously, I had just gotten my first LDRD (Laboratory Directed Research and Development) project funded. It was a computational project to model the impact and seismic consequences of the dinosaur-killing cometary impact. With a few modified milestones, we had some funding to pay for our time. All we needed was

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[18] From D.H. Levy, "Pearls on a string," *Sky & Telescope* **86**, no. 1, p. 39 (1993), reprinted with permission from *Sky & Telescope*. The original quotation was from C.S. Shoemaker and E.M. Shoemaker, "A Comet Like No Other," Chapter 2, p. 7 in *The Great Comet Crash: The Impact of Comet Shoemaker-Levy on Jupiter*, edited by J.R. Spencer and J. Mitton (Cambridge University Press, Cambridge, UK, 1995), reprinted with permission from Cambridge University Press.

[19] D.H. Levy, "Pearls on a string," *Sky & Telescope* **86**, no. 1, p. 39 (1993), reprinted with permission from *Sky & Telescope*.

permission to use the brand-new Intel Paragon, the most powerful machine in the world. And we needed people who knew how to run the code or could learn how. Dave Crawford, a new postdoc, was immediately in: his background in planetary geology and experimental impact physics was perfect. Best of all (unlike me), he was a computer whiz. Tim Trucano agreed to start running simulations and teach us how to use CTH, Sandia's three-dimensional (3-D) multi-material shock physics code. Allen Robinson, who had written a parallel version of the code that he was porting to the Paragon, would also help. A big unclassified problem would be a perfect exercise to test the new hardware and software. With additional help from Marlin Kipp and Gerry Kerley, we would quickly be running simulations.

On July 13, I wrote a memo to Ed Barsis, Mike McGlaun, and members of the team. Subject: "Apojove Meeting: What should we do about the impact of comet Shoemaker-Levy 1993e?"

> Comet 1993e was discovered last March, and is predicted to impact Jupiter. Its orbit has been refined over the last month, and it is now widely believed the impact will take place in July, 1994. The orbital period is about two years - it was captured by Jupiter last July. It will reach apojove, the high point in its highly eccentric orbit tomorrow, July 14, and will spend the next year accelerating up to its impact velocity of 60 km/s. At that velocity, the largest fragment will have a kinetic energy equivalent of about one billion megatons of TNT, releasing an order of magnitude more energy than the K/T dinosaur-killer. The resulting flash will overwhelm all objects in the sky except the sun, and should be visible in the daytime sky.
>
> We are well-positioned to make a major contribution toward both computational predictions and observations of the event. It is important that we get an early start and that we come up with a unified plan. Let's have an 'apojove' meeting tomorrow, so we can begin moving in the right direction the same day that the comet does. Time: 9:00 am, Wednesday, July 14, 1430 conference room (880/C-35C).

This was not an exaggeration, based on what we knew at the time. Planetary scientist Clark Chapman had written in the News and Views section of *Nature*, on June 10[20]:

> John Lewis estimates that a fireball formed perhaps 1,000 km below Jupiter's cloud deck might ascend through the clouds in an awesome display. If the comet fragments were to hit the front side of Jupiter, the explosions would be visible from Earth in broad daylight as the separate objects followed each other down into Jupiter's clouds.

Ed Barsis gave us the green light. 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.

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. At a comet "Pre-Crash Bash" on August 23–24, 1993, at the Lunar and Planetary Laboratory in Tucson, 120 scientists met for a brainstorming workshop. Despite the disappointment about no direct observations from Earth, researchers expressed the hope that it would be observed

[20] C.R. Chapman, "Comet on Target for Jupiter," *Nature* **363**, pp. 492–493 (1993), reprinted with permission from Macmillan Publishers Ltd.

by the Galileo spacecraft, on its way to Jupiter at the time of impact. Maybe, if we were lucky, we'd see evidence of the impact flash reflected from Jupiter's moons.

Three groups presented preliminary computational simulations, including Dave Crawford. According to a summary write-up, dated September 20, 1993, by workshop organizer Jay Melosh,[21]

> Kevin Zahnle described his work on energy deposition of entering comets, following up on his model originally developed to model airblasts from meteorites entering Venus' atmosphere and the 1908 Tunguska event on Earth. He argued that the projectile would break up as it entered, thus increasing its drag and depositing its energy in a relatively small altitude interval. The energy deposited would then heat the surrounding gas, which would expand upward in a classic fireball. For km size projectiles, most of this energy deposition takes place about 200 km below the upper cloud decks, and so is not directly visible, but the fireball should become visible when it rises back up into the upper atmosphere, about 1 minute later. He argued that ablation is not important for large projectiles, although what 'large' meant was debated by the participants, and he reported that a check by Chris Chyba showed that his results changed somewhat when a different ablation model is used. Temperatures in the shock wave ahead of the entering projectile were estimated to reach 30,000° during the high speed part of the entry. Zahnle closed his talk by showing a video of a numerical computation of the expansion of a fireball in a stratified atmosphere modeling that of Jupiter.
>
> Several participants showed results from numerical computations currently in progress. Tom Ahrens presented a computation using an SPH hydrocode result that followed the entry of a 10 km diameter projectile. He and T. Takata found that the projectile penetrated relatively deeply, depositing most of its energy 500 km below the 1-bar level. The impact generated a 6 km/sec plume and partitioned about 70 % of its energy to atmospheric heat. David Crawford described similar computations that use the Sandia hydrocode CTH, although his work mainly focused on the projectile. It was clear that several groups are ready to do hydrocode computations of the comet entry, but due to the need for lengthy supercomputer runs none has yet encompassed the entire impact process. A major point of interest was whether any atmospheric gasses would be ejected at high enough speed to enter space around Jupiter and perhaps affect the radiation belts or magnetosphere. None of the computations presented showed such high speed jets, but it was not clear that any of them have been carried out with sufficient accuracy to be sure of their absence. Other issues were the importance of thermal radiation (not included in any of the hydrocodes) and the need for an accurate equation of state.

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. Dave and I got permission to attend and present Sandia's work at the October 18 meeting of the American Astronomical Society's Division of Planetary Science meeting in Boulder. At the request of the AAS (American Astronomical Society) press officer, I drafted a press release:

> 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 under-

[21] Reprinted with permission from Jay Melosh; see summary link, http://www.surveyor.in-berlin.de/himmel/SL-9/Jupiter-SL9.txt.

> stand what happens within nuclear weapons. The computer program can simulate the extreme states of matter that result from energetic events such as explosions and hypervelocity impacts. In recent years, it has been used to help design shields to protect satellites from collisions with orbiting space junk. Now it has been used to study the collision of the ultimate piece of space junk: a 3 km diameter body of ice moving at 60 kilometers per second.
>
> The impact will be similar in size to the one 65 million years ago that left a 180-km diameter crater in Mexico and is thought to have wiped out the dinosaurs. For that asteroid-earth impact, the atmosphere had almost no effect on the asteroid. When the object slammed into the ground the pressure increased instantaneously, and shock waves converted the kinetic energy to mechanical and thermal energy, resulting in an explosion a million times as big as the biggest nuclear test. However, Jupiter does not have a solid surface, so next year's event will be very different in character. Jupiter's hydrogen/helium atmosphere increases in pressure gradually over a few hundred kilometers from the vacuum of space to the equivalent of hundreds of earth atmospheres.
>
> 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. At the time the comet starts to disintegrate, it has lost less than two percent of its kinetic energy. This means that as much as 98 percent of the comet's energy is carried to a depth of more than 120 km, where it is catastrophically released.
>
> 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. Other models have previously suggested mechanical wave interactions within the comet body lead to states of tension that exceed the strength of the comet, causing it to break apart.

Only two other competing groups were doing supercomputer simulations. One was led by my PhD advisor, Tom Ahrens, and the other consisted of partners Kevin Zahnle and Mordecai-Mark MacLow. They also issued press releases and were more explicit in their efforts to predict something that would be observable to astronomers. According to Ahrens, the plume from a 10-km-diameter cometary impact would be ten thousand times as bright as Jupiter and last several minutes. Unfortunately, it would cool down by the time it rotated into the view of Earth-based telescopes and only be visible in the infrared. Zahnle and MacLow also predicted a bright fireball, as hot as the Sun, rising above the cloud tops on Jupiter's far side. They pointed out that it would be visible to the NASA probes Galileo and Voyager 2 and that it might even brighten Jupiter's moons enough to be detected from Earth.

At the end of the year, we were still focused on the entry problem. How deeply would the fragments penetrate before they exploded? In December, we told *Sandia Science News* that as much as 98 % of the energy of the largest pieces of the original comet would be carried beneath Jupiter's clouds, where it would be explosively released. This claim eventually led to the major point of contention among the modeling groups, with Zahnle and MacLow claiming that the fragments would explode much higher in the atmosphere than we said they would. However, they were using a code with very limited equation of state options, so their comet fragments expanded during the descent. Their fragments were therefore larger and had more drag than ours. Because we had a better equation of state, our comet fragments remained mostly in the solid phase until they vaporized beneath the clouds.

The *Sandia Science News* article went on to say:

> The current results will give atmospheric scientists a starting point from which to determine whether the collisions will make giant mushroom clouds, create a new red spot on the planet, or be swallowed up without a trace. It will also help astronomers know what to expect to see.[22]

But unlike the other groups, we still hadn't made any specific predictions of what might be observed. Our disagreement with the other group about the depth of penetration was not going to be settled because no measurement could unambiguously make that determination.

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.

Unfortunately, like penetration depth, there was no apparent way to determine plume height or angle for something that was to happen on the back side of Jupiter. That is, until the predicted impact location started to change.

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.

The University of Maryland had set up an electronic bulletin board where I was able to keep up with the latest developments. That's how I found out quickly that on February 1, Jet Propulsion Laboratory had revised their orbit and impact predictions. Here's what I emailed to the Sandia modeling team:

> Attached are the latest impact predictions for the comet train, posted to the bulletin board last week. According to the table a few of the main fragments are predicted to hit about 4 ½ degrees past the limb. With the 1.7 degree uncertainty given, they could possibly hit within 3 degrees, making a direct observation of the fireball possible (and it will be rotating toward us). Even better, at Gene Shoemaker's talk in Houston on Saturday, he showed images from the repaired Hubble Space Telescope. There are several smaller fragments that are OFF the axis of the train, i.e.[,] in somewhat different orbits. Gene said orbits had not been calculated for these off-axis fragments, and [he] would not speculate about whether they might hit on this side of the limb, but in my opinion there is still hope for directly viewing a smaller hit.

From that moment on, our primary focus was on the 2 % of the impact energy that would contribute to the potentially observable fireballs. The projected impact points continued to migrate closer to the limb. We worked hard to get the word out,

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[22] *Sandia Science News*, vol. 28 (December 1993), Sandia National Laboratories, second page of unnumbered four-page article, reprinted with permission from Sandia National Laboratories.

but we were still considered outsiders in the planetary astronomy community and were not yet on the “A” list for national science journalists. On March 19, 1994, local reporter Lawrence Spohn of the now-defunct *Albuquerque Tribune* wrote an article entitled “Sandia computer plots Jupiter impact,” in which Dave was quoted:[23]

> Depending on how close they are to Jupiter’s horizon — as viewed from the Earth — the fireballs, or portions of them, actually might be visible through special telescopes on Earth. ‘In fact some of the fragments will not disappear behind the planet until they have already entered the thin upper atmosphere (about 250 miles) above the cloud,’ Crawford said. ‘Less than a minute later, the top of the hot fireball will rise back into view[,]’ he predicted, although the Sandia team cautioned that still may not be bright enough to be seen from Earth.

This was the first publication of our prediction. It’s always nice to get local press, but we quickly realized that the *Albuquerque Tribune* was not going to help to (1) get our prediction to the astronomers who were finalizing plans for their observational campaign and (2) document our prediction in a way that we would get full credit for it as a *scientific* prediction.

To help take care of the first issue, Dave and I prepared a poster for presentation at the spring meeting of the American Geophysical Union (AGU) and I traveled to Baltimore to present it. I was delighted when Heidi Hammel stopped to talk to me. She was a principal research scientist at the Massachusetts Institute of Technology who was the member of the Science Observation Team for the Hubble Space Telescope Jupiter Campaign in charge of the Wide Field Planetary Camera. She recently described her memory of the event in a telephone conversation with Mark:[24]

> I remember going to the AGU meeting, which had a special session about predictions for SL9. Mark and Dave had a poster predicting these giant impact plumes. Mark said we had to be sure to image the limb of Jupiter with Hubble, because those plumes would be so high that the tops of them would be visible from Earth, even though the impacts would happen just out of view. I was pretty skeptical, since my expectation was that these comet fragments would vanish without a trace into Jupiter. But, nevertheless, who knew? So we went ahead and set up an imaging sequence for Jupiter’s limb for the A impact (the first one expected) as well as limb-imaging sequences for the impacts of the brighter (and thus probably larger) fragments.

Now we had real skin in the game, but we wanted to take it further and go on record in the scientific literature. We knew we had to get a rapid publication out *before* the impact. We submitted a paper to AGU’s *Geophysical Research Letters* (GRL) on June 1, in which we said in the abstract, “For sufficiently large fragments, impact-generated fireballs will rise into line-of-sight over the Jovian limb (less than 1 min after impact for a 3-km diameter fragment).”[25] Our paper was accepted 10 days later and published in the July 1 issue, an unprecedented turnaround time for that journal, according to the editor.

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[23] L. Spohn, “Sandia computer plots Jupiter impact,” *Albuquerque Tribune*, March 19, 1994, p. A-5. Quote is reprinted with permission of David A. Crawford, Sandia National laboratories, in email to J. Asay, March 7, 2015.

[24] Private communication from Heidi Hammel to Mark Boslough, 2014.

[25] M.B. Boslough, D.A. Crawford, A.C. Robinson, and T.G. Trucano, “Mass and penetration depth of Shoemaker-Levy 9 fragments from time-resolved photometry,” *Geophysical Research Letters* **21**, 1555 (1994).

We weren't the only ones publishing specific predictions. Tom Ahrens and his team made essentially the same prediction in the same July 1 issue of GRL, saying in the abstract, "Earth-based observers can detect these plumes as these expand over the SW limb of Jupiter and come into Earth view some minutes after impact!"[26] Exclamation points are unusual in scientific literature!

Not all scientists were as confident as we were that there would be fireworks. On the same day as the GRL issue, science writer Dick Kerr published a news article in the July 1 issue of *Science* on pages 31–32 entitled, "Bets Range from Boom to Bust for Jovian Impacts." He wrote:[27]

> … astronomers may get a view of fireballs rising into view from the impact sites on the planet's backside, waves rippling across the Jovian clouds, and internal gases spewing out. Alternatively, the collision could simply fizzle—in full view of every telescope in the world from modest amateur rigs to the Hubble Space Telescope.

But Kerr also cited a study suggesting that the largest fragment would only be about a half km in diameter, much smaller than the ones we modeled:

> One-kilometer impacters, according to most studies, would be enough to produce fireballs rising into view from Jupiter's far side, dredge up bountiful amounts of Jupiter's interior, and send easily observed ripples around the planet. At half a kilometer, no one is making any promises.[28]

Fortunately, we had included a size caveat in our prediction.

Kerr closed by reminding readers that predictions based on computer models depend on assumptions: "Computer simulations have yet to agree on how deeply a 1-km sphere of ice would penetrate, whether the impacter would ultimately explode, and how high the fireball might rise."[29]

We had selected GRL, a subscription-only journal, for our formal prediction paper, but we decided that we wanted our predictions to be more widely known. So we wrote it up for *Eos*, the newspaper-like Transactions of the American Geophysical Union that gets mailed to every member of the organization. Wanting to get attention, we needed a catchier title. We called our paper "Watching for Fireballs on Jupiter" and timed it perfectly. It appeared in the July 5 issue and showed up in members' mailboxes only a few days before the first impact, fragment A, which collided with Jupiter on July 16.

Only one prediction paper followed our last one. It was in the high-profile journal *Nature*, written by comet expert Paul Weissman. It was called "The big fizzle is coming." Predictions are always more meaningful when there are disagreements.

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[26] T.J. Ahrens, T. Takata, J.D. O'Keefe, G.S. Orton, "Radiative signatures from impact of comet Shoemaker-Levy 9 on Jupiter," *Geophysical Research Letters* **21**, 1551 (1994).

[27] R. Kerr, "Bets Range from Boom to Bust for Jovian Impacts," *Science* **65**, p. 31 (1994), reprinted with permission from American Association for the Advancement of Science.

[28] *Ibid.*, p. 31, reprinted with permission from American Association for the Advancement of Science.

[29] *Ibid.*, p. 32, reprinted with permission from American Association for the Advancement of Science.

In the final days before impact week, Dave and I were asked to do many local television interviews. It was trial by fire, as neither one of us had any prior TV experience. We also decided to put our money where our mouths were. We both bought amateur 8-inch telescopes and plane tickets to Hawaii, where Jupiter would be high in the night sky for many of the impacts. We would be watching the planet at night and reading the University of Maryland bulletin board in the daytime.

My most memorable experience was watching Jupiter from the top of Haleakala as one of the largest fragments collided. We didn't see our predicted plume. It just wasn't bright enough to see with our little telescopes and our eyes that weren't sensitive to infrared radiation. But we saw the remarkable aftermath firsthand, as the dark spot from the collapsed plume rotated into our view.

Heidi Hammel recalls the excitement at the Space Telescope Science Institute:[30]

> When those first images came in, which would show the A plume, we saw a bright spot right on the limb. But none of us really believed it at first. 'It's got to be a moon,' I said. 'Probably Io, since it is so bright. Where's the astronomical almanac? Someone check for the location of Io.' But when we found that no moons were predicted to be at that location, we started to get excited. All of us crowded in around the screen to wait for the next images, which would be when the impact site itself rotated into view (about an hour later). The iconic image of astronomers crowded around the screen — and the video of champagne bottles — followed, as we got our first glimpse of big black impact sites on Jupiter. 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.

When we returned from Hawaii, our work wasn't over. Many of the observed phenomena had not been anticipated by us or by anyone else. We now had a wealth of data that still needed to be explained and the answers weren't immediately obvious.

Much to our annoyance, planetary scientist Clark Chapman (now a close colleague and friend) downplayed our predictions in his News and Views piece for *Nature* magazine, called "Dazzling demise of a comet," in which he said:[31]

> As the crash approached, comet researchers hesitated to predict more than a modest display — in Paul Weissman's phrase, a 'cosmic fizzle.'… The spectacular show during the subsequent week exceeded even the most optimistic predictions about the event's potential visibility from the Earth, nearly 800 million kilometres away. No one doubted that significant events would occur at the impact sites around Jupiter's limb, hidden from our sight. But the prominent visibility of high plumes, hotspots and enormous long-lasting dark splotches on the face of Jupiter was wholly unexpected. What does it mean?
>
> One of the most impressive and unexpected aspects of the comet impacts was the dramatic plumes that reached more than 2000 km above Jupiter's cloud tops, clearly depicted in pictures by the Hubble Space Telescope. Some numerical modellers had tentatively hoped that one or two of the later impacts, which occurred much closer to the Earth-facing side of Jupiter, might manage to peek above Jupiter's limb before thinning into invisibility… Indeed the effects are so large, even for the largest estimated sizes of the comet fragments, that it seems likely that our understanding of atmospheric impact physics will have to be revised to account for the amazing phenomena that have been seen….

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[30] Heidi Hammel email communication to Mark Boslough, Jan. 25, 2015.

[31] C.R. Chapman, "Dazzling demise of a comet," *Nature* **370**, pp. 245–246 (28 July 1994), reprinted with permission from Macmillan Publishers Ltd.

The scientific community's work was now cut out for it to put together a comprehensive model. At Lalit Chhablildas' suggestion, I organized the first post-impact conference session at the Hypervelocity Impact Symposium in Santa Fe later that summer. We called it "Comet Day," and it was attended by Gene and Carolyn Shoemaker, as well as by many of the observational astronomers and computational modelers who had made predictions. Miles O'Brien of CNN attended and interviewed me—my first time on national television.

Over the next year, we ran more simulations and published our paper, "Numerical modeling of Shoemaker-Levy 9 impacts as a framework for interpreting observations," in the July 1, 1995 issue of GRL. Our principal conclusions were stated in the abstract:[32]

> Among the observations that have already been at least partially explained in a way that appears to be consistent with the impact models are: the sources and timings of multiple flashes observed from Earth, the temperatures and durations of the single flashes observed from the Galileo spacecraft, and the asymmetry of the plumes and ejecta patterns observed by the Hubble Space Telescope. Further modeling subsequent to the impacts has shown that (contrary to our pre-impact expectations) fireball trajectory data do not provide strong constraints on either fragment mass or maximum penetration depth.… After more data become available and correlated, and more simulations are performed, we expect that fragment size estimates will become more precise.

Dave Crawford began working on a definitive estimate of the size of the comet, which he published in a paper[33] "Comet Shoemaker-Levy 9 fragment size estimates: How big was the parent body?" He concluded that the biggest fragments were greater than 1 km in diameter, but of low density. The original comet, before it broke up, was probably about 1.4 km in diameter. The fact that our plume sizes and velocities were underestimated had a simple explanation. Even with the most powerful computer in the world at the time, our simulations lacked sufficient resolution.

While Dave was working on size estimates, I turned my attention back to the Earth. A week after the impact, Congress had changed NASA's authorization bill to require the agency to conduct surveys for threatening asteroids and comets. Regarding planetary defense, David Levy put it this way, "Shoemaker-Levy 9 killed off the giggle factor."[34] There was also increasing interest within the national labs, and, thanks in part to the efforts of Sandian Dick Spalding, the Department of Defense began releasing satellite data on large "superbolides" in the Earth's atmosphere including a massive explosion over the south Pacific on Feb. 1 of that year.

Even though our simulations were not fully resolved, we noticed something about them that had implications for Earth impacts. In our animations, the eye is drawn to the ballistic fireballs rocketing upward into space, but in terms of energy, most of the

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[32] M.B. Boslough, D.A. Crawford, T.G. Trucano, A.C. Robinson, "Numerical modeling of Shoemaker-Levy 9 impacts as a framework for interpreting observations," *Geophysical Research Letters* **22**, pp. 1821–1824 (1995), reprinted with permission of John Wiley and Sons, copyright 2012.

[33] See *Annals of the New York Academy of Sciences*, Vol. 822, pp. 155–173 (May 1997).

[34] C.R. Chapman, in *The Great Comet Crash: The Impact of Comet Shoemaker-Levy 9 on Jupiter*, ed. by John R. Spencer and Jacqueline Mitton, p. 105, Cambridge University Press, Cambridge, UK, 1995), reprinted with permission of Cambridge University Press.

action is at the bottom, where the comet exploded. Even after the explosion, the vaporized comet continued to move downward. Was that also true for explosions in the Earth's atmosphere?

I started looking at the history of airbursts in the Earth's atmosphere, the most famous being the 1908 Tunguska explosion in Siberia. Another one was at Sikhote-Alin, also in Siberia, in 1947. It had been witnessed by a painter, who rendered it on canvas. It ended up on a 1957 Soviet postage stamp that had been reprinted in various publications on meteorites. It showed an unusual cloud that looked remarkably like our plume model.

I started running simulations of small impacts into the Earth's atmosphere on my desktop workstation, but for lack of computational horsepower, they were limited to two-dimensional axial symmetry. Nevertheless, I convinced myself of two things: small impacts like Tunguska (1) can produce plumes that rise hundreds of kilometers into space, potentially endangering satellites in low-Earth orbit, and (2) can produce a jet of vapor that continues to move downward under its own momentum, causing more damage at the surface than a nuclear explosion of the same yield.

Interest in the impact threat continued to grow after 1994. In April 1995, Dave and I were invited to present papers at the United Nations International Conference on Near-Earth Objects, organized by John Remo of Harvard University and Sandian Bill Tedeschi. The following month, Lawrence Livermore National Laboratory held a meeting on planetary defense, where I first presented my conclusions about plume-forming impacts on the Earth. Edward Teller was in the front row with his eyes closed, but Gene Shoemaker was attentive (but skeptical).

The following year I extended my Tunguska model in an effort to explain the mysterious yellow-green silica glass found only in the Libyan Desert of western Egypt, publishing only an abstract associated with a meeting on that subject in Bologna, Italy. I tried to tie everything together in a single, final paper for the proceedings of the United Nations conference, called "Shoemaker-Levy 9 and Plume-forming Collisions on Earth."[35] John Remo was the editor, and he arranged to have our simulation, along with the 1957 postage stamp showing the apparent Sikhote-Alin plume, on the cover of the book. That would be my last word on the subject for the next 8 years as I turned my attention to other work.

Postscript

In the fall of 2005, I got a call from a British filmmaker. She wanted to know if I could do some simulations in support of a documentary she was producing for the BBC (British Broadcasting Corporation) and *National Geographic* about the Libyan Desert Glass. During my 8 years away from the field, a lot had happened. Both the code and Sandia's computers had become much more powerful. Dave had added

[35] See *Near-Earth Objects, The United Nations International Conference*, edited by John L. Remo (Annals of the New York Academy of Sciences, New York, NY), Vol. 822, pp. 236–282 (1997).

adaptive mesh refinement, and we had a new supercomputer called Red Storm. There would be no issues with resolution.

I was ultimately invited to join an expedition to the Great Sand Sea. With new LDRD funding, I was able to run simulations that resurrected interest in planetary airbursts (perhaps too much uncritical interest as well, I later discovered). My documentary appearance led to more invitations, including a 2008 expedition to ground zero of the Tunguska explosion on the centennial anniversary. In 2009, I was invited to be the "token skeptic" for an episode of NOVA focused on a group that, in my view, had taken my airburst models too far. Inspired by an incorrect animation of one of my simulations for the Libyan Desert Glass documentary, they had proposed that a giant comet explosion had changed the climate and wiped out the North American megabeasts and Clovis Culture 12,900 years ago.

I presented my airburst models at Planetary Defense Conferences every 2 years, arguing that the risk was greater than previously acknowledged. Then, on Valentine's Day evening in 2013 (in our time zone), a half-megaton airburst occurred in Chelyabinsk, Russia. Within a few days, I got a call from the producers of NOVA: Did I want to go? It turned out to not be a plume-forming event, because the asteroid entered the atmosphere at a very shallow angle. But because of the huge quantity of data from mobile phones and dashboard videos, my colleagues were able to determine the trajectory and energy deposition rate precisely in a way that I could use to initialize and validate a high-fidelity model. I was also able to bring back some meteorites for analysis.

A couple months later, we held our biannual Planetary Defense Conference in Flagstaff, Arizona, including a hastily organized technical session about Chelyabinsk. In attendance was Carolyn Shoemaker, whom we honored for her lifetime achievements at our banquet. We presented her with a pendant made from one of the meteorites I had brought back from Russia.

I also gave a presentation about an idea I had been considering for years. If airbursts generate upward plumes, an equal but opposite force must be pushing downward against a planet. I had concluded (in contradiction to opinions that have prevailed for nearly two decades) that the observed wave in Jupiter's atmosphere was generated by this reaction force. And if that happened on Jupiter, then it could be argued that such a plume-forming airburst could create a similar wave at a fluid interface on Earth: a tsunami!

While I was preparing my presentation, I thought I'd run the idea by Heidi Hammel, who had been my friend and pen pal ever since we first met that spring in Baltimore. She was pleased that I was still interested in her 1995 paper that showed images of the observed waves, and she made an observation about our favorite comet: "Shoemaker-Levy 9 is the gift that keeps on giving."[36]

[36] Private communication by email from Heidi Hammel to Mark Boslough, 2014.