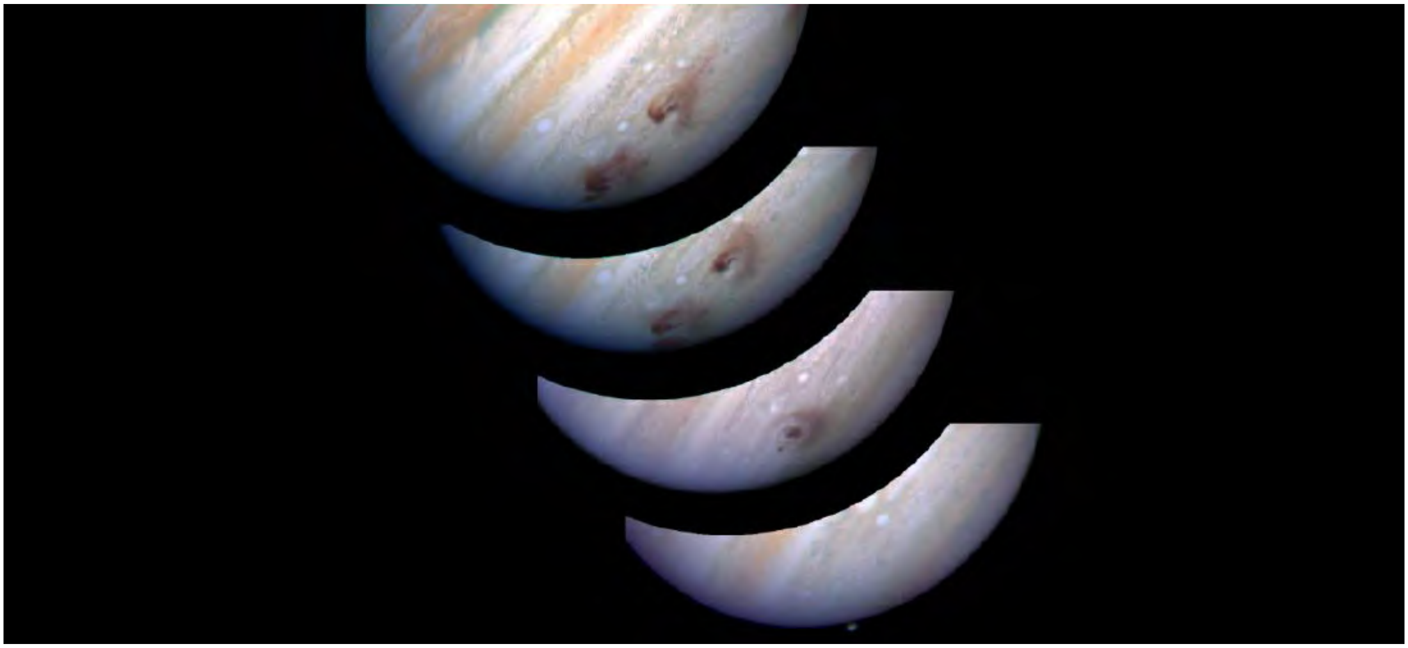
Feature Story

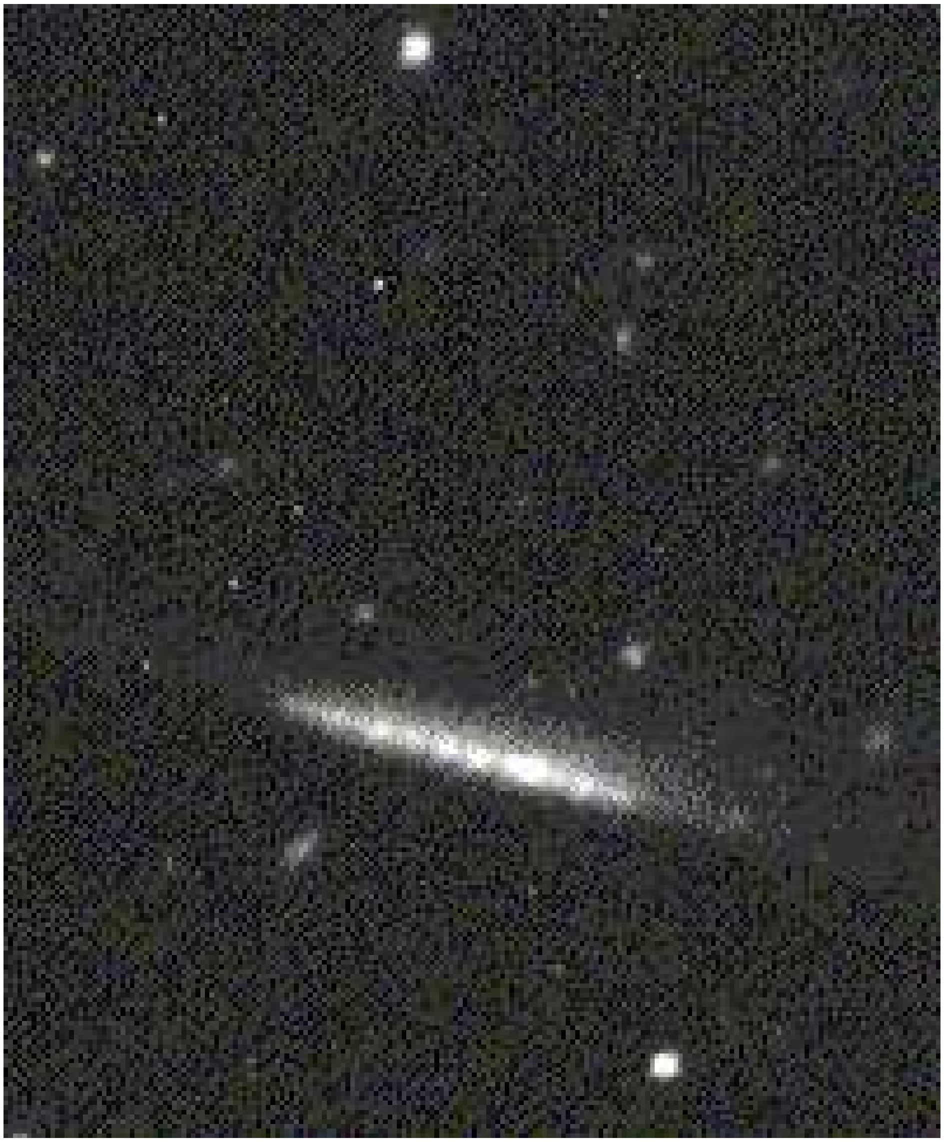


The Scar on Jupiter: Discovery of Comet Shoemaker-Levy 9 and Its Impact Into Jupiter 25 Years Later

On March 24, 1993, in the midst of a photographic search for near-Earth objects at the fabled Palomar Observatory, Drs. Carolyn and Eugene Shoemaker and Dr. David Levy acquired an image in the vicinity of planet Jupiter using surplus film. This image surprised the observers when they first examined it. Expecting to find yet another small asteroid trail, they instead found an elongate object comprising several large clumps all strung out in a chain thousands of kilometers long in the night sky, each with its own cometary tail. Its orbital position proved to be quite close to Jupiter, and it did not take long to determine that it was in fact orbiting that giant planet and would come very close to the cloud tops the following year.

The discovery of this strange comet was both serendipitous and completely unexpected, and the rest of the world was startled when the image was released three days later. No object like it had ever been seen before. It would be named P/Shoemaker-Levy 9 after its discoverers (SL-9 for short). We had observed comets break apart during close encounters with the Sun into irregular clumps, but the linear geometry of this object indicated that it had passed very close to Jupiter in July 1992 and been ripped apart by tidal forces, something we had not observed or even predicted before. The original comet may have been captured by Jupiter as far back as 1929 or so. More surprises were to come.

In May, the scientific world was stunned to learn that the fragments of this cometary object would in fact strike the giant planet during the week of July 16, 1994. The innumerable impact of asteroids and comets was known to be responsible for the thousands of craters on the Moon and other planets (including those few craters remaining on Earth), but this was going to be the first time we would witness an impact collision of two planetary bodies as it occurred. More than a hundred scientists, including the two authors of this piece, met to discuss the comet and its pending impact and plan observations. One such meeting was the "Comet Pre-Crash Bash" held in Tucson, Arizona, in August 1993. A revolution was taking place in planetary science.



Discovery image of Comet Shoemaker-Levy 9. Credit: Palomar Observatory.

The discovery of SL-9 and its subsequent impact into the giant planet Jupiter in July 1994, a little over a year later, occurred during a rather remarkable period in space exploration history. Voyager had just finished its glorious tour of the four giant outer planets with its daring flyby of Neptune and its large moon Triton in 1989. Voyager's tour was a revolution of its own, with the first discoveries of geologically active worlds among the moons of the outer solar system. Also anticipated in 1993 was the Mars Observer global mapping mission in the first return to the Red Planet since the Viking landers almost 20 years before (the mission failed but was replaced by the successful Mars Global Surveyor in 1997), and the impending arrival of the Galileo probe at Jupiter, then in interplanetary cruise. What we did not expect after Voyager was a fundamental redefinition of the solar system.

Several major discoveries occurred in rapid succession beginning in 1991. First came the discovery of a large impact crater buried under sedimentary rock on the Yucatán Peninsula and linked to the extinction of dinosaurs and most life on Earth 66 million years ago. This ~180-kilometer-wide geologic scar would be named Chicxulub, "tail of the devil," and was a classic case of a "smoking gun," linking large impacts of the type seen on the Moon with catastrophic effects here on Earth. Evidence for such an event had been found in metal-rich deposits scattered across the globe, but this was the first evidence for the actual impact site itself, confirming the role of this and possibly other large impacts in the evolution of life in Earth.

Only a year later, in 1992, the discovery by Luu and Jewitt of the first object beyond the orbit of Neptune since the discovery of Pluto back in 1930 demonstrated that the region beyond the furthest gas giant planet is indeed likely to be populated by many small icy and rocky objects. Discovery of more Kuiper belt objects followed within months, confirming the existence of this hypothesized zone, a major component of our solar system, and vastly expanding its known limits. Pluto remains the largest of these objects, but it would take another 20 years before we got our first close look at any of them, with New Horizons at Pluto in 2015.

The discoverers of SL-9, from left to right, Eugene and Carolyn Shoemaker and David Levy, during a press conference the week of the impact in July 1994. Credit: NASA Goddard Space Flight Center.

Then in 1993–1994 came SL-9 and its impact into Jupiter. The scientific importance of the events associated with SL-9 in 1993–1994 cannot be understated. It demonstrated in dramatic fashion the continuing importance of impact processes in the planetary environment. That disrupted comets such as SL-9 have struck Jupiter many times in the past was made clear when Jay Melosh and Paul Schenk realized that odd chains of craters on the large jovian moons Ganymede and Callisto recorded similar past occurrences, on average once every 200 years or so. The discoveries in Mexico, at Jupiter, and in the Kuiper belt all pointed to the urgent need to understand just how crowded (and dangerous) our solar system neighborhood is. One of the last large impacts to do observable damage to Earth's surface was Meteor Crater in Arizona, which formed roughly 50,000 years ago. (For more details of this impact, see LPI Contribution No. 2040 at https://www.lpi.usra.edu/publications/books/barringer_crater_guidebook/.) Clearly these things do not happen very frequently on human timescales, but they do occur, and thanks to the efforts of NASA, several groundbased survey programs, such as the Catalina Sky Survey, and spacebased surveys, such as NEOWISE, we now have a nearly complete (>90%) survey of objects larger than 1 kilometer on orbits crossing that of Earth's. The surveys are now working to identify 90% of the near-Earth objects larger than 140 meters.

Those surveys need to be supplemented with data from other groundbased or spacebased platforms to identify near-Earth objects in the part of space not currently observable from Earth. Once complete, those surveys will identify potentially hazardous objects in the asteroid-related population. However, cometary objects in the outer solar system, some of which may never have entered the inner solar system before, will remain a largely uncharacterized threat. Interested readers can track the surveys' progress using a JPL website (https://cneos.jpl.nasa.gov/stats/).

While some of these surveys were spurred by the SL-9 impact, it is now understood that most impact cratering events on Earth are produced by asteroids. As the Chelyabinsk air burst illustrated (see the May 2013 LPIB issue at https://www.lpi.usra.edu/publications/newsletters/lpib/lpib133.pdf), hazardous impacts can occur with frequencies commensurate with a human lifetime. This event occurred in 2013 when a small object entered and broke up high in the atmosphere over Siberia, not far from the location of the 1908 Siberian Tunguska airburst. The monitoring of smaller, more frequent NEO bolides into the atmosphere, in the form of fireballs, is reported by U.S. government sensors (https://cneos.jpl.nasa.gov/fireballs/).

HST astronomers react to the first images of the impact of fragment A into Jupiter's atmosphere, July 16, 1994. Credit: NASA Goddard Space Flight Center.

The discovery of SL-9 also coincided with several major cultural and technical events. First, the Hubble Space Telescope (HST) had just been launched in 1990, but with an incorrectly ground mirror. Happily, the flaw was precisely known and fixable with corrective mirrors (or spectacles, as some called them) that would be installed in December 1993 during one of the most daring and most important space shuttle missions ever conducted.

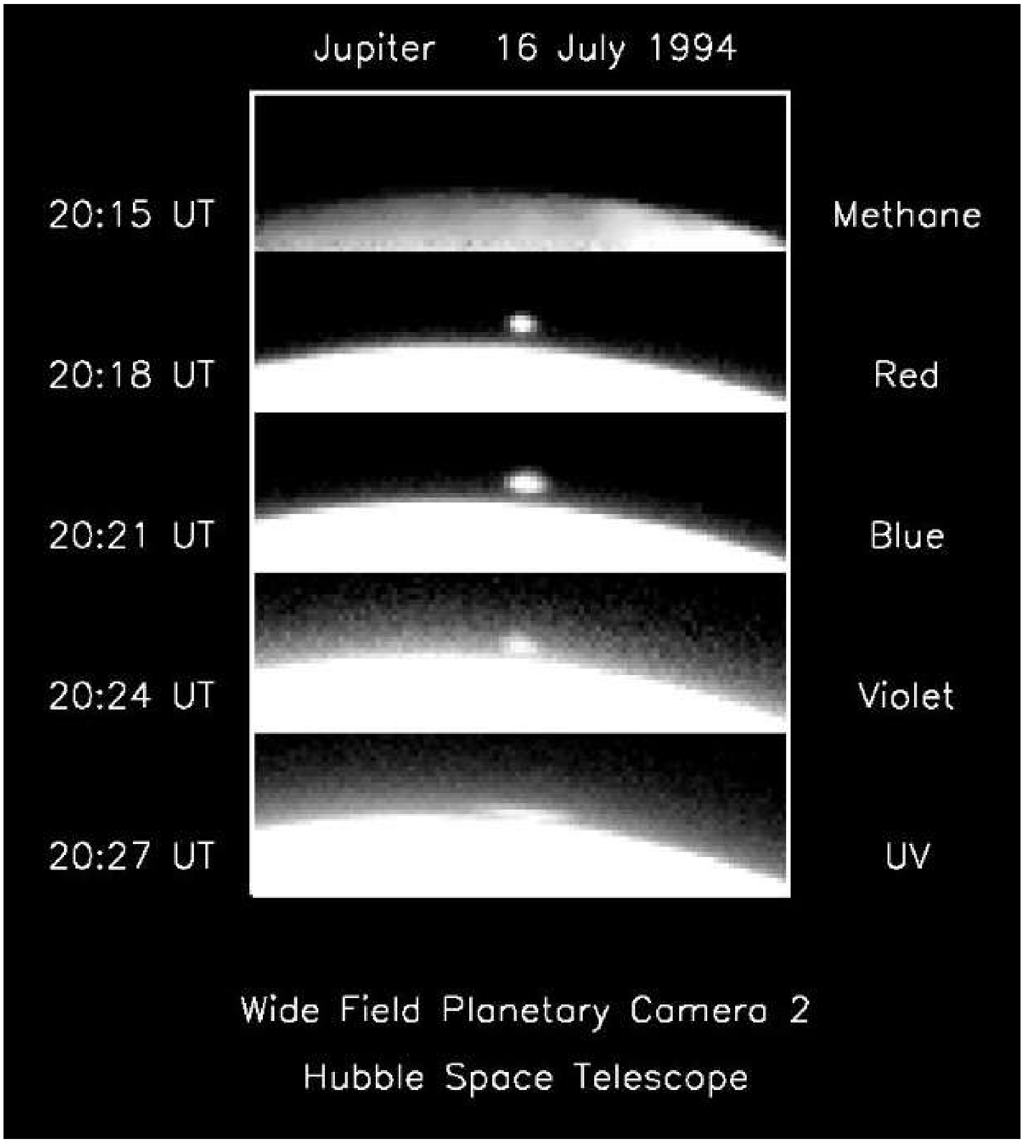
This would position the telescope to be fully operational when the comet's fragments struck Jupiter 8 months later, just in time to produce some of the best astronomical images of the decade. The week of impact had been already scheduled for other observations, but fortunately the Space Telescope Institute was able to reassign some of that time to observe the impacts and their effects.

Second, the Internet had just been opened up to the public, and the comet's discovery and subsequent impacts into Jupiter in 1993–1994 was the first major global event covered on the new World Wide Web (WWW). NASA generated a website at the Jet Propulsion Laboratory (JPL) for the dissemination of data. During the week of the impacts, the SL-9 home page was accessed 1.1 million times, making it the most accessed home page in the world up to that time. By March 1996, that site was accessed more than 7 million times; these were extraordinary numbers at that time, and all those views helped share the wonder of a planetary system in action.

The repaired HST confirmed that there were ~25 observable fragments in the linear chain that make up SL-9, often described as a string of pearls in space, as beautiful as they were violent, each fragment capable of producing multi-megaton impact blasts as they plummeted into Jupiter's atmosphere. Most of the world's telescopes were focused on Jupiter that week, as it took six days for the long chain of objects to consecutively strike the planet. Although numerical models of the impact suggested they could be observed from Earth, nobody was certain we would see anything, either through direct observations or through photographic exposures.

There were many predictions for what we might see, with the biggest unknowns being the sizes and masses of each fragment. It turned out that most of the fragments were less than 1 kilometer in size and consisted of tightly packed clusters of loose debris. The impact velocities were predicted to be ~60 kilometers per second, however, so we could be sure there was plenty of energy for each impact.

Many of us went to our closest observatories on July 16 to hopefully see the impact of the first object, fragment A (the 25 or so fragments were named A through W), but were disappointed to not see a flash or scar of any kind. Meanwhile, observatories from Spain to South Africa were making their first observations and reporting the detection of a major fireball. We were all astonished the next morning, however, to see on the Internet that the HST, fulfilling the promises of its makers, had indeed witnessed and imaged a large fireball erupting out of the shadow of the nighttime Jupiter, up into sunlight far above the limb of the planet. The impact



debris formed a giant plume of hot gas and debris expanding above the cloud tops of the giant planet, leaving a dark circular scar the size of planet Earth as it collapsed down onto the cloud tops. Videos of the press conferences from the week can be found at *https://svs.gsfc.nasa.gov/11822*.

The first HST images of the first fragment impact, July 16, 1994, showing a time-lapse sequence of the expanding impact-generated gas plume and its subsequent collapse. Credit: Space Telescope Science Institute.

Many people, including both professional and amateur astronomers, contributed to the observing campaign in 1993–1994 and subsequent data analysis (indeed, quite a few books were published detailing these events). By the end of the week, the entire southern hemisphere of Jupiter was populated by large dark clouds, residual effects of the preceding impact events. These scars were visible from Earth and were monitored by amateur astronomers around the globe for several months afterward, contributing greatly to our understanding of chemical and meteorological processes in Jupiter's atmosphere.

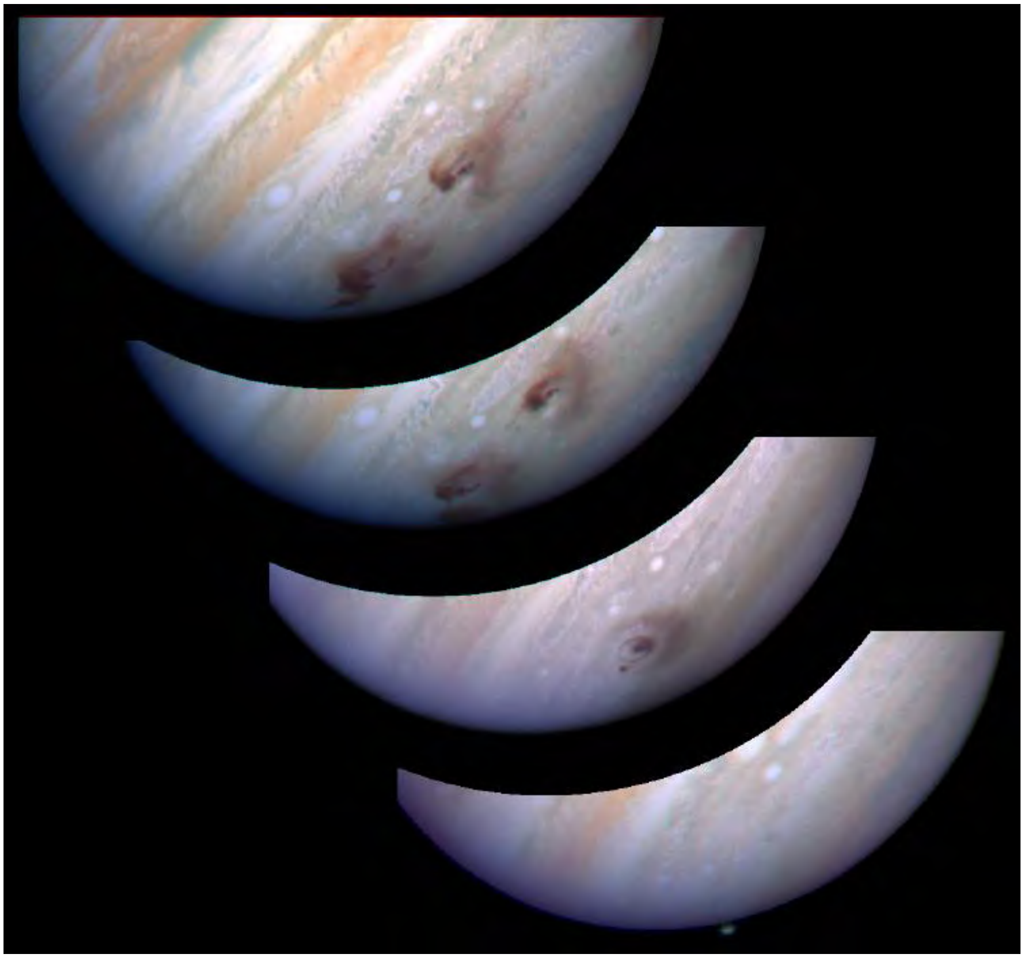
Observatories both on Earth and in space shared their observations as the fragments continued to hit Jupiter, including infrared and ultraviolet movies. The HST had its own scare

Infrared image of Jupiter showing the hot gas plume erupting on the edge of the planet (at lower left). Bright spot at right is Jupiter's moon Io. Credit: Max Planck Institute for Astronomy.

when the spacecraft entered the emergency hibernation mode known as "safing" and had to be rebooted twice just one week before the impacts. Even the Galileo orbiter, millions of kilometers and a year out from its target, Jupiter, captured several impact events. Galileo was the only observatory that could directly observe the moment of each impact, all of which occurred just out of our view on the backside of Jupiter. Galileo's Solid State Imager recorded the fireball flash, and the Near Infrared Mapping Spectrometer also recorded the initial fireball produced by the impact. Several minutes later, it was also able to record the moment when, after a vapor-rich plume rose 3000 kilometers above the atmosphere, atmospheric heating occurred when that impact plume fell back into the atmosphere.

The impacts into Jupiter were also a test of how well our models did at predicting the effects of large impact events. Since this was an impact into a very deep atmosphere, rather than a rocky surface, the calculations were relatively simple and relatively accurate. One surprise was that the fireball and eruption cloud that followed did not bring up much water from deep inside Jupiter. This turned out to be related to the incoherent or rubbly nature of the incoming projectiles, which broke apart very quickly high in Jupiter's atmosphere. Thus they did not penetrate very deeply into the watery cloud decks below.

The observations also caused the community to reassess the effects of impacts on Earth. The phenomena of a ballistic vapor-rich plume caused Mark Boslough and David Crawford to reassess impact events, particularly airburst events like Tunguska, a phenomena seen again in modified form during the Chelyabinsk airburst of 2013 (see the May 2013 LPIB issue at https://www.lpi.usra.edu/publications/newsletters/lpib/lpib133.pdf). Also observed were plumes of sulfur following the SL-9 impact on Jupiter. Although a portion of that sulfur may have been dredged up from the atmosphere, David Kring, Jay Melosh, and Don Hunten realized that impacting asteroids (sometimes with more than 5% sulfur) and comets could deliver significant amounts of sulfur to Earth's atmosphere, producing climate-altering sulfuric-acid aerosols. Asteroids as small as 300 meters across could produce global effects and larger impacting objects could depress global average temperatures by 2°C for more than three years.



Time-lapse sequence showing the changing shape of the dark impact scars on Jupiter, summer 1994. Credit: Space Telescope Science Institute.

It has been 25 years since the impact of SL-9 captured our imaginations. Who can tell what cosmological event is next on our horizons? The collisions of planetary objects are now recognized as fundamental to their formation and evolution. Examples abound, including the large Rheasilvia impact basin on the south pole of asteroid Vesta, which delivered HED meteorites to Earth. At least five objects have been observed striking Jupiter since 1994, some recorded live by amateur astronomers (see Wikipedia page "Jupiter impact events"). One such event was first detected by Anthony Wesley in July 2009, 15 years after SL-9, and a fireball flash was witnessed by the same observer in 2010. Other impact events no doubt occurred before 1994, but astronomers were not lucky enough to have observed them, and cameras were not as sensitive as they are today. Jupiter sucks in a lot of space debris. Dozens of small impact craters have also formed in the past 25 years on both the Moon and Mars. Clearly the solar system is a very active place. We need not worry too much, as these events are very rare on Earth on the timescale of human evolution, thanks to our protective atmosphere.

As for the discoverers of SL-9, Gene Shoemaker passed away just six years later in a accident in the Australian desert, doing what he loved best, searching for ancient impact scars on our own home planet. Carolyn Shoemaker retains her life-long interest in NEOs, even though she is no longer able to continue her observing. David Levy is still actively studying the skies, looking for other heavenly bodies that are still waiting to be discovered.

About the Authors

Paul Schenk, a staff scientist at the LPI, uses Voyager, Galileo, and Cassini stereo and monoscopic images to map the topography and geology of the icy outer planet satellites. He is also a Participating Scientist on the Dawn and Cassini missions, studying impact cratering on small bodies and plume deposition processes on Enceladus, as well as a co-investigator on the New Horizons mission to Pluto and beyond, responsible for cartography and topography.

David Kring, a staff scientist at the LPI, conducts research that explores the origin of the solar nebula and its evolution into a geologically active planetary system; the geologic history of the Earth, Moon, Mars, and several smaller planetary bodies; impact cratering on the Earth, its effect on Earth's environment, and its possible role in the biological evolution of our planet; and the chemical and physical properties of meteorites. He has worked extensively with the Chicxulub impact crater, gives frequent public lectures, and has been involved with a variety of print, radio, and television science productions in an effort to educate the general public.