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After a historic 2005 encounter with comet Tempel 1, the Deep Impact spacecraft took on an extended mission that would provide a bonus for space scientists—and great savings to taxpayers. Its observations are helping astronomers recognize other Earth-like bodies and shedding light on the origin and history of our solar system.

Comet chasing makes deep impact on science

by Leonard David
Contributing writer

More bang for the buck: That is a fitting legacy for NASA's Deep Impact spacecraft. Launched in January 2005, it accomplished its primary mission later that year, in a celestial July 4 fireworks encounter with comet Tempel 1.

Deep Impact consisted of two parts: the Impactor and Flyby spacecraft. The Flyby segment unleashed the 815-lb copper-core Impactor that plowed into the comet, excavating debris from the interior of its nucleus. Images captured by cameras aboard both spacecraft caught the action: A large dust cloud billowed out from the comet but masked a clear view of the resulting impact crater. Still, the imagery revealed Tempel 1 to be far dustier and less icy than expected.

While Deep Impact's tangle with Tempel 1 was a history-making Independence Day event—one that delighted not just spacecraft designers but also comet specialists around the world—it was also a prelude of things to come.

Good to go

In the aftermath of the encounter at Tempel 1, mission scientists won approval from NASA to make use of the still healthy Flyby spacecraft—loaded with a 'good to go' set of instruments: two telescopes with digital color cameras and an infrared spectrometer.

In its extended mission mode, Deep Impact's name morphed into EPOXI—an abbreviation combining EPOCh (extrasolar planet observations and characterization) and DIXI (Deep Impact extended investigation—the flyby of comet Hartley 2). The spacecraft is still called Deep Impact.

During the initial phases of EPOXI, Deep Impact's EPOCh campaign that ended in August 2008 also provided scans of the Earth, in both visible and infrared wavelengths. Its observations are intended

Close-up view of Hartley 2 was taken during the flyby on November 4, 2010, by the spacecraft's medium-resolution instrument. Image credit: NASA/ JPL-Caltech/UMD.

to help gauge how to recognize Earth-like worlds around other stars. It was also one of three spacecraft to find clear evidence of water on the Moon.

The total cost of Deep Impact was $267 million (not including the launch vehicle)—$252 million for spacecraft development and $15 million for mission operations. The EPOXI extended mission price tag, $42 million, covers operations from 2007 to the project's ending at the close of FY11. This includes mission and science operations for both EPOCh and DIXI operations.

Stunning as well as surprising

On November 4, 2010, the spacecraft's onboard cameras captured spectacular images of comet Hartley 2 as part of the EPOXI mission. This was a much-heralded first: the first time in history that two comets—Hartley 2 and Tempel 1—had been imaged by the same spacecraft, by the same instruments, with the same spatial resolution.

The overall objective of the Hartley 2 flyby was identical to that of the trip to Tempel 1: to discover more about the origin and history of our solar system by learning more about the composition and diversity of comets. These objects hold material from the early days of the solar system, before the planets formed. Delving into the makeup of comets could help unravel the mysteries of planetary formation.

Moving from fuzzy to full-frame clarity, images of Hartley 2 took shape as Deep Impact drew closer to the surface, reorienting itself to maintain its focus on the comet nucleus. At the same time, the craft continued to point its high-gain antenna at Earth to begin downlinking nearly 5,800 images.

Hartley 2 proved stunning as well as surprising. Deep Impact flew through a storm of fluffy particles of water ice spewed out by the comet. Imagery relayed back to

Earth captured carbon dioxide jets streaming outward from the peanut-shaped body's rocky ends.

The comet's nucleus, or main body, is some 1.2 mi. long and 0.25 mi. across at the 'neck,' or narrowest portion of the object. The mass of the comet's nucleus is estimated at roughly 280 million metric tons.

An image montage shows Hartley 2 as the EPOXI mission approached and flew under it. The images progress in time clockwise, starting at the top left. The Sun is to the right. Image credit: NASA/JPL-Caltech/UMD.

Deep Impact's visitation of Hartley 2 came in the midst of a cometary ice storm powered by jets of carbon dioxide gas carrying a couple of tons of water ice off the comet every second. The eye-popping images showed, at the same time, that a different process was causing water vapor to belch out of the comet's midsection.

"This is the type of moment that scientists live for," says Don Yeomans, a JPL senior research scientist who keeps a watchful eye on near-Earth objects.

Crystal snow globes

"We haven't even begun to get the science out of the data we have now," observes University of Maryland astronomer Michael A'Hearn, science team leader and principal investigator for the spacecraft's Deep Impact and EPOXI missions. "There should be a steady stream of results over a couple of years," he tells *Aerospace America*.

Recalling his reaction to the images of a hyperactive Hartley 2, "It was instantly obvious to all of us what we had," A'Hearn says. "Large chunks, and that they were probably ice…so our main reaction was elation. This was something that was sort of expected 10 years ago," he recalls, but not seen by other NASA missions, specifically the Deep Space 1 flyby of comet Borrelly in 2001, by the Stardust mission to comet Wild 2 in January 2004, or by Deep Impact's 2005 encounter with comet Tempel 1.

"It just wasn't there. So, in some sense, it was, 'Oh, this is what we've been expecting for the last four comets and not finding,'" he says. "What it illustrates is that there is a class of comets that really works in a different way from the other comets."

Jessica Sunshine, EPOXI deputy principal investigator at the University of Maryland, points out that the carbon dioxide jets blast out water ice from specific locations in the rough areas, resulting in a cloud of ice and snow. "Underneath the smooth middle area, water ice turns into water vapor that flows through the porous material, with the result that close to the comet in this area we see a lot of water vapor."

A'Hearn points to evidence of large chunks around comets such as Hartley 2 having been found with the powerful Arecibo radio telescope in Puerto Rico. But the Arecibo telescope is not able to detect individual particles or to determine the makeup of the chunks. Around Hartley 2, Deep Impact clearly imaged clouds of ice particles ranging in size from golf balls to basketballs.

Recalls EPOXI mission coinvestigator Peter Schultz of Brown University, "When we first saw all the specks surrounding the nucleus, our mouths dropped." Stereo images disclose that there are snowballs in front of and behind the comet's nucleus, "making it look like a scene in one of those crystal snow globes."

Sunshine notes that it was previously thought that water vapor from water ice was the propulsive force behind jets of material coming off a comet's nucleus.

"We now have unambiguous evidence that solar heating of subsurface frozen carbon dioxide, directly to a gas—a process known as sublimation—is powering the many jets of material coming from the comet," Sunshine says. "This is a finding that could only have been made by traveling to a comet, because ground-based telescopes can't detect carbon dioxide, and current space telescopes aren't tuned to look for this gas," she notes.

The spacecraft at Hartley 2 provided the most extensive observations of a comet in history, notes Ed Weiler, associate administrator for the Science Mission Directorate at NASA Headquarters. "Scientists and engineers have successfully squeezed world-class science from a repurposed spacecraft at a fraction of what a new science project would have cost the taxpayers."

A separate saga

Even as scientists exult over the comet Hartley flyby, the extended journey of Deep Impact is a separate saga.

Built and designed by Ball Aerospace & Technologies, Deep Impact has an extra dividend for space science discovery, says David Taylor, president and CEO of the Boulder, Colorado, company.

"Deep Impact is proving to be a spacecraft that keeps on giving," Taylor says. "When it launched in January of 2005, the Deep Impact mission [to Tempel 1] was the priority, so it's extremely rewarding to see a 'three-peat performance' six years later that provides more beneficial science data."

"Because the vast majority of mission costs are [for] the initial design, testing, and launch, the recycled Deep Impact provided savings on the order of 90% that of a hypothetical mission with similar goals, starting from the ground up," according to a Ball Aerospace press statement.

Tim Larson, the EPOXI project manager at JPL, also emphasizes Deep Impact's ability to take on the job of surveying comet Hartley 2. The comet was discovered in March of 1986 by Malcolm Hartley, an English-born astronomer currently based in Australia at the Anglo-Australian Observatory in New South Wales.

"The spacecraft was still in good shape, willing to do more work. It just needed a new reason for living," Larson says. "And NASA, in its effort to go green by reusing spacecraft and recycling as much as possible, approved a new mission for the project and enabled us to embark on this new effort of retargeting the spacecraft to go to comet Hartley 2."

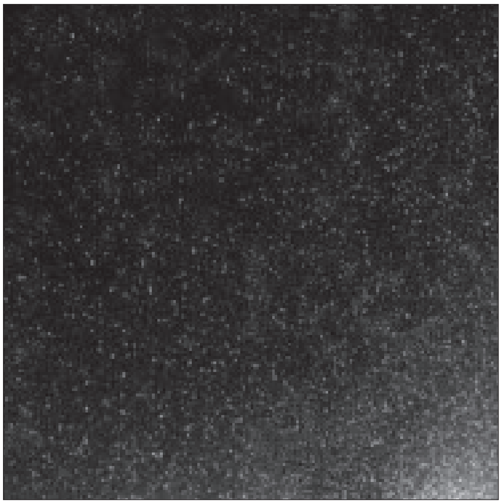
To get in synch with the comet, Larson explains, the EPOXI mission had to adjust the trajectory of the spacecraft. And after three-and-a-half orbits around the Sun, seven burns of on-board thrusters, and three gravity assists around Earth, Deep Impact got close to the comet to accomplish this bonus mission.

Humming along

In the months leading up to its closest encounter with Hartley 2 late last year, Deep Impact responded to multiple commands to align itself for optimum viewing. Approximately the size of a subcompact car, the spacecraft had already used about half of its 85 kg of hydrazine fuel to complete the encounter with Tempel 1.

Before its Hartley 2 meeting, Deep Impact spent over a year and a half in 'hibernation,' with one brief wake-up (less than one day total in cruise state), says Amy Walsh, the systems engineering lead at Ball Aerospace for the EPOXI mission. "Essentially we ran our safing sequence and also disabled our autonavigation program…just to make sure that it didn't get confused."

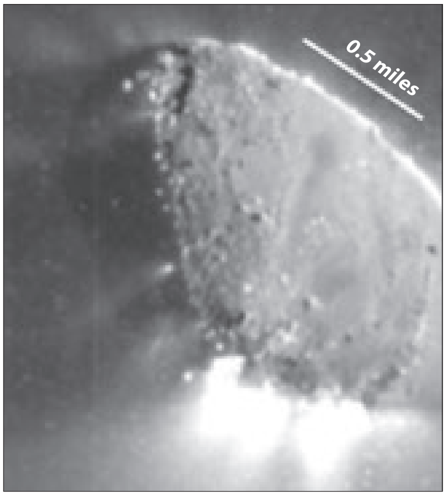
It was in late July 2005 that the spacecraft was put in hibernation. For the next two years it was awakened roughly once every six months for health and safety checks, then put back to slumber.



This zoomed-in image from EPOXI's high-resolution instrument shows the particles swirling in a 'snowstorm' around the nucleus of Hartley 2. Scientists estimate the largest particles range in size from golf balls to basketballs. They have determined these are icy particles rather than dust. The particles are believed to be very porous and fluffy. Image credit: NASA/JPL-Caltech/UMD.

As Deep Impact was revved up for Hartley 2, the spacecraft was found to be stable in terms of electronics and other systems. "Everything was humming along," says Walsh. "So it ended up being a very clean and uneventful hibernation phase," she tells *Aerospace America*.

As plans for the Hartley 2 flyby jelled, spacecraft sequences were fleshed out, reviewed, and wrung out on test benches, with Ball Aerospace putting its seal of approval on the sequences, Walsh notes.

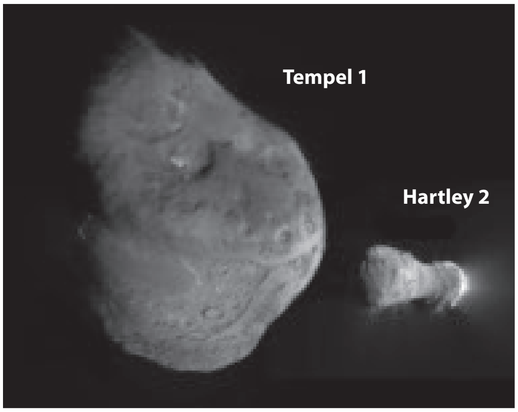


This enhanced image—one of the closest taken of Hartley 2—shows jets and where they originate from the surface of the object. There are jets outgassing from the sunward side, the night side, and along the terminator—the line between the two sides. The Sun is to the right. Image credit: NASA/JPL-Caltech/UMD.

Still, there was a big unknown concerning the comet encounter: Exactly where would the celestial wanderer be?

"We had confidence in our spacecraft's ability to perform the encounter. We knew that the products we were putting onboard were those needed in order to follow the comet. But what we didn't know was whether the comet was going to hold still and let its picture be taken. It had moved around quite a bit. So the thing that we were doing at the last minute was updating target tables.

"We were doing trajectory correction maneuvers right up until two days before encounter, to try and make sure that our closest approach was right in the window that we were aiming for," Walsh explains. "It was pretty well spot on. The autonavigation solutions matched up really well with ground-based solutions. In the end, the



Deep Impact provided imagery of Tempel 1 and Hartley 2. Credit: NASA/JPL-Caltech/UMD/McREL.

comet did settle out and not do any moving around on us."

The spacecraft was clocked as traveling by Hartley 2 at a speed of 27,560 mph.

Nail biting on encounter day

On encounter day, the spacecraft team had further tension regarding just how energetic the comet would turn out to be…and there were sure to be surprises.

"Essentially, we were doing the same kind of thing we did on the last comet flyby, only without the Impactor," Walsh says. "One thing we decided not to do is go into our debris shield mode...instead we imaged comet Hartley 2 the entire way through."

That decision did not come without extra nail-biting, Walsh admits. "It was something that definitely got a lot of scrutiny," with concern over what Deep Impact would bump into in terms of particle hits of dust and ice. Although the comet was throwing off large bits of particles, the scientific consensus centered on the roughly 435-mi. separation between the spacecraft and Hartley 2.

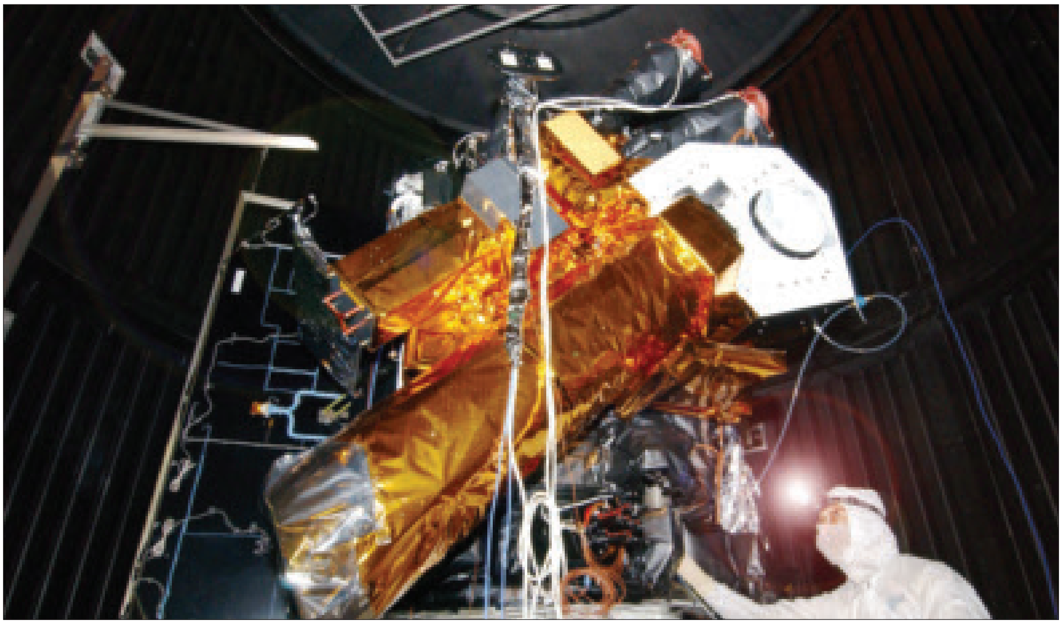
From that flyby distance, "the risk to the spacecraft was less than on the prime mission," says A'Hearn. Also, given that all the big things are very close to the comet's nucleus, it was deemed fairly safe. "This is an extended mission. You are willing to take bigger risks. You don't need to push it down to smaller risks."

A'Hearn reports that a look back at data post-encounter points to about nine particle hits on Deep Impact. "The relatively small ones didn't do any damage, just enough to deflect the spacecraft. You see it in the gyros and in the attitude control system reacting," he explains.

One nagging problem has plagued the exploits of the Deep Impact spacecraft. Images taken by EPOXI's high-resolution camera were out of focus because of an error in its testing prior to launch. However, through a deconvolution algorithm, image processing experts have been able to "undo the defocus." That task is hard to do, with great care taken to sharpen the imagery while not introducing artifacts in the high-resolution photos.

Error bars and different cultures

Looking back on his experience as principal investigator for both missions, A'Hearn offers advice on the balance that needs to be struck between scientists and spacecraft engineers.



The Deep Impact spacecraft was designed and built by Ball Aerospace. Credit: Ball Aerospace.

A key lesson he learned is how important it is to sit with the engineers and do tradeoffs, to get the best you can without overstressing either the spacecraft or the instrument…or the engineers themselves.

"The engineers want to know your requirements, and they'll make sure these can be met. The scientists want to know what the spacecraft is capable of doing, and we'll use it as best we can. So that totally different mindset is why it's important to have an iterative discussion," A'Hearn says.

But, he continues, "The biggest thing is understanding the problems of language." So many common terms are used differently by scientists and engineers, he notes. "I still keep stumbling over terms that don't mean quite the same thing" in the two communities.

An example, he says, is error bars on data. "Astronomers nearly always think in plus and minus one sigma. Engineers always think plus and minus three sigma. Unless you are very precise in your terminology, you are liable to convey the wrong impression." He also highlights the nature of test beds and of critical sequences that can mean dissimilar things in the two different cultures.

Two days after the closest approach to Hartley 2, the spacecraft entered a departure phase, making look-back observations during this 21-day segment of the mission. At the end of that phase, and after a final calibration run, the spacecraft was set to be decommissioned, and destined to continue following its endless orbit of the Sun.

On the other hand, discussions of running Deep Impact in an observatory mode are now under way. Ideas on uses for the craft include watching for near-Earth objects, or serving as an additional test bed for an 'Interplanetary Internet' concept.

"I've enjoyed operating this spacecraft," says Walsh. "It has performed really well all the way around. The overall health of the spacecraft is excellent. I'd be happy to keep going and find new targets."