ICE & STONE 2020

WEEK 28: JULY 5-11

Presented by The Earthrise Institute

#28

Authored by Alan Hale

THIS WEEK IN HISTORY

JULY 5, 1687: British physicist Isaac Newton publishes his Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy), usually known as the Principia, wherein he lays out what is now known as his Law of Universal Gravitation. Part of Newton's work in the Principia was based upon his calculations of the Great Comet of 1680 – a future "Comet of the Week" – and his methodology was utilized by Edmond Halley to calculate the orbits of comets, including the one that now bears his name (1P/Halley), which is the subject of a previous "Special Topics" presentation.

JULY 7, 1992: The comet that would later become known as Comet Shoemaker-Levy 9 passes just 43,000 km above the top of Jupiter's atmosphere and is ripped apart into over 20 fragments by tidal forces from Jupiter's gravity. The comet would be discovered a little over eight months later, and in July 1994 each of the fragments would impact Jupiter's atmosphere. Comet Shoemaker-Levy 9 is next week's "Comet of the Week."

JULY 7, 2017: A meteoroid, perhaps 30 cm in diameter, enters Earth's atmosphere above southwestern Australia and, after traveling through the atmosphere for about 90 seconds, exits back into interplanetary space. An analysis of the observations indicates that the Earth's gravitational influences placed the object into an orbit like that of a Jupiter-family comet that will cause it to make close approaches to Jupiter – the first to take place in early 2025 – that, over the next few hundred thousand years may eventually eject it from the solar system.

JULY 8, 2020: The Apollo-type asteroid (242450) 2004 QY2 will pass 0.163 AU from Earth. It was brightest – about 14th magnitude – last week, and is still close to 15th magnitude, although it will fade rapidly over the coming weeks as it passes interior to Earth's orbit.

COVER IMAGE CREDIT:

Front and back cover: As part of the global effort to hunt out risky celestial objects such as asteroids and comets, ESA is developing an automated telescope, nicknamed 'Flyeye', for nightly sky surveys. This telescope – to be installed on Mount Mufara in Sicily – is the first in a future network that would completely scan the sky and automatically identify possible new near-Earth objects, or NEOs, for follow up and later checking by human researchers.

The telescope splits the image into 16 smaller subimages to expand the field of view, similar to the technique exploited by a fly's compound eye. Such fly-eyed survey telescopes provide a very large field of view: 6.7° x 6.7° or about 45 square degrees. 6.7° is about 13 times the diameter of the Moon as seen from the Earth (roughly 0.5 degrees).

Artist's impression courtesy of ESA/A. Baker

5 6 7 8 9 JULY 10 11

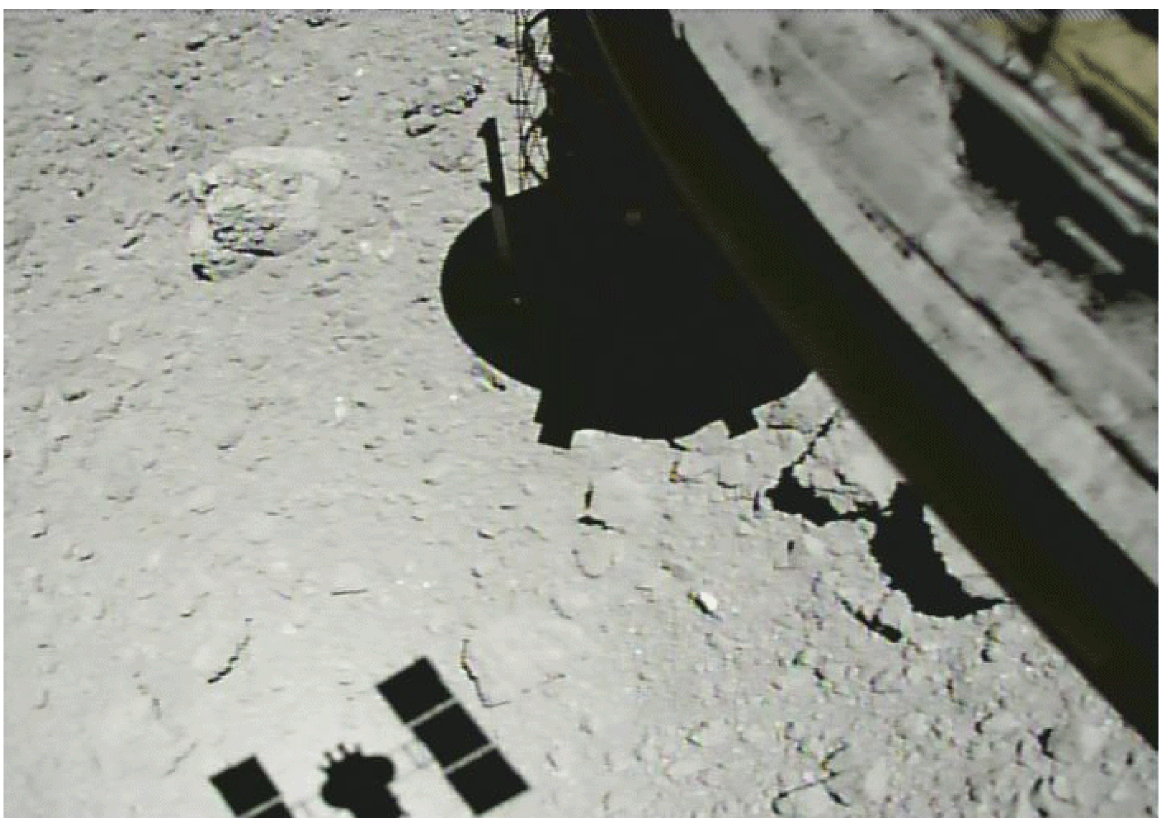
JULY 10, 1992: ESA's Giotto spacecraft has a flyby encounter with Comet 26P/Grigg-Skjellerup. Giotto had previously passed by Comet 1P/Halley in 1986, and the mission as a whole, including the encounter with Comet Grigg-Skjellerup, is discussed in this week's "Special Topics" presentation.

JULY 10, 2010: While en route to Comet 67P/Churyumov-Gerasimenko, ESA's Rosetta spacecraft flies by the main-belt asteroid (21) Lutetia. The Rosetta mission, including its encounters with main-belt asteroids, is discussed in this week's "Special Topics" presentation.

5 6 7 8 9 10 JULY 11

JULY 11, 2019: JAXA's Hayabusa2 spacecraft, in orbit around the near-Earth asteroid (162173) Ryugu, successfully touches down on Ryugu's surface and collects samples of sub-surface material. Hayabusa2, with its samples, is now en route back to Earth and is expected to return this coming December. The Hayabusa2 mission is discussed in a future "Special Topics" presentation.

Image of asteroid Ryugu taken by JAXA's Hayabusa2 spacecraft with the small monitor camera (CAM-H) during a touchdown rehearsal operation on October 25, 2018. Courtesy of JAXA.



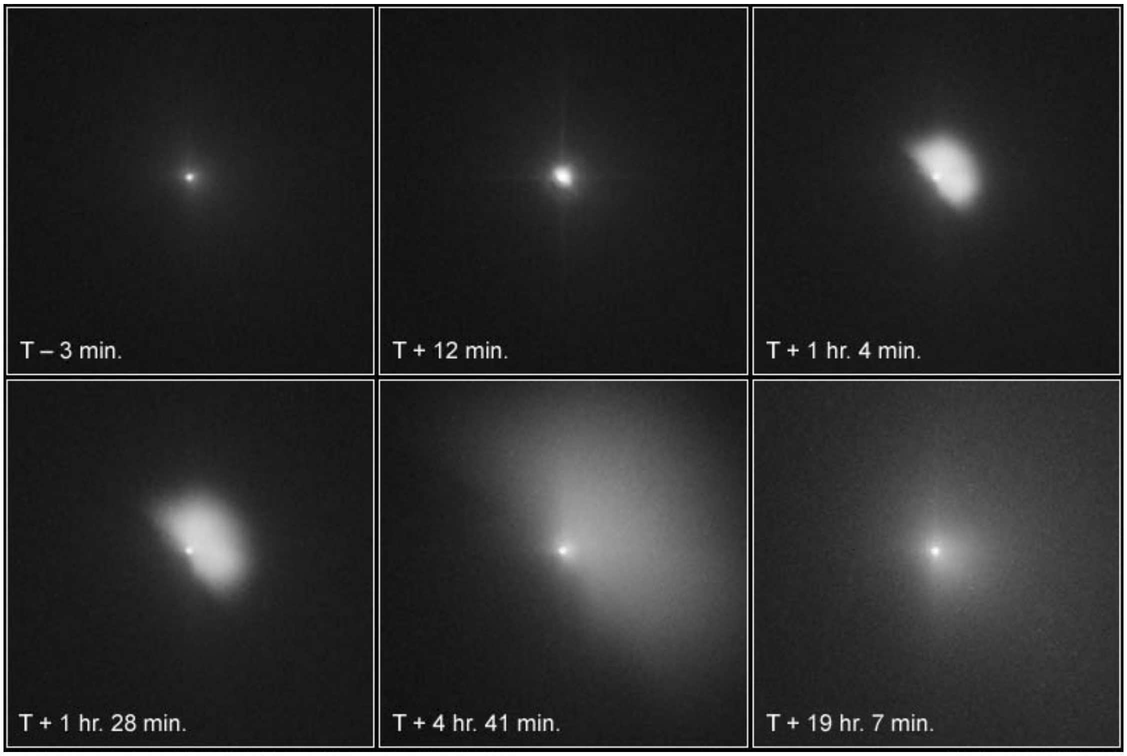
COMET OF THE WEEK: 9P/TEMPEL 1

Perihelion: 2005 July 05.31, q = 1.506 AU

With the various comprehensive survey programs that are currently operational, the discovery of previously-unknown short-period comets happens all the time these days. The situation was very different during the mid-19th Century, when only a handful of such objects were known, and the discovery of each one was almost a novelty. Such was the case with a comet discovered on April 3, 1867 by French astronomer Wilhelm Tempel at Marseilles Observatory, which was found to have a perihelion distance of 1.56 AU and an orbital period of 5.6 years. Tempel's comet was followed for almost five months and reached a peak brightness of close to 9th magnitude, and it became only the third comet, and the first Jupiter-family comet, to have its spectrum observed, a feat accomplished by the British astronomer William Huggins.

A close approach to Jupiter (0.36 AU) in 1870 increased the comet's perihelion distance to 1.77 AU and its orbital period to almost exactly six years, however the viewing geometry at both the 1873 and 1879 returns was quite favorable and it was successfully recovered both times. However, another close approach to Jupiter (0.55 AU) in 1881 increased the perihelion distance still further to 2.07 AU and the orbital period to 6.5 years, with the returns alternating between favorable and unfavorable. This, combined with the increased perihelion distance, created distinctly less favorable viewing conditions, and

Comet 9P/Tempel 1 on May 1, 2005. Image courtesy Michael Jaeger and Gerald Rhemann in Austria.



Hubble Space Telescope images of the inner coma of Comet Tempel 1 before and after the Deep Impact impact on July 4, 2005; the time tags are referenced to the time of the impact. Images courtesy NASA.

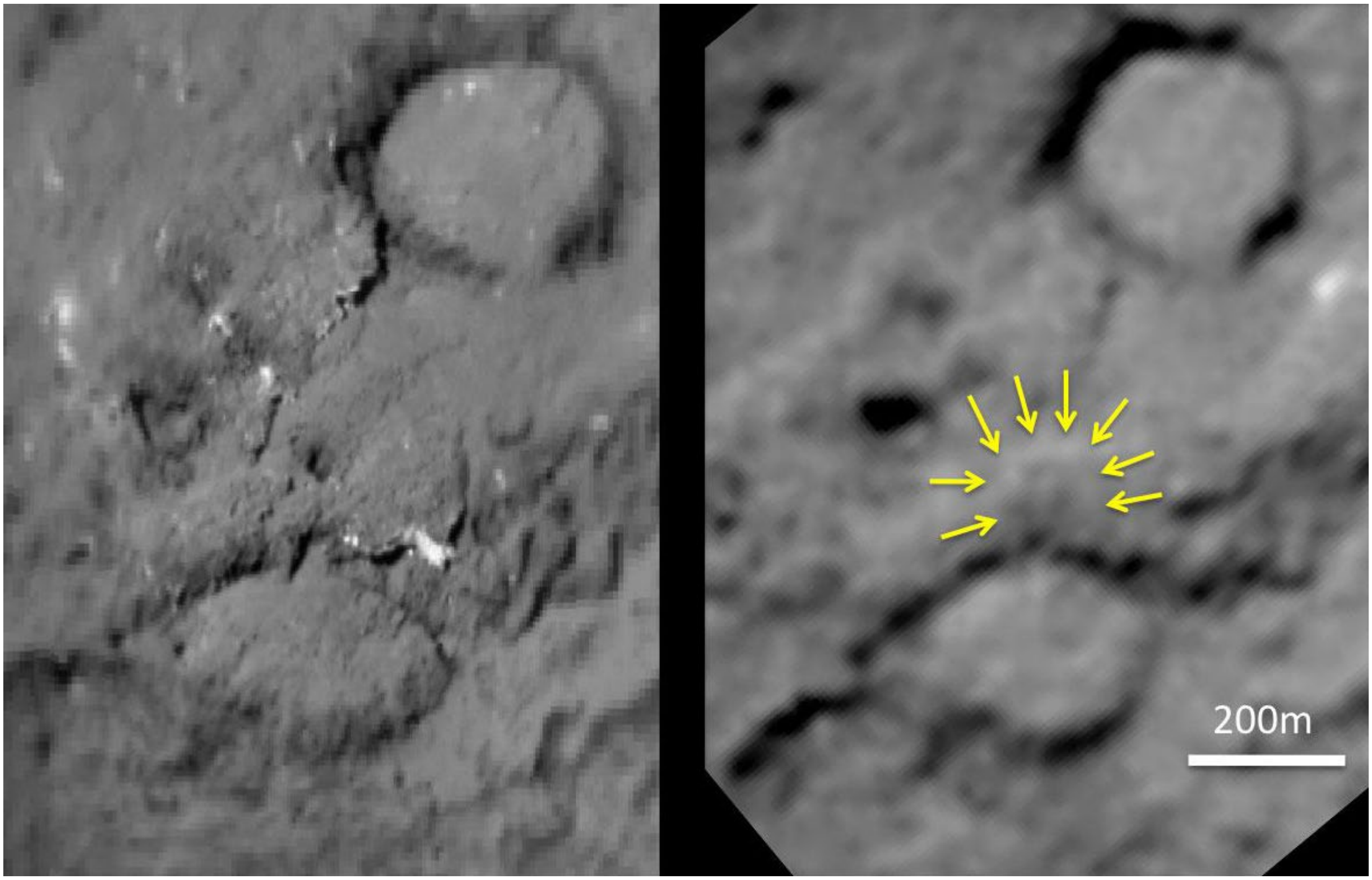
after unsuccessful recovery attempts at the next few returns the comet was considered "lost."

During the early 1960s Yale University graduate student Brian Marsden – who would later become one of the top experts on cometary orbits in the world and who would for over two decades be Director of the IAU's Minor Planet Center as well as its Central Bureau for Astronomical Telegrams – undertook a study (published in 1963) that analyzed several of the "lost" periodic comets and their prospects for future recovery. Marsden found that, during the intervening decades, additional close approaches to Jupiter had decreased Comet Tempel 1's perihelion distance to less than what it was at the time of its discovery, and thus that it should be easily recoverable. The viewing geometry at the next perihelion passage, in early 1967, was very unfavorable, however later that year Elizabeth Roemer of the Lunar and Planetary Laboratory in Arizona took several photographs in an attempt to recover it, and while first inspections didn't reveal anything, she later found a faint image on a single exposure taken on June 8 that was consistent with the comet's location and motion. However, without any confirming photographs the recovery could not be considered "safe," and any formal announcements of such were held in abeyance.

The viewing conditions at the comet's subsequent return in 1972 were much more favorable, and on January 11 of that year Roemer, assisted by Larry Vaughn, successfully recorded the comet as an 18th-magnitude object on two photographs taken at Steward Observatory in Arizona. The actual time of perihelion passage turned out to be only two hours later than the predicted time, a most remarkable achievement considering that almost a century had elapsed since the last confirmed observations of the comet. Among other things, the recovery observations verified that the object Roemer had photographed in 1967 was indeed Comet Tempel 1.

With a current orbital period close to 5½ years successive returns of Comet Tempel 1 alternate between favorable and unfavorable viewing geometry. The returns of 1972, 1983, 1994, 2005, and 2016 were all favorable, and on the best of these the comet achieved a peak brightness between 9th and 10th magnitude. Meanwhile, in late 1997 the comet was imaged just a few months past aphelion, and at the very end of that year a team led by Philippe Lamy of the Laboratoire d'Astronomie Spatiale in France detected the bare nucleus of Comet Tempel 1 in images taken with the Hubble Space Telescope; these indicated a diameter of 7.8 by 5.6 km and a rotational period of about 25 hours.

In 1999 NASA approved the Deep Impact mission, with Comet Tempel 1 being the destination comet. Deep Impact was launched from Cape Canaveral, Florida on January 12, 2005, and on July 3 of that year the main spacecraft launched a 370-kg projectile which struck the comet's nucleus the following day. The overall intent of the Deep Impact mission was to excavate sub-surface cometary material and create a debris cloud that the main spacecraft would then subsequently fly through. This debris cloud was found to contain water ice as well as various silicates, hydrocarbons, metal sulfides (including iron



The Deep Impact impact site on the nucleus of Comet 9P/Tempel 1. Left: Composite image taken by Deep Impact in July 2005. Right: Annotated image obtained by Stardust on February 15, 2011. Images courtesy NASA.

pyrite, aka "fool's gold") among numerous other substances. The impact and debris cloud were detectable from Earth – a unique opportunity to observe real-time laboratory cometary science in action – and one of the observing platforms was NASA's Submillimeter Wave Astronomy Satellite (SWAS), which was brought out of hibernation for the event; while SWAS detected water in the comet's environment, it did not detect any excess amounts. The actual impact occurred at the wrong time of the night for me to observe, however on the first night after the impact the comet appeared to me to have brightened by almost a full magnitude and was distinctly more "condensed" in its interior, although these effects subsided during subsequent days.

The impact was expected to create a crater, however the debris cloud prevented the main spacecraft from observing this. Two years later, NASA sent its Stardust spacecraft, which has passed through the coma of Comet 81P/Wild 2 – the Week 1 "Comet of the Week" – and collected samples which it returned to Earth two years later, towards Comet Tempel 1. Stardust passed 200 km from the comet's nucleus on February 15, 2011, during its next return – making Tempel 1 the only comet to have been visited by spacecraft on two separate returns – and images that it took do show a shallow crater roughly 150 meters in diameter with a small debris mound near the center.

Comet Tempel 1 most recently passed through perihelion in August 2016, and was at aphelion (4.75 AU) in May 2019. The first post-aphelic images were obtained this past January by Francois Kugel and Claudine Rinner at the Observatoire Chante-Perdrix in Dauban, France. The comet next passes perihelion in early March 2022, although the viewing geometry is somewhat unfavorable. Some close approaches to Jupiter after that will once again move its perihelion distance out to 2 AU and it will remain a rather distant and faint object, although additional approaches to Jupiter during the 22nd Century will bring it back in again. On October 22, 2183, Comet Tempel 1 will pass only 0.02 AU from Mars, and if any human colonists are living on Mars at that time they should be able to enjoy some close-up views of this somewhat "renegade" comet that has made some interesting contributions to our understanding of these objects.

ADJOINING PAGE: The nucleus of Comet Tempel 1 just over one minute after impact, as imaged by the Deep Impact flyby probe. Image courtesy NASA.

SPECIAL TOPIC: PAST SPACECRAFT MISSIONS

The majority of what we know about the various planets and many of the other objects in our solar system has come from spacecraft missions sent to those bodies. Even with the best telescopes here on Earth many of these objects are little more than points of light in the sky, and it was only when we began to make up-close observations with visiting spacecraft that we truly began to understand the other residents of our solar system as worlds in their own right. Even the first missions to the moon – the Luna 2 and 3 missions sent by the then-Soviet Union in 1959 – significantly increased our knowledge about Earth's natural satellite, and the first successful interplanetary mission – NASA's Mariner 2 mission to Venus in 1962 – substantially increased our knowledge of our nearest planetary neighbor, including the confirmation of Earth-based measurements that suggested Venus' surface is very hot.

What could probably be considered the first "small bodies" mission was NASA's Mariner 9 mission, which was launched from Cape Canaveral, Florida on May 30, 1971 and which arrived at, and went into orbit around, Mars that November. As Mariner 9 was approaching Mars it took the first up-close images of Mars' moons Phobos and Deimos in late October, revealing them to be irregularly shaped objects with impact craters on their surfaces. Phobos and Deimos have been extensively examined by later spacecraft missions, beginning with the Viking orbiters in the late 1970s and including spacecraft currently in orbit around Mars, and they are discussed in detail in a future "Special Topics" presentation.

In a similar fashion, the twin Voyager 1 and 2 missions have examined some of the smaller moons of the outer planets. Voyager 1 discovered two small inner moons of Jupiter when it flew by that planet in 1979 and three moons of Saturn when it passed by that world in 1980; Voyager 2 found an additional small inner moon of Jupiter in 1979 and then went on to discover eleven moons around Uranus in 1986 and five moons around Neptune in 1989. The Cassini spacecraft that orbited Saturn between 2004 and 2017 examined several of the Voyager-discovered moons in some detail and also discovered eight additional moons. Along with Phobos and Deimos, these objects are also discussed in a future "Special Topics" presentation.

Beginning in the 1980s, several "small bodies" have been the primary or secondary destinations of several spacecraft missions sent by various nations and space agencies. This presentation will take a look at each of these in roughly chronological order. It should be kept in mind that various additional missions have been proposed, with initial development sometimes started, over the years, but have ended up being cancelled for budgetary and/or political reasons before they were ever completed and launched.

One of the first spacecraft images of a "small body" from close range: the Martian moon Phobos, as photographed by NASA's Mariner 9 spacecraft on December 1, 1971. Courtesy NASA.

The return of Comet 1P/Halley in 1986 created widespread interest in sending spacecraft missions to that object, and several nations in fact did so. Conspicuous by its absence was the U.S., where Congress had failed to fund such a mission. In response to this disappointment felt by many American scientists, planetary scientist Robert

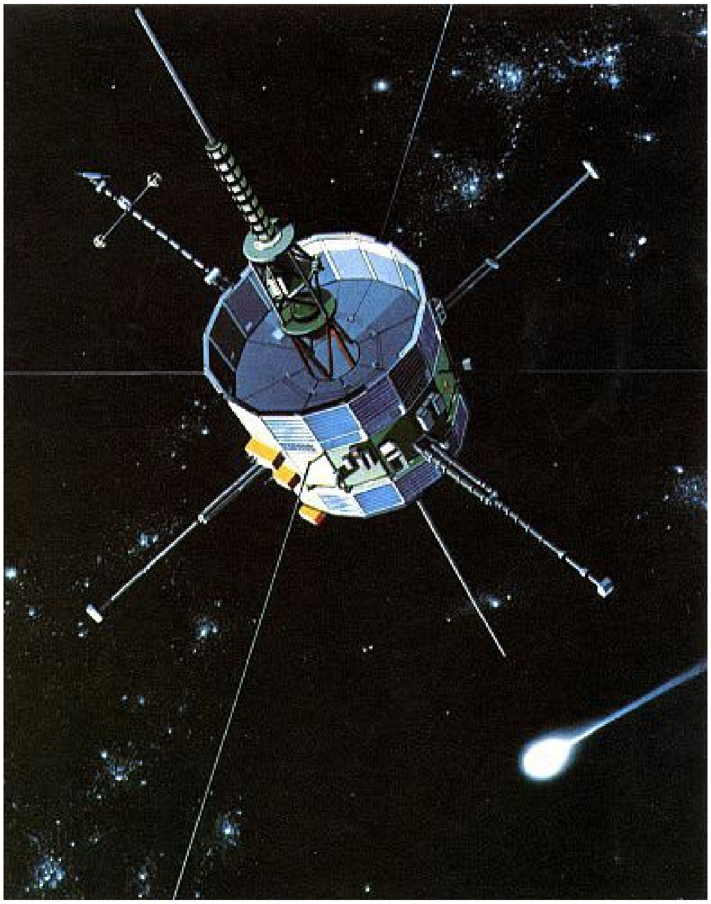
Farquhar at NASA's Goddard Space Flight Center in Maryland proposed an alternate idea: utilize an already-existing spacecraft, the International Sun-Earth Explorer 3 (ISEE-3), and send it to an encounter with Comet 21P/Giacobini-Zinner a few months before the various other spacecraft arrived at Comet Halley.

ISEE-3 had been launched on August 12, 1978, as part of an international three-spacecraft mission to study the interaction between the solar wind and the earth's magnetosphere from the L1 Lagrangian point 1.6 million km sunward of Earth, and by the early 1980s had successfully completed its original planned mission. On June 10, 1982, ISEE-3 was moved from its position at L1 and, in a highly complex series of maneuvers which involved five flybys of the moon – the last one being only 120 km above the lunar surface on December 22, 1983 – was then placed in a flight path toward Giacobini-Zinner. At that time the spacecraft was re-christened the International Cometary Explorer (ICE).

ICE successfully encountered Comet Giacobini-Zinner – a future "Comet of the Week" – on September 11, 1985, passing through the comet's ion tail 7700 km "downstream" from its nucleus, and becoming the first spacecraft to visit a comet. While ICE did not carry any cameras or imaging equipment, it did contain several scientific instruments which reported on the electrical environment around the comet and its interaction with the solar wind. Among other things, ICE reported that the comet's magnetic field reversed polarity directly at the ion tail and detected a large proportion of ionized water molecules.

Following its encounter with Comet Giacobini-Zinner, ICE went on to a relatively distant encounter (0.19 AU) with Comet Halley in late March 1986 and then continued to carry out observations of solar phenomena and the interplanetary space environment until its mission was formally ended in 1997. In 2014 ICE returned to the Earth's vicinity and a privately-funded recovery effort led by space entrepreneur Dennis Wingo successfully re-established contact with it and was able to command it to perform a firing of its thrusters. However, not enough propellant was left to allow ICE to be maneuvered into a location where a future recovery could be performed, and after a couple of months contact was lost.

The international armada of spacecraft that visited Comet Halley in March 1986 is discussed in some detail in that comet's "Comet of the Week" presentation. The armada included two Japanese probes, Sakigake and Suisei, which studied the comet from a distance, and two probes from the Soviet Union, Vega 1 and 2, which, after passing by Venus in mid-1985 and deploying surface landers and

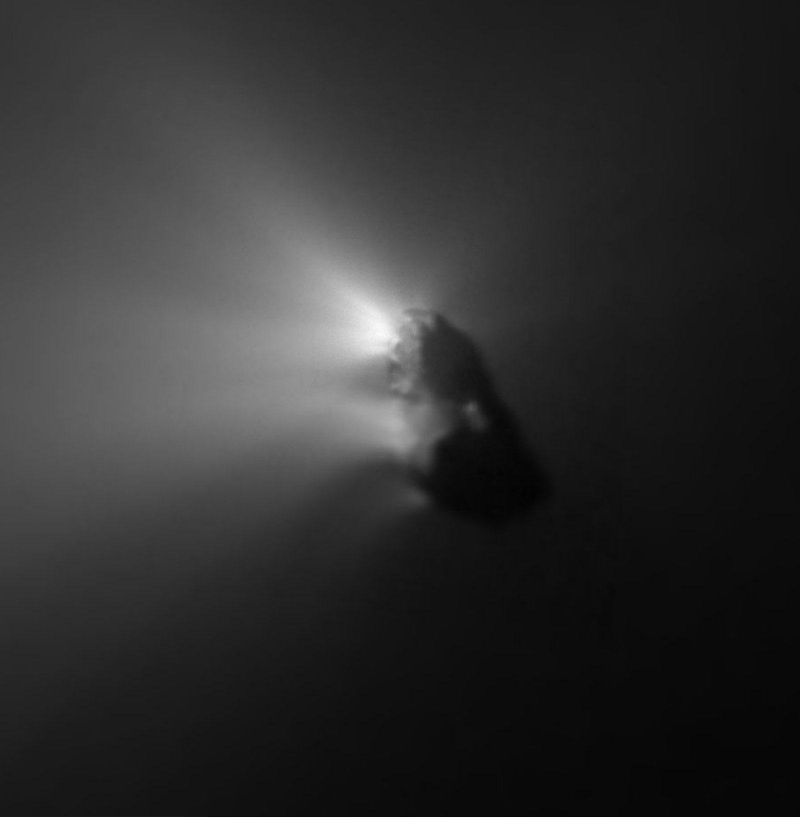


Artist's conception of the International Cometary Explorer (ICE) encounter with Comet 21P/Giacobini-Zinner in September 1985. Courtesy NASA.

atmospheric balloons, passed within a few thousand km of Halley's nucleus and returned the first-ever direct images of a cometary nucleus. The highlight was ESA's Giotto mission which passed 600 km from Halley's nucleus on March 14, 1986 and returned relatively sharp images of the nucleus as well as many important scientific observations of the nucleus and the near-nucleus environment.

Giotto went on to another cometary encounter, with Comet 26P/Grigg-Skjellerup, passing 200 km from that object's nucleus on July 10, 1992. Because of the "sand-blasting" that occurred when Giotto has passed through Halley's inner coma – exacerbated by the comet's retrograde orbital motion which in turn created very high relative velocities, and thus very high kinetic energies, for impacting dust particles – Giotto's camera was no longer functional, but some of its other scientific instruments were still intact and were able to make some important measurements.

NASA's Galileo mission to Jupiter was originally scheduled to be deployed from the Space Shuttle in late 1986, however the Challenger disaster earlier that year not only delayed the Galileo launch by three years but also forced a longer and more circuitous trajectory that included gravity-assist flybys

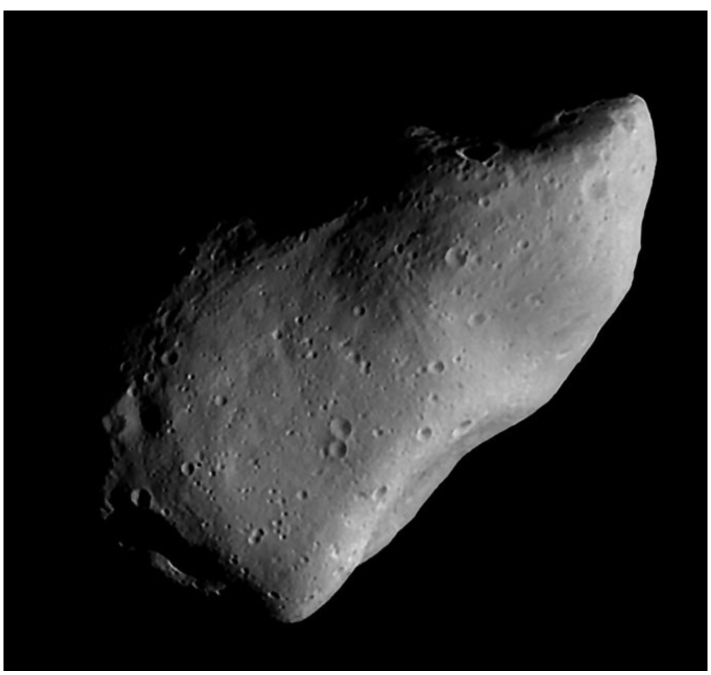


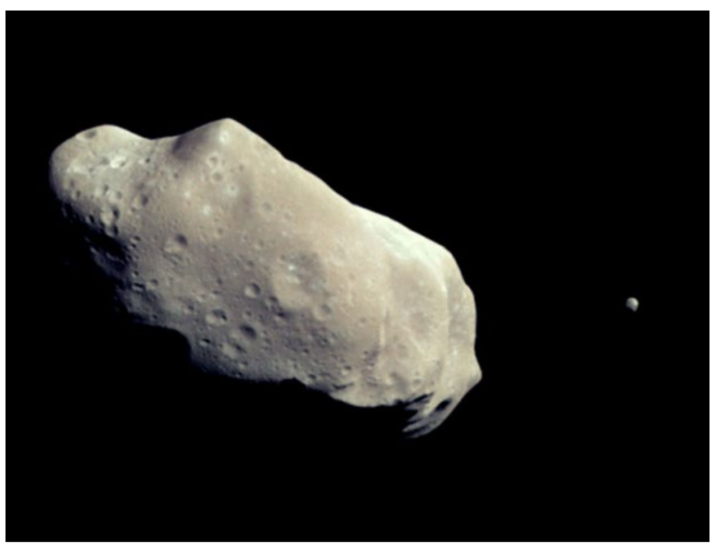
The nucleus of Comet 1P/Halley, as imaged by ESA's Giotto spacecraft on March 14, 1986. Courtesy ESA.

of Earth and Venus and two passages through the main asteroid belt. After being deployed from the Space Shuttle Atlantis on October 18, 1989, during its first passage through the asteroid belt Galileo flew by the asteroid (951) Gaspra on October 29, 1991, the first encounter of an asteroid by a spacecraft. On the next passage through the asteroid belt Galileo passed by the asteroid (243) Ida on August 28, 1993, and the images taken during that encounter revealed the presence of a 1.5-km-diameter moon that has since been named Dactyl. This was the first confirmed example of an asteroid's being accompanied by an orbiting moon, and this topic is discussed in a future "Special Topics" presentation. While en route to Jupiter Galileo observed the impacts of some of the fragments of Comet Shoemaker-Levy 9 into Jupiter during July 1994, in fact it had the only vantage point of any human-built platform that had a direct view of the impacts. Comet Shoemaker-Levy 9 is next week's "Comet of the Week."

The incorporation of a "faster, better, cheaper" policy for spacecraft missions by NASA's management during the mid-1990s allowed for the development of several smaller low-cost missions during subsequent years, quite a few of these being to the solar system's "small bodies." One of the earlier missions was the Near-Earth Asteroid Rendezvous (NEAR) mission, later renamed NEAR Shoemaker in honor of planetary geologist Eugene Shoemaker, which was launched on February 17, 1996. NEAR Shoemaker's primary destination was the large near-Earth asteroid (433) Eros, but while en route to Eros NEAR Shoemaker passed by the main-belt asteroid (253) Mathilde on June 27, 1997. NEAR Shomaker arrived at Eros in late 1998 but an aborted engine burn prevented an insertion into orbit, so that event had to wait until the next encounter with Eros which took place on February 14, 2000. NEAR Shoemaker then spent the next year in orbit around Eros before performing a soft-landing onto Eros' surface on February 12, 2001. The NEAR Shoemaker mission, and some of its findings, are discussed in the Week 4 "Special Topics" presentation on Eros.

NASA's Deep Space 1 mission was intended as a technology test bed, including the testing of an ion propulsion engine. Following its launch on October 24, 1998, Deep Space 1 passed just 26 km from the





The main-belt asteroids encountered by Galileo while en route to Jupiter. Left: (951) Gaspra on October 29, 1991. Right: (243) Ida on August 28, 1993. The small moon Dactyl is at right. Both images courtesy NASA.

The nucleus of Comet 19P/Borrelly, as imaged by NASA's Deep Space 1 spacecraft on September 21, 2001. Courtesy NASA.

Mars-crossing asteroid (9969) Braille on July 29, 1999, however problems with the tracking system and some of the onboard instruments allowed images to be obtained from only a farther distance. Deep Space 1 then went on to a successful encounter with Comet 19P/Borrelly on September 21, 2001, with images revealing the nucleus to be a bowling pin-shaped object roughly 8 km by 4 km across.

NASA's Stardust mission was launched on February 7, 1999, and while passing through the asteroid belt passed 3000 km from the main-belt asteroid (5335) Annefrank on November 2, 2002. Stardust's primary destination was Comet 81P/Wild 2, which it encountered on January 2, 2004, and via means of a very lightweight, porous substance called "aerogel" collected material samples from that comet's coma which it returned to Earth two years later; this is discussed in more detail in Comet Wild 2's Week 1 "Comet of the Week" presentation. Meanwhile, as discussed in this week's "Comet of the Week" presentation, Stardust later went on to an encounter with Comet 9P/Tempel 1 on February 15, 2011 and successfully recorded images of the impact crater that the projectile from the Deep Impact mission created in 2005. Stardust was shut down after its encounter with Comet Tempel 1.

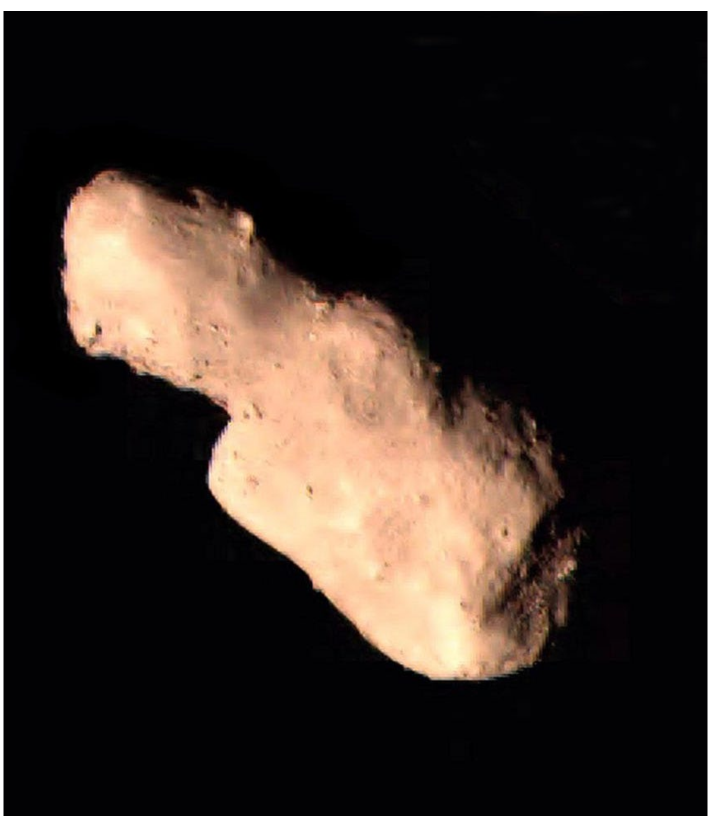
Meanwhile, as also discussed in this week's "Comet of the Week" presentation, the Deep Impact mission was launched on January 12, 2005, and arrived at Comet 9P/Tempel 1 on July 4 of that year. After flying through the debris cloud created by the projectile's impact onto the comet's nucleus, the remaining portion of the spacecraft was given two new missions: light-curve analyses of extrasolar planets that were being discovered via the "transit" (or "photometric") method; and an encounter with a second comet. These two missions were combined in the mission name EPOXI, for Extrasolar Planet Observation and Deep Impact eXtended Investigation. After the first planned destination comet (85P/Boethin) was not recovered during its 2008 return (and in fact is now believed to have disintegrated), EPOXI went on to a successful encounter 700 km from the nucleus of Comet 103P/Hartley 2 on November 4, 2010. The images of Comet Hartley 2 show a peanut-shaped object some 2 km long with significant jetting activity at both ends but with a smooth, inactive plain between those two ends. Following this encounter EPOXI still had a small amount of fuel left and its thrusters were fired for an encounter with the Apollo-type asteroid (163249) 2002 GT in January 2020, however communications with EPOXI broke off in 2013 and the mission was subsequently declared lost.

JAXA's Hayabusa mission was an ambitious mission that was designed to travel to the Apollo-type asteroid (25143) Itokawa, perform detailed studies of it, and collect samples for return to Earth. Following its launch on May 9, 2003, Hayabusa arrived at Itokawa on September 12, 2005 but thereafter the mission was beset by several difficulties: a planned surface rover, MINERVA, failed, and the brief touchdown/sample collection effort on November 25 also apparently failed. After Hayabusa left Itokawa in December

Main-belt asteroid (253) Mathilde, as imaged by the Near-Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft on June 27, 1997. Courtesy NASA.

The nucleus of Comet 103P/Hartley 2, imaged by the EPOXI mission on November 4, 2010. Courtesy NASA.

contact was lost, although contact was eventually restored several months later; several more months elapsed before power could be fully restored. This forced a three-year delay in Hayabusa's planned return to Earth, but this finally happened on June 13, 2010. Once the sample-containing capsule was recovered from its touchdown site in the Australian outback researchers found that approximately 1500 grains (with a total mass slightly less than one gram)

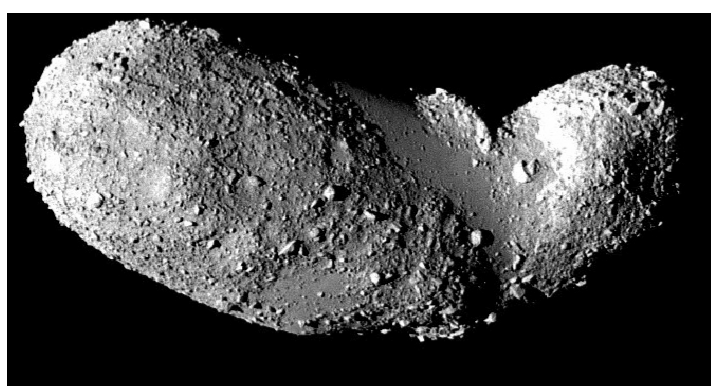


had in fact been collected during Hayabusa's brief touchdown on Itokawa's surface.

As its mission name implies, the rationale for NASA's Dawn mission was to examine conditions that existed during the era of the solar system's formation. Following its launch on September 27, 2007 Dawn arrived at the large main-belt asteroid (4) Vesta on July 16, 2011. Dawn remained in orbit around Vesta for the next 13½ months before leaving on September 5, 2012, en route to the largest main-belt asteroid (and "dwarf planet") (1) Ceres, where it arrived on March 6, 2015 – becoming the first spacecraft to orbit around two different bodies. Dawn has remained in orbit around Ceres ever since, although after running out of maneuvering fuel the mission was declared ended on October 30, 2018, and contact was broken off. Some of the results from Dawn are discussed in the Week 1 "Special Topics" presentation.

The China National Space Administration (CNSA) launched its Chang'e 2 spacecraft on October 1, 2010, with its primary mission being a study of the moon from lunar orbit in preparation for the Chang'e 3 mission which landed on the lunar surface in December 2013. Following the completion of its original mission Chang'e 2 was moved to the sun-Earth L2 Lagrangian point 1.5 million km directly anti-sunward of Earth, however in April 2012 it was moved from L2 for an encounter with the Apollo-type asteroid (4179) Toutatis, which it passed by at a distance of just 3.2 km on December 13 of that year.

One of the most ambitious spacecraft missions was ESA's Rosetta mission, which was launched from Kourou, French Guiana on March 2, 2004. The early phases of Rosetta's mission involved several gravity-assist flybys of Earth and Mars, and encounters with the small main-belt asteroid (2867) Steins on September 5, 2008 and the larger main-belt asteroid (21) Lutetia on July 10, 2010. After its encounter with Lutetia Rosetta was placed in a state of hibernation,



Two near-Earth asteroids imaged by visiting spacecraft. Left: (4179) Toutatis, imaged by the Chang'e 2 spacecraft on December 13, 2012. Courtesy CNSA. Above: (25143) Itokawa, imaged by JAXA's Hayabusa spacecraft during its approach in 2005. Courtesy JAXA.

The Kuiper Belt asteroid (486958) Arrokoth imaged by NASA's New Horizons spacecraft on January 1, 2019. Courtesy NASA.

from which it was "woken" in January 2014. On August 6 of that year Rosetta arrived at Comet 67P/Churyumov-Gerasimenko, which it would spend the next two years orbiting and studying as the comet approached perihelion (in August 2015) and then receded. While in the comet's vicinity Rosetta deployed the Philae lander in November 2014, and after the mission was completed Rosetta successfully touched down on the comet's surface on September 30, 2016. Comet 67P is a future "Comet of the Week" and the Rosetta mission is discussed in more detail in that object's presentation.

Another ambitious mission is NASA's New Horizons mission, which was launched from Cape Canaveral, Florida on January 19, 2006. New Horizons made a somewhat distant encounter (101,000 km) of the small main-belt asteroid (132524) APL on June 13 of that year, and following a gravity-assist flyby of Jupiter in February 2007 it proceeded on to its primary destination, Pluto and its system of moons, which it flew by on July 14, 2015; this encounter is discussed in more detail in next week's "Special Topics" presentation. Following its passage by Pluto New Horizons encountered the Kuiper Belt asteroid (486958) Arrokoth on January 1, 2019; this encounter, along with the Kuiper Belt as a whole, is discussed in a future "Special Topics" presentation. New Horizons still continues sufficient power for another encounter, and provided that a suitable destination can be identified, may pass by a more distant Kuiper Belt object sometime during the 2020s.

Two "small bodies" spacecraft missions are ongoing at this time, both of these being sample-collection missions involving near-Earth asteroids: JAXA's Hayabusa2 mission to (162173) Ryugu and NASA's OSIRIS-REx mission to (101955) Bennu. Hayabusa2 has now left Ryugu on its way back to Earth and is scheduled to arrive this coming December, while OSIRIS-REx, which has been in orbit around Bennu since late 2018, is scheduled to collect its samples later this year, and will depart Bennu in March 2021 for arrival at Earth in September 2023. These two missions are discussed in a future "Special Topics" presentation.

Not every mission that has been sent towards "small bodies" in the solar system has been successful. The joint NASA/U.S. Defense Department Clementine mission, which was primarily a technology test bed mission, spent 2½ months orbiting the moon during early 1994 – during which time a radar experiment detected evidence for water ice in permanently shadowed craters near the moon's south pole, a topic that will be discussed in a future "Special Topics" presentation – and was then expected to be sent to the Apollo-type asteroid (1620) Geographos, however a power failure that occurred after Clementine left lunar orbit caused that part of the mission to be aborted. NASA'S COmet Nucleus TOUR (CONTOUR) mission was launched on July 2, 2002, and was expected to fly by Comet 2P/Encke in November 2003 and Comet 73P/Schwassmann-Wachmann 3 in June 2006, with a possible third encounter – Comet 6P/d'Arrest in August 2008 or possibly a long-period comet if one came by which could be reached – however once it departed Earth orbit in August 2002 contact with it was lost. A failure analysis, which included ground-based images showing three objects moving along the expected trajectory, concluded that the spacecraft had undergone some kind of catastrophic failure during or just after the orbital boost maneuver.

The missions described here are certainly not the last word in spacecraft missions to small bodies; various other missions are being planned and are in development at this time. These are all discussed in a previous "Special Topics" presentation.

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