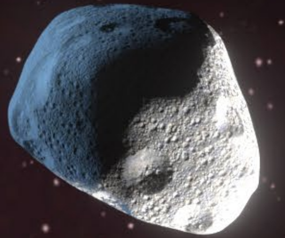


ICE & STONE 2020

WEEK 25: JUNE 14-20

Presented by The Earthrise Institute

#25

Authored by Alan Hale

THIS WEEK IN HISTORY

JUNE **14** 15 16 17 18 19 20

JUNE 14, 1770: The renowned French comet hunter Charles Messier discovers a moderately bright comet in Sagittarius. 2½ weeks later this comet passed just 0.015 AU from Earth, the closest confirmed cometary approach to Earth in history. The comet, named after Swedish mathematician Anders Lexell, who computed its orbit, was later perturbed into a much larger orbit by a close encounter with Jupiter, and is now "lost." It is discussed in a previous "Special Topics" presentation.

JUNE 14, 1968: The well-known Apollo-type asteroid (1566) Icarus passes 0.042 AU from Earth, a much-publicized encounter that remains Icarus' closest approach to Earth since its discovery in 1949. During this approach astronomers obtained the first successful radar-bounce observations of a solar system "small body."

JUNE 14, 2090: Asteroid (1566) Icarus will pass 0.044 AU from Earth, the closest approach it will have made to our planet since the encounter in 1968.

14 15 JUNE **16** 17 18 19 20

JUNE 16, 1729: Comet Sarabat (new style designation C/1729 P1), discovered in early August 1729 by French scientist Nicolas Sarabat, passes through perihelion at the large heliocentric distance of 4.051 AU – a perihelion distance record for a comet that stood for almost two centuries. Despite its large distance, Comet Sarabat could be detected with the unaided eye, and, intrinsically, is the brightest comet ever recorded.

JUNE 16, 2015: Asteroid (1566) Icarus passes 0.054 AU from Earth, the closest approach it has made to our planet with the past half-century.

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). In the telescope, a single mirror of 1 m equivalent aperture collects the light from the entire 6.7° x 6.7° field of view and feeds a pyramid-shaped beam splitter with 16 facets. The complete field of view is then imaged by 16 separate cameras.

Artis's impression courtesy of ESA/A. Baker

14 15 16 17 **JUNE 18** 19 20

JUNE 18, 1178: Five Anglican monks at Canterbury, England report seeing a "flaming torch" rising from the moon, suggestive of an impact onto the lunar surface. There has been conjecture that this putative impact event created the crater Giordano Bruno, located on the moon's far side just beyond the northeastern limb, although the evidence for this is, at best, inconclusive. The topic of lunar impacts is part of this week's "Special Topics" presentation.

JUNE 18, 2009: NASA's Lunar CRater Observation and Sensing Satellite (LCROSS) mission is launched – together with NASA's Lunar Reconnaissance Orbiter (LRO) mission – from Cape Canaveral, Florida. In early October LCROSS was deliberately crashed into the crater Cabeus near the moon's South Pole, and the presence of water was successfully detected within the impact plume. The LCROSS mission, and its rationale, is discussed in this week's "Special Topics" presentation.

JUNE 18, 2020: Comet Lemmon C/2019 U6 will pass through perihelion at a heliocentric distance of 0.914 AU. This comet, currently visible from the southern hemisphere, has brightened unexpectedly rapidly within the recent past, and if this trend continues it could conceivably become visible to the unaided eye late this month, around the time it becomes accessible from the northern hemisphere. Information about Comet Lemmon and other visible comets is available at the Comet Resource Center.

14 15 16 17 18 **JUNE 19** 20

JUNE 19, 2004: Astronomers Roy Tucker, David Tholen, and Fabrizio Bernardi discovery the asteroid now known as (99942) Apophis from Kitt Peak National Observatory in Arizona, although it was "lost" after two nights until its accidental discovery from Siding Spring Observatory in New South Wales six months later. On April 13, 2029, Apophis will pass just 0.00026 AU from Earth – closer than the orbits of geosynchronous satellites – the closest predicted approach of a "large" asteroid to Earth in history. This event, and others like it, are discussed in a previous "Special Topics" presentation.

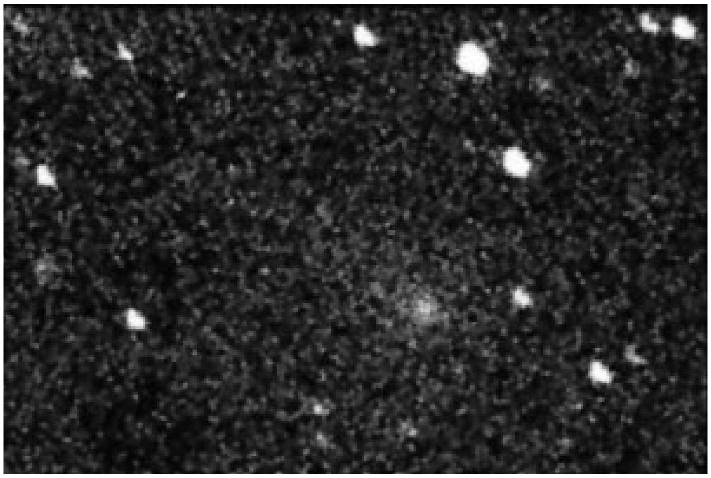
14 15 16 17 18 19 **JUNE 20**

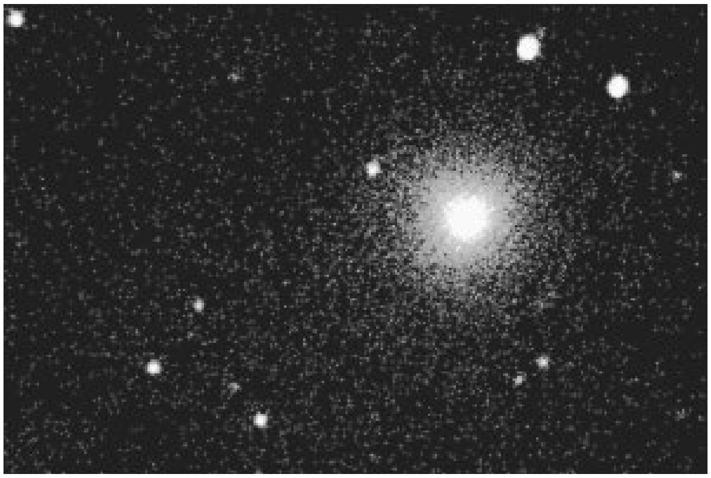
JUNE 20, 1990: David Levy and Henry Holt discover the asteroid now known as (5261) Eureka from Palomar Observatory in California. Eureka was the first-known example of a "Mars Trojan" asteroid. Trojan asteroids are the subject of a future "Special Topics" presentation.

JUNE 20, 2020: The main-belt asteroid (1846) Bengt will occult the 6th-magnitude star HD 167665 in Sagittarius. The predicted path of the occultation crosses the east-central Pacific Ocean (just north of the Hawaiian Islands), western and northern Mexico, and the southern and eastern U.S. from southern Texas to Pennsylvania.

COMET OF THE WEEK: LINEAR C/2001 A2

Perihelion: 2001 May 24.52, q = 0.779 AU



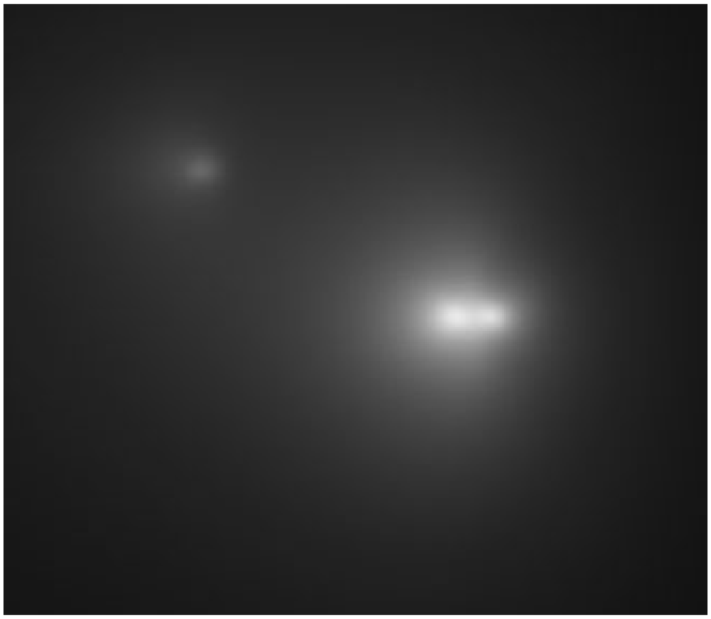


Two CCD images I took of Comet LINEAR that illustrate its rapid rise in brightness. Both images are 30-second exposures. Left: evening of March 23, 2001, with a 32-cm telescope. Right: evening of April 15, 2001, with a 20-cm telescope.

At the beginning of the 21st Century the discovery of comets and near-Earth asteroids was dominated by the first of the comprehensive sky surveys, the LIncoln Near-Earth Asteroid Research (LINEAR) program run by MIT's Lincoln Laboratory and based at White Sands Missile Range in New Mexico, that had become fully operational in 1998 (and which is discussed in a future "Special Topics" presentation). Of the 42 ground-based comet discoveries made in 2001, 20 of these were made by LINEAR (with a handful of these being shared with a couple of the other surveys operational at the time), and indeed, five of the first six comet discoveries that year were made by LINEAR. LINEAR would continue dominating discoveries for another few years before similarly comprehensive surveys started going on-line and producing their own impressive rates of detecting comets and near-Earth asteroids.

The first moderately bright naked-eye comet of the 21st Century was discovered by LINEAR on January 15, 2001, with pre-discovery images extending back to January 3 later being identified. The comet was a relatively dim 16th or 17th magnitude at the time of its discovery, and although the moderately small perihelion distance suggested it would become bright enough for visual observations, there otherwise didn't seem to be anything unusual about it, and it brightened slowly as it approached the inner solar system. Around mid-March, however, it underwent a rapid increase in brightness, from about 13th magnitude at that time to close to 8th magnitude shortly after the beginning of April.

The reason for Comet LINEAR's dramatic increase in brightness soon became apparent. Around the end of April images taken with large telescopes revealed that the comet's nucleus had split into two fragments, and from astrometric measurements of these Zdenek Sekanina at the Jet Propulsion Laboratory in California was able to determine that the splitting event had occurred between mid- and late March – right at the time that brightness upsurge began.



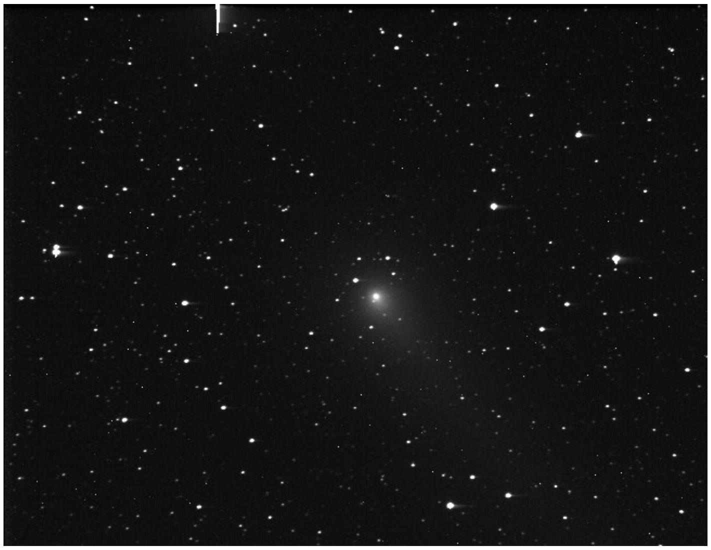
The split nuclei of Comet LINEAR: Nucleus "A" (upper left) and the split Nucleus "B" on May 16, 2001, taken with the 8.2-meter Very Large Telescope at the European Southern Observatory in Chile. Courtesy European Southern Observatory.

Photograph of Comet LINEAR I took on the morning of June 16, 2001, from the outskirts of Harare, Zimbabwe.

Comet LINEAR's brightness surge did not stop then, although it proceeded further in fits and starts rather than continuously. By the beginning of May its brightness had increased to 6th magnitude; shortly thereafter it became inaccessible from the northern hemisphere, although it remained visible from the southern hemisphere, with observers there reporting it as being close to 5th magnitude during the latter part of that month before it passed through conjunction with the sun (50 degrees south of it) in early June, after which it emerged into the southern hemisphere's morning sky.

Shortly before the end of May the secondary nucleus began its own fragmenting, which triggered another outburst in brightness that became apparent around the middle of June. It so happened that I was in Zimbabwe at the time preparing to observe the total solar eclipse on June 21, and on the morning of the 16th I could easily detect the comet with my unaided eye near magnitude 3.5; I could detect a two-degree tail in binoculars, and could trace this tail out to almost twice that long in photographs I took then.

By the latter part of June Comet LINEAR had faded slightly, to about 4th magnitude, and also had become accessible again from the northern hemisphere. It passed closest to Earth (0.24 AU) at the very end of the month and faded somewhat steadily after that point; there were reports of a brief outburst around the middle of July, but within another week it had dropped below naked-eye visibility. After going through opposition at the beginning of August it faded more rapidly, with visual observations remaining possible until early September and the final observations being obtained three months later.



CCD image of Comet LINEAR taken remotely by Muazzez Lohmiller on July 21, 2001, with the Center for Astrophysics MicroObservatory network. Courtesy Muazzez Lohmiller.

SPECIAL TOPIC: LUNAR AND PLANETARY IMPACTS

From lunar orbit. The famous "Earthrise" image taken by Apollo 8 astronaut William Anders on December 24, 1968. Courtesy NASA.

Ever since the Italian astronomer Galileo Galilei turned his primitive telescope towards the moon on November 30, 1609 and saw them for the first time, we've known that the moon is covered with craters. These come in all sizes, from very large ones several hundred km across down to meter-size and smaller. For a long time following their first detection the physical mechanism responsible for the craters was long debated, with some researchers arguing for an impact origin and others arguing for a volcanic origin or some other mechanism (including glacial activity). By the middle decades of the 20th Century the impact origin theory was gaining a stronger and stronger foothold among scientists – especially after impact craters on Earth began to be positively identified as such – and once rock and soil samples brought to Earth by the Apollo astronauts were analyzed these conclusively established this theory as being correct. It is now apparent that the overwhelming majority, if not almost all, of craters on the moon are the result of impact events.

Unlike Earth, the moon does not have any kind of substantial atmosphere, and thus any objects that intercept the moon would do so unimpeded, whereas most smaller objects will disintegrate in Earth's atmosphere. While larger objects would still survive their passage through Earth's atmosphere and strike the surface leaving impact craters – at least, those striking the land surface would do so – active geological processes like plate tectonics and weathering act to remove those craters within a geologically short period of time. The moon, however, is a geologically "dead" place where such processes are not operating, and thus craters formed by impacts would remain indefinitely. Thus, the large number of such craters on the moon compared to Earth – despite the fact that Earth presents almost 13 times the surface area to impacting objects that the moon does.

The one process operating on the moon that tends to "erode" craters is the continuing impacts by additional objects. Older craters will accordingly be "over-written" by younger craters where more recent objects have struck the same basic geological location. Since the ejecta from impacts will themselves rain down upon the lunar surface relatively nearby the original impact, older craters will also tend to be "over-written" by these smaller "satellite" craters. Based upon expected rates of impact events, it is possible to make approximate determinations of a crater's age by examining the amount of "impact erosion" it has experienced.

Some of the oldest craters on the moon are the large basins that are called "maria" (plural for "mare" which comes from the Latin word for "seas," since early moon-watchers thought that these darker regions might be bodies of water akin to seas and oceans on Earth). Many of these are the results of impacts by large "proto-planets" that struck the moon during its early geological history when it was volcanically

View of the cratered lunar surface from Earth. Image courtesy Joe R. of Austin, Texas.

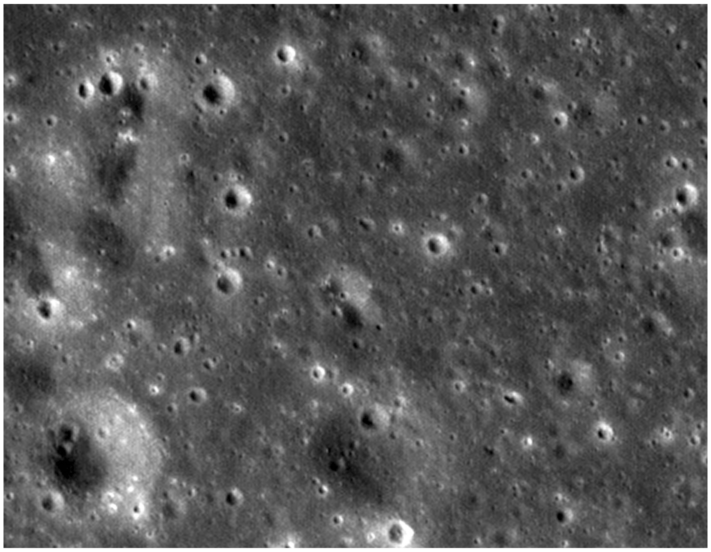
active, with the resulting craters subsequently being filled by basaltic lava which has since been pulverized by impacting objects over the intervening aeons. The largest confirmed impact-created mare is Mare Imbrium, which is over 1100 km in diameter and which was formed from an impact 3.9 billion years ago.

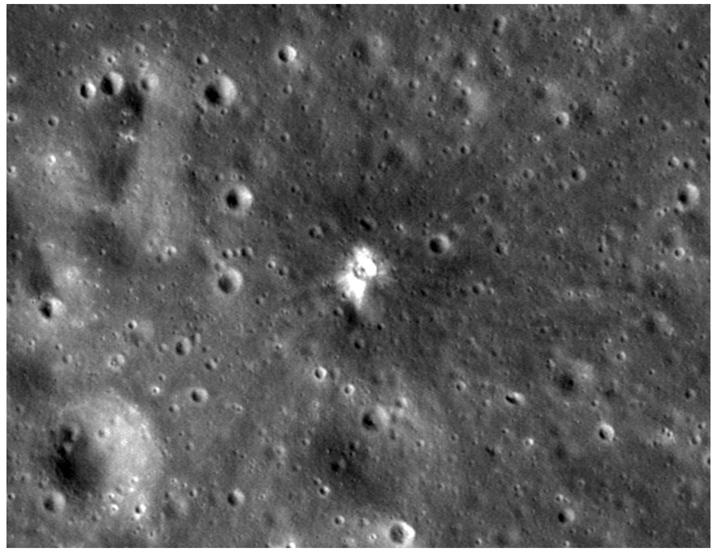
In addition to their erosive effects on older craters and to their accompanying systems of "satellite" craters, younger craters are also often accompanied by systems of lighter-colored "rays" radiating out from them. These are caused by lighter-mass ejecta material (pebbles and dust) raining down onto the lunar surface following the impact. Copernicus (approximate age 800 million years) and Tycho (approximate age 108 million years) are craters with prominent ray systems; that of Tycho is especially prominent around the time of full moon.

We would obviously expect the moon to continue being struck by impacting objects from time to time. During the Leonid meteor storm on November 18, 1999 – which will be discussed in a future "Special Topics" presentation – at least five brief flashes of light were detected on the moon's unlit portion, these apparently being due to meteoroids from the Leonid stream striking the moon's surface. A NASA-operated program to detect meteoroid impacts on the unlit portion of the near-side lunar surface began operations in 2006 and has recorded numerous such events; the brightest (and apparently) largest such event occurred in the Mare Imbrium on March 17, 2013, apparently caused by an object 30 to 40 cm across with an approximate mass of 40 kg. Just over four months later NASA's Lunar Reconnaissance Orbiter (LRO) spacecraft detected a brand new 18-meter-wide crater – complete with a system of rays several km long – at the site of this event.

In considering the rate at which large objects would strike the moon, at face value there is little chance that there would have been such an event during human history. However, a curious event occurred on June 18, 1178, when five Anglican monks in Canterbury, England reported seeing "the upper horn [of the moon] split in two" and then "a flaming torch" rising up from the moon. Some scientists have proposed that this supposed event produced the 22-km-wide crater Giordano Bruno, which is located on the moon's far side (although just beyond the moon's northeastern limb and sometimes visible from Earth when the libration angle is favorable). Giordano Bruno is indeed a young crater with an extensive ray system, however conventional dating techniques place its approximate age at 4 million years. The additional fact that no one else on Earth reported seeing this event, plus the fact that an impact event of this size should have created a strong and lengthy meteor storm here on Earth that instead never took place, argues rather strongly against the interpretation that the Canterbury event, whatever it was, and the crater Giordano Bruno are related. For now, what the Canterbury monks saw on that occasion back in the 12th Century remains a mystery.

Since the beginning of the Space Age there have been several small lunar craters created by the deliberate impacts of spacecraft onto the lunar surface, beginning with the then-Soviet Union's Luna 2 spacecraft on September 13, 1959 and which included several probes of NASA's Ranger series between 1962 and 1965. The most scientifically ambitious mission involving a lunar impact was NASA's Lunar CRater Observation and Sensing Satellite (LCROSS) mission, which was launched (together with LRO) on June 18, 2009. LCROSS' mission plan called for it to impact a permanently-shadowed crater near the moon's south pole in an attempt to detect the presence of water ice (the presence of which had first been suspected in radar experiments conducted with the joint NASA/U.S. Defense Department lunar-orbiting Clementine mission in 1994). LCROSS's Centaur booster successfully impacted the lunar surface in the crater





"Before" (left) and "after" (right) images taken by NASA's Lunar Reconnaissance Orbiter (LRO) mission of the March 17, 2013 impact in the Mare Imbrium. The "before" image was taken on February 12, 2012 and the "after" image was taken on July 28, 2013. Both images courtesy NASA.

Cabeus on October 9, 2009, and the accompanying "Shepherding Spacecraft" successfully detected the presence of water in the impact plume before its own impact a few minutes later. (The reasons for water's presence in such an environment is discussed in a future "Special Topics" presentation.)

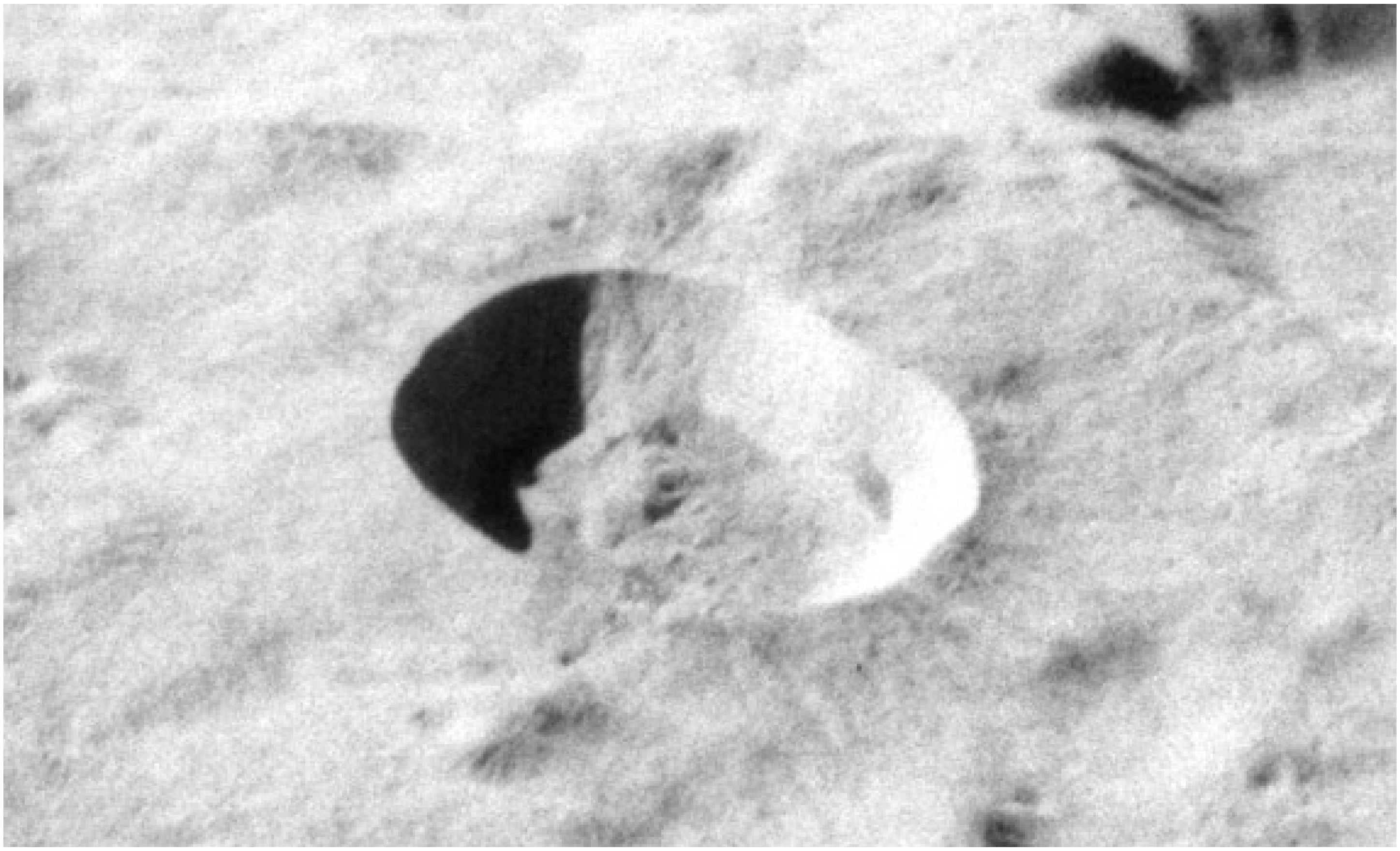
The moon, of course, is not the only body that gets struck by impacting asteroids and comets; the various other worlds of our solar system are struck as well. I've already mentioned that Earth gets struck; the existence of meteorites (discussed in a couple of previous "Special Topics" presentations) proves that, as does the existence of various terrestrial impact craters, such as the Chicxulub crater in Mexico that marks the site of the K-T impact (discussed in another previous "Special Topics" presentation) and other craters that are the subject of a future "Special Topics" presentation.

Mercury, being an essentially airless world similar to the moon, is also covered with impact craters of all sizes, as shown by images taken by NASA's Mariner 10 spacecraft in the mid-1970s and by NASA's MESSENGER mission that orbited Mercury from 2011 to 2015. Because of Mercury's surface gravity which is somewhat higher than the moon's, ray systems and "satellite" crater systems are not as extensive as they are on the moon. The largest impact crater on Mercury is the Caloris Basin – one of the largest impact craters in the entire solar system – which is approximately 1500 km in diameter and which was apparently formed by the impact of a 100-km "protoplanet" approximately 3.8 billion years ago. A small crater – perhaps 16 meters across – was artificially created when MESSENGER was deliberately impacted onto Mercury's surface on April 30, 2015.

Venus' dense atmosphere prevents smaller objects from hitting the surface, and weak (although nevertheless ongoing) volcanic activity and other geological processes tend to erase surface craters after a few hundred million years. About a thousand impact craters have been identified on Venus' surface, the largest of these being Mead with an approximate diameter of 280 km.

The first impact craters ever detected on an extraterrestrial body other than the moon were recorded on Mars by NASA's Mariner 4 spacecraft that passed by that planet in July 1965; among other

The full moon. The large, dark circular basin above center is the Mare Imbrium; the rayed crater below its southern rim, to the left, is Copernicus; Tycho is the very prominent rayed crater to the lower left. Photograph copyright Gregory H. Revera, licensed via Creative Commons.

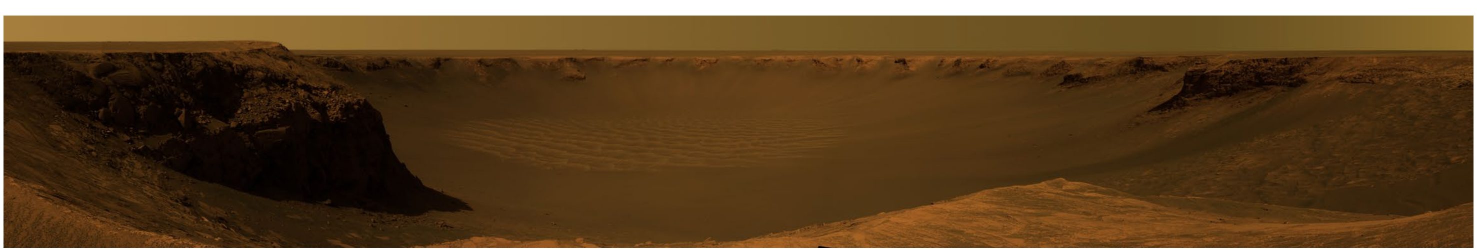


The far side lunar crater Giordano Bruno, photographed during the Apollo 16 mission, April 1972. Courtesy NASA.

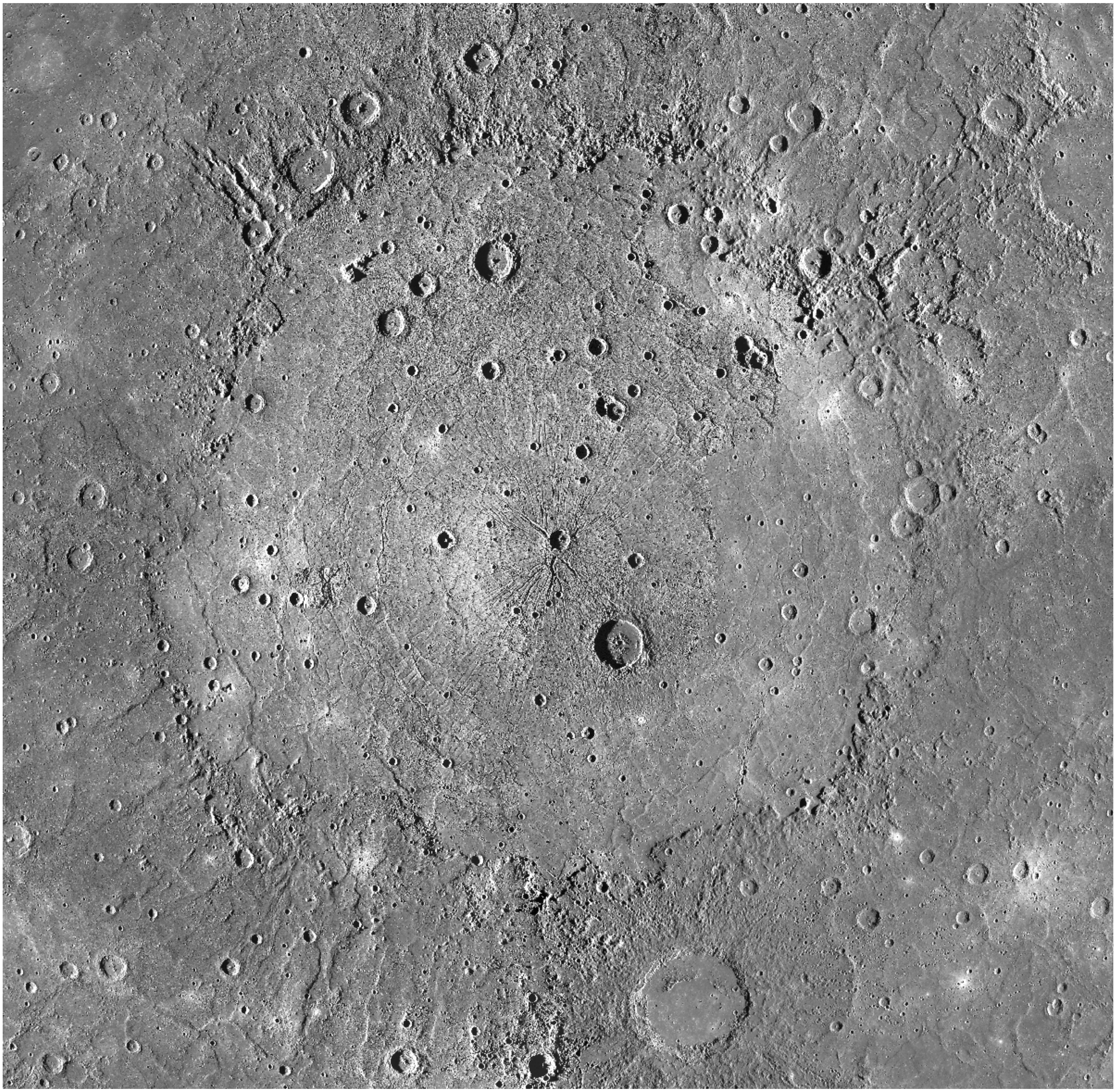
things, the existence of craters on Mars forced a re-thinking – almost a paradigm shift – concerning the possibilities of Martian life. In retrospect, this was a bit of an over-reaction, since in hindsight the existence of Martian craters is not a surprise. Mars' atmosphere is relatively thin and thus does not prevent much in the way of smaller objects from striking the surface, and meanwhile while there are no plate tectonics, occasional volcanism, together with weathering processes like wind erosion, act to wear down craters over geologically long periods of time.

Over 40,000 impact craters down to a diameter of 5 km have been identified on Mars' surface, and there are certainly many times this number of smaller craters. Martian craters have figured in the surface exploration of the planet; the Spirit rover, which landed in January 2004, did so in the crater Gusev, an old evolved crater some 166 km in diameter, while Opportunity, which landed that same month, explored several craters during its 14 years of exploration, the largest of these being Endeavour (diameter 22 km). The Curiosity rover has been exploring the crater Gale (diameter 154 km) ever since its touchdown in August 2012. Meanwhile, new Martian craters are appearing all the time; in one dramatic incident, on March 28, 2012 NASA's Mars Reconnaissance Orbiter (MRO) spacecraft detected a fresh 50-meter-wide impact crater – surrounded by several smaller fresh craters – near the Martian Equator south-southwest of Olympus Mons, however these craters did not appear in images taken the previous day, thus allowing the time of impact to be narrowed down to within a one-day period.

One would expect Jupiter, with its large size and mass (and thus large gravitational field) to experience numerous impacts on a regular basis, although because Jupiter has no solid surface there are obviously no impact craters. Impacts onto Jupiter



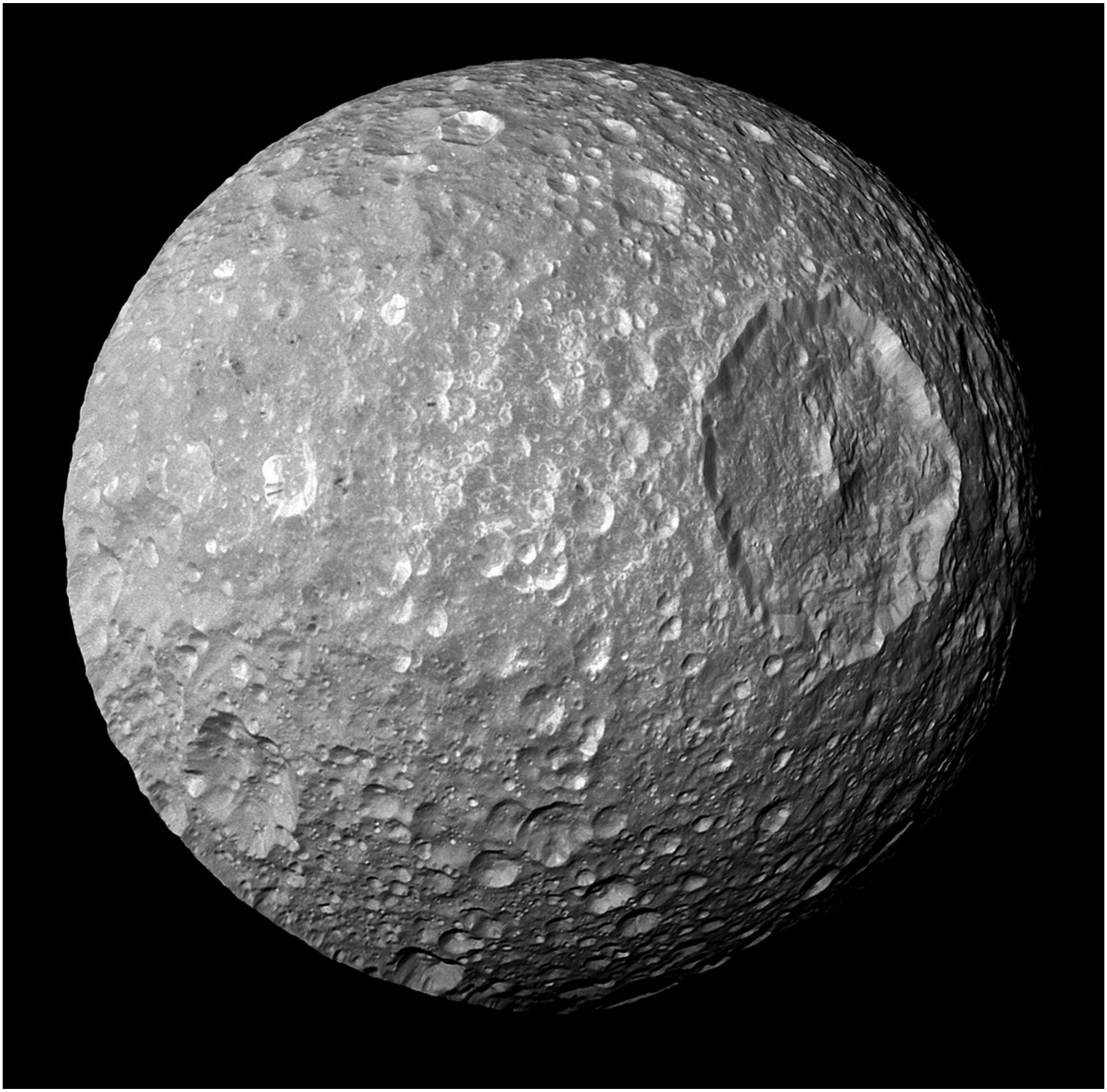
Ground-based panorama mosaic of Mars' crater Victoria (diameter 750 meters), taken by the Opportunity rover from the northwestern rim between October 16 and November 6, 2006. Image courtesy NASA.



Mosaic of Mercury's Caloris Basin, created from images taken by NASA's MESSENGER spacecraft. Image courtesy NASA.

have nevertheless been detected, by far the most dramatic of these being those of the fragments of Comet Shoemaker-Levy 9 1993e during July 1994. This comet is a future "Comet of the Week" and these impacts, and impacts onto Jupiter in general, are discussed in that presentation.

The various planets' moons, along with the solar system's other "small bodies," are also subject to impacts, and when appropriate these events are discussed in other "Special Topics" presentations. Those moons that are geologically active in some way do not have many impact craters, for obvious reasons; indeed, Io (Jupiter I), because of its continuous extensive volcanic activity, has essentially no impact craters, and Europa (Jupiter II), with its likely sub-surface liquid water ocean, has relatively few craters. Other geologically active moons with few craters are Enceladus (Saturn II) which exhibits ongoing geyser activity over parts of its surface; Titan (Saturn VI) which in addition to an active geology also has a dense atmosphere to stop smaller objects; Miranda (Uranus V) which exhibits evidence of (geologically) recent cryovolcanism over some regions of its surface; and Triton (Neptune I) which, as is the case with Enceladus, exhibits ongoing geyser activity. (It is possible,



Composite image of Mimas, with the prominent crater Herschel at right, taken by NASA's Cassini spacecraft on February 13, 2010. Image courtesy NASA.

incidentally, that Triton is a captured object from the Kuiper Belt, something that will be discussed in a future "Special Topics" presentation.) The Sputnik Planitia region of Pluto has a very fresh surface indicative of very (geologically) recent geological activity, and the New Horizons mission detected no craters within it, although it detected quite a few craters elsewhere on Pluto's surface.

Most of the other moons that have been examined in detail exhibit relatively heavily cratered surfaces. Indeed, Ganymede (Jupiter III) and Callisto (Jupiter IV) exhibit "chains" of craters that are possibly indicative of impacts by fragmented comets like Shoemaker-Levy 9. One rather interesting example of an impact crater is found on Mimas (Saturn I), which exhibits one very large crater, named Herschel, with a diameter of 139 km (Mimas itself having an average diameter of 396 km). On the first images of Mimas returned by Voyager 1 during its passage by Saturn in 1980 the presence of Herschel gave it an appearance strikingly reminiscent of the "Death Star" that was in the movie "Star Wars" three years earlier. In a real sense this could be considered a classic example of "life imitating art."

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