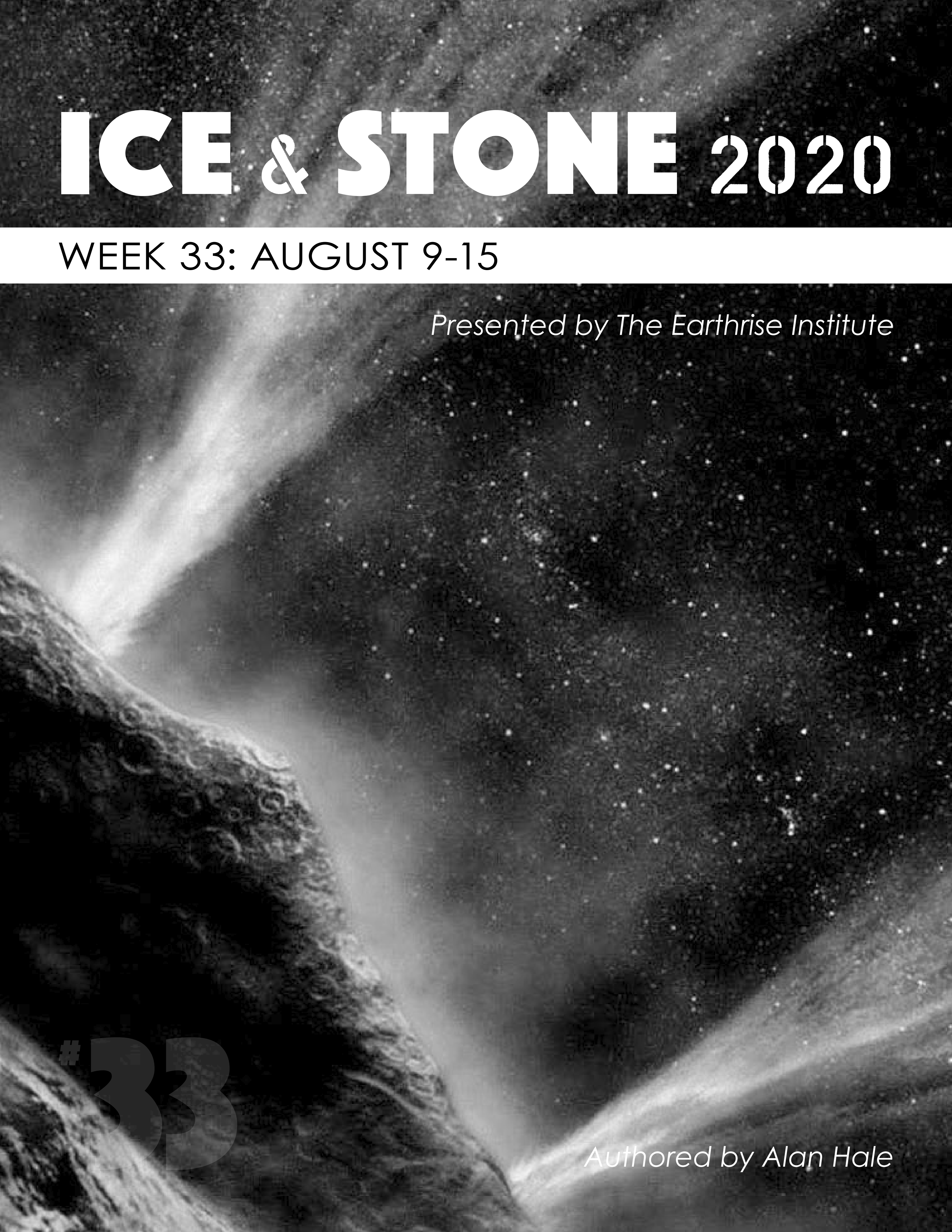


ICE & STONE 2020

WEEK 33: AUGUST 9-15

Presented by The Earthrise Institute

Authored by Alan Hale

ABOUT ICE AND STONE 2020

It is my pleasure to welcome all educators, students, and anybody else who might be interested, to Ice and Stone 2020. This is an educational package I have put together to cover the so-called “small bodies” of the solar system, which in general means asteroids and comets, although this also includes the small moons of the various planets as well as meteors, meteorites, and interplanetary dust. Although these objects may be “small” compared to the planets of our solar system, they are nevertheless of high interest and importance for several reasons, including:

a) they are believed to be the “leftovers” from the formation of the solar system, so studying them provides valuable insights into our origins, including Earth and of life on Earth, including ourselves;

b) we have learned that this process isn’t over yet, and that there are still objects out there that can impact Earth and threaten our existence upon it; and

c) we have also learned that many of these objects contain valuable resources that we can utilize here on Earth as well as in space, should humanity make the decision to expand out into the solar system.

Ice and Stone 2020 will cover various facets of our knowledge about these objects. I do not intend this to be a substitute for formal classroom educational courses, however I do intend this to supplement the material in such courses, and to act as a resource for additional information.

Throughout each week of 2020 Ice and Stone 2020 will unveil new “presentations” about different aspects of our solar system’s “small bodies.” Specifically, each week will feature:

a) “This Week in History” -- a brief summary of important events in the study of “small bodies” during that particular week in history. This will include such events as spacecraft encounters, asteroid flybys, important discoveries, and notable publications and announcements, each of which will include a short summary. Some of the events are those that will be taking place in the future.

b) “Comet of the Week” -- a short discussion of an important comet that was visible during that corresponding week in the past. These could be comets that were especially bright, or that are scientifically important in some way. A small number of these are comets that are expected to be visible during 2020 or in later years.

c) “Special Topic” -- each week will feature a moderately in-depth discussion of some topic related to the study of “small bodies.” Some representative topics include: main-belt asteroids, near-Earth asteroids, “Great Comets,” spacecraft visits (both past and future), meteorites, and “small bodies” in popular literature and music.

Throughout 2020 there will be various comets that are visible in our skies and various asteroids passing by Earth -- some of which are already known, some of which will be discovered “in the act” -- and there will also be various asteroids of the main asteroid belt that are visible as well as “occultations” of stars by various asteroids visible from certain locations on Earth’s surface. Ice and Stone 2020 will make note of these occasions and appearances as they take place. The “Comet Resource Center” at the Earthrise web site contains information about the brighter comets that are visible in the sky at any given time and, for those who are interested, I will also occasionally share information about the goings-on in my life as I observe these comets.

I will make the assumption that Ice and Stone 2020 participants have some knowledge about basic astronomy, including knowledge about the various planets as well as basic astronomical terms like “magnitude.” I will also assume that participants have -- or at least know where to find -- basic information about orbits, including terms like “perihelion” and “astronomical unit” (or “AU”). The term “q” that appears throughout various presentations refers to an object’s perihelion distance from the sun, usually given in AU.

The Earthrise Institute is pleased to be partnering with various organizations in Ice and Stone 2020. We especially acknowledge RocketSTEM, which will be hosting our presentations and assist in putting together lesson plans around them. The Las Cumbres Observatory, a worldwide network of automated telescopes placed at some of the top observing sites in the world, will be available for participants who might wish to image some of the objects that are visible.

2020 marks some very special anniversaries for me. It was 50 years ago, on February 2, 1970, that I saw my very first comet -- which, coincidentally, also happened to be the first comet ever observed from space. And it was 25 years ago, on July 23, 1995, that I discovered the comet that brought me worldwide recognition and forever changed my life. As I begin to approach the later years of that life it is my intent with Ice and Stone 2020 to share both the knowledge and the joy that I have gained throughout that life with the future generations of humanity, all over the world, so that they can use that knowledge -- however they see fit to do so -- to build a worthy future.

Alan Hale

Founder, The Earthrise Institute

THIS WEEK IN HISTORY

AUGUST 9 10 11 12 13 14 15

AUGUST 9, 1996: The NEAT program based in Hawaii discovers an apparent asteroid, designated 1996 PW, that is found to be traveling in a near-parabolic comet-like orbit with an approximate orbital period of 5600 years. 1996 PW was the first known long-period "Damocloid," and these objects are discussed in a future "Special Topics" presentation.

9 AUGUST 10 11 12 13 14 15

AUGUST 10, 1972: A tiny asteroid, probably somewhere between 10 and 20 meters in diameter, enters the earth's atmosphere above Utah and, traveling almost due northward, passes within 60 km of Earth's surface above Montana before returning to interplanetary space. This incident is discussed in more detail in a previous "Special Topics" presentation.

9 10 AUGUST 11 12 13 14 15

AUGUST 11, 2020: The main-belt asteroid (4151) Alanhale, which I have used as an illustrative example in several previous "Special Topics" presentations, will be at opposition. It is currently located in northeastern Capricornus and traveling towards the west-southwest, and is about 17th magnitude.

COVER IMAGE CREDIT:

Front and back cover: An artist's concept depicting a view of comet Wild 2 as seen from NASA's Stardust spacecraft during its flyby of the comet on Jan. 2, 2004..

Courtesy NASA/JPL-Caltech

9 10 11 AUGUST 12 13 14 15

AUGUST 12, 1877: Asaph Hall at the U.S. Naval Observatory in Washington, D.C. discovers Mars' smaller, outer moon, Deimos. Mars' two moons, and the various small moons of the outer planets, are the subject of this week's "Special Topics" presentation.

AUGUST 12, 1978: NASA's International Sun-Earth Explorer 3 (ISEE-3) satellite is launched from Cape Canaveral, Florida. Originally part of a three-satellite international mission to study the interaction of the solar wind with Earth's magnetosphere, ISEE-3 was based at the sun-Earth L1 Lagrangian point 1.6 million km sunward of Earth. After the completion of its original mission, in 1982 ISEE-3 was moved from L1 for a series of lunar flybys which propelled it – under the new name International Cometary Explorer (ICE) – to an encounter with Comet 21P/Giacobini-Zinner in 1985, becoming the first spacecraft to encounter a comet. The ISEE-3/ICE mission is discussed in a previous "Special Topics" presentation, and Comet 21P/Giacobini-Zinner is a future "Comet of the Week."

AUGUST 12, 2020: The annual Perseid meteor shower is expected to be at its peak. Under favorable conditions the Perseids can produce up to 100 meteors per hour, but the last-quarter moon will detract from the 2020 shower. The Perseids are associated with Comet 109P/Swift-Tuttle, which is a future "Comet of the Week," and the association between comets and meteor showers in general is discussed in a future "Special Topics" presentation.

AUGUST 12, 2027: NASA's Lucy mission, planned for launch in 2021, is scheduled to fly by the Jupiter Trojan asteroid (3548) Eurybates. The Lucy mission is discussed in a previous "Special Topics" presentation, and Trojan asteroids are the subject of a future "Special Topics" presentation..

9 10 11 12 AUGUST 13 14 15

AUGUST 13, 1898: Gustav Witt at the Berlin Observatory in Germany discovers the asteroid now known as (433) Eros; it was independently discovered the same night by Auguste Charlois at Nice Observatory in France. Eros was the first-known near-Earth asteroid and has passed relatively close to Earth on several occasions since then; it was orbited by the Near-Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft for one year in 2000-01 which then soft-landed onto Eros' surface. Eros is the subject of a previous "Special Topics" presentation.

AUGUST 13, 1930: An apparent tiny asteroid enters the earth's atmosphere above South America and explodes in an airburst above the surface near the Curuca River in far western Brazil. A Franciscan friar, Fedele d'Alviano, interviewed local witnesses to the event, but his report went unnoticed for the next six decades. Events of this nature are the subject of a previous "Special Topics" presentation.

AUGUST 13, 1994: Amateur astronomer Don Machholz in California discovers a comet, now known as Comet 141P/Machholz 2. The comet was accompanied by several "companion" comets, all but one of which soon disappeared, but the largest companion also appeared at the comet's next return in 1999. Another dim companion accompanied the comet at its most recent return in 2015. Comet 141P returns to perihelion this coming December 20 under moderately favorable viewing circumstances, and it will be covered at the appropriate time in the Comet Resource Center.

AUGUST 13, 2013: Karen Meech and Olivier Hainaut obtain the final – to date – images of Comet Hale-Bopp C/1995 O1 with the European Southern Observatory's Very Large Telescope in Chile; the comet's heliocentric distance was 36.4 AU, the largest distance at which any comet has ever been detected. Comet Hale-Bopp was a previous "Comet of the Week."

AUGUST 13, 2015: Comet 67P/Churyumov-Gerasimenko passes through perihelion at a heliocentric distance of 1.243 AU. Comet 67P was last week's "Comet of the Week" and this return is the one during which it was visited by ESA's Rosetta mission; various elements and results of this mission are discussed in last week's Presentation.

9 10 11 12 13 **AUGUST 14** 15

AUGUST 14, 1992: A stony meteoroid enters the atmosphere and breaks apart near Mbale, Uganda. Several meteorite fragments reach the ground, and one of these, after its fall was broken by branches of a banana tree, hits a boy in the head (although, fortunately, causing no injuries). Meteorite falls of this nature are discussed in a previous "Special Topics" presentation.

AUGUST 14, 2014: A team of scientists led by Rhonda Stroud and Andrew Westphal announces that they have located what appear to be dust grains from interstellar space in samples returned to Earth by the Stardust spacecraft following its collection flyby of Comet 81P/Wild 2 – the Week 1 "Comet of the Week" – in 2004. The Stardust mission is discussed in a previous "Special Topics" presentation, and dust in the solar system is the subject of a future "Special Topics" presentation.

9 10 11 12 13 14 **AUGUST 15**

AUGUST 15, 2018: Pluto occults a 13th-magnitude star in Sagittarius, an event which is successfully observed from the U.S. and Mexico. Despite Pluto's being almost three decades past perihelion passage, the occultation reveals that it is still accompanied by a thin atmosphere. Pluto is discussed in a previous "Special Topics" presentation.

COMET OF THE WEEK: MRKOS 1957D

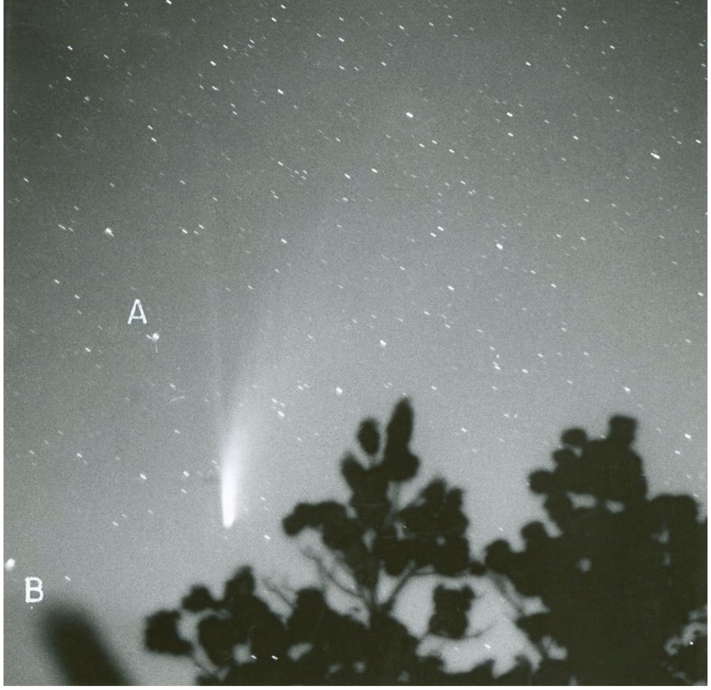
Perihelion: 1957 August 1.44, q = 0.355 AU

Comet Mrkos on August 13, 1957, as photographed by Alan McClure north of Los Angeles, California. Several "synchronic bands" are visible in the dust tail.

During the mid-20th Century the northern hemisphere went several decades without a bright naked-eye comet; what bright comets that did appear during that time were primarily visible from the southern hemisphere. This changed during 1957, when Comet Arend-Roland 1956h became bright and conspicuous during April and May, reaching 1st magnitude and displaying both a prominent dust tail and a distinct anti-tail. This was a previous "Comet of the Week" and the details of its appearance are discussed in that Presentation.

But 1957 wasn't over as far as bright comets were concerned, for another one appeared just a few months later. Unlike Comet Arend-Roland, however, which was discovered several months in advance thus creating widespread anticipation of its appearance, this second visitor approached the inner solar system from the deep south and then spent the last several weeks prior to perihelion passage hidden in sunlight on the far side of the sun from Earth. When it burst into view around the beginning of August it was already bright and fully developed.

The first person to report seeing the comet was a Japanese observer, Sukehiro Kuragano, who saw it on the morning of July 29, but unfortunately his report was delayed for two weeks. An American Airlines pilot, Peter Cherbak, saw the comet while flying over Nebraska on July 31, and after confirming his sighting the following morning notified Griffith Observatory in Los Angeles, but this report, too, was delayed. Numerous independent discoveries followed over the next few mornings, including one by a 15-year-old British amateur astronomer, Clive Hare, who saw the comet on August 3. Meanwhile, on the morning

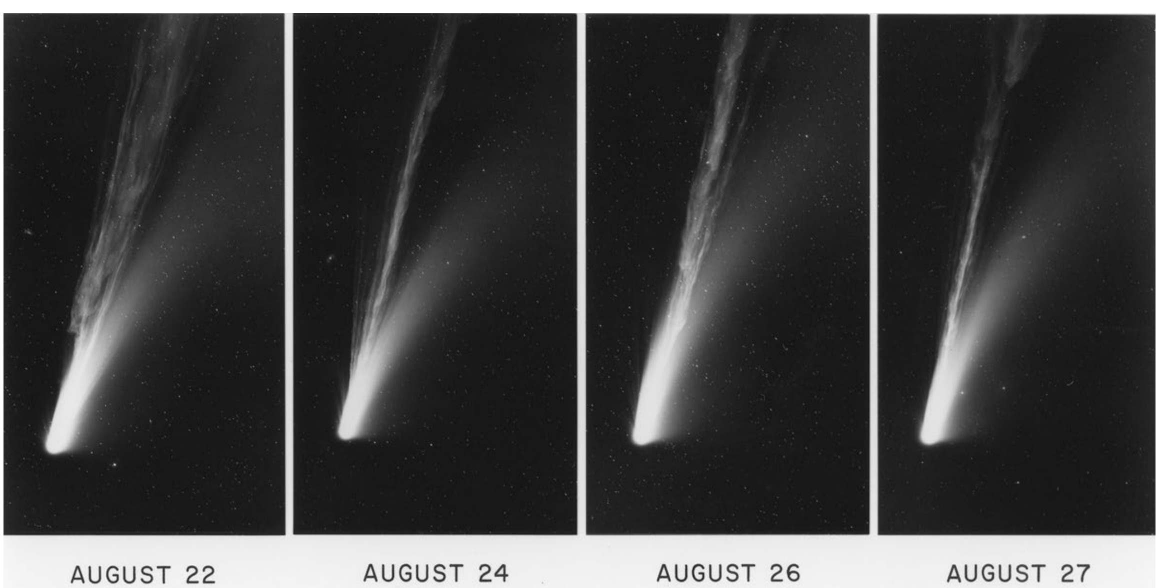


Comet Mrkos on the evening of August 14, 1957. The stars marked "A" and "B" are references for comparing the comet's motion on photographs taken other nights. Courtesy Royal Astronomical Society of Canada.

of August 2, Antonin Mrkos, who was part of the visual comet-hunting program being conducted at Skalnate Pleso Observatory in then-Czechoslovakia (present-day Slovakia), was measuring the morning skyglow at the observatory on Lomnicky Stit when he noticed a comet's tail extending from below the horizon, and shortly thereafter he saw the comet's head rising. Having discovered nine previous comets he knew exactly what to do and notified the IAU's Central Bureau for Astronomical Telegrams (then located at Copenhagen Observatory), which very quickly announced the discovery as "Comet Mrkos." Even after the other, and earlier, discoveries became known the IAU decided to leave the name unchanged in order to prevent confusion. (Nowadays the IAU's practice is to wait to assign names to newly-discovered comets in case earlier discoveries might come to light, so if this type of scenario were to happen again the final naming would more accurately reflect the actual precedence of discoveries.)

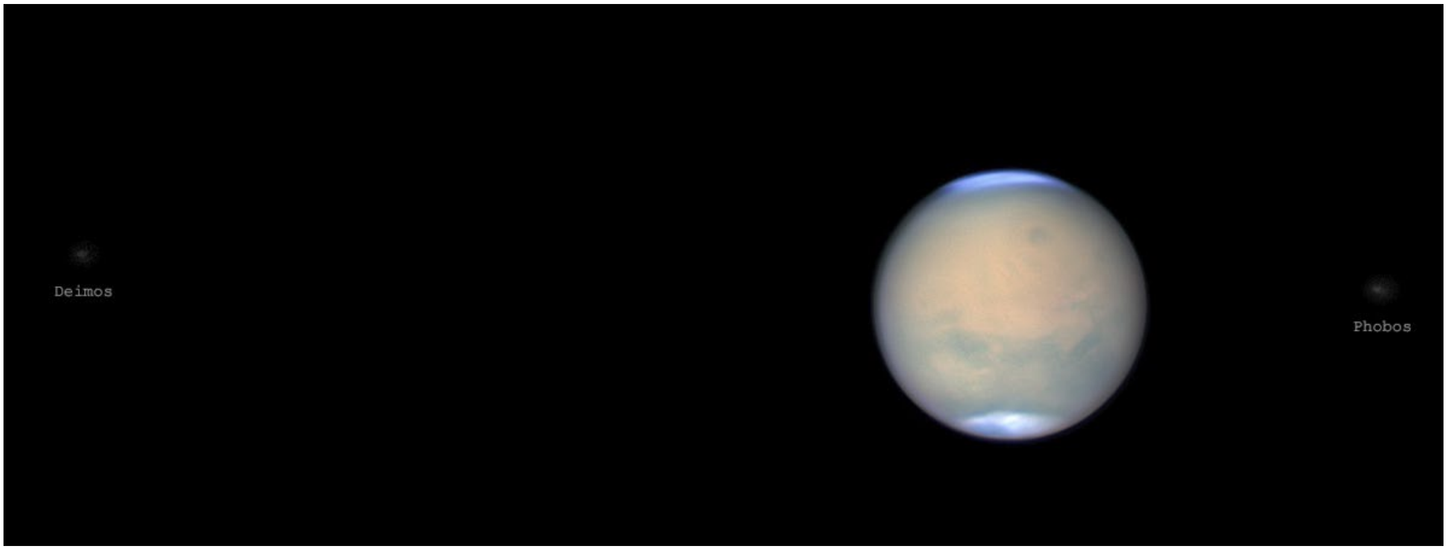
Comet Mrkos was initially a morning-sky object located well north of the sun, and it moved eastward, being directly north of the sun on August 5 and thereafter becoming primarily visible in the evening sky after dusk. By an interesting coincidence, during the second week of August it was located in the same position relative to the horizon that Comet Arend-Roland had occupied less than four months earlier. Its brightness was reported as being as high as 1st magnitude in early August, and it faded fairly slowly thereafter, still being around 3rd magnitude during the latter part of that month. In addition to a prominent ion tail which reached a maximum length of about 10 degrees, the comet also displayed a bright and prominent curved dust tail, initially around 5 degrees long in early August but increasing to 15 degrees around mid-month. This tail featured several of what are called "synchronic bands," which have been observed in a handful of other bright dusty comets; the mechanisms that produce these and other features in cometary tails are the subject of a future "Special Topics" presentation. The recent Comet NEOWISE C/2020 F3 exhibited a relatively similar overall appearance, although Comet Mrkos was apparently slightly brighter.

Although still as bright as 4th magnitude in early September, Comet Mrkos faded more rapidly that month, dropping below naked-eye visibility towards the end of that month and fading further to 7th magnitude when it disappeared into evening twilight during October. Following conjunction with the sun it was recovered as a faint object in the morning sky in February 1958 and thereafter followed until July. According to orbital calculations it should return in approximately 6000 years.



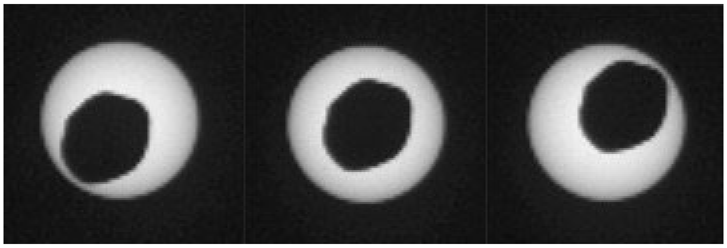
A series of photographs of Comet Mrkos taken on several nights in late August 1957 by Charles Kearns, George Abell, and Byron Hill with the 1.2-meter Schmidt telescope at Palomar Observatory in California. Changes in the structure of the ion tail are quite apparent. Courtesy Palomar Observatory.

SPECIAL TOPIC: SMALL PLANETARY MOONS



Ground-based photograph of Mars and its two moons, taken July 25, 2018, around the time of Mars' most recent opposition. Courtesy Reddit user bubbleweed.

Throughout "Ice and Stone 2020" I have generally used the term "small bodies of the solar system" to refer to comets and asteroids. However, there is another type of "small body" that we encounter throughout the solar system: these are the smaller moons that accompany many of the major planets. The dividing line between what is and what is not a "small body" in this context is certainly a matter of definition, however I think it can be reasonably argued that objects like Earth's moon, the four Galilean moons of Jupiter, Saturn's moon Titan, and Neptune's moon Triton, are all large and unique worlds in and of themselves. (Triton may well be a captured object from the Kuiper Belt, and is discussed within that context in other "Special Topics" presentations.) Some of Saturn's other moons, and Uranus' first five known moons, can perhaps also be argued as being "not-'small'" in this same context. Many of the other planetary moons within our solar system, including almost all of those found in recent years, are, however, quite "small" in this context, and moreover are misshapen and non-spherical like many asteroids and comets, and thus are properly discussed within the context of "small bodies."



A sequence of images of Phobos transiting the sun, as viewed by the Curiosity rover on August 20, 2013. Courtesy NASA.

The first two such objects to be discovered were the two moons of Mars. Mars had long been believed – not necessarily always for scientific reasons – to possess moons, and during the exceptionally close opposition of Mars in August 1877 – which, incidentally, was not much closer than the opposition on this coming October 13 – American astronomer Asaph Hall utilized the recently-constructed 66-cm refractor at the U.S. Naval Observatory in Washington, D.C. to search for such objects. Late on the evening of August 11 (August 12 UT) Hall detected a faint moving object near Mars, however poor weather prevented his confirming it until five nights later. After spotting the object again on the night of the 16th he saw it yet again on the following night, at which time he discovered another Martian moon.

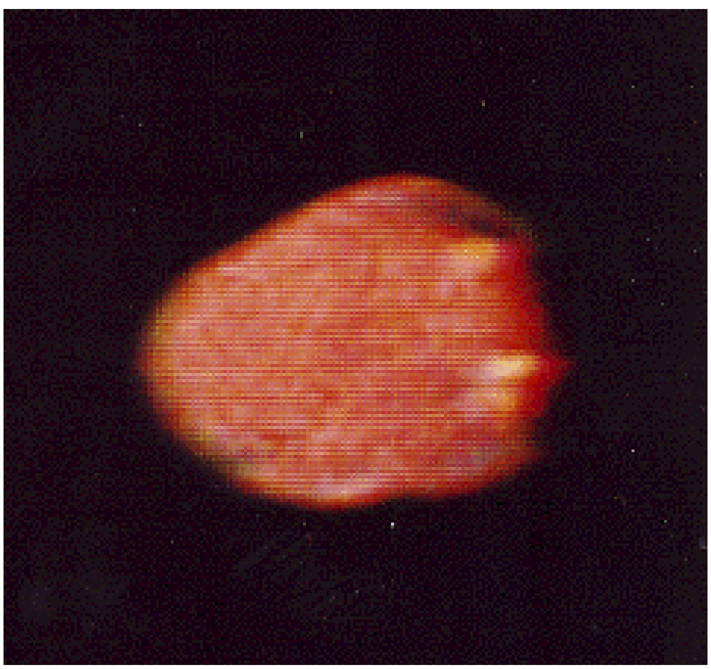
The two new moons were named Phobos and Deimos (from the Greek mythological characters representing "fear" and "terror," respectively). Deimos, the first of the two moons that Hall discovered, is the smaller and outer of the two, being about 15 by 12 by 11 km across and orbiting 20,000 km above Mars' surface with an orbital period of 30.3 hours; Phobos, meanwhile, is 27 by 22 by 18 km across and orbits only 6000 km – less than two Mars radii – above Mars' surface with an orbital period of 7.7 hours. Since Mars' rotational period is slightly over 24.5 hours a ground-based observer on Mars would see Phobos rise in the west, transit the sky, and set in the east twice each day. Its angular size would be about 12 arcminutes, slightly

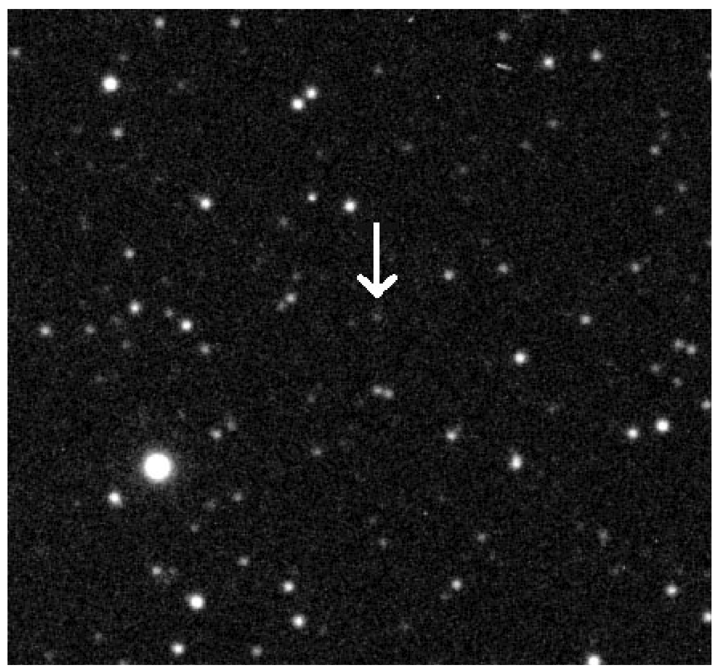
Mars Reconnaissance Orbiter images of Mars' two moons. Left: Phobos. Stickney is the large crater at the lower right. Right: Deimos. Both images courtesy NASA.

over half the apparent diameter of the sun in that planet's sky.

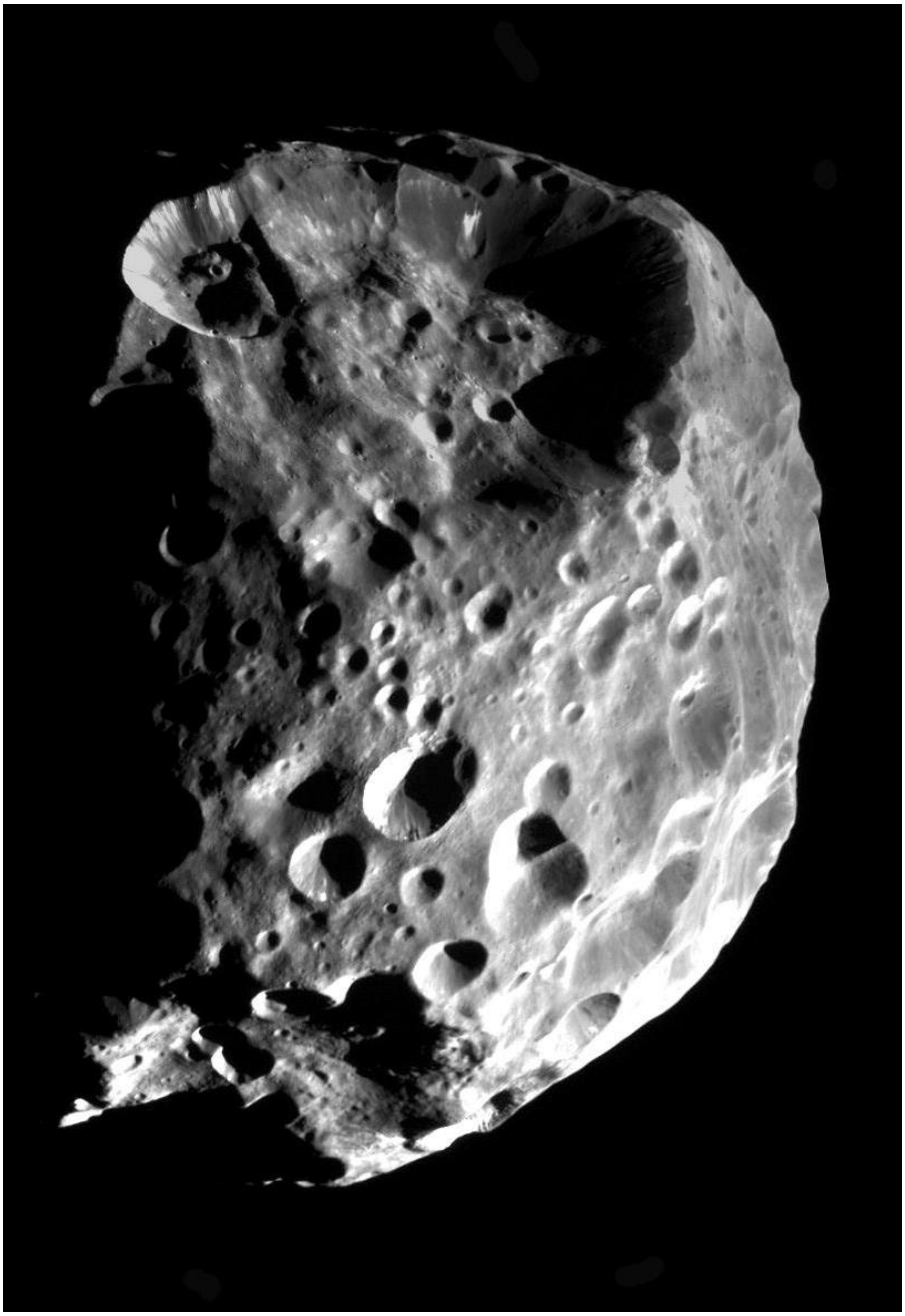
Phobos and Deimos became the first of the solar system's "small bodies" to be examined up close by a spacecraft, when NASA's Mariner 9 mission photographed them in late October 1971 as it was approaching Mars for insertion into orbit. The two moons have been photographed extensively by the various Mars-orbiting missions since then, and can perhaps be considered as the best-studied of the solar system's "small bodies." Phobos has numerous craters, including a large 9-km-wide crater, Stickney (named for Asaph Hall's wife Chloe Stickney), which has an accompanying system of grooves and chains of craters; Deimos, meanwhile, also has craters, but also smoother plains than does Phobos, as it appears that some of the craters have been filled in.

It had long been thought that Phobos and Deimos are captured asteroids, most likely from the main asteroid belt. However, there are some compositional





Jupiter's inner moon Amalthea, as imaged by NASA's Voyager 1 spacecraft in March 1979. The reddish coloration is likely due to sulfur coming from the volcanically active moon Io. Courtesy NASA. RIGHT: Image of the moon Jupiter VIII (Pasiphae) taken with the Las Cumbres Observatory network on July 8, 2019.



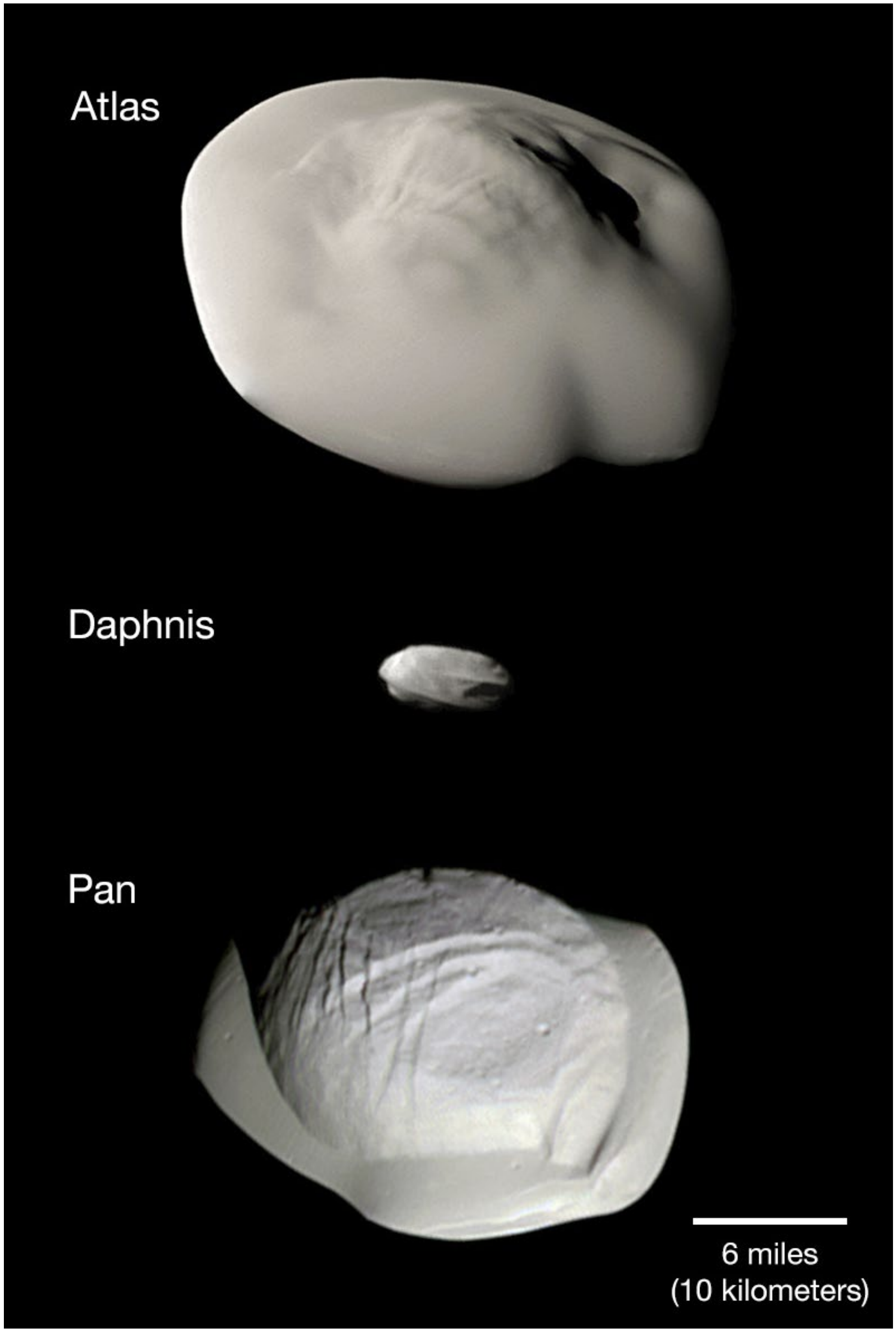
Saturn's outer moon Phoebe, as imaged by the Cassini spacecraft on June 11, 2004 as it was approaching Saturn. Courtesy NASA.

differences between the two moons and the main-belt asteroids closest to Mars, and there are also dynamical difficulties involved in a "capture" scenario given the near-circular orbits of the two moons. It is thus conceivable that the moons formed from material blasted up from Mars' surface by a large impacting object billions of years ago that later coalesced. In any event, tidal forces are gradually drawing Phobos closer to Mars, and at some point in the distant future these will overcome Phobos' internal strength and it will be ripped apart into pieces – presumably to impact the Martian surface at some point afterwards.

Following the discovery of the four Galilean moons of Jupiter by the Italian astronomer Galileo Galilei in 1610, no additional moons of Jupiter were discovered for almost three centuries. Jupiter's fifth-known moon was finally discovered on September 9, 1892 by American astronomer Edward Barnard, who spotted it visually with the 91-cm refractor at Lick Observatory in California. The new moon was named Amalthea and it is much smaller than the Galilean moons, being about 250 km across in its longest dimension, and it orbits well inward of Io. Amalthea has the distinction of being the last solar system moon to be discovered visually.

Another Lick Observatory astronomer, Charles Perrine, initiated a photographic search for additional moons of Jupiter in late 1904, and on December 3 of that year

Montage of Cassini images of some of the "shepherd" moons of Saturn, to scale. Atlas orbits just outside the outer edge of the "A" ring, Daphnis orbits within the Keeler Gap in the "A" ring, and Pan orbits within the Encke Gap in the "A" ring. Courtesy NASA.



successfully discovered one, since named Himalia. Early the following year Perrine discovered a seventh moon of Jupiter, later named Elara. Both of these objects orbit Jupiter well outside the orbit of Callisto, and are much smaller than the Galilean moons, Himalia being about 170 km in diameter and Elara being about half that size.

Up through the late 1970s six additional moons were discovered orbiting around Jupiter, all of these being quite small – ranging in size from 16 to 60 km in diameter – and orbiting well outside the Galilean moons. Four of these moons are traveling in retrograde orbits. Meanwhile, as they were passing by Jupiter in 1979 the twin Voyagers 1 and 2 spacecraft discovered three previously-unknown small inner moons around that planet, two of these orbiting interior to Amalthea and the other orbiting between it and Io.

What could perhaps be considered the first-known "small body" moon of Saturn is Phoebe, which was discovered by American astronomer William Pickering on March 18, 1899 on photographs that had been taken the previous August; it has the distinction of being the first planetary moon to be discovered via photography. Phoebe is somewhat large, with an average diameter of 213 km, and orbits Saturn quite distantly with an orbital period of 1.5 years; like some of the aforementioned outer moons of Jupiter, its orbit is retrograde.

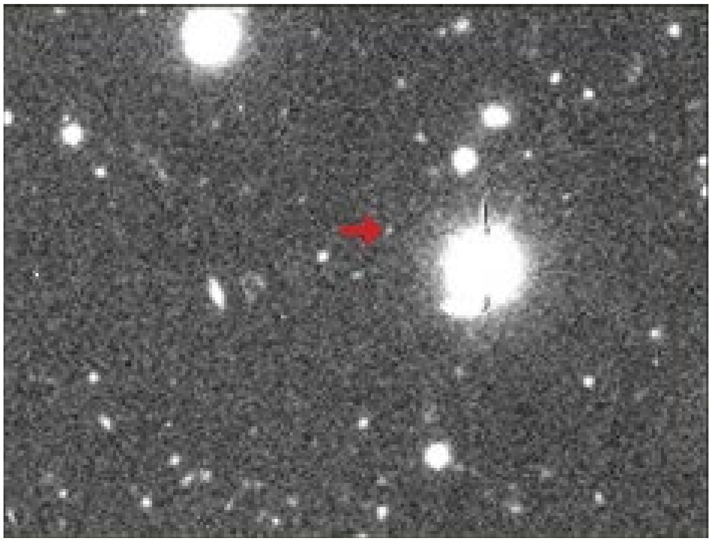
In late 1966 Saturn's rings were presented edge-on to Earth, and right around the time of the ring-plane crossing French astronomer Audouin Dollfus took advantage of the lack of glare from the rings to make searches for any small inner moons of Saturn. In mid-December he discovered such a moon, which he named Janus, however it later turned out that some of the astrometric positions of Janus could not be reconciled within a consistent orbit. By the late 1970s it was becoming apparent that what was believed to be Janus was actually two small moons traveling in the same orbit, and this second moon was later given the name Epimetheus. Janus is about 180 km in diameter and Epimetheus is slightly smaller with an average diameter of 120 km.

In 1980-81 Saturn's rings were again presented edge-on to Earth, and the world's astronomers took advantage of this to look for additional small moons close to Saturn. There were numerous reports of such objects, and meanwhile both Voyager spacecraft passed by Saturn during this same time frame (Voyager 1 in November 1980 and Voyager 2 in August 1981) and these detected four additional small inner moons. After all the various reports were sorted out there were a total of 18 known moons around Saturn; some of these occupied the same orbits of already-known larger moons (at their respective Lagrangian points) and some of the other newly-discovered ones were "shepherd moons" gravitationally confining the newly-discovered thin "F" ring of Saturn or some of the interior gaps in the previously-known rings.
More recently, the Cassini mission which orbited Saturn between 2004 and 2017 discovered at least seven additional small inner moons as well as several tiny "moonlets" – with a diameter of a few hundred meters or less – which may or may not be "moons" depending upon how that term might be defined.

Voyager 2 discovered eleven previously-unknown moons around Uranus when it passed by that planet in early 1986, although one of these was not identified in the Voyager images until over a decade later. Astronomers utilizing the Hubble Space Telescope discovered two additional small inner moons of Uranus in 2003. Meanwhile, in addition to Triton Neptune had one other known moon, Nereid, which was discovered by Gerard Kuiper in 1949; it has an approximate diameter of 340 km and travels in an elongated orbit with an orbital period of just under one year. Voyager 2 discovered seven additional moons of Neptune when it passed by that planet in August 1989; one of these, Proteus, is larger than Nereid (approximate diameter 420 km). Another small inner moon, named Hippocamp, was discovered in 2013 in images taken with the Hubble Space Telescope.

Starting in the late 1990s and extending for the next several years some astronomers made attempts to find very small distant outer moons of the solar system's giant planets. These efforts were very successfully, and the number of known moons has grown dramatically since they started. Almost all of these moons are indeed very small, just a few km in diameter for those around Jupiter and Saturn, and a few tens of km in diameter for those around Uranus and Neptune. A relatively large percentage of these are in retrograde orbits. Especially in the case of Neptune, they are far enough away from the sun's gravitational influence that they can orbit their planet distantly and still remain within that system; Neptune's most distant moons, Psamathe and Neso, have average orbital distances close to 1/3 of an AU and have orbital periods of 25 and 26 years, respectively.

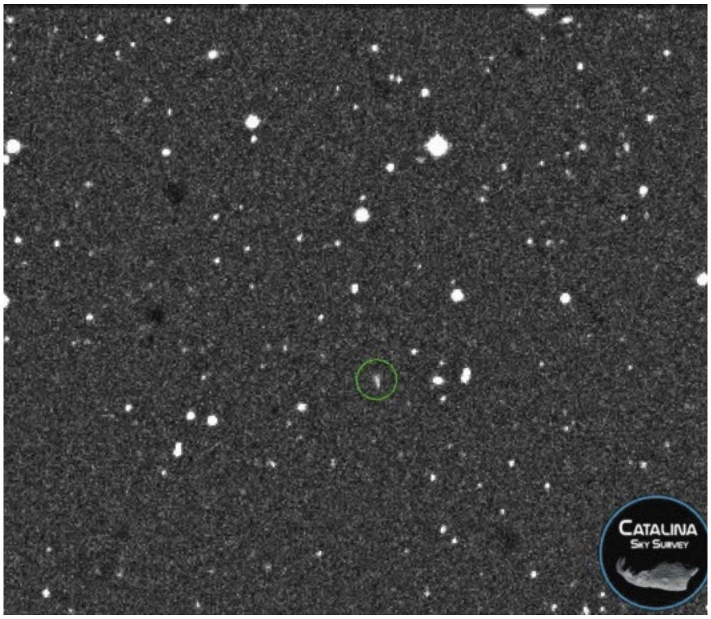
At this time Jupiter has 79 confirmed moons (a total which includes the Galilean moons); Saturn has 82 (including Titan and the other "large" moons); Uranus has 27; and Neptune has 14. Additional possible moons of Jupiter and Saturn have been reported but these objects have not yet been confirmed. Meanwhile, it is entirely possible that even more moons may yet be discovered – especially very tiny ones around Uranus and Neptune – and there may well be as-yet-unidentified moons in data that has already been taken. To illustrate this, just this past October twenty additional moons of Saturn were identified in images taken with the 8-meter Subaru Telescope in Hawaii as far back as December 2004, with additional images of all of these then being identified in images taken in 2006 and/or 2007.



Discovery image of Neptune's outer moon Psamathe, taken with the 8-meter Subaru Telescope at Mauna Kea in Hawaii on August 29, 2003. With an orbital period of 25 years it has the second-longest period of any known moon in the solar system. Courtesy Scott Sheppard, David Jewitt, and Jan Kleyna.

Most of these recently-discovered distant small outer moons have not been studied in any detail; no space missions have examined them, and they are too faint and small for detailed examinations with Earth-based instruments. (For example, the Saturn moons announced last year are all around 25th magnitude and are all 5 km across or smaller.) Since a significant number of them are traveling in eccentric and/or retrograde orbits, it is likely that many, if not most or almost all, of them are captured asteroids. For Saturn and the planets beyond it, where more volatile substances like water can exist in solid form, a reasonable percentage of these objects may be captured cometary nuclei.

As far as can be determined, all of these moons are "permanent" in the sense that, at least over timescales



Images of the recent temporary "Earth moon" 2020 CD3. Left: One of the discovery images, taken February 15, 2020, during the course of the Mount Lemmon Survey in Arizona (a part of the Catalina Sky Survey). Courtesy Catalina Sky Survey/Kacper Wierzchos. Right: Color image taken with the 8-meter Gemini North Telescope in Hawaii on February 24, 2020. Courtesy The International Gemini Observatory/NSF's National Optical-Infrared Astronomy Research Laboratory/AURA/Grigori Fedorets.

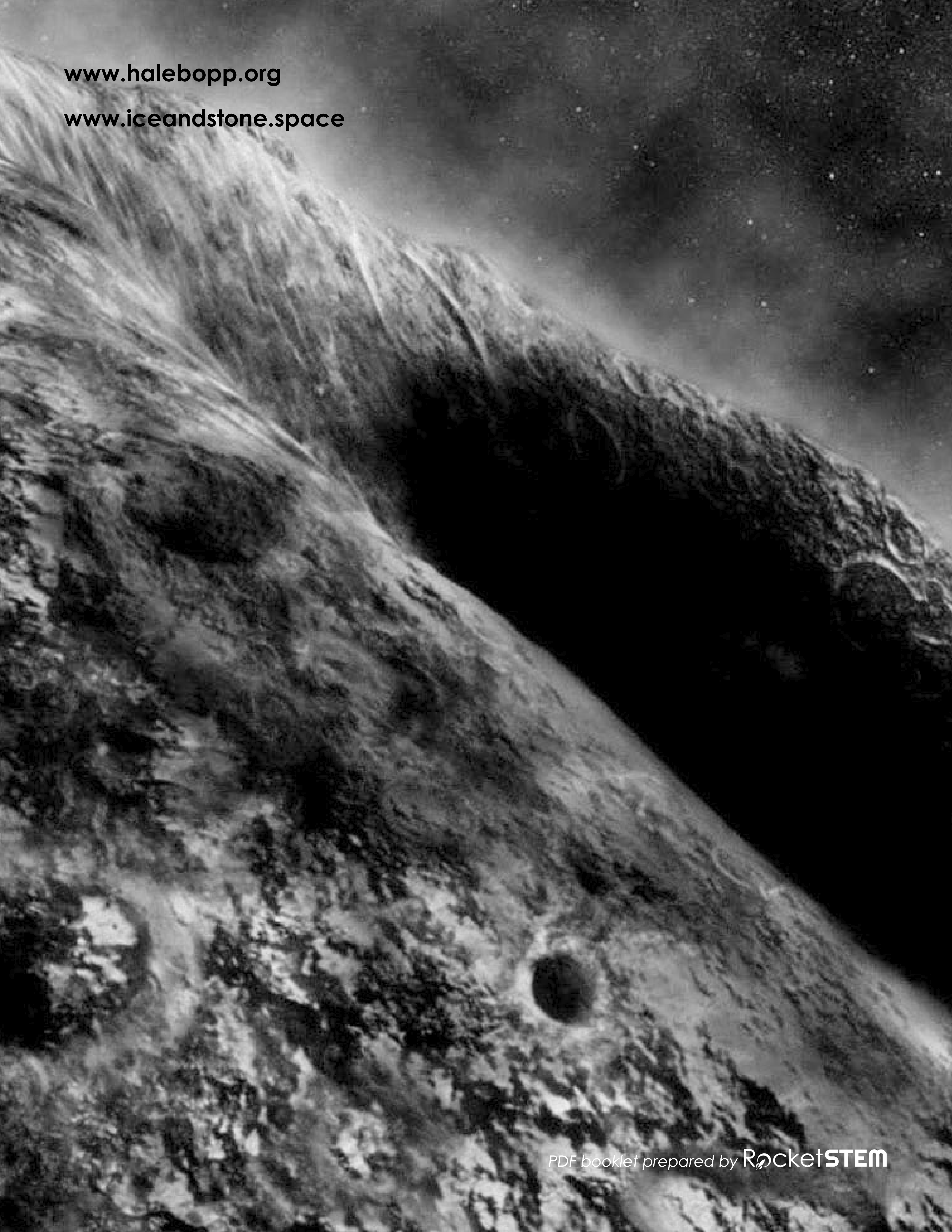
of a few centuries, they are gravitationally bound to the planet that they are orbiting. This nevertheless raises the question as to whether or not there might exist "temporary" moons. Numerical simulations suggest that this situation can happen, and indeed it almost certainly does happen from time to time, although – especially in the case of Jupiter – such objects would eventually be scattered away.

There have actually been a few cases of comets that have been "captured" as temporary moons of Jupiter. The first clear example of such is Comet 82P/Gehrels 3, which studies have shown has experienced several episodes of being a temporary moon of Jupiter, most recently between 1967 and 1973 prior to its discovery in 1975. It will again be a temporary moon of Jupiter for a five-year period centered around 2060. The most famous example of a temporary cometary moon of Jupiter is Comet Shoemaker-Levy 9 1993e, the disrupted fragments of which impacted that planet in 1994; this was a previous "Comet of the Week" and these events are discussed in that object's Presentation.

It turns out that Earth has recently had a couple of temporary second moons. The small asteroid 2006 RH120, discovered by the Catalina Sky Survey program in Arizona in September 2006, was found to be traveling in a geocentric orbit with an approximate orbital period of three months and a perigee distance close to the moon's orbit. 2006 RH120 is only two to three meters in diameter and is likely a fragment of lunar rock blasted up after an impact, and after orbiting Earth for a little over a year and a half it left Earth orbit in mid-2007. It will return to Earth's vicinity (0.028 AU) in August 2028 although this is probably not close enough to produce another "capture" at that time. For what it's worth, 2006 RH120 is the top-ranked "easily retrievable" near-Earth object on the 2013 list prepared by Garcia Yarnoz et al. (discussed in the "Special Topics" presentation on "Resources in 'Small Bodies'").

Meanwhile, earlier this year, on February 15, 2020, Theodore Pruyne and Kacper Wierzchos with the Mount Lemmon Survey in Arizona discovered the asteroid designated as 2020 CD3. Like 2002 RH120, 2020 CD3 is a very tiny object, no more than two to three meters in diameter, and even though it was only followed for six weeks, this was enough to indicate that it had been in a geocentric orbit (with an approximate orbital period of eight weeks) since about 2015 or 2016, but after May 2020 it is escaping back into a heliocentric orbit. It will pass close to Earth again in 2044 but will probably remain far enough away so that it will not be "captured" into geocentric orbit again. From an overall perspective, the discovery of two such objects within the recent past suggests that this is a relatively common phenomenon; indeed, studies indicate that a bright fireball observed over the desert regions of South Australia on August 22, 2016 may have been a temporary "moon" of Earth prior to its entry into the atmosphere. With ever more comprehensive survey programs continuing to come on-line we will likely see more such discoveries within the years to come.

In addition to the major planets, quite a few asteroids, both in the main asteroid belt and those that pass by Earth, have moons of their own, as do some of the Kuiper Belt objects (including Pluto, which is accompanied by its large moon Charon plus four more recently-discovered smaller moons). These objects are discussed in the appropriate "Special Topics" presentations.



www.halebopp.org
www.iceandstone.space
PDF booklet prepared by RocketSTEM