ICE & STONE 2020

WEEK 37: SEPTEMBER 6-12

Presented by The Earthrise Institute

Authored by Alan Hale

THIS WEEK IN HISTORY

SEPTEMBER **6** 7 8 9 10 11 12

SEPTEMBER 6, 1618: The German astronomer and mathematician Johannes Kepler observes Comet 1618 I (new style C/1618 Q1) – the first of three "Great Comets" that appeared that year – through a small telescope, the first recorded telescopic observation of a comet.

6 7 SEPTEMBER **8** 9 10 11 12

SEPTEMBER 8, 1991: Tom Gehrels with the Spacewatch program in Arizona discovers the comet now known as Comet 125P/Spacewatch. A very faint object of 21st magnitude at the time, this was the first comet to be discovered with a CCD.

SEPTEMBER 8, 2016: NASA's OSIRIS-REx mission is launched from Cape Canaveral, Florida. OSIRIS-REx's destination was the near-Earth asteroid (101955) Bennu, at which it arrived in late 2018 and has been orbiting ever since. After collecting soil samples next month, OSIRIS-REx will depart from Bennu next April with arrival back at Earth scheduled for September 2023. The OSIRIS-REx mission is discussed in a future "Special Topics" presentation.

6 7 8 SEPTEMBER **9** 10 11 12

SEPTEMBER 9, 1892: Edward Barnard at Lick Observatory in California discovers Jupiter's fifth known moon, Amalthea, the first moon of Jupiter discovered in almost three centuries, and the last moon in the solar system to be discovered visually. The small moons of the solar system's planets are discussed in a previous "Special Topics" presentation.

6 7 8 9 SEPTEMBER **10** 11 12

SEPTEMBER 10, 2016: A team of explorers from the Asociacion de Astronomia del Chaco in Argentina discovers a large underground meteorite near the town of Gancedo. The Gancedo meteorite is the largest fragment of the Campo del Cielo meteorite fall and is the third-largest known meteorite in the world. It and other large meteorites are discussed in a previous "Special Topics" presentation.

COVER IMAGE CREDIT:

Front and back cover: The Jovian Trojans are uniformly dark with a hint of burgundy color, and have matte surfaces that reflect little sunlight, as illustrated in this artist's concept showing the packs of Trojans. Courtesy NASA/JPL-Caltech

SEPTEMBER 11

SEPTEMBER 11, 1909: Max Wolf at Heidelberg Observatory in Germany recovers Comet 1P/Halley during its return to perihelion in 1910. This return of Comet Halley was a very favorable one in terms of viewing geometry, and is discussed in the "Special Topics" presentation on that object.

SEPTEMBER 11, 1969: Svetlana Gerasimenko at Alma Ata Observatory in what is now Kazakhstan takes a photograph of Comet 32P/Comas Sola, and upon performing astrometric measurements of it Klim Churyumov accidentally discovers another comet on the same photograph. Comet 67P/Churyumov-Gerasimenko was the destination of ESA's Rosetta mission, which orbited the comet's nucleus from 2014 to 2016 before landing on the surface. Comet 67P is a previous "Comet of the Week," and the Rosetta mission is discussed in that presentation.

SEPTEMBER 11, 1985: The International Cometary Explorer (ICE) mission – formerly the International Sun-Earth Explorer 3 (ISEE-3) spacecraft – flies by Comet 21P/Giacobini-Zinner, becoming the first spacecraft to encounter a comet. The ICE mission is discussed in a previous "Special Topics" presentation, and Comet 21P/Giacobini-Zinner is next week's "Comet of the Week."

SEPTEMBER 11, 1999: The LINEAR program in New Mexico discovers the Apollo-type asteroid now known as (101955) Bennu. Bennu was the destination of NASA's currently-ongoing OSIRIS-REx sample return mission, which is discussed in a future "Special Topics" presentation.

SEPTEMBER 11, 2015: A team of astronomers led by Tabitha Boyajian (then at Yale University) and which includes "citizen scientists" announces their discovery of very unusual and irregular drops in brightness of the star designated KIC 8462852 and informally known as "Boyajian's Star." The brightness drops are possibly due to a swarm of "exocomets," and the star is discussed in a previous "Special Topics" presentation.

SEPTEMBER 11, 2020: The main-belt asteroid (16151) 1999 XF230 will occult the 6th-magnitude star HD 223807 in Aquarius. The predicted path of the occultation crosses west-central France, the central Atlantic Ocean, central Florida, the southern tip of Texas, north-central Mexico (including the city of Monterrey and central Baja California Sur), and the east-central Pacific Ocean.

SEPTEMBER 12

SEPTEMBER 12, 1811: The Great Comet of 1811 passes through perihelion at a heliocentric distance of 1.035 AU. This was one of the brightest and best-observed comets in the 19th Century and appeared in quite a bit of the popular culture at the time, and is a future "Comet of the Week."

SEPTEMBER 12, 1904: Edward Barnard at Yerkes Observatory in Wisconsin discovers an asteroid later designated as 1904 RD. It would remain "lost" for almost a century before Gareth Williams at the Minor Planet Center identified it as being identical to the asteroid now known as (12126) 1999 RM11, which had been discovered by the LINEAR program in September 1999. This is a "Jupiter Trojan," which is the subject of a future "Special Topics" presentation, and Barnard's discovery represents the first observations of such an object.

SEPTEMBER 12, 2005: JAXA's Hayabusa mission arrives at the Apollo-type asteroid (25143) Itokawa. Hayabusa managed to collect a handful of soil samples from Itokawa and, following an adventurous journey, successfully returned these to Earth in June 2010. The Hayabusa mission is discussed in a previous "Special Topics" presentation.

COMET OF THE WEEK: 2I/BORISOV I/2019 Q41

Perihelion: 2019 December 8.55, q = 2.007 AU

Comet 2I/Borisov during its passage through the inner solar system, 2019-20. Image taken with the 8.1-meter Gemini North Telescope in Hawaii on November 12, 2019. The bright spiral galaxy is LEDA 1168242. Courtesy NSF's National Optical-Infrared Astronomy Research Laboratory/NSF/AURA/Gemini Observatory.

According to our present understanding of how the solar system formed and evolved, all the various comets, including those passing through the inner solar system as well as those in the Kuiper Belt and the Oort Cloud, are the "leftovers" from the planet formation process. Over the lifetime of the solar system, various processes, including gravitational perturbations by the planets (especially Jupiter) as well as gravitational influences by stars passing near or through the Oort Cloud, have ejected many comets from the solar system into interstellar space. If, as would seem logical to suspect, the same processes operate in other planetary systems as well, we would accordingly expect interstellar space to contain many, perhaps large numbers of, comets that have been ejected from their original planetary systems. The existence, or non-existence, of such objects, along with the frequency with which we might encounter them, would then tell us much about how valid our understanding might be and about the number of planetary systems in the Galaxy and how the formation processes operate there, and physical studies of any interstellar comets that might pass through the solar system would tell us much about how conditions in other planetary systems are similar to and/or different from the conditions within ours.

The detection of comets arriving from interstellar space has thus been of very high interest to astronomers. Ever since their importance was realized there had been no confirmed detections of any such objects, until October 2017 when the Pan-STARRS

Comet 2I/Borisov during its passage through the inner solar system, 2019-20. Image I took with the Las Cumbres Observatory facility at McDonald Observatory in Texas on December 21, 2019, right around the time of the comet's maximum brightness.

program in Hawaii detected the object now known as 1I/'Oumuamua. The true physical nature of this object was never able to be determined; although it did not exhibit any overt cometary activity, it did exhibit some circumstantial evidence of such. Its story is the subject of a future "Special Topics" presentation.

Two years later the second interstellar object passed through the inner solar system, and this one was clearly a comet. It was discovered on the morning of August 30, 2019, by an amateur astronomer in the Crimea, Gennady Borisov, who over the past several years has carried out a moderately successful CCD-based search program for comets at small elongations from the sun. This particular comet, his 8th overall comet discovery, and which he made with a recently-completed 65-cm telescope that he had built himself, was an 18th-magnitude object at an elongation of 38 degrees and located a few degrees east-northeast of the "twin" stars Castor and Pollux in Gemini. As orbital calculations were performed over the next couple of weeks its interstellar nature quickly became quite obvious, as it was found to be traveling on a strongly hyperbolic orbit with an eccentricity of 3.4. Meanwhile, astronomers with the Zwicky Transient Facility program in California were able to identify some pre-discovery images of the comet to as far back as December 13, 2018, at which time its heliocentric distance was 7.9 AU.

Comet Borisov brightened fairly rapidly as it approached perihelion, being at 16th magnitude in early October and then reaching a peak brightness of magnitude 14.5 around the time of its closest approach to Earth (1.94 AU) in late December, remaining in the morning sky throughout that time. By early 2020 it had begun fading and, traveling southward, entered southern circumpolar skies in early February, where it remains at this time. Theoretically the comet may still be detectable with very large telescopes, although the most recent observations that I am aware of were obtained in early July with the Hubble Space Telescope.

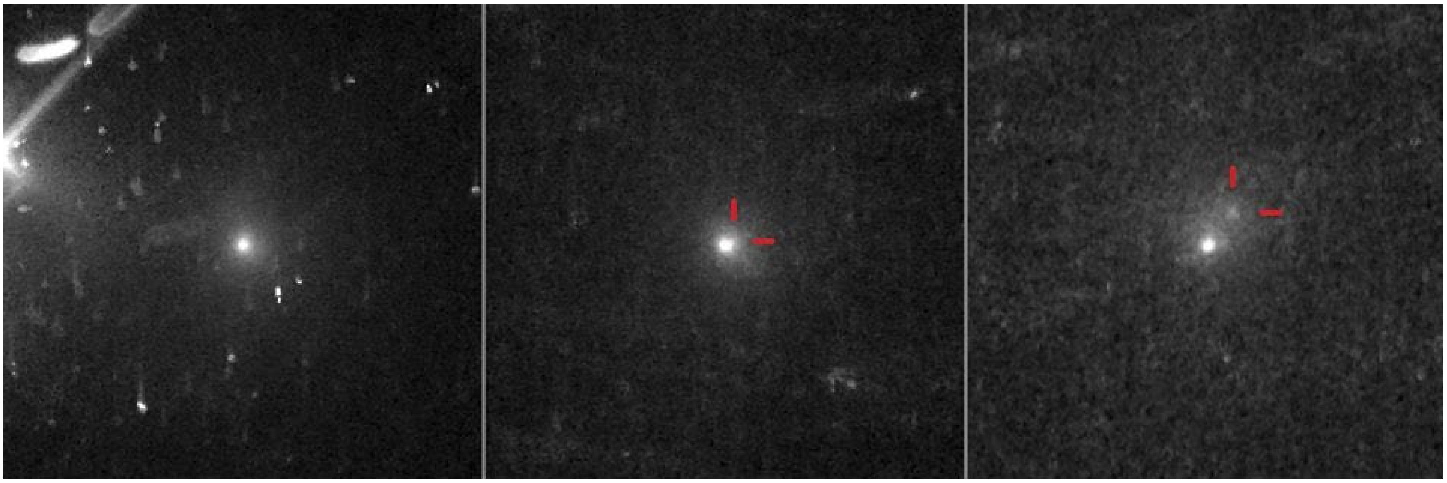
Astronomers began making physical observations of Comet Borisov early on, and for the most part it

Gennady Borisov poses next to the 0.65-meter telescope he built and used to discover the comet named after him from his home in Crimea. Courtesy of Gennady Borisov.

has behaved more-or-less like a solar-system comet would behave. Its overall chemical composition is also somewhat similar to those of ordinary solar-system comets, although there are some subtle differences, one of these being an unusually high ratio of carbon monoxide to water – rare, although not unheard-of, in solar-system comets. This suggests that Comet Borisov formed in an unusually low-temperature environment, perhaps at a large distance from its parent star, and/ or that the parent star was a low-temperature object such as an M dwarf (which constitute roughly 75% of all stars in the Galaxy).

Studies with the Hubble Space Telescope indicate that Comet Borisov's nucleus is roughly 400 to 1000 meters in diameter. In late March the comet exhibited a brief flare in brightness and Hubble images showed the existence of an accompanying fragment, which led to some initial speculation that the comet might be breaking up. This fragment was apparently quite small, however, and although Hubble images from July still show it, the comet itself appears to remain intact.

An examination of Comet Borisov's trajectory prior to its entering the solar system indicates that it came from near the plane of our Galaxy, in Cassiopeia not far from the location of the Double Cluster in Perseus. One early study suggested that roughly one million years ago the comet passed 5.7 light-years from the double-star system Kruger 60 (HD 239960) in Cepheus – currently located 13.2 light-years away, but approaching the solar system – although this "miss distance" seems too large to be a plausible origin point. A more recent study has identified several other stars that the comet would have passed close to with the (astronomically) recent past, the closest of these



[Hubble Space Telescope](#) images of Comet 2I/Borisov, showing the receding of the fragment first detected in late March 2020. Left to Right: May 6, May 29, and July 6, 2020. Courtesy NASA/Karen Meech/Daniel Bamberger.

being a "miss" of just 0.22 light-year (14,000 AU) from the star Ross 573 – a 10th-magnitude star in Eridanus, and currently about 70 light-years away – roughly 910,000 years ago. (Incidentally, both components of Kruger 60 as well as Ross 573 are M dwarf stars.) A lot of uncertainties still remain, however, and it is rather likely that we will never conclusively determine Comet Borisov's point of origin. Meanwhile, it will depart the solar system in the direction of the constellation Telescopium – somewhat to the south of Sagittarius – which is also in the plane of our Galaxy. One can only speculate as to what Comet Borisov might encounter in the future during its almost endless journey through the depths of interstellar space.

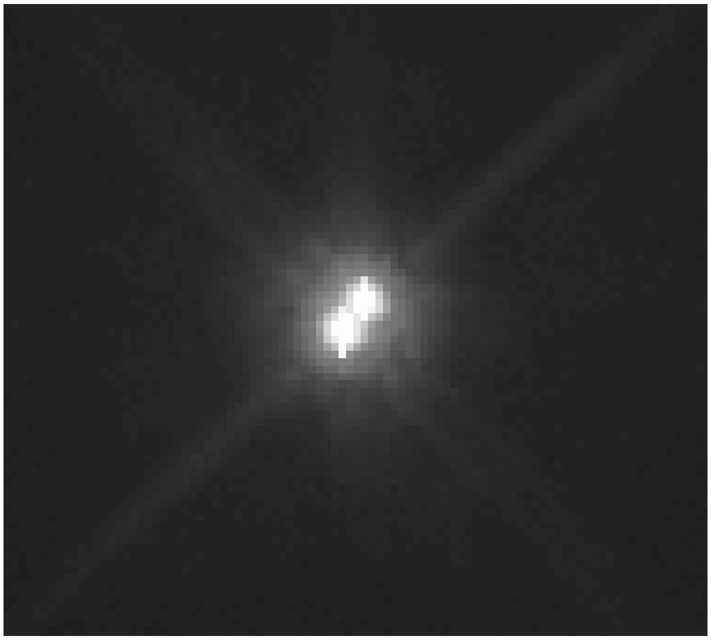
The possible parent star of Comet 2I/Borisov: Ross 573 (arrowed) in Eridanus. The bright star (7th magnitude) at left is HD 21779. Courtesy SIMBAD/Aladin/Digitized Sky Survey.

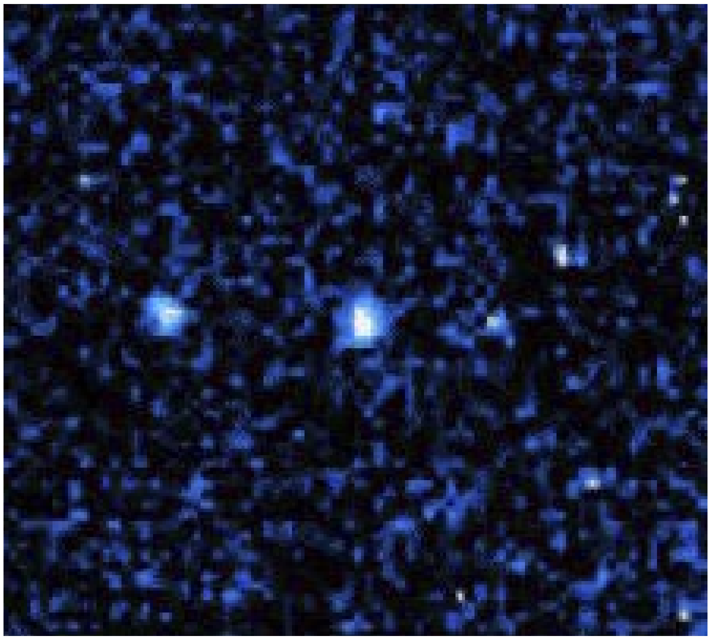
SPECIAL TOPIC: "SMALL BODIES" MOONS

Images taken by NASA's Galileo mission on August 28, 1993 of the main-belt asteroid (243) Ida and its moon Dactyl. Left: Ida and Dactyl; Dactyl is the small object on the right side of the image. Right: Close-up of Dactyl. Both images courtesy NASA.

The "Special Topics" presentation four weeks ago was on the subject of the small moons of the various planets in the solar system. It would seem reasonable to think that the bodies that possess moons don't stop with the major planets, but that many of the "small bodies" that are the focus of "Ice and Stone 2020" also possess moons. Indeed, this has been found to be true.

What could perhaps be considered as the first confirmed moon of a "small body" is Pluto's large moon Charon, which was discovered in 1978 (and which is discussed as part of the overall "Special Topics" presentation on Pluto several weeks ago). However, since Pluto somewhat straddles the (arbitrary) line between what is and what is not a "planet" – being a member of the recently-created category of "dwarf planets" – and since Charon is a unique world in its own right that is 1.3 times the diameter of (1) Ceres and thus would be a "dwarf planet" were it not part of the Pluto system, it would

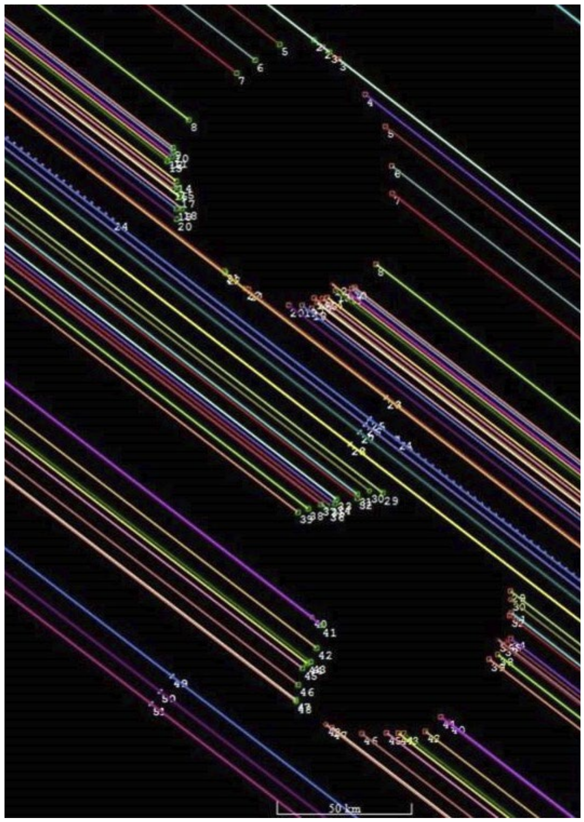




Hubble Space Telescope images of distant "small bodies" moons. Left: The "Jupiter Trojan" asteroid (617) Patroclus and its moon Menoetius. Right: The Kuiper Belt object 1998 WW31 (center) and its moon (left). Both images courtesy NASA.

seem to be stretching things a bit to refer to it as a "small body" moon. At around the same time as Charon's discovery, a couple of moons around main-belt asteroids were suspected as a result of one-time occultation events, however neither of these reported objects has been confirmed. The first confirmed example of a moon accompanying an asteroid finally came on August 28, 1993, when NASA's Galileo spacecraft flew by the main-belt asteroid (243) Ida – which is 60 km by 19 km in size in its longest and shortest dimensions – and images taken during the flyby revealed a 1.5-km somewhat spherical moon that has since been named Dactyl.

Since that time over 400 moons orbiting around "small bodies" in the solar system have been detected, although, curiously, besides Dactyl and one short-lived exception none of these have been found by visiting spacecraft despite all the various objects that have been visited. They have been discovered via a variety of techniques and around bodies all over the solar system, from near-Earth asteroids, to the main asteroid belt, to "Jupiter Trojan" asteroids – discussed in a future "Special Topics" presentation – and the Kuiper Belt (discussed in last week's "Special Topics" presentation). Some of the moons are tiny objects relative to their primary body, like Dactyl, while others are large enough such that the objects in question can almost be considered as "binary" systems, in a manner that the Pluto/Charon system can perhaps be so considered. Overall, the consensus among astronomers is that roughly 2% of asteroids in the main belt and in the near-Earth population contain moons, although based upon what has been detected thus far that percentage goes up to about 11% for objects within or beyond the Kuiper Belt.



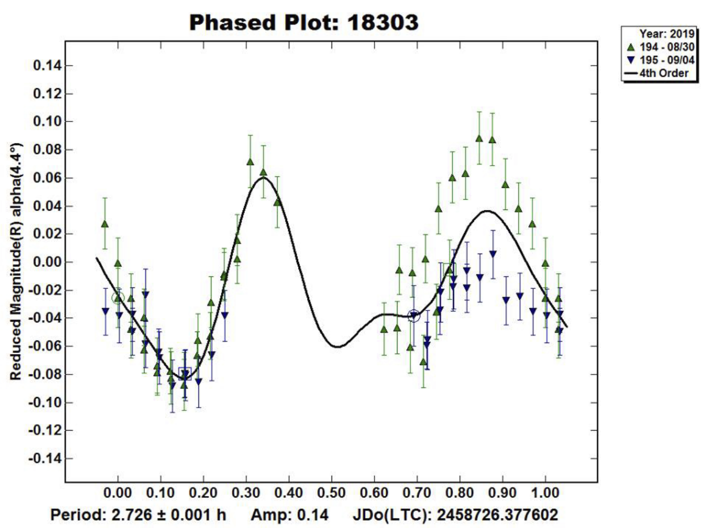
Ground-track recordings of the disappearances and reappearances of the star HD 215553 (in Aquarius) during the occultation of the main-belt asteroid (90) Antiope and its moon on July 19, 2011. The moon, which had already been discovered in 2000, is almost the same size as its parent body, making this a true "binary" system. Image courtesy Kuriwa Observatory, licensed via Creative Commons.

Many of the asteroid moons have been discovered via direct detection, either with the Hubble Space Telescope or with large ground-based telescopes, often equipped with "adaptive optics" systems (that compensate for atmospheric turbulence). The first-discovered asteroid from the ground, which was also the first confirmed asteroidal moon after Dactyl, was detected around the large main-belt asteroid (45) Eugenia on November 1, 1998 by a team led by William Merline using the 3.6-meter Canada-France-Hawaii Telescope (CFHT) at Mauna Kea Observatory in Hawaii. This moon, originally designated S/1998 (45) 1 and now formally named Petit-Prince, is roughly 13 km in diameter (as compared to 214 km for Eugenia itself) and orbits around Eugenia every 4.8 days.

Direct imaging is, in large part, the only feasible method of detecting moons around more distant asteroids. The first moon around a "Jupiter Trojan" asteroid was discovered on September 22, 2001 – again by Merline's team, this time using the 8.1-meter Gemini North Telescope on Mauna Kea – around (617) Patroclus (which is a destination for NASA's upcoming Lucy mission, discussed in a previous "Special Topics" presentation). The first Kuiper Belt object (other than Pluto) found to have an accompanying moon is 1998 WW31; the moon was discovered on December 22, 2000 by a team led by Christian Veillet utilizing the CFHT.

Some asteroid moons have been detected during occultation events – a subject covered in a previous "Special Topics" presentation. Even for moons discovered via other methods, occultations – especially those observed by a large number of observers aligned across the event's path – can provide detailed information about a moon's – and parent body's – size and shape.

Additional moons have been discovered by means of time-resolution photometry – usually by teams of observers located at different sites around the world. Almost all asteroids exhibit regular and periodic changes in their brightness as a result of rotation, but the presence of a moon can introduce additional changes in brightness as a result of passing in front of and behind its parent object (as well as its own rotation). The "light curve" of such a system can be complex and can require a detailed mathematical analysis to untangle, but the end result can reveal physical information about both objects as well as parameters of the moon's orbit around its parent body.

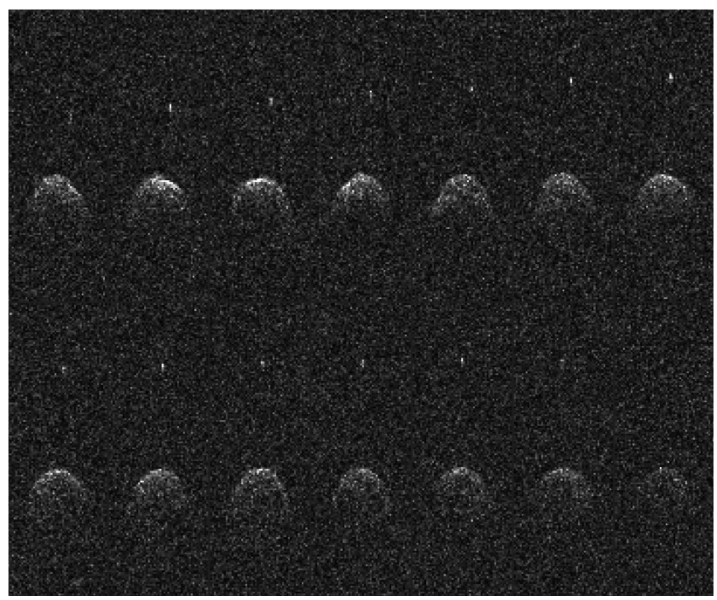


Rotational light-curve plot of the main-belt asteroid (18303) 1980 PU, revealing the presence of an accompanying moon. The discovery was announced in October 2019. Plot courtesy Vladimir Benishek (Belgrade Astronomical Observatory) and colleagues.

Especially for asteroids that pass near Earth, another method of detecting accompanying moons is via radar bounce experiments. Both the large 300-meter Arecibo radio telescope in Puerto Rico (which recently suffered a significant structural accident) and the 70-meter Deep Space Network tracking antenna in Goldstone, California have been used extensively in bouncing radar signals of Earth-approaching asteroids (and comets as well), and in addition to providing information about an object's surface topography these experiments have also found several of these objects to be accompanied by moons. The moon of the Amor-type asteroid (65803) Didymos – recently given the name Dimorphos, and the destination of NASA's planned Double Asteroid Redirection Test (DART) mission, discussed in a previous "Special Topics" presentation – was discovered by photometry during an approach to Earth in 2003 but was also confirmed around that same time by radar bounce experiments conducted at Arecibo.

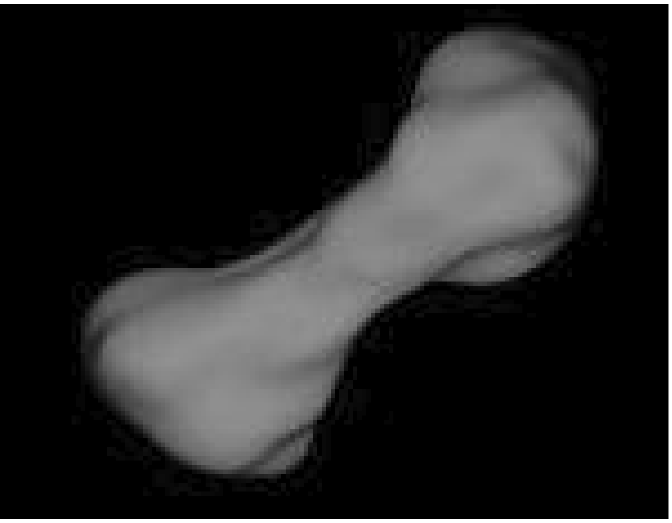
Those asteroids that have moons are not necessarily restricted to having just one moon; at this writing at least 15 are known to have two or more moons. Pluto, as was discussed in its "Special Topics" presentation, has five known moons, and the "dwarf planet" (136108) Haumea has two moons, as does at least one other known Kuiper Belt object, (47171) Lempo. The first main-belt asteroid known to have two moons is (87) Sylvia, the first of these being discovered in 2001 via the Keck II 10-meter telescope at Mauna Kea, the second one being discovered in 2004 from the European Southern Observatory in Chile; these two objects have been named Romulus and Remus, after the mythical founders of Rome. (45) Eugenia, as it turns out, also has a second moon, this one being discovered in 2004 and being about half the size of Petit-Prince; it is not been formally named as this time but is designated as S/2004 (45) 1. At least three near-Earth asteroids are now known to have two moons: the Amor-type asteroids (3122) Florence – one of the largest near-Earth asteroids – and (153591) 2001 SN263, and the Apollo-type asteroid (136617) 1994 CC. (153591) 2001 SN263 is the scheduled destination of the planned Brazilian ASTER mission (discussed in a previous "Special Topics" presentation).

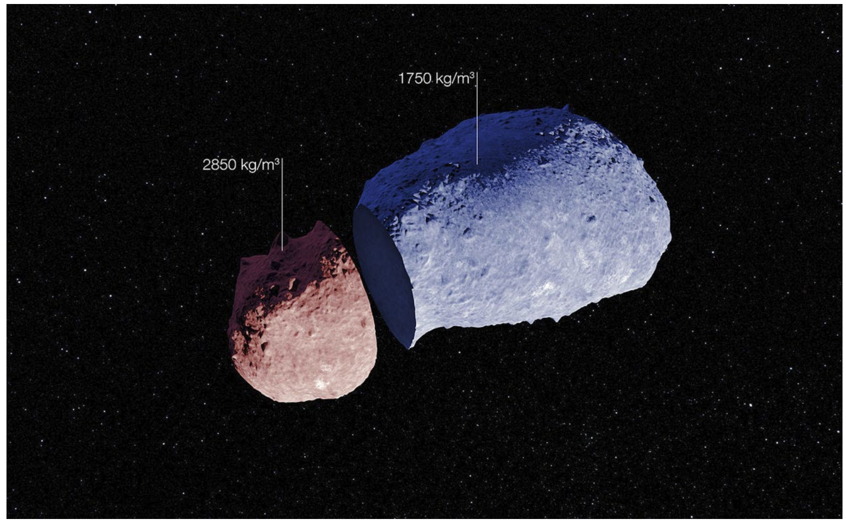
The origins of these asteroidal moons are not known with any real certainty, and in fact the origins may vary in specific cases. Especially in those cases where a large disparity in size exists, it would seem likely that the moons are debris knocked off the parent body via an impact at some point in the past. In other cases, especially the "binary" asteroids where the moons are of similar size compared to their parent body, some type of "capture" scenario may be involved. This may also be true in those cases where the orbital separation is quite large; for example, the moon (roughly seven km across) of the large main-belt asteroid (379) Huenna (about 90 km in diameter) orbits at a distance of 3400 km.



A sequence of radar images of the near-Earth asteroid (65803) Didymos obtained over three nights in November 2003 by the Arecibo radio telescope in Puerto Rico. The moon Dimorphos is the small object at the top of the respective images. Courtesy Arecibo Observatory/NASA.

All of the above parent bodies of "small bodies" moons are asteroids; as of now there are no confirmed cases of moons around comets, although this may well be due to the clouds of obscuring material that prevent close examination of cometary nuclei. In October 2015 images taken of the nucleus of Comet 67P/Churyumov-Gerasimenko – a previous "Comet of the Week" – by ESA's Rosetta mission revealed the presence of a small four-meter-wide object, informally dubbed "Churyumoon," orbiting the

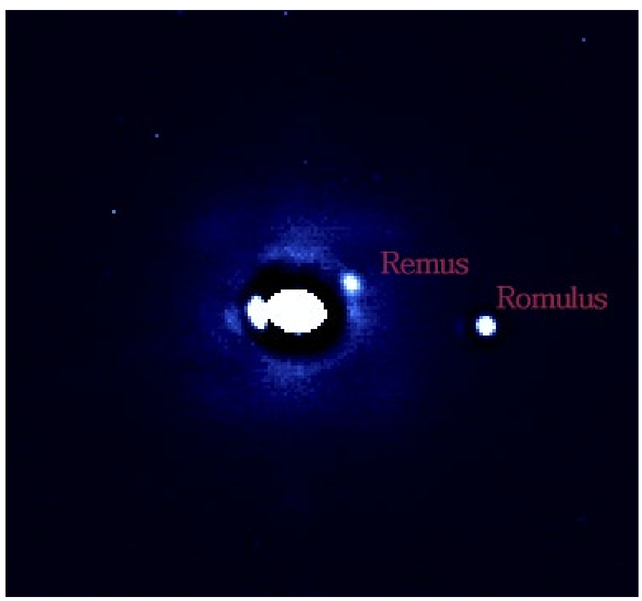




Examples of "contact binaries." Left: A representation of the main-belt asteroid (216) Kleopatra from radar images obtained with the 300-meter radio telescope at Arecibo, Puerto Rico. Kleopatra also has two small moons (named Alexhelios and Cleoselene). Courtesy Arecibo Observatory/NASA. Right: A color-coded schematic of the two lobes of the near-Earth asteroid (25143) Itokawa, showing their different respective densities as measured by the New Technology Telescope at the European Southern Observatory in Chile. The surface topography is from JAXA's Hayabusa mission. Courtesy European Southern Observatory.

nucleus at a distance of 2 to 3 km, however this object only survived two days before disappearing (and apparently dissipating).

Although these are not parent body/moon systems per se, what appears to be a non-trivial fraction of the solar system's "small bodies" are what are called "contact binaries," i.e., two objects seemingly stuck together. The best-known examples are Comet 67P/Churyumov-Gerasimenko which was visited by ESA's Rosetta mission and the Kuiper Belt object (486958) Arrokoth which was visited by NASA's New Horizons mission in early 2019, however several of the objects that have been radar-imaged as well as a few others that have been visited by spacecraft exhibit this same basic structure. It is rather likely that most, if not almost all, of these "contact binaries" started out as two separate objects that collided – presumably with a low relative velocity – and stuck together via mutual self-gravity. Such an interpretation seems especially likely in the case of the Apollo-type asteroid (25143) Itokawa, which was visited and orbited by JAXA's Hayabusa mission in 2005; based upon detailed studies conducted with the New Technology Telescope at the European Southern Observatory in Chile, the two lobes exhibit dramatically different overall densities and thus clearly must represent two different objects that collided and became one.



The main-belt asteroid (87) Sylvia and its moons Romulus and Remus, as imaged by the Very Large Telescope at the European Southern Observatory in Chile. Courtesy European Southern Observatory/Franck Marchis.

The presence of these "contact binaries" in the solar system today helps reinforce our models of how the planets in our solar system originally formed. According to these models, in the early days of the solar system when the population of "small bodies" was much larger and more crowded than it is today, they collided and stuck together, growing larger and gravitationally attracting additional objects. Eventually these accumulating "planetesimals" grew large enough to become "protoplanets" – objects the size of (1) Ceres and (4) Vesta, which are likely surviving objects of this type – with these then becoming the seed material of the planets that exist today. The comets and asteroids that we see now are the "leftovers" of this long-ago process and can accordingly provide valuable clues as to the conditions that existed at that time. This is a significant part of the reason why astronomers are so interested in these objects in the first place, for they can tell us a lot about our own origins.

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