Air and Space this Week

Item of the Week

Asteroid Day 2021

Originally appeared June 21, 2021

KEY WORDS: Asteroid Gaspra Ida Dactyl Mathilda Eros Itokawa Lutetia Vesta Toutatis Ryugu Bennu Lucy Psyche Zenghe Cantillo

The largest impact event in recorded history occurred on June 30, 1908, when a large asteroid/comet struck Siberia near a town called Tunguska. The object exploded just prior to impact, flattening an entire forest. The pressure wave from the explosion was detected over a thousand miles away. June 30 has been named "Asteroid Day," a reflection of the importance of Tunguska in understanding the threat impact events pose.

"Asteroid Day is a UN-sanctioned global awareness campaign" with a "mission to inspire, engage, and educate the public about asteroids." The focus today is on the asteroids themselves; I'll cover the threat they pose to Earth and possible mitigation tactics in a later Item.

CELEBRATE ASTEROID DAY!

Celebrate Asteroid Day, 2021, by learning more about the asteroids we have visited to date, what we have learned, what asteroid missions are still ongoing, and what NASA and other agencies are planning for future asteroid studies. Find out more about this international annual event at: https://asteroidday.org.

One way you can observe Asteroid Day is by learning more about asteroids, both here and…

The Fernbank Science Center is offering a day-long on-line programming event. FCS' Scott Harris has put together a nice schedule of talks on various items pertaining to asteroids and impacts. He'll hold forth about impact sites around the Earth, four presentations will focus on impact features in North America, one will discuss the Chicxulub impact (the one that "killed the dinosaurs"), and one will talk about NASA's DART mission, a test to see what it would take to deflect a potential asteroid from impacting the Earth (and the focus of a future Item of the Week). The programming starts at 9 AM EDT and concludes at 2 PM EDT. See: https://www.facebook.com/fernbankcenter for more information

WHAT ARE ASTEROIDS?

I've found a number of definitions for "asteroid," and I favor a modified version of that in Wikipedia, "Historically, [the term "asteroid" has] been applied to any astronomical object orbiting the Sun that did not resolve into a disc in a telescope and was not observed to have characteristics of an active comet such as a tail. Virtually all asteroids were found to orbit the Sun between the orbits of Mars and Jupiter. Subsequent observations found asteroids outside of the Mars-Jupiter “main belt,” including some that had a “Trojan” relationship with one of the Solar System planets or some other odd orbit, and a few that had some of the characteristics of a comet. One was found to have to share a new category of Solar System objects, a dwarf planet, with Pluto.

Naming Scheme: Over a million asteroids have been discovered to date. Some have names related to where they are in the Solar System, but most have been named, often whimsically, by those who discovered them. The name of the asteroid is preceded by a number signifying the order with which it was discovered. Hence, 4 Vesta, was the fourth asteroid discovered. Asteroid 1, Ceres, was the one “promoted to dwarf planet status, there is no longer an asteroid 1 anything.

“Meteoroid” vs. “Asteroid” Neither term, both in general use, is well-defined or even appropriate. In usage, meteoroids are likely to be smaller than asteroids, but no rigorous size-based definition has come forward. Worse, the root word for “meteoroid” is the same as for meteorology, dating back to when meteors were thought to be a purely atmospheric phenomenon. “Asteroid” would mean “little stars,” which is laughably inappropriate. “Planetoid” is similarly poorly-defined; think “too big to be an asteroid but … Even in a usually-precise discipline like astronomy, long-term usage dies hard, and here we are.

WHY STUDY ASTEROIDS?

Early on in asteroid investigations, a primary question was their origin. Were they the remnants of a planet between Mars and Jupiter that was somehow fractured into pieces, or were they left-over debris from the formation of the Solar System that never formed into a planet?

One thing is reasonably sure, most asteroids are too small to have undergone any sort of internally-driven modification; they are “**primitive**,” unaltered from the time of their formation, and as such, provide important clues to the initial composition of the proto-Solar nebula and the formation and evolution of the Solar System.

The origin question has been (almost entirely) resolved with the addition of two key observations. First, the cumulative mass of the million-plus asteroids now known is much too small to be from even a Mars-sized planet. Second, analysis of the incoming trajectories of iron meteorites, which are likely to have come from the core(s) of differentiated parent bodies since broken up by impact, show that no one body could be the source of all of the iron meteorites known.

The pristine nature of asteroids remains of intense scientific, and even economic, interest. That’s why the USA, Japan, and China all have mounted sample return missions, all presently on their way back to Earth.

WHAT ARE ASTEROIDS MADE OF?

We already know the basics of asteroid composition from telescopic observation of how they reflect different wavelengths of light. Different materials reflect different "colors" (including those with wavelengths shorter or longer than visible light) by different, but diagnostic amounts. By comparing the reflectance spectrum of an asteroid to that of known materials in the lab, we can be fairly accurate in our estimate of the asteroid's composition, at least of its surface materials. [**LEARNERS:** For a tip to help explain spectral analysis, see the Education: News & Tips section of the airandspacethisweek.com website.]

Several asteroid nomenclature schemes are presently in use. All are based on reflectance spectra, and perhaps albedo (overall reflectivity in visible light). Some are more detailed than we need to consider here. The one I favor at this level is aligned with meteorite types.

S-type Asteroids: Spectra resemble that of stony meteorites, by far the most common that strike Earth (~96% of meteorites seen to fall are stony-type)

C-type Asteroids: Spectra resemble that of a class of meteorites called carbonaceous chondrites, known to be the most primitive in the Solar System.

M-type Asteroids: Spectra resemble metal, not rock; mostly iron.

V-type: Some meteorites have a reflection spectrum that so closely matches that of asteroid 4 Vesta that they are virtually certain to have come from there, blasted off Vesta's surface by the impact of another meteoroid.

While all asteroids are of scientific importance, the M-type asteroids, containing a LOT of iron, nickel, and other useful metals, may also be of ***economic importance***! More on that later.

ASTEROIDS VISITED TO DATE

NOTE: See the website for a version of this Item that is very fully documented. It's your information resource for all of the spacecraft and asteroids discussed below!

Phobos and Deimos (?)

The origin of Mars' two moons has not been conclusively determined. They are relatively tiny, with circular orbits very close to Mars and in its equatorial plane, and reflectance spectra that are consistent with that of C-type asteroids. Their size, and Mars' location near the asteroid Main Belt, led to an early interpretation that they are asteroids captured by Mars a considerable time after Mars' formation. Both have a bulk density lower than that of a solid object, suggesting that both are rubble piles, with a non-trivial amount of void space.

Their orbits are really weird, especially that of Phobos. It is very close to Mars' Roche Limit, and is known to be spiraling inward, doomed to impact Mars in ~50 million years. It is inside of a Mars synchronous orbit, meaning it orbits faster than Mars turns on its axis. This makes Phobos rise in the west and set in the east, and the Phobosian month to be shorter than the Martian day!

Seeing asteroids up close in recent years show that Phobos and Deimos are similar to other asteroids. But explaining their circular, equatorial orbits is difficult if they were captured asteroids.

Two other processes that formed Phobos and Deimos have been proposed. First, it could be that Phobos and Deimos are the last two surviving fragments of a martian moon that had been disrupted by impact. Second, Phobos and Deimos could have been formed from a mass of material ejected from Mars by a very large impact.

The "surviving fragments" model isn't talked about much, but it does have some support that should/could get more notice. In 1982, Schultz and Lutz-Garahan published a paper where they reported on studies of craters on Mars whose shapes indicated they were formed by grazing impacts. They found a number of such craters, grouped by age and orientation of the impact direction. They interpreted the observations that each group represented the break-up of a martian moon (since the parent body was in Mars orbit, its demise would produce many more grazing impacts than those formed at random). The orientation of the impacts changed with changes in Mars' polar position (supported by other data, too). What if those moons were surviving fragments, hitting a surface whose polar position changed with time?

Recognition that Earth's Moon was most likely formed by material blasted off Earth v.1 by the impact with a very large planetesimal lends support to the idea that Phobos and Deimos might have formed the same way. Reflectance data from the *Mars Global Surveyor* does show some similarity with material known to be on Mars.

Personally, I favor a combination of the two non-capture models. Mars was hit early in its history (there are large, but ancient impact basins on Mars). Ejected material in Mars orbit accreted to form a number of small moons, whose orbit decay took place over a long period of Mars history. The sets of different-age and different-orientation grazing craters reflect the demise of the individual moon(lets), on a surface where there was significant polar wander over time. Phobos will expire soon (in geologic time), Deimos will stand alone.

We'd know more if the Fobos-Grunt mission of the USSR had not failed. A proposal for a Phobos mission to NASA's Discovery program (**P**hobos **A**nd **D**eimos and **M**ars **E**nvironment) lost out to the *Psyche* and *Lucy* missions (see below).

951 Gaspra (29 October 1991)

Mission planners took advantage of the *Galileo* Jupiter mission having to pass through the Asteroid Belt to fly by an asteroid for the first time, 951 Gaspra. It is an S-type, a little smaller than Deimos (~4 miles in the longest dimension). It has a density somewhat lower than solid rock, but higher than that of Phobos, and its surface is less heavily cratered than other asteroids we have subsequently encountered. Both may be due to Gaspra's age (the object, not necessarily the material from which it formed). Analysis of Gaspra's orbit and others indicated it belongs to a family of asteroids derived from the impact breakup of a larger parent body –

the “Flora family.” Its present surface hasn’t had enough time for a lot of craters to form, or its surface to be fragmented by smaller impacts, which could lower its bulk density.

243 Ida (28 August 1993)

NASA’s wizardly trajectory planners weren’t done with the *Galileo* Jupiter mission; they engineered a second asteroid fly-by on the way to Jupiter. This time everyone was surprised when 243 Ida was found to have its own moon, a time object that was named Dactyl. Ida is also an S-type asteroid, a member of the Koronis Family. Its surface is more heavily cratered than Gaspra’s (indicating greater age), but its association with the impact that formed the Koronis suggests a younger age. Dactyl is so tiny that it wasn’t seen initially, but rather was discovered by a more detailed analysis of fly-by images some five months afterward.

254 Mathilda (27 June 1997)

The *Near Earth Asteroid Rendezvous* spacecraft (renamed after launch as *NEAR Shoemaker* in honor of famed and beloved planetologist Eugene Shoemaker) was sent to make an extended study of asteroid 433 Eros, a body with a highly-elliptical orbit that crosses the orbit of Mars. *En route*, it flew by Mathilda, a C-type asteroid larger than either Gaspra or Ida. It has a very rugged shape, caused by large impact features, and its low density suggests it’s more pile of rubble than a solid or near-solid body. Its albedo is so low that its surface features are named after coal-producing areas on Earth. It has an unusually slow rotation rate compared to other asteroids, which meant that *NEAR* was able to see only one side as it flew past.

433 Eros (orbit insertion: 14 February 2000; landing: 12 February 2001)

The next step in our up-close study of asteroids was the *NEAR Shoemaker* mission, which after its fly-by of Mathilda was to orbit asteroid 433 Eros, allowing for extended study. The mission manager was trajectory/orbit wizard Robert Farquhar at the Applied Physics Lab at Johns Hopkins. There were a number of glitches in getting *NEAR* to orbit such a small body, the first time an orbit of an asteroid was attempted. ***But Bob F. epitomized the theme of NASA doing the near-impossible, and doing it with style (as only NASA can), so it is no surprise to me that not only did* NEAR *orbit Eros successful, it did so on <u>Valentine’s Day no less</u>!***

NEAR-Shoemaker at Eros gives another example of “doing it with style.” Not only was this the first time a spacecraft orbited an asteroid, ***Farquhar and the NEAR team managed to actually LAND on Eros, even though it was not designed to do so!*** *NEAR* had been in orbit around Eros for over a year, its scientific objectives amply met, when the decision was made to try a landing, more as an engineering exercise, but also a science bonus, since *NEAR* would able to get very detailed observations very close to touch-down. Eros’ gravity is tiny, so the *NEAR* orbit could be gently tweaked to that the impact speed was low enough for possible survival (~4 MPH). The spacecraft continued to transmit after “impact,” but no further images were obtained. NASA Style!

Unlike Phobos, Deimos, and some (other) asteroids, Eros proved to be mostly solid, but it is covered by a *regolith* of impact-generated debris.

25143 Itokawa (Japan, landings in November, 2005; sample returned to Earth on 13 June 2020)

Japan has a major interest in exploring asteroids, and mounted the first successful sample return mission, *Hayabusa*, which sampled Itokawa in two locations and returned the material to Earth successfully. It was in part an engineering test; it used an ion engine. A solar flare damaged *Hayabusa*'s solar panels, and the loss of some of its power generating capacity gave the Japanese mission operators a chance to demonstrate some "style" of their own. They adjusted the trajectory and time line to add an additional gravitational slingshot pass of Earth and stylishly overcame the loss of one of the spacecraft's reaction wheels. *Hayabusa* rendezvoused with Itokawa on September 12, 2005. It was not in orbit around Itokawa, rather, it was in a close heliocentric orbit. Its second (of three) reaction wheels failed on 3 October, requiring a LOT of style on the part of the controllers to manage the spacecraft.

Itokawa, unlike Eros, was clearly a rubble pile-type asteroid, in fact, it may well be a contact binary (two chunks glommed together). Its surface had very few craters and was covered by boulders and other rocks of various sizes; its bulk density suggests that it has a porosity of ~40%.

Several close approaches to Itokawa were attempted, including one in which *Minerva*, the mini-rover aboard *Hayabusa*, was deployed. *Minerva* was the size of a one-pound coffee can, and was more of a hopper than a rover, but alas, it released after the pre-programmed ascent part of the dip toward Itokawa started, causing it to be higher than planned, causing *Minerva* to miss its landing.

Sampling touch-down events were next. The plan was for *Hayabusa* to land, then fire projectiles into the surface of Itokawa to splash up material for collection. Two landings were made, but the projectile system did not operate. A small amount of dust-sized material was kicked up when *Hayabusa* touched down, and those were collected by the spacecraft.

The controllers had yet another style opportunity; a thruster leaked, causing a temporary communications disruption and the depletion of most of its thruster fuel. In spite of its many malfunctions, *Hayabusa* managed to get back to Earth and eject its sample cannister on 13 June 2010. Analysis of the thousand-plus dust grains returned show that Itokawa's chemistry closely matches that of LL-Chondrite meteorites.

2867 Šteins

The European Space Agency is also interested in asteroid exploration, and comets, too. They sent the *Rosetta* spacecraft with its *Philae* lander out on a mission to land on comet Churyumov-Gerasimenko, with passes by asteroid 2867 Šteins (5 September 2008) and large asteroid 21 Lutetia (10 July 2010) along the way.

Šteins is a small, irregularly-shaped rocky body, about three miles in its longest dimension. Its shape is due in part to the presence of a large impact feature. It has no known asteroid family affiliation.

21 Lutetia

ESA's *Rosetta* spacecraft flew by asteroid 21 Lutetia on 10 July 2010, on its way to orbiting (and landing on) comet Churyumov-Gerasimenko. Lutetia is large, and irregular (~80 miles in its longest dimension). *Rosetta* was able to image about half of Lutetia's surface, showing it to have a number of impact craters and surface fractures, and a thick regolith cover. ESA had targeted Lutetia because its pre-fly-by density estimate made it an M-type asteroid. This would be the first metal asteroid encountered. The *Rosetta* fly-by refined the density estimate; it's too high for Lutetia to be solid rock. More likely it is a metal-rich body with a deeply-fragmented surface. Several lines of evidence suggest that Lutetia is very old, a left-over planetesimal dating from the earliest days of the Solar System. Its reflectance spectrum closely matches that of enstatite chondrite meteorites, known to be ancient, but they form closer to the Sun than Lutetia's present orbit. Therefore, Lutetia likely formed closer to the Sun, and is akin to the planetesimals from which the inner planets were built. Gravitational interactions with one or more of the inner planets likely boosted it to its present orbit.

4 Vesta

Vesta is a very unusual asteroid, in part because of its large size (~325 miles in the longest dimension), but also because we have numerous pieces of it here on Earth. It is the only known differentiated asteroid (layered by differences in material density) and once had active geologic activity (some investigators call Vesta, the "smallest terrestrial planet"). It was orbited by the *DAWN* spacecraft on 16 July 2011, and studied intensively for about a year before *DAWN* moved on to orbit dwarf planet Ceres.

Pre-fly-by spectral analysis of Vesta showed that different parts of its surface closely matched three odd classes of meteorites, howardites, eucrites, and diogenites (HED). This interpretation was confirmed by observations by *DAWN*; over 1200 HED meteorites are known and they are so important that they have their own class: V-type. Eucrites are basaltic in nature, ancient lavas blasted from the surface of Vesta; Howardites are basalt-rich fragments of impact-generated regolith, blasted from the surface of Vesta; and Diogenites are plutonic igneous rocks, formed deep within (the parent body of) Vesta and blasted by impact from Vesta.

There is an enormous body of knowledge now on Vesta; the Reference section below can help you dig deeper into our understanding of this important asteroid.

4179 Toutatis

China's first foray into asteroid exploration came when the *Chang'e 2* spacecraft flew by 4179 Toutatis on 13 December 2012. Toutatis is a Near-Earth Object, routinely crossing the orbit of Mars (but not Earth, at least yet, although it can get very close). Its about 3 miles in its longest dimension and it has the reflectance spectrum of the S-type asteroids. Its elliptical orbit allows it to approach Earth to within 4 lunar-distances (!); it also routinely approaches Jupiter closely, which increases the chance of its orbit altering with time. It will likely get boosted from the Solar System in a geologically-short amount of time.

Asteroids rarely are found in the kind of gravitational resonances that, for example, govern the distance of the Galilean satellites from Jupiter. Toutatis is an example of one, however. It has a low inclination relative to the Ecliptic (the plane in/near which all of the planets orbit), which makes for a number of gravitational interactions that manipulate its orbit. It is in a 3:1 resonance with Jupiter (it makes four orbits every time Jupiter orbits once) and a 4:1 resonance with Earth. In spite of rumors arising from time to time, a collision between Earth and Toutatis is unlikely in the time-frame of the latter's survival in the Solar System.

Earth-based radar data indicated that Toutatis was irregularly shaped, a finding confirmed by images from *Chang'e 2*. Toutatis is likely a contact binary. It has a large crater at one end and many surface fractures.

162173 Ryugu

Japan's Space agency decided to build on the success of their *Hayabusa* mission to Itokawa with a visit to asteroid 162173 Ryugu with a much more capable *Hayabusa 2* spacecraft. Ryugu was a desirable target because it is a C-type asteroid, akin to carbonaceous chondrite meteorites, some of the most primitive material in the Solar System, little changed from the Solar Systems formation. Ryugu is also an "easy" target (fuel-wise) to reach.

Hayabusa 2 carried three hopper/rovers and a larger rover, and would blast a crater into Ryugu, then sample material from well beneath the asteroid's surface.

Hayabusa 2 was launched on December 3, 2014. It used Earth for a gravitational slingshot assist before heading on to Ryugu, arriving there on 27 June 2018. It successfully deployed the MINERVA-II 1a and 1b rovers successfully. Both free-fell from 55 m to the asteroids surface, from which they returned data until the batteries were exhausted. Both had limited mobility, but managed to rove a bit of Ryugu's surface. The larger MASCOT hopper was released from the main spacecraft successfully on 3 October 2018, making two small hops during the one Ryuguan day it operated.

Hayabusa 2 made its first touchdown and sampling on 21 February 2019. The explosive impactor was deployed on 5 April 2019, creating a 10m diameter crater. A second sampling run was then made to acquire some of the excavated material on 11 July 2019. The final action an Ryugu came on 3 October 2019 with the deployment of rover MINERVA-II 2.

Hayabusa 2 departed Ryugu on 13 November 2020. It swung by Earth, dropping its sample cannister on 5 December 2020. It still had plenty of fuel aboard, so it was sent on a (very) extended fly-by mission to the tiny asteroid 1998KY26, arriving there in July 2031.

101955 Bennu

Asteroid 101955 Bennu is of scientific interest for the same reason Ryugu was; it is a C-type asteroid, likely unaltered since the origin of the Solar System. NASA's ***O**rigins, **S**pectral **I**nterpretation, **R**esource **I**dentification, **S**ecurity, **R**egolith **Ex**plorer* (*OSIRIS-REx*) spacecraft was launched on 8 September 2016, arrived a Bennu in December, 2018. It orbited Bennu for an extended period, mapping its surface in detail for over a year before sampling the surface. A shot of nitrogen gas mobilized surface materials, which were then collected and stowed in a return capsule (derived from the return capsule used by the *Stardust* spacecraft). It initiated its return to Earth this last May 10. It will be a long way home, requiring a path that will take it inside of Venus' orbit twice before flying back home, where it will drop a capsule containing about a kilogram of material on 24 September 2023.

Like *Hayabusa 2*, *OSIRIS-REx* has enough fuel aboard to be re-directed to a second asteroid target, should that be feasible.

PLANNED ASTEROID MISSIONS

Lucy

Lucy is lucky number 13 on the roster of NASA's Discovery missions. It is designed as a survey of six different asteroids. First up is a main belt asteroid, named 52246 Donaldjohanson (aka asteroid 1981 EQ5), after the discoverer of the Lucy hominid skeleton; hence the name of the spacecraft. It is another C-type asteroid, likely to date to the formation of the Solar System. It is a fragment from asteroid 163 Erigone, one of 2000 members of a family of debris blasted from Erigone by an impact event. The next five asteroid targes are Trojan-style asteroids, trapped in one of the five Lagrangian points of gravity stability in the Sun-Jupiter system.

Trojan asteroids were discovered some time ago, and their exploration was one of the high-priority goals in the most recent NASA Planetary Science Decadal Surveys. We know little about them (except that most have a low albedo). They are called that because the first few (except one) discovered around the L4 point (in Jupiter's orbit, but ~60° ahead of Jupiter) were named after Greek figures in the Trojan War. The first few discovered around the L5 point (in Jupiter's orbit, but ~60° behind Jupiter) were named after Trojan figures. *Lucy* will visit the "Greek Camp" first, flying by four different asteroids, one of which is known to have a little moon of its own, *a la* Dactyl). *Lucy* will then drop back into the inner Solar System and use Earth for a gravitational assist that will allow it to visit one asteroid in the "Trojan Camp."

Lucy's launch window opens on 16 October 2021; it will make the Donaldjohanson fly-by in April, 2025. The four Greeks will be flown by between August, 2027 and November, 2028. The final fly-by, of 617 Patroclus, will be in March, 2033.

Psyche

Asteroid 16 Psyche has long been known as somewhat of an oddball. Its reflection spectrum clearly indicates it is one of the rare M-type asteroids, like 21 Lutetia, metallic, not rocky, in nature. Scientists believe it to be a larger remnant of a planetary core exposed when an impact destroyed its parent body (Psyche is big, it's the size of Massachusetts!). There is both a scientific, and economic interest in Psyche, because such a core fragment would be a treasure-house of iron, nickel, and other metals (if you could get it where it was needed). NASA has a mission planned to study Psyche up close, scheduled for launch next year.

We know Psyche is metallic, both from its reflection spectrum (M-type) and from its observed gravitational influences on other asteroids. Its longest dimension is over 150 miles, and its density is somewhere between 4 and 7 grams/cubic centimeter, greater than that of silicate rock. Psyche's high density and very high radar reflectivity attests to its metallic nature, estimates (until recently) were that it was a solid object, ~95% metallic.

A recent paper in *The Planetary Science Journal*, with a University of Arizona ***undergraduate*** as its lead author, suggests that Psyche might not be quite like it seemed. David Cantillo and his collaborators hypothesized that Psyche might not be a solid chunk of metal, but rather be more like other asteroids studied, with a regolith (broken outer fragmented surface) of impact-gardened material, containing a large component of material from the objects that impacted it.

Cantillo *et al*. modeled the potential regolith using various potential mixtures of metal fragments, and rock fragments, either from itself of delivered to it by impacts with smaller rocky asteroids. They found that the best spectral match was for a material that was 82.55% metallic (down from ~95% estimated previously), mixed with 7% low-iron pyroxene and 15% carbonaceous chondrite. Their surficial material, in an extensive regolith with some porosity, could allow for both the metallic reflectivity and the lower density estimate cited above.

Another study of Psyche suggests that observed variations in the surface albedo of Psyche could be due to ferrovolcanism, that's right, volcanoes that erupt iron. Solid iron flows would be highly radar-reflective and very dense; the rest of Psyche's surface could be more like that described by Cantillo et al., and the interior would not necessarily have to be pure metal. Both their density estimates align with the 4 g/cc value cited above.

Solid or with a busted up, dirtied surface or shiny iron lava flows, Psyche is an interesting and important scientific target, with possibly large economic value!

ZhengHe

China wants to join the asteroid sample return club and the comet sample return club, and plans to do both with the *ZhengHe* mission, planned for launch some time in 2024.

China does things with style, too, evidenced by their selection of asteroid 469210 Kamo'oalewa, from the Hawaiian name for "oscillating celestial fragment," as their asteroid target. It is the best example of a "quasi-satellite" of Earth, not quite co-orbiting the Sun with Earth and not quite orbiting Earth.

ZhengHe will be powered by solar-electric propulsion. After launch, it will rendezvous with, then orbit Kamo'oalewa, mapping its surface with a variety of remote sensors. It will deploy a nano-orbiter and nano-lander, then use an explosive charge to create a crater so that *ZhengHe* can sample the asteroid's interior. After sample collection, *ZhengHe* will return to Earth, drop its samples as did other asteroid sample return missions, then use both Earth and Mars as gravitational slingshots to assists its voyage to comet 311P/PANSTARRS, where observations will be conducted for over a one-year period.

DESTINY+

The **D**emonstration and **E**xperiment of Space **T**echnology for INterplanetary vo**Y**age with **P**haethon f**L**yby and d**U**st **S**cience) mission is joint Japan/Germany venture; projected to launch some time in 2024. Its objective is "asteroid" 3200 Phaeton. Long-time fans of A+StW will recall mention of Phaeton as a "rock comet," having the general characteristics of an asteroid, but with the observed shedding of rocky material and gas, like a comet. 3200 Phaeton is the known parent body for the December Geminid meteor shower, a relationship first noted by Fred Whipple, also known for his "dirty snowball" model for comets and his WWII work in developing radar-deceiving chaff, aluminized strips of the right length to reflect radar energy, concealing any metal objects (planes) behind it. Any such objects between asteroid and comet is bound to be of interest to understanding both.

In mythology, Phaeton is the under-loved son of Helios, the driver of the Solar Chariot. He tricks dear old Dad into letting him drive the Chariot, to the detriment of all Humanity, and the destruction of Phaeton.

Destiny+ will also be a technology demonstrator, using solar panels of ultra-light construction and solar-electric ion propulsion, similar but larger to that on *Hayabusa* and *Hayabusa 2.*

REFERENCES

Asteroids in General

Asteroid Day: https://asteroidday.org

Missions to Asteroids: https://en.wikipedia.org/wiki/List_of_missions_to_minor_planets

Origin of Asteroids: https://www.discovermagazine.com/the-sciences/the-asteroid-belt-wreckage-of-a-destroyed-planet-or-something-else

Asteroid Spectral Types: https://en.wikipedia.org/wiki/Asteroid_spectral_types

Asteroids Visited to Date:
https://en.wikipedia.org/wiki/List_of_minor_planets_and_comets_visited_by_spacecraft#List_of_minor_planets_visited_by_spacecraft

Asteroid Shape Models: https://3d-asteroids.space/asteroids

UH Planetary Science Research Discoveries pdfs: (NOTE – this is an important resource!):
http://www.psrd.hawaii.edu/Archive/Archive-Meteorites.html

Tunguska

https://en.wikipedia.org/wiki/Tunguska_event

https://www.nasa.gov/feature/ames/tunguska-revisited-111-year-old-mystery-impact-inspires-new-more-optimistic-asteroid

Asteroids Visited to Date ("Distant Incidental Fly-bys," comets, Ceres, and KBOs not Included)

Phobos and Deimos

Origin: https://www.thoughtco.com/mars-moon-mystery-3073184

Doomed Phobos: https://www.space.com/20346-phobos-moon.html

Schultz PH and Lutz-Garahan AB (1982) Grazing Impacts on Mars: A Record of Lost Satellites: *Proceedings of the 13th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston, pp A84–A96

951 Gaspra

State of asteroid knowledge immediately after fly-by: https://www.jpl.nasa.gov/news/galileo-flyby-of-gaspra-yields-new-information

https://en.wikipedia.org/wiki/951_Gaspra

https://www.jpl.nasa.gov/images/highest-resolution-gaspra-mosaic

https://www.planetary.org/articles/03011636-galileo-gaspra

https://pubs.er.usgs.gov/publication/70017940

Flora Family: https://en.wikipedia.org/wiki/Flora_family

243 Ida and Dactyl

https://rps.nasa.gov/resources/94/ida-and-dactyl

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2001JE001759

Koronis Family: https://duckduckgo.com/?q=Koronis+family+of+asteroids&ia=web

253 Mathilde

https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/253-mathilde/in-depth

https://en.wikipedia.org/wiki/253_Mathilde

https://nssdc.gsfc.nasa.gov/planetary/mission/near/near_mathilde.html

433 Eros

Near Earth Asteroid Rendezvous mission: https://en.wikipedia.org/wiki/NEAR_Shoemaker and https://www.lpi.usra.edu/books/AsteroidsIII/pdf/3047.pdf

NEAR: https://solarsystem.nasa.gov/missions/near-shoemaker/in-depth

NSSDCA: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1996-008A and https://nssdc.gsfc.nasa.gov/planetary/near.html

Landing: https://www.spaceflightnow.com/near/010212nearlands

Gene Shoemaker

https://en.wikipedia.org/wiki/Eugene_Merle_Shoemaker

https://www.planetary.org/profiles/eugene-shoemaker

https://science.howstuffworks.com/eugene-shoemaker-buried-on-moon.htm

15143 Itokawa

https://en.wikipedia.org/wiki/Hayabusa

https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2003-019A

https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/25143-itokawa/in-depth

https://www.cambridge.org/core/services/aop-cambridge-core/content/view/59B0FDF3384BA752837FB5823A43B4C2/S174392130700350Xa.pdf/nature_of_asteroid_itokawa_revealed_by_hayabusa.pdf

2867 Šteins

https://en.wikipedia.org/wiki/Rosetta_(spacecraft)

https://en.wikipedia.org/wiki/2867_%C5%A0teins

https://www.esa.int/Science_Exploration/Space_Science/Rosetta/Encounter_of_a_different_kind_Rosetta_observes_asteroid_at_close_quarters

21 Lutetia

https://en.wikipedia.org/wiki/21_Lutetia

https://www.planetary.org/articles/2579

https://www.nasa.gov/topics/solarsystem/features/rosetta_images20100710.html

https://dspace.mit.edu/bitstream/handle/1721.1/110553/Sierks_2011_open_access.pdf;jsessionid=D66B145693F3833B220E1711B46085EC?sequence=1

https://www.space.com/13597-asteroid-lutetia-earth-birth.html

4 Vesta

https://en.wikipedia.org/wiki/4_Vesta

https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/4-vesta/in-depth

https://www.space.com/12097-vesta-asteroid-facts-solar-system.html

https://solarsystem.nasa.gov/missions/dawn/overview

NSSDCA: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2007-043A

https://www.nasa.gov/mission_pages/dawn/main/index.html

https://solarsystem.nasa.gov/missions/dawn/technology/spacecraft

https://www.planetary.org/articles/10091306-what-did-dawn-learn-at-vesta

http://www.psrd.hawaii.edu/Nov07/HEDs-Vesta.html

https://geology.com/articles/vesta-meteorites

HED meteorites: https://en.wikipedia.org/wiki/HED_meteorite

HED meteorites: https://curator.jsc.nasa.gov/antmet/hed/hed_what.cfm

HED meteorites: https://www.amnh.org/exhibitions/permanent/meteorites/building-planets/vesta

The "smallest terrestrial planet": https://meetingorganizer.copernicus.org/EPSC-DPS2011/EPSC-DPS2011-97-3.pdf

"Dawn; the Vesta–HED connection; and the geologic context for eucrites, diogenites, and howardites": https://onlinelibrary.wiley.com/doi/full/10.1111/maps.12108

4179 Toutatis

https://en.wikipedia.org/wiki/4179_Toutatis

https://www.planetary.org/articles/12141551-change-2-imaging-of-toutatis

https://www.lpi.usra.edu/sbag/meetings/jan2013/presentations/sbag8_presentations/TUES_0930_CE_Toutatis.pdf

http://cosmicdiary.org/fmarchis/2012/12/14/change-successfully-imaged-toutatis

https://en.wikipedia.org/wiki/Chang%27e_2

https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2010-050A

162173 Ryugu

https://solarsystem.nasa.gov/missions/hayabusa-2/in-depth

https://www.nasa.gov/directorates/heo/scan/services/missions/universe/Hayabusa2.html

https://en.wikipedia.org/wiki/162173_Ryugu

http://europlanet.dlr.de/Hayabusa2/MASCOT/index.html

101955 Bennu

https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/101955-bennu/overview

https://solarsystem.nasa.gov/news/1483/osiris-rex-resources/?page=0&per_page=40&order=created_at+desc&search=&tags=Bennu%2COSIRIS-REx&category=324

OSIRIS-REx: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2016-055A

Upcoming Missions

Lucy

https://en.wikipedia.org/wiki/Lucy_(spacecraft)

http://lucy.swri.edu/mission/Spacecraft.html

https://www.nytimes.com/2017/01/06/science/nasa-psyche-asteroid.html

https://en.wikipedia.org/wiki/52246_Donaldjohanson

https://en.wikipedia.org/wiki/3548_Eurybates

https://en.wikipedia.org/wiki/15094_Polymele

https://en.wikipedia.org/wiki/11351_Leucus

https://en.wikipedia.org/wiki/21900_Orus

https://en.wikipedia.org/wiki/617_Patroclus (A Greek spy in the Trojan Camp, perhaps?)

Roster of Discovery-class missions: https://en.wikipedia.org/wiki/Discovery_Program

Psyche

https://en.wikipedia.org/wiki/16_Psyche

https://www.nasa.gov/psyche

https://psyche.asu.edu

Cantillo et al. paper summary: https://www.sciencedaily.com/releases/2021/06/210610135741.htm

Their *Planetary Science Journal* paper: https://iopscience.iop.org/article/10.3847/PSJ/abf63b

BTW, lead author Cantillo is also an accomplished musician (*e.g.* https://soundcloud.com/user-377179712/summer-rain).

Iron volcanism: https://skyandtelescope.org/astronomy-news/iron-volcanos-maybe-not-science-fiction-after-all

ZhengHe

https://en.wikipedia.org/wiki/ZhengHe_(spacecraft)

https://www.hou.usra.edu/meetings/lpsc2019/pdf/1045.pdf

https://www.nature.com/articles/d41586-019-01390-5

China’s Cooperation Plan for Lunar and Deep Space Exploration: http://www.unoosa.org/documents/pdf/copuos/2018/copuos2018tech19E.pdf

https://en.wikipedia.org/wiki/469219_Kamo%CA%BBoalewa

Quasi-satellites: https://en.wikipedia.org/wiki/Quasi-satellite

DESTINY+ (**D**emonstration and **E**xperiment of Space **T**echnology for INterplanetary vo**Y**age with **P**haethon f**L**yby and d**U**st **S**cience); joint ISAS/JAXA mission; projected launch: 2024

https://www.isas.jaxa.jp/j/researchers/symp/sss13/paper/P2-132.pdf

https://fanfun.jaxa.jp/jaxatv/files/20170920_dlr_e.pdf

https://en.wikipedia.org/wiki/DESTINY%2B

https://en.wikipedia.org/wiki/3200_Phaethon

https://web.archive.org/web/20170914034331/http://www.lcpm12.org/wp-content/uploads/2017/08/1415-1435-Toyota.pdf

https://www.dlr.de/content/en/articles/news/2020/04/20201112_destiny-germany-and-japan-begin-new-asteroid-mission.html

Phaeton in mythology: https://en.wikipedia.org/wiki/Phaethon

Last Edited on 21 June 2021