 by Emily Lakdawalla

ROCK ON

Planetary scientists are sending robotic emissaries to unmask the secrets of asteroids throughout the solar system.

Countless tiny worlds travel among the stately orbits of the solar system's planets. These worlds populate the asteroid belt, congregate in clumps along planets' orbits, and make excursions to just about every region, with occasionally striking results. Some formed where we find them now; others migrated from elsewhere. And although they might look like boring planetary debris, they are our best connections to the earliest history of the solar system.

Since 1990, a dozen missions have visited asteroids, comets, and Kuiper Belt worlds. In combination with observations from optical and radio astronomy, data from these missions have helped us understand both how the planets formed and how the giants herded the non-planets into their present-day locations (*S&T:* Mar. 2021, p. 22).

But the scientific theories we've devised based on these discoveries are only useful insofar as their predictions stand up to more observations. Two new missions will soon test the theories that grew from the last three decades of work, by exploring parts of the solar system we haven't visited yet: The Lucy mission will complete a flyby tour of at least seven asteroids caught along two parts of Jupiter's orbit, while Psyche will head to its eponymous asteroid, 16 Psyche, located in the main belt between Mars and Jupiter.

Both spacecraft are from NASA's Discovery program, each developed and launched quickly with a relatively small budget of "only" $450 million. Both feature enormous solar panels, some of the biggest ever sent beyond Earth. And both face several-year cruises and planet flybys before they reach their science targets. Together, Lucy and Psyche will test whether existing theories of planet formation and migration can explain their target asteroids' unique properties and current locations.

The Story So Far

In The Beginning, all was gas and dust. Then, gas began to condense onto dust grains, which helped the grains stick together upon collision. At the center of the swarm, the proto-Sun ignited and blasted out intense radiation, transmuting stable atoms into the radioactive isotope aluminum-26. This isotope was then trapped in condensing grains rich in calcium and aluminum. Scientists have analyzed such ceramic-like grains carried to Earth in meteorites and determined that these solar-system-forming events took place 4.568 billion years ago.

The solar nebula's gas dragged on the tiny dust particles as they orbited the prenatal Sun, moving them into crossing paths. The resulting collisions were slow, the particles nudging together gently enough that they didn't fly apart. Planetesimals grew from such gentle processes of pebble-collecting very quickly, doubling in size every thousand or so years. Arrokoth, the tiny Kuiper Belt world visited by New Horizons in 2019, bears signs of this construction process (*S&T:* Feb. 2020, p. 34).

Close to the young Sun, the planetesimals were mostly rock. Farther away, where colder temperatures prevailed, both rock and ice could condense, and planetesimals grew larger, faster. Within half a million years, uncountable tiny particles had merged into fewer, but still numerous, worlds hundreds to thousands of kilometers in diameter. They were loose piles of dust, gravel, fluffy ice, and empty space; their self-gravity could hold the particles together but couldn't pack them tightly.

Meanwhile, the radioactive Al-26 was rapidly decaying into magnesium-26, generating heat. Bigger worlds trapped that heat, warming up. In some of them, ices turned to liquids or gas. Gases escaped but liquids flowed, collapsing or filling pore spaces. The liquids chemically reacted with rocks, making new minerals and sometimes even creating short-lived underground oceans of salty liquid. Where worlds became sufficiently hot, the rock began to melt, and still-solid metal grains fell down toward their centers. This process, called *differentiation*, produced onion-layered worlds with metal cores enclosed in mantles of rock (and, if far enough from the Sun, ice), with or without a top layer of never-melted, cold material.

The Al-26 heat wave ended early in solar system history, except inside the largest worlds. Nowadays, nearly every small body in the solar system is too cold to retain interior liquids, but they preserve their layered structure.

Al-26 wasn't the only thing to dramatically change these small worlds. When the giant planets grew big enough, their orbits began to shift, sending the giants plowing through the planetesimals around them and scattering the small worlds across the solar system to where we find them today. The details and timing of this re-sorting should be imprinted in the worlds' characteristics — which we've only seen from afar.

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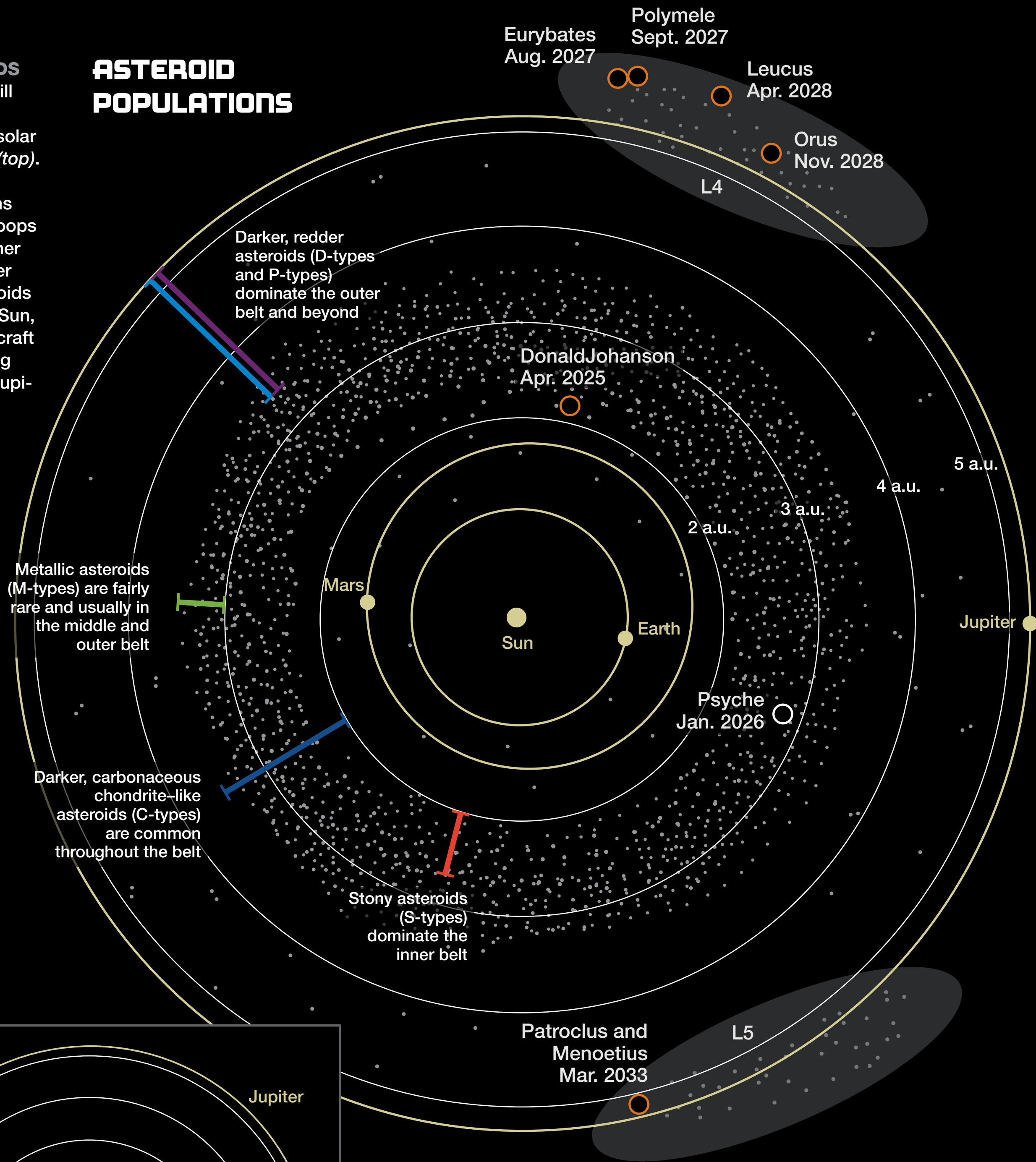
◀ **16 PSYCHE** This artist's illustration shows one option for how Psyche might look. Scientists think the asteroid is a blend of rock and metal, which might be mixed together (as shown here) or in discrete sections.

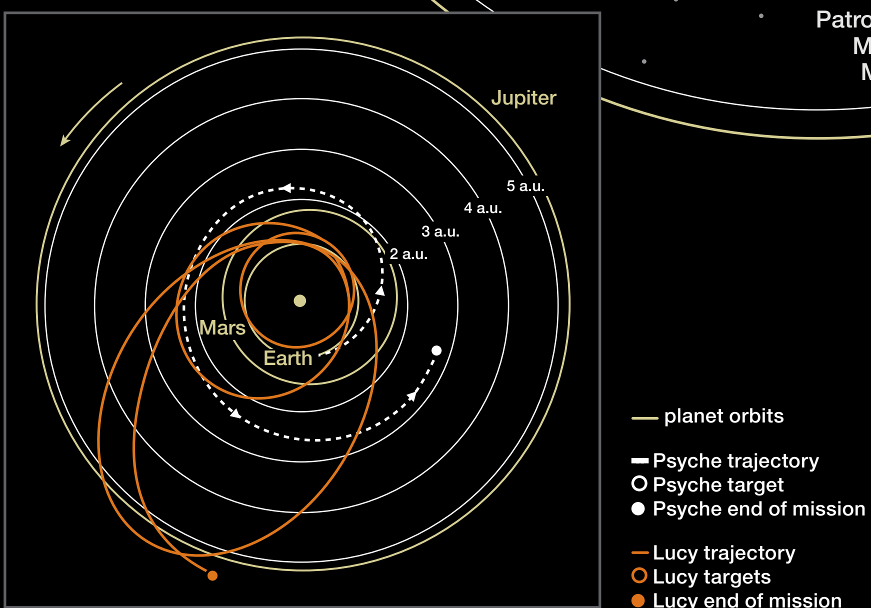
PETER RUBIN / NASA / JPL-CALTECH / ASU

TO THE ASTEROIDS Psyche and Lucy will investigate several targets among the solar system's asteroids *(top)*. To get there, they'll take circuitous paths *(bottom)*. As Lucy loops in and out of the inner solar system, Jupiter and its Trojan asteroids revolve around the Sun, enabling the spacecraft to visit objects along different points of Jupiter's orbit.

ASTEROID POPULATIONS

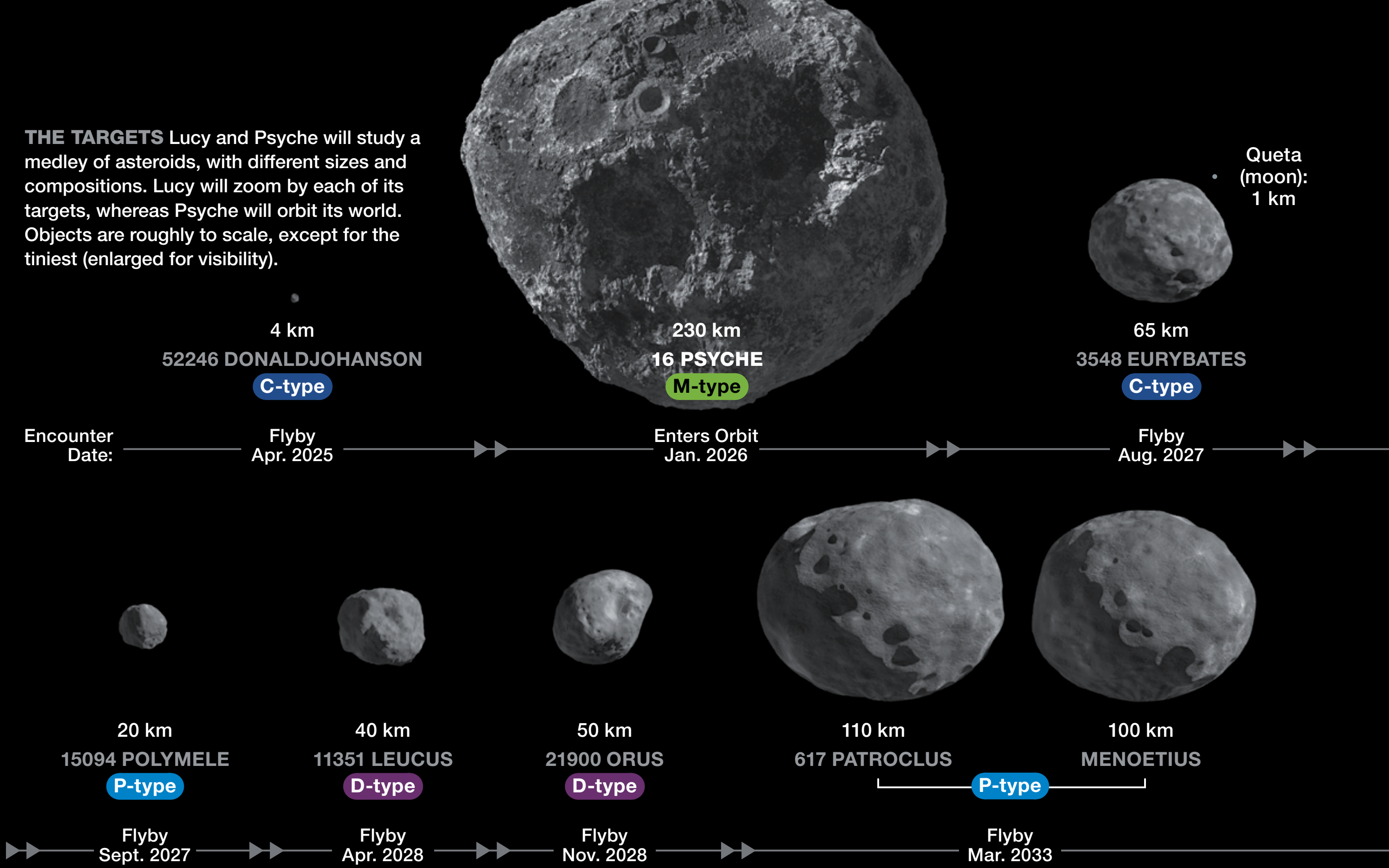


LUCY AND PSYCHE

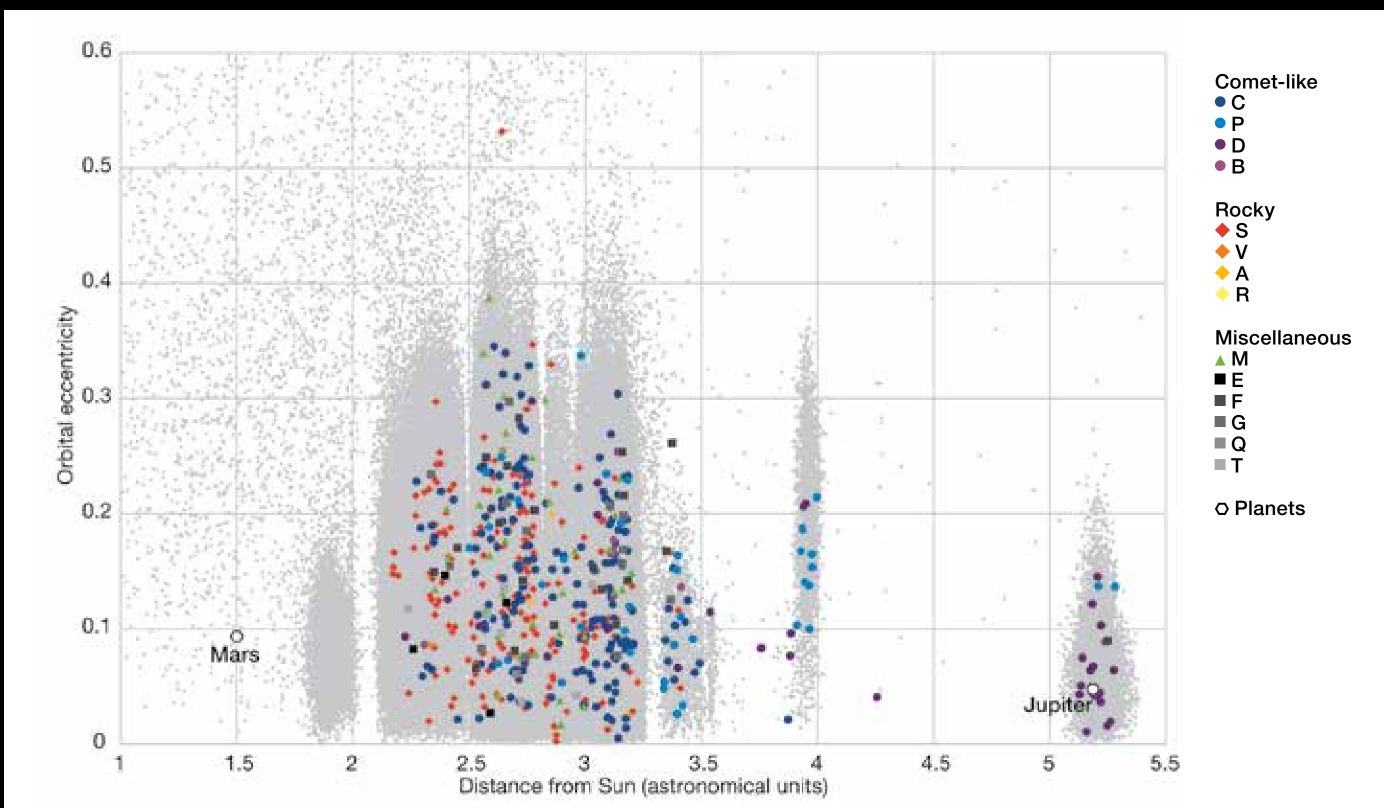


SPACECRAFT HAVE SO FAR VISITED 14 ASTEROID SYSTEMS (ONE HAS A MOON). THE PSYCHE AND LUCY MISSIONS WILL ADD ANOTHER SEVEN SYSTEMS, INCLUDING ONE ASTEROID WITH A MOON AND ONE BINARY ASTEROID.

TERRI DUBÉ / S&T



THE TARGETS Lucy and Psyche will study a medley of asteroids, with different sizes and compositions. Lucy will zoom by each of its targets, whereas Psyche will orbit its world. Objects are roughly to scale, except for the tiniest (enlarged for visibility).



ASTEROIDS GALORE Asteroids (dots) form distinct orbital clumps, controlled in large part by Jupiter. Rocky bodies are more common closer to the Sun, whereas dark red, comet-like surfaces dominate the outer regions. Carbonaceous asteroids occur throughout the belt.

LUCY TARGETS: NASA GSFC; PSYCHE: PETER RUBIN / NASA / JPL-CALTECH / ASU

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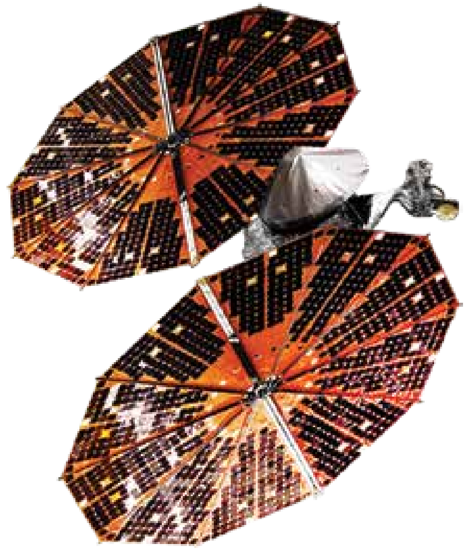


◀ **LUCY SPACECRAFT** Lucy stretches more than 14 meters (46 feet) from tip to tip, thanks to its 7-meter-wide, decagonal solar panels.

Small World Diversity

These beginnings created an assortment of small bodies, and there are patterns in their differences. Using spectroscopy, astronomers have identified numerous distinct classes and matched many with meteorites found on Earth. There are some compositional trends that make sense: Asteroids are rockier and more metal-rich closer to the Sun, while extremely dark, comet-like surfaces are more common farther out.

But atop the general trends are weird outliers. One oddball group, the 40 or so *M-type asteroids* in the main belt, appear dark in optical telescopes but bright to radar and may be rich in metals. Psyche is the largest such world.

There are also groupings among orbital properties. Just as the rings of Saturn have open lanes and denser parts, so too does the asteroid belt, for similar reasons. At Saturn, moons shepherd ring particles; in the asteroid belt, distant large worlds (primarily Jupiter) herd small bodies into denser belts and groupings through the rhythmic gravitational shoving of orbital resonances. There are also families of asteroids traveling similar orbital paths that are likely the fragments of a single primordial world that was shattered in a collision millions of years ago. The asteroids 162173 Ryugu and 101955 Bennu, recently visited by spacecraft, might be members of the same asteroid family, for example (*S&T:* May 2020, p. 14).

Between the main and Kuiper belts, a surprising number of small worlds travel around the Sun on orbits that have roughly the same period (11.9 Earth years) and average solar distance (5.2 astronomical units) that Jupiter does. They always lead or trail Jupiter on their orbital paths, clustering at two points on the giant's orbit located 60° ahead and 60° behind the planet, at the *Lagrangian points* L_4 and L_5. Here, the Jovian and solar gravitational fields balance the centripetal force of an object moving with them. These are the Trojan asteroids (*S&T:* June 2016, p. 16), named for characters in the ancient Greek epic *The Iliad*. Scientists know of a few Trojan asteroids for Neptune, Earth, and Mars, too, but no planet has as many as Jupiter does.

Jupiter's Trojan asteroids come in three spectral types (P, D, and C), all of which are also common in the asteroid belt. C-types exist throughout the belt; the very dark, red-colored P- and D-types make up larger proportions of the belt farther from the Sun. It seems straightforward to assume that P-, D-, and C-types all formed within the belt.

However, P- and D-type asteroids bear striking similarities to another population of very dark, reddish worlds: comet nuclei. Furthermore, one main-belt asteroid, Ceres, has a shocking amount of ice in it, which is difficult to explain unless it originally formed much farther out, possibly as far out as the primordial Kuiper Belt. Therefore, it's possible that the Trojan asteroids are more ice-rich and comet-like than a typical asteroid from the inner main belt.

Other evidence also points to a distant origin for one Trojan system. Equal-mass binaries are rare among asteroids but common in the Kuiper Belt. Theoretical work suggests it's not impossible for such a binary pair to remain partnered during an inward journey from the Kuiper Belt to a Trojan orbit. The Nice model of planetary migration predicts that about 10 such pairs might have been flung into Jupiter's domain, of which about one is likely to survive still paired. In fact, we've found exactly one: the L_5 binary pair 617 Patroclus-Menoetius.

So did Trojans form inside Jupiter's orbit and travel outward, or are they primordial Kuiper Belt objects like Arrokoth? That's what Lucy will find out.

Lucy to the Trojans

Lucy launched on October 16th to survey Jupiter's Trojan population, visiting at least seven Trojans in five different systems. Following two Earth flybys and one practice run at a main-belt asteroid in 2025, Lucy will make close passes by four Trojan systems in the leading (L_4) cloud in 2027 and 2028. One more Earth flyby will toss Lucy to a fifth encounter, with Patroclus-Menoetius in the L_5 cloud, in 2033.

The L_4 targets were selected for navigational reasons, by optimizing Lucy's orbital path to meet as many worlds as possible. The luck of the draw yielded a nicely representative sample that includes all spectral types, a range of sizes, the

▲ **CATCHIN' SOME RAYS** Engineers check one of Lucy's solar arrays, which will power the spacecraft as it flies out to Jupiter's orbit. After launch, one array did not fully deploy; as of press time engineers were still assessing the problem but did not expect any effect on the mission.

LUCY SPACECRAFT ILLO: SWRI; LAB PHOTO: LOCKHEED MARTIN largest member of the only known collisional family (Eurybates), and one ultra-slow rotator (Leucus).

The Lucy mission plan looks a lot like a string of New Horizons flybys. Because the flybys are so fast and the bodies so small, Lucy won't completely map each world, but it will obtain enough information to address questions of mass, shape, volume, density, surface composition, interior structure, and impact-cratering history. Its instruments draw on heritage from both New Horizons and OSIRIS-REX and comprise multiple cameras as well as a thermal infrared spectrometer.

Science observations will begin a year before each flyby, as the Lucy Long-Range Reconnaissance Imager (L'LORRI) studies how each asteroid's brightness changes with time from angles not achievable from Earth. The viewing angle also will place each body against a totally different field of stars than observers will be seeing from Earth, which will improve the precision of orbit predictions and therefore improve the precision of Lucy's navigation. As the spacecraft approaches, it will also use L'LORRI to search for satellites. We already know that one of the Lucy targets, Eurybates, has a moon, and there could be others.

All of the optical instruments will map as much of the surface of each world as they can see throughout the flyby. The instruments are clustered together on a movable pointing platform so that Lucy can keep its huge, decagonal solar panel arrays pointed at the Sun throughout most of each encounter. For targets that spin relatively quickly, Lucy will be able to map the full globe (or full potato, considering that they are not round). But some — especially Leucus, with its 445-hour day — will only show one sunlit hemisphere to Lucy when the spacecraft is close enough to map its landforms.

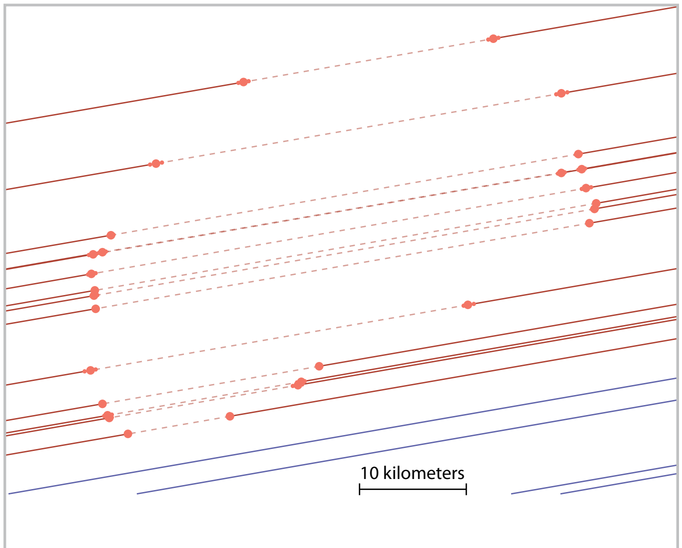
After Lucy, we will have visited enough of these (icy?) worlds for astronomers to responsibly infer what virtually all the Trojans are like, as well as the many asteroids of the outer part of the main belt that share the Trojans' qualities. That, in turn, will hopefully tell researchers where the objects came from and suggest how they arrived at their current locations.

Psyche: A Metal Asteroid?

Psyche is the largest of the M-type asteroids, measuring 290 by 245 by 170 kilometers across (about 180 by 150 by 105 miles). When the Psyche mission was first proposed to NASA, astronomers thought the asteroid could be more than 80% metal. Since then, observers have measured Psyche's mass and dimensions better, which has resulted, paradoxically, in less certainty about what it's made of.

Mass and volume estimates yield an approximate density, and Psyche's density is probably (but not certainly) just a little higher than that of the very densest rocky components of meteorites. Depending on what kinds of rock and metal make up Psyche and on how porous it is, the asteroid may be much less metallic than expected, about 30% to 60%.

No matter the answer to the composition puzzle, it's hard to explain how worlds as dense as Psyche formed. We know for sure that there is metal-rich material among the asteroids, because approximately 5% of all meteorite falls are made of a mix of iron and nickel. Scientists are relatively confident in their understanding of how these meteorites formed: If you begin with a differentiated world and shatter it in a collision with another asteroid, then some fragments will come from the core and be mostly or all metal. The problem with explaining Psyche's formation by the same mechanism is how to reassemble a big enough pile of core fragments to build an asteroid 200 km across without also incorporating lots of rock fragments. Perhaps lots of hit-and-run impacts spalled off chunks of mantle, leaving an intact core behind? It's a



GET INVOLVED

Teams of amateur astronomers are already contributing to the Lucy mission. Volunteers are assisting mission astronomers by providing careful observations of how long stars wink out (or don't) as Trojans pass in front of them as seen from various locations. The stellar occultations have already yielded improved orbit ephemerides and size and shape estimates for Lucy's targets — for instance, thanks to amateurs, we now know that slow rotator Leucus is surprisingly elongated and likely heavily cratered, while Patroclus' binary partner Menoetius seems to have a huge impact crater that has gouged a void out of its south pole. Such information makes flyby planning simpler and more efficient.

The Lucy team welcomes observers from around the world. Read more at **https://is.gd/lucyoccultation**.

▲ **11351 LEUCUS** Based on more than a dozen teams' observations (chords), this plot is a projection of the shadow the Trojan Leucus created when passing in front of an 11th-magnitude star in late 2019. The dots mark sites that saw the star wink out; blue lines are observers who saw no occultation, clarifying the asteroid's extent. Combined with other occultations, these results indicate that Leucus has an oblong, irregular shape.

MARC W. BUIE ET AL.

possible but unlikely scenario.

Looking at meteorites for clues, there are two types that match Psyche's probable density: pallasites and CB chondrites. Both of these are mixtures of metal and rock: pallasites have blebs of green olivine and dark pyroxene embedded within metal, and CB chondrites have metal blobs surrounded by a matrix of chondritic rock. Maybe Psyche is the remnant of an ancient collision that created an intimate mixture of rock and metal? Or maybe Psyche has a layer of rubbly (and therefore porous) pallasite-like material over a more metal-rich core?

Or maybe Psyche simply accreted from unusually metal-rich material, like the innermost planet, Mercury. If Psyche formed in the same conditions, not only has it moved dramatically outward from the Sun since it first formed, but it also may represent a fossil record of material from the innermost solar system.

We just don't know what Psyche is. It's virtually guaranteed that Psyche's actual history will surprise us and challenge our freshly minted models of solar-system formation.

◀ **PSYCHE THE SPACECRAFT** Tip to solar-paneled tip, Psyche spans nearly 25 meters, a little longer than a tennis court.

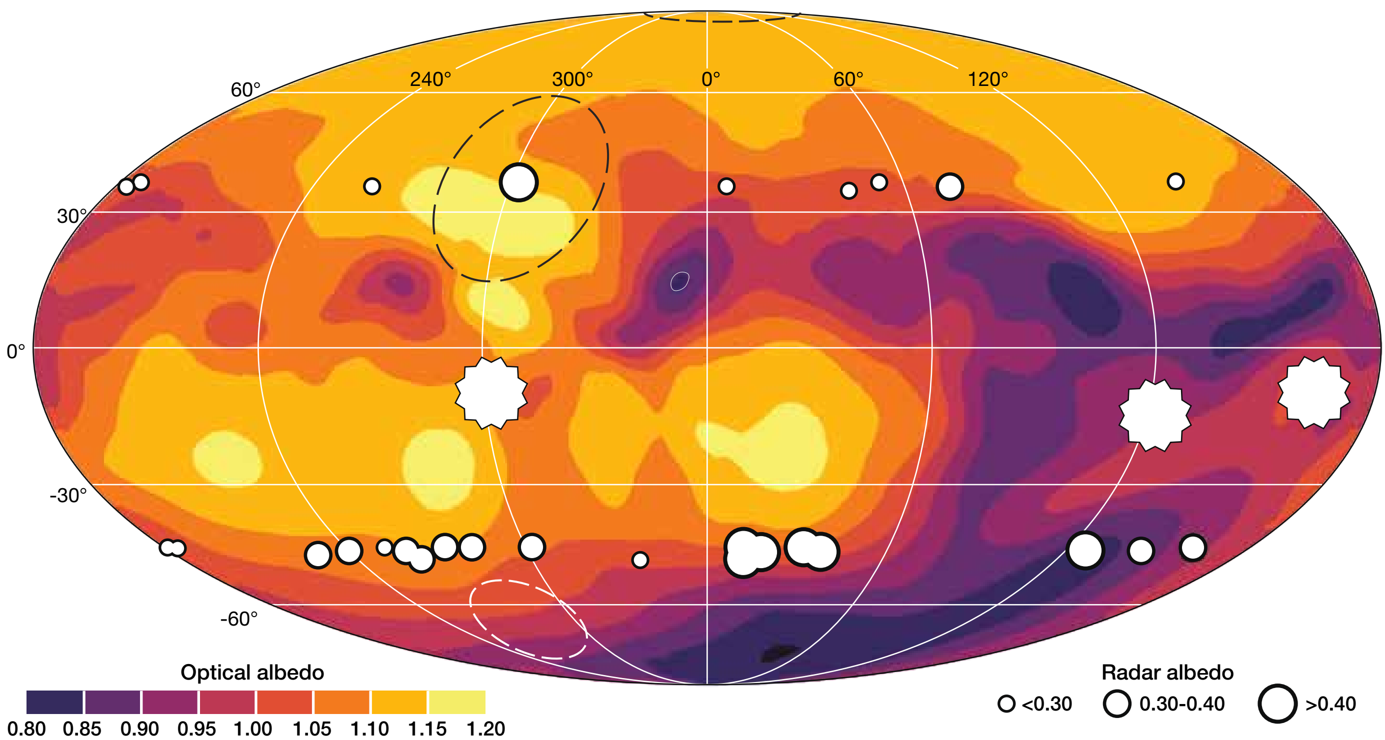
Psyche to Psyche

The Psyche mission focuses on a single world, mapping it at all scales and determining its geologic history, just as Dawn did at Vesta and Ceres (*S&T:* Dec. 2016, p. 16). The Dawn experience tells us that while the pretty pictures from Psyche will provide instant gratification, understanding the strange world will likely take years of scientific puzzling.

After its scheduled launch in August 2022, Psyche will swing by Mars on its way to a January 2026 arrival. Psyche's pathway to its target asteroid looks very similar to Dawn's, because both employ solar electric propulsion. Large solar panels supply electricity to generate magnetic fields that accelerate heavy xenon ions to high speeds, producing very efficient but gentle thrust. Long periods of engine thrust will accelerate and then decelerate the spacecraft, matching the asteroid's velocity for a slow approach and capture into orbit.

Psyche has instruments that can build up global maps of color, brightness, topography, composition, and magnetic-

▼ **MYSTERY SURFACE** Researchers extrapolated from how Psyche's brightness varies as it spins to create this contoured map of how the asteroid's reflectivity, or *albedo*, changes across its surface. Some potential craters (dashed circles) appear in 3D reconstructions. Radar observations also provide albedo information: White dots indicate the part of the asteroid that was pointing straight at Earth during a radar measurement; that location would have been responsible for most of the reflection back at Earth. The size of the dot indicates how well the asteroid reflected the ping: larger means more reflective. Some radar-bright areas also appear to coincide with optically bright areas, which might be places where ancient *ferrovolcanism* — consisting of iron-rich lava — erupted. Observers also saw three bright spots (white sunbursts) in 2019 that weren't apparent in earlier observations, for reasons unknown.



PSYCHE SPACECRAFT: ARIZONA STATE UNIVERSITY; ALBEDO MAP OF PSYCHE: M. K. SHEPARD ET AL. / *PLANETARY SCIENCE JOURNAL* 2021 and gravitational-field strength over many orbits' worth of observations. Although the asteroid likely doesn't create a global magnetic field today, an ancient one frozen into its surface would suggest it began as the core of a differentiated body. Psyche's paired magnetometers will operate long before arrival, getting contextual measurements of the solar field before they ever sense the asteroid.

On approach, the first science will come from the Psyche Multispectral Imagers, a pair of color cameras that are based on the Curiosity rover Mastcam science cameras. Curiosity has two cameras for stereo vision; Psyche carries two just in case one fails. From a distance, the imagers will help with optical navigation, search for satellites, and produce the first global views.

Different orbital altitudes permit different types of science. Psyche's first orbital phase, about 2 months long at 700 km altitude, will allow navigators to determine the gravity field, enabling lower orbits. At the end of this phase we'll know Psyche's mass, volume, and density.

The next orbit will be much lower, an average 290 km (roughly one asteroid diameter) above the surface. For almost three months, the cameras will capture frame-filling views, mapping the asteroid in full color. Gravity science and magnetometer measurements will continue. We'll begin to know whether Psyche's mass is evenly distributed, or if it has weird concentrations of higher- and lower-density material inside.

Once the photo-mapping is complete, Psyche will drop lower. The next orbit, at 170 km altitude, will allow Psyche to complete the required mapping of the global magnetic field, perhaps identifying magnetism locked into Psyche's rocks left over from its geologic past.

The lowest orbit, below 85 km, belongs to the Gamma-ray and Neutron Spectrometer (GRNS), derived from the one on the Messenger mission to Mercury. It will map Psyche's elemental composition, finally telling us what the asteroid is made of. Then, and only then, will the Psyche team have all the maps with all the kinds of data designed to answer our questions about what the world is and where it formed.

It's Gonna Rock

Lucy is an astronomer's mission, Psyche a geologist's. Lucy's science will establish facts generalizable to a class of worlds never before visited, tying its in-situ measurements to thousands of Trojan asteroids observable as only the faintest points of light from Earth. Psyche, meanwhile, will perform a deep study of one especially strange world whose origin is entirely mysterious. The data from both missions will either confirm or complicate current explanations for how the asteroid belt formed.

Because it's only going as far as the main asteroid belt, Psyche doesn't have to travel as far as Lucy. Even though it'll take almost two years to gather the full data set, Psyche will be completing its primary mission at about the time that Lucy is gearing up for its first Trojan encounter. If you're an asteroid fan, mark your calendars for 2027.

DART

Another asteroid mission is scheduled to launch in late 2021: the Double Asteroid Redirect Test (DART). It's not a science mission but an engineering one: Its goal is to change an asteroid's orbit by slamming something heavy into it. The ultimate question the mission will help us answer is, Can humans prevent a calamitous asteroid impact on our home planet?

Before you panic, DART isn't going to change a near-Earth asteroid's orbit around the Sun. Its target is smaller. DART aims at a collision with Dimorphos, the moon of the near-Earth asteroid 65803 Didymos, in fall 2022. A small Italian-built satellite, LICIACube, will separate from DART to watch the impact unfold, sending pictures home to Earth. Meanwhile, ground-based optical and radar measurements will enable us to precisely time Dimorphos' orbit around Didymos both before and after the collision. That way, we can see the orbital effect of smashing a mass into an asteroid without actually changing the orbit of the whole Didymos-Dimorphos system, creating no additional risk to Earth.

▲ **65803 DIDYMOS** This illustration depicts the rocky, near-Earth asteroid Didymos (left), which is about 780 m across and comes with a 160-m-wide satellite called Dimorphos. Researchers plan to smash the DART spacecraft into Dimorphos, shortening the satellite's 12-hour orbit around Didymos by several minutes.

ESA

If you're not an asteroid fan, you might be wondering why these tiny worlds deserve so much attention, when there are much larger planets and moons not being explored. The answer: By studying these tiny worlds, we're actually studying the planets. Once Lucy and Psyche's data have returned to Earth, we'll find out if any theorist is right about how the solar system got its start, or if they'll have to go back to their chalkboards again. Whether they're right or wrong, the adventure is going to be fun.

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