EXPLORE JUPITER'S TROJAN ASTEROIDS UP CLOSE p. 28

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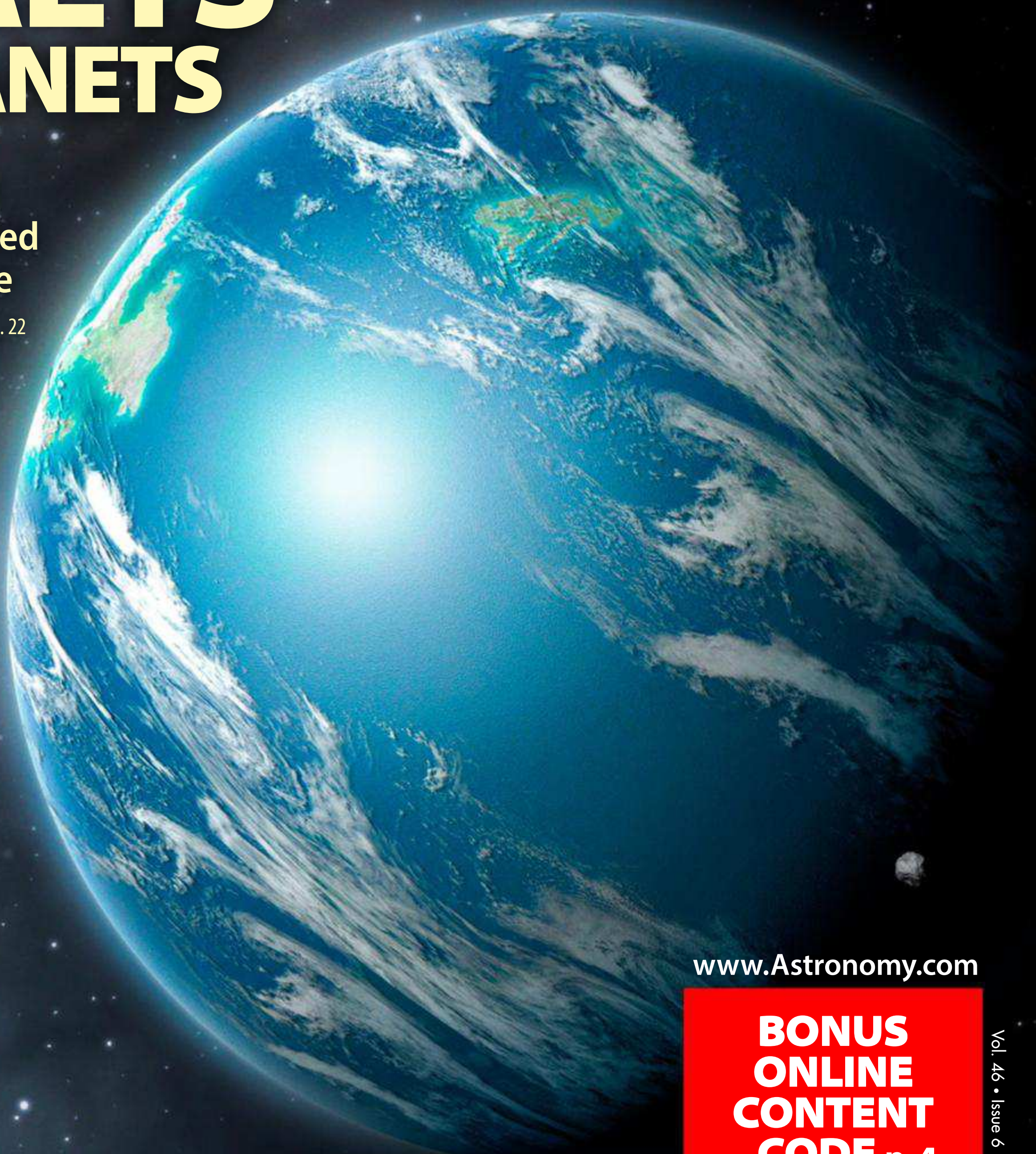

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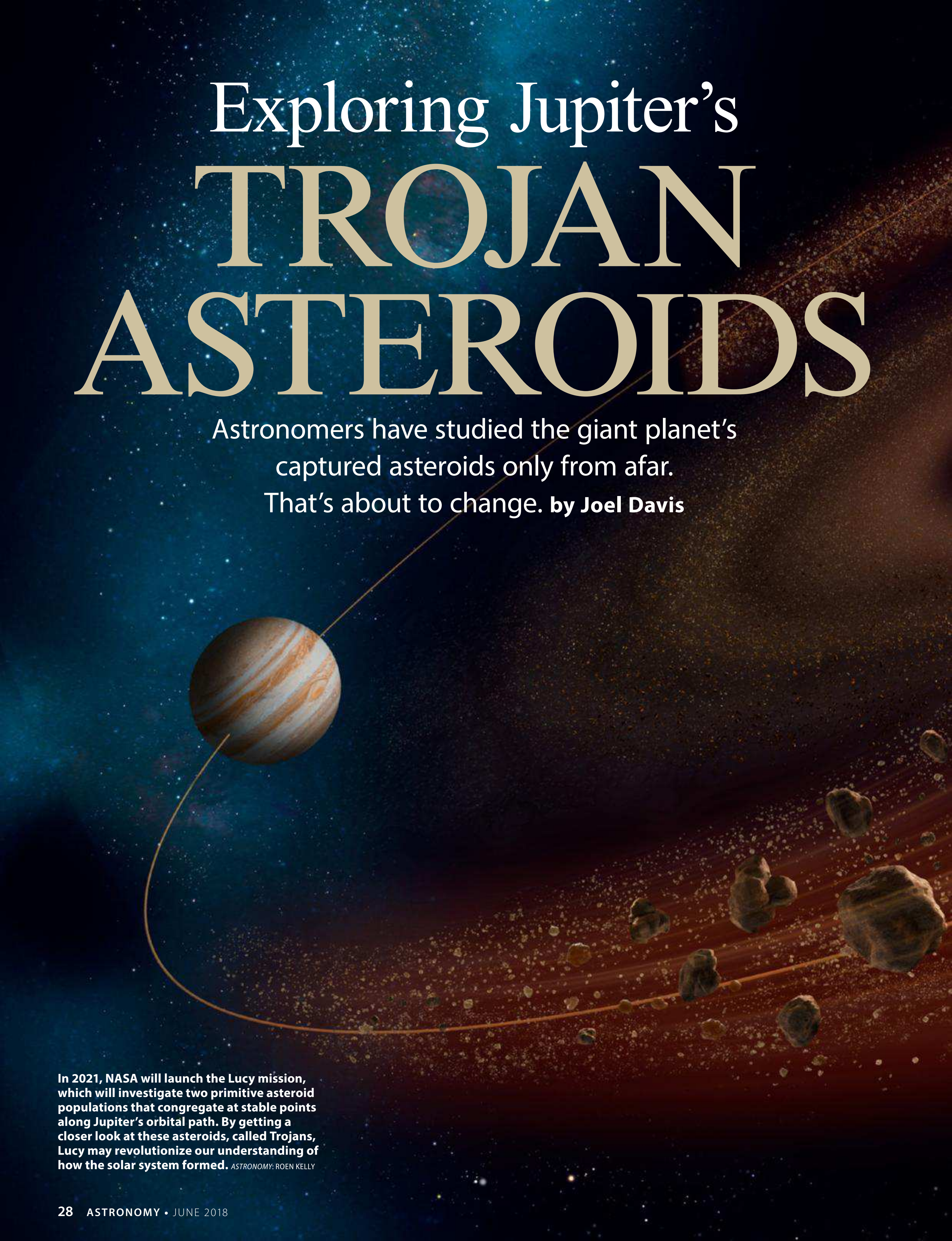
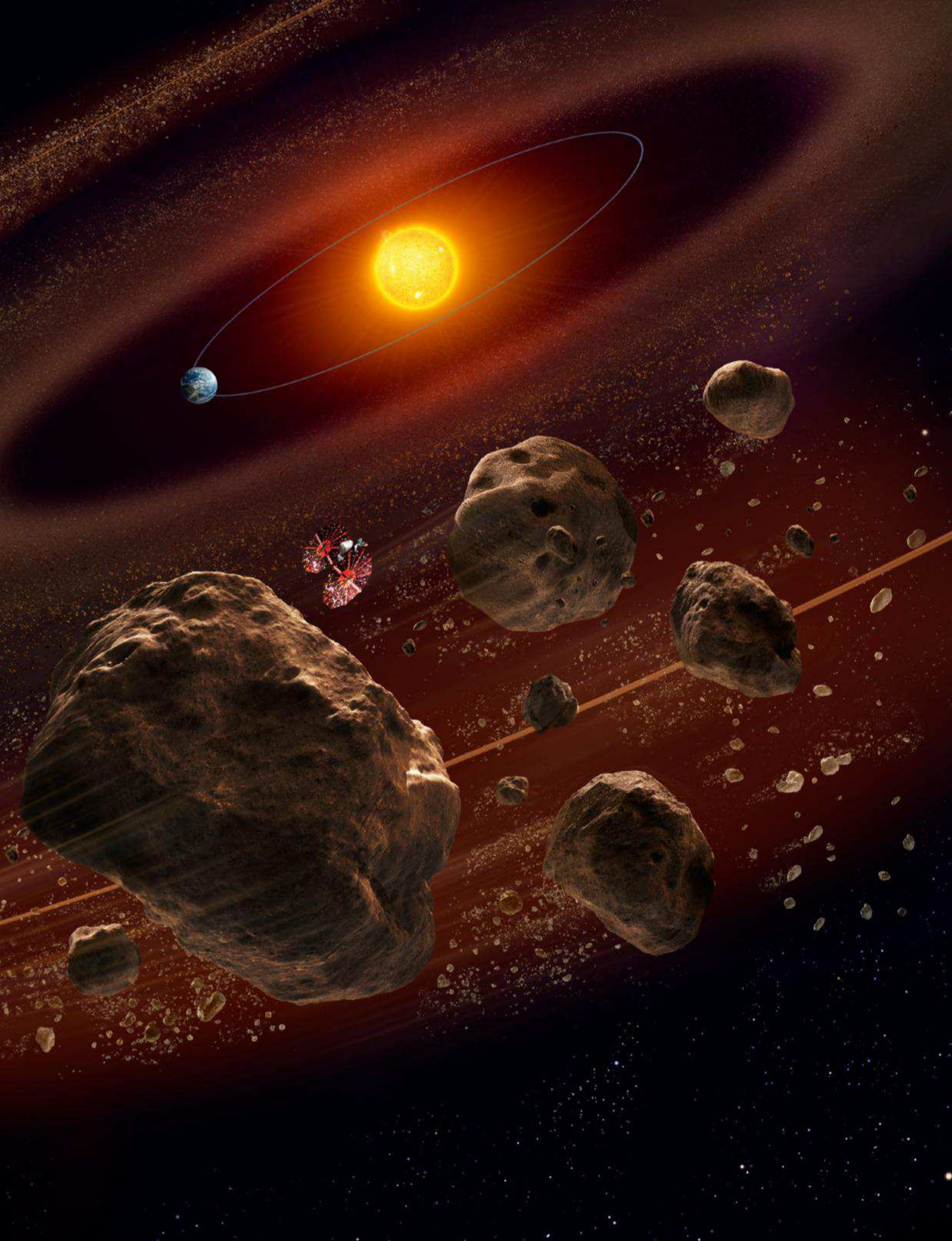
Exploring Jupiter's TROJAN ASTEROIDS

Astronomers have studied the giant planet's captured asteroids only from afar. That's about to change. **by Joel Davis**



In 2021, NASA will launch the Lucy mission, which will investigate two primitive asteroid populations that congregate at stable points along Jupiter's orbital path. By getting a closer look at these asteroids, called Trojans, Lucy may revolutionize our understanding of how the solar system formed. *ASTRONOMY*: ROEN KELLY



Jupiter is by far the largest and most massive planet in the solar system. And befitting a world named for the Roman king of the gods, Jupiter has an impressive entourage. It includes a set of faint and dusty rings, 67 known or suspected moons, and two swarms of asteroids that precede and follow the planet in its orbit. These last are the Trojan asteroids.

For all we've discovered about Jupiter, its moons, and even its gossamer rings, we know precious little about the Trojans. Pioneers 10 and 11, the two Voyagers, Galileo, and Juno have all returned a wealth of data about the jovian system. Until now, though, the only way to study the Trojans has been from afar, with ground-based and Earth-orbiting telescopes.

That's about to change. In 2017, NASA gave the go-ahead for a new Discovery-class robotic mission set for launch in 2021. The space probe will visit and explore six different Jupiter Trojans — and a main belt asteroid for good measure. So little is known about the Trojans that the data will certainly revolutionize our understanding of these ancient bodies. What the spacecraft uncovers could confirm some current theories of the solar system's early evolution — or turn it all upside down.

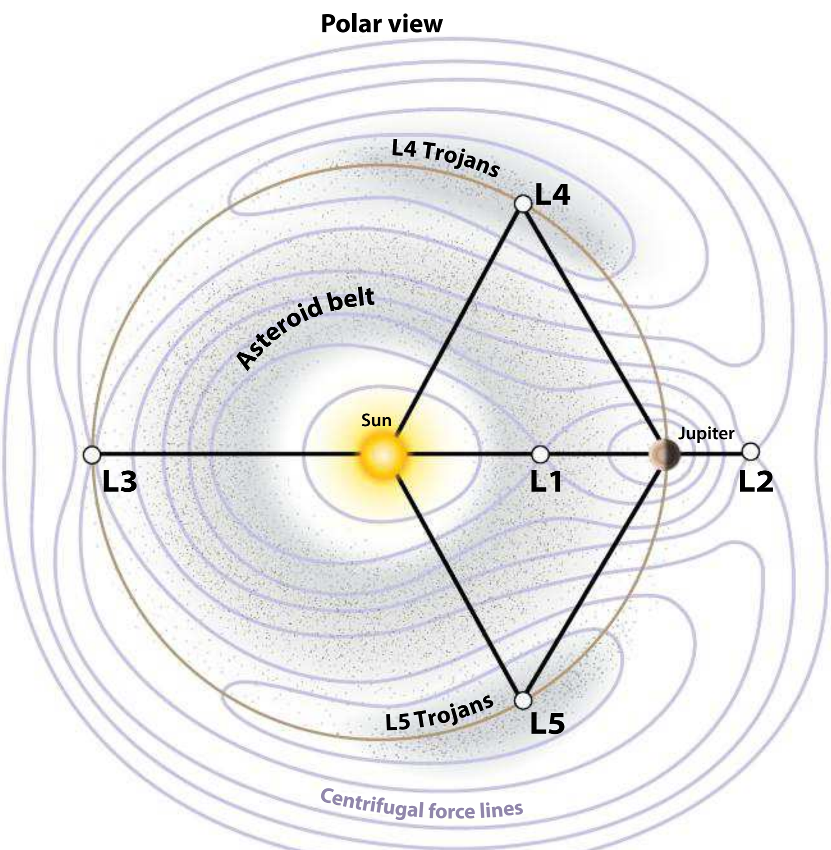
The sweet spots

Every planet has several gravitational "sweet spots" where a relatively tiny body, like an asteroid, can maintain a fairly stable position in relation to two larger bodies, such as the Sun and the planet, or the planet and its moon. The gravitational pull between the two large bodies provides enough centrifugal force to keep the smaller object orbiting with them. These sweet spots are called Lagrangian points, named for Joseph-Louis Lagrange, who identified two of them in 1772.

Five Lagrangian points exist for each such system. L1, L2, and L3 (discovered by mathematician Leonhard Euler a few years before Lagrange identified the other two) fall on a straight line drawn through the two large masses. L1 lies between the two bodies; L2 lies beyond the smaller of the two objects, but still on the line between them; and L3 lies behind the larger of the two objects, again still on the line between them. L1, L2, and L3 are unstable regions; almost any external force will knock objects at these points out of orbit. So it's extremely rare for natural objects such as moons or asteroids to occupy these locations. Spacecraft must periodically use some sort of station-keeping propulsion to stay at these Lagrangian points.

L4 and L5 are the third points of two equilateral triangles drawn in the plane of the two large objects, and both of these points are usually quite stable. The base of the triangle is the line between the large objects, say, the Sun and Jupiter. The other two sides of the triangles are the lines from each large body to points lying about 60° ahead (L4) and 60° behind (L5) in the orbit of the smaller of the two large objects (Jupiter, in this case).

Jupiter's Lagrangian points



Every planet has a set of five Lagrangian points where much smaller objects, such as asteroids, can maintain somewhat stable positions relative to the Sun and the planet.
ASTRONOMY: ROEN KELLY AFTER NASA/WMAP SCIENCE TEAM; JUPITER ABOVE: NASA/ESA/A. SIMON (GSFC)

Jupiter's Trojan asteroids

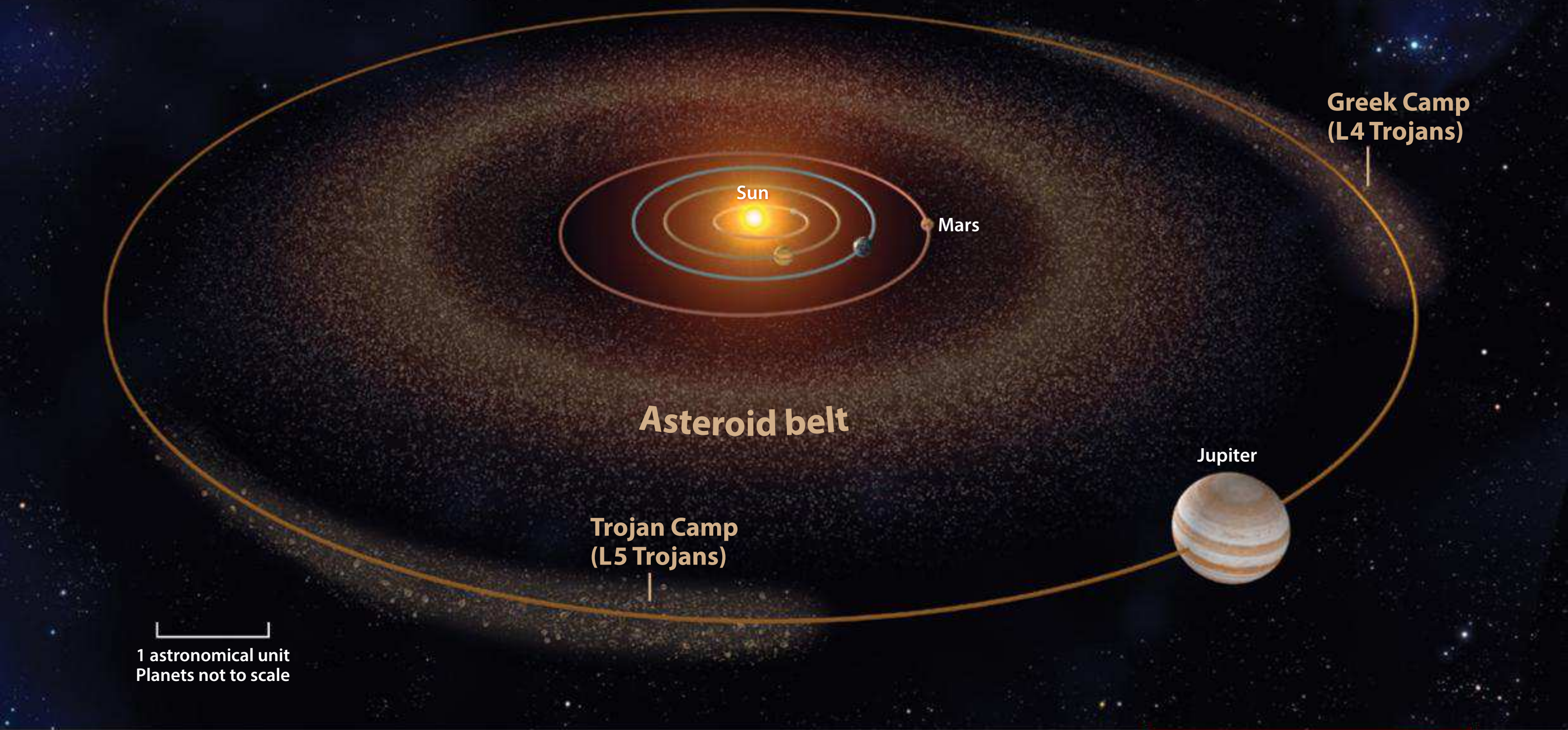
Jupiter's leading and trailing Lagrangian points are stable over the age of the solar system. Like the Sargasso Sea — the enormous circular gyre in the North Atlantic Ocean — they have accumulated eons' worth of objects. These bits of cosmic flotsam and jetsam are the Jupiter Trojan asteroids. They follow heliocentric orbits with nearly the same semi-major axis as Jupiter, about 5.2 astronomical units. (An AU is the average Earth-Sun distance of 483 million miles, or 778 million kilometers.) As they orbit the Sun, the Trojans tend to move closer to, or farther from, Jupiter. The planet's gravitational pull accelerates or decelerates the asteroids, causing them to librate — or oscillate — around the L4 and L5 points. This shepherds the Trojans into two elongated regions around those points. Each region stretches about 26° along Jupiter's orbit (a physical distance of about 2.5 AU), and is about 0.6 AU wide at the widest point.

Many Jupiter Trojans have orbital inclinations

Camping with the Trojans

Jupiter's Trojan asteroids are divided into two main groups. Asteroids in the Greek Camp (leading Jupiter at L4) are named after Greek heroes, while those in the Trojan Camp (trailing Jupiter at L5) are named after Trojan heroes.

ASTRONOMY: ROEN KELLY



(or tilts in their orbital planes) larger than Jupiter, and some much larger. For example, the Trojans 2009 WN204 and 2010 BK101 have inclinations of 40.3° and 40.2°, respectively, while 2146 Stentor has an orbital inclination of 39.3°. Still, the gravitational dance between the planet and the Sun always brings them back to these two "sweet spots" along Jupiter's orbit.

The first official Trojan was discovered February 22, 1906, by German astronomer Max Wolf. Eight months later, August Kopff discovered a second asteroid near Jupiter's L5 point; the following February, Kopff found a third, this one near L4. Austrian astronomer Johann Palisa, a prolific discoverer of asteroids, followed up with multiple observations of all three, and he worked out their orbits. It was Palisa who suggested that asteroids in Jupiter's orbit be named for heroes of the Trojan War, and the first three Trojan asteroids were named Achilles, Patroclus and Hektor. As more of these bodies were discovered, a naming convention developed; asteroids near the L4 point were named for Greek heroes (the so-called "Greek Camp") and those near L5 for Trojan heroes (the "Trojan Camp"). However, 617 Patroclus (at L5) and 624 Hektor (at L4) were named before this convention took root. So each camp has a "spy" in its midst!

By 1961, more than half a century after Wolf identified the first Trojan, only 13 more had been discovered. With further improvements in instrumentation, the number increased, first slowly and then in a rush. By early 2017, more than 6,500 had been spotted: 4,184 at Jupiter's L4 point and 2,326 at L5. Scott Sheppard, an astronomer at the Carnegie Institution for Science and a decorated detector of small bodies within the solar system, has said that the number of Jupiter Trojans may well exceed the total number of objects in the main asteroid belt.

But despite the plethora of discovered Jupiter Trojans, we actually know relatively little about them. Most of our observations have been made with Earth-based telescopes. And although astronomers have discovered fewer Trojans in the L5 cloud than in the L4 cloud, this could be a result of observational biases in their coverage.

Lucy in the sky

About 3.2 million years ago, in what is today the Awash River valley in Ethiopia, a small apelike creature died. How it happened is unknown: Perhaps she fell from a tree, or perhaps she was on some journey and lost her way. But there she lay, parts of her skeleton lost to the wind and rain. Rocks, dirt, and volcanic dust covered her bones, layer after layer, as millennia passed.

Then in 1974, a team of paleoanthropologists

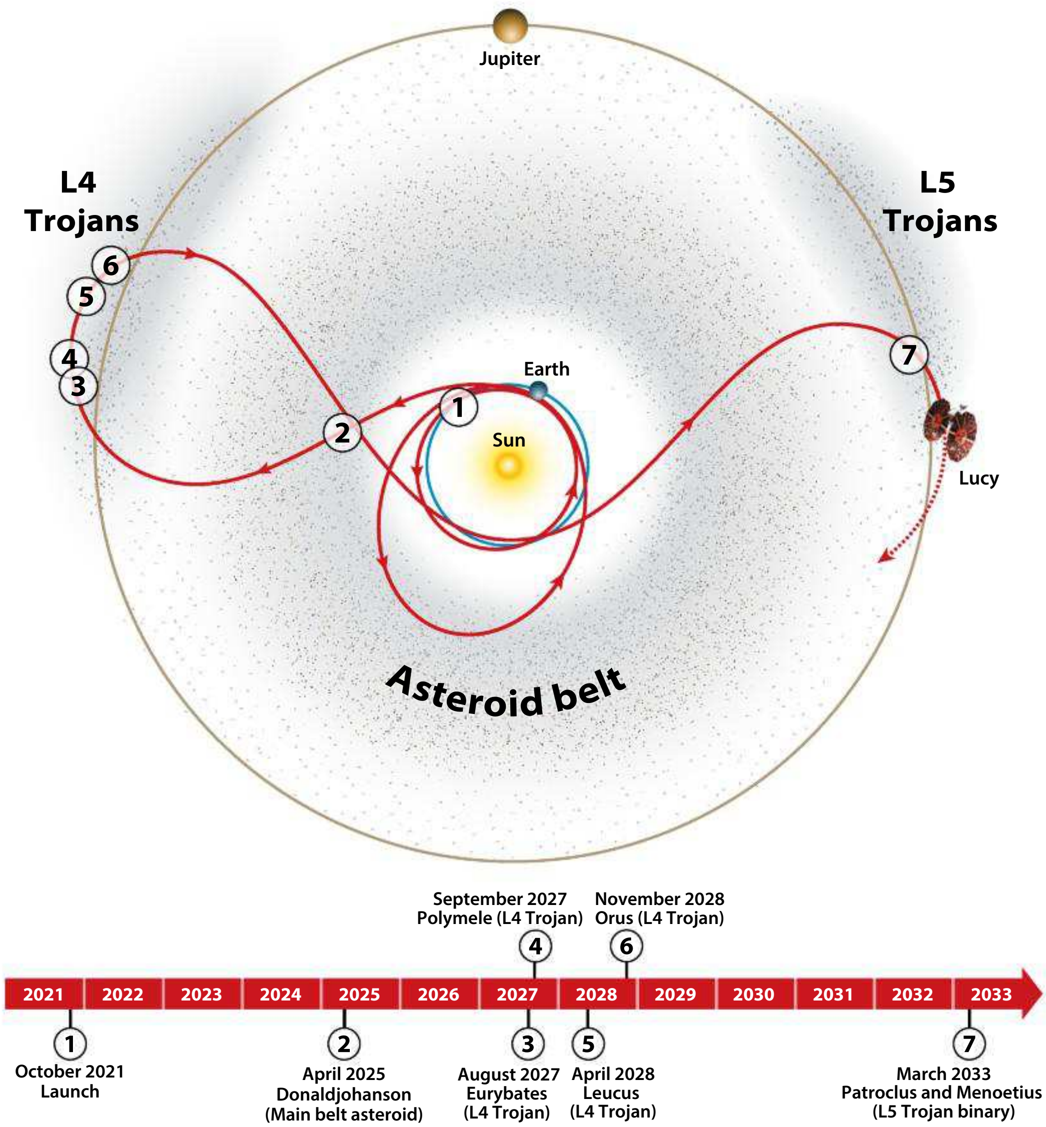
So little is known about the Trojans that the data will certainly revolutionize our understanding of these ancient bodies. What the spacecraft uncovers could confirm some current theories of the solar system's early evolution — or turn it all upside down.

FAST FACTS: JUPITER'S TROJANS

- The largest known Jupiter Trojan, 624 Hektor, is just 140 miles (225 km) wide, smaller than the 15 largest main belt asteroids. At least 24 moons are larger than Hektor.
- The smallest known Trojan is 2002 CO208, discovered in February 2002 by the Lincoln Near-Earth Asteroid Research project (LINEAR) near Socorro, New Mexico. It's an estimated 4 miles (6.6 km) in diameter. Smaller objects surely exist in both camps, but no one knows the actual numbers or sizes. The size distribution of the discovered Trojans suggests that the smaller bodies are the remains left by collisions of larger Trojans.
- Hektor is the most elongated jovian Trojan at 125 by 230 miles (200 by 370 km). Observations made with the Keck II 10-meter telescope in 2006 showed that it has a distinctive dumbbell shape. So it's likely a contact binary — two asteroids "glued together" by their mutual gravitational attraction.
- Hektor is one of only two known Trojans with a companion. Skamandrios is about 7.5 miles (12 km) in diameter and orbits Hektor at a distance of 390 miles (630 km). The other is 617 Patroclus, a binary asteroid whose companion, Menoetius, has nearly the same diameter.
- 11351 Leucus, one of Lucy's targets, has a very slow rotation period — about 440 hours, or more than 18 Earth days. Most asteroids have rotation periods between 2 and 20 hours. Only 62 main belt asteroids are known to have rotation periods greater than Leucus. — **J.D.**

Twelve years, seven targets

This diagram illustrates the path Lucy will take during its 12-year journey, which will take it close by four L4 asteroids, two L5 asteroids, and one main-belt asteroid for good measure. *ASTRONOMY*: ROEN KELLY AFTER SOUTHWEST RESEARCH INSTITUTE



led by Donald Johanson found about 40 percent of her fossilized skeleton. She was a member of the hominin species *Australopithecus afarensis*, and she's probably the most famous pre-human fossil in history. Her scientific name is AL 288-1, but everyone knows her as Lucy. The name comes from the equally famous Beatles song, "Lucy in the Sky With Diamonds," which Johanson's team listened to at camp the night of their discovery.

Now, a spacecraft bearing her name will journey into the sky in search of scientific diamonds. It will take — to steal from another Beatles tune — a long and winding road to get there. But the results will be worth the wait.

For the Lucy mission, this is a second chance. The mission's principal investigator, Hal Levison of the Southwest Research Institute (SwRI) in Boulder, Colorado, notes that a mission named Lucy was proposed once before. "There was a call in 2010 for new Discovery missions," he says, "and one of the proposals then was for a mission also called Lucy." This first proposal was based on the New Horizons spacecraft and had different targets, only one of which was a Jupiter Trojan. It was not approved.

When the next call for Discovery missions was made in 2014, Levison decided to "reboot" it with the same name but with a new purpose. "The people involved in the first proposal were rather distracted by New Horizons, as you can imagine," he says. "I decided it would be a good thing to change the focus of the mission a little bit and really study the Trojan asteroids." SwRI and NASA's Goddard Space Flight Center in Greenbelt, Maryland, sought each other out to create the new Lucy proposal, with Lockheed Martin designing and building the spacecraft.

Lockheed Martin has a long and successful record building spacecraft for NASA, including the OSIRIS-REx asteroid sample-return mission, the 2001 Mars Odyssey orbiter, and the Mars InSight mission slated for launch in 2020. Tim Holbrook is the company's deputy program manager for Lucy. The science team, led by Levison and Catherine Olkin, is based at SwRI in Boulder. The Goddard Space Flight Center is the NASA facility managing the project, with Keith Noll serving as project scientist.

The new Lucy will not look like New Horizons. "When you look at Lucy, you see the size, the physical characteristics, and structure of the Mars Odyssey orbiter. It also incorporates all the latest-generation spacecraft systems — like the avionics package — from OSIRIS-REx," explains Holbrook. "We've also looked back at other spacecraft we have built in recent years, such as the planned InSight Mars lander. We [are] pulling together the best of the best."

The spacecraft will be 11.5 feet (3.5 meters) tall at launch, and 44 feet (13.5 m) across when it is fully deployed and its two circular solar arrays are unfurled. Lucy will have what Holbrook calls "a dual-mode propulsion system" that uses oxidizer and hydrazine for the mission's five major burns, and just hydrazine for smaller trajectory-adjusting maneuvers and station-keeping.

Lucy's Trojan targets are 3548 Eurybates, 15094 Polymele, 11351 Leucus, and 21900 Orus in the L4 Greek Camp, plus 617 Patroclus and its binary companion, Menoetius, in the L5 Trojan Camp. The spacecraft will gather data on the surface composition, surface geology, and the interior and bulk properties of the Trojan targets (plus one main belt asteroid named 52246 Donaldjohanson). And it will do it from close range. The Lucy team will also use the spacecraft's radio telecommunications hardware to measure Doppler shifts — or changes in a signal's frequency that are induced when an object is moving relative to an observer. As Lucy orbits a Trojan, minute variations in the asteroid's mass concentration will cause the craft to slightly speed up or slow down. These tiny changes in speed will shift Lucy's radio signal, allowing astronomers to deduce how much mass is required to account for the shift.

Two of Lucy's three scientific instruments are lifted directly from New Horizons, and the third from OSIRIS-REx. The L'Ralph telescope, built by the Goddard Space Flight Center, is a color optical CCD imager and infrared spectroscopic mapper. The original on New Horizons was named for Jackie Gleason's character in *The Honeymooners* television series. LORRI, a high-resolution visible light imager, is Lucy's version of the LOng-Range Reconnaissance Imager aboard New Horizons; it is from the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland. The Thermal Emission Spectrometer (TES) is an upgraded version of the OSIRIS-REx instrument, built at Arizona State University in Tempe.

UP CLOSE AND PERSONAL WITH ASTEROIDS

Occasionally 2 Pallas is visible to the naked eye. But for 190 years, all the other asteroids have been little more than moving points of light seen through binoculars or telescopes. What we knew of them was limited to their size and to what we could glean from the light reflected off their surfaces.

That changed dramatically in 1991, when the Galileo spacecraft flew past 951 Gaspra on its way to Jupiter. On Valentine's Day in 2000, the NEAR-Shoemaker spacecraft went into orbit around the near-Earth asteroid Eros, and sent back a wealth of images and other information about that body. The probe eventually landed on the asteroid's surface, making it the first space probe to soft-land on an asteroid. In all, eight main belt asteroids and three near-Earth asteroids have been visited, orbited, or landed upon by space probes from China, the European Space Agency, Japan, and the United States. What we know about the Jupiter Trojans, though, is pretty much at the level of what we knew about main belt asteroids before 1991.

"Our understanding of the main belt population was revolutionized by those missions," notes Lucy principal investigator Hal Levison. "Lucy is going to go to almost as many objects as we have visited in the main belt throughout the history of space exploration. All in one fell swoop." — **J.D.**

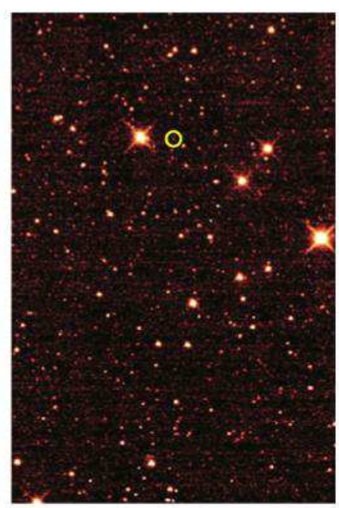
Date(s)	Asteroid	Spacecraft	Mission(s)
10/29/1991	951 Gaspra	Galileo	Flyby
8/28/1993	243 Ida/Dactyl	Galileo	Flyby
7/29/1999	9969 Braille	Deep Space 1	Flyby
1/23/2000	2685 Masursky	Cassini-Huygens	Flyby
2/14/2000-2/12/2001	433 Eros	NEAR-Shoemaker	Orbit, landing
11/2/2002	5535 AnneFrank	Stardust	Flyby
10/4-10/19/2005	25143 Itokawa	Hayabusa 1	Station-keeping, landing, sample retrieval, departure
12/5/2008	2867 Steins	Rosetta	Flyby
7/16/2011	4 Vesta	Dawn	Orbit
12/13/2012	4179 Toutatis	Chang'e 2	Flyby
3/6/2015	1 Ceres	Dawn	Orbit

The long and winding road

Lucy's journey to the Jupiter Trojans will be a long one, lasting nearly 12 years from start to finish. The current timeline calls for the spacecraft to launch in October 2021. Two flybys of Earth in October 2022 and December 2024 will slingshot the spacecraft through the asteroid belt toward the Greek Camp at Jupiter's L4 region. In April 2025, Lucy will make a close flyby of 52246 Donaldjohanson, a main belt asteroid 2.4 miles (4 km) wide and named for the discoverer of the original Lucy — an appropriate first encounter!

In August 2027, the spacecraft will reach its first Trojan target, Eurybates, about 39 miles (64 km) in diameter. The main belt includes many so-called asteroid "families" created by collisions, but only one such family is known in the Trojans. And Eurybates is its largest known member.

A month later, Lucy will fly by Polymele. This 13-mile-diameter (21 km) object is probably also a fragment from an ancient collision. Then in



NASA/JPL-CALTECH/UCLA

Astronomers discovered asteroid 2010 TK7 (circled in yellow), the first known Earth Trojan asteroid, by searching for asteroid candidates with NASA's Wide-field Infrared Survey Explorer (WISE). This image was taken in October 2010.

OTHER TROJAN ASTEROIDS

Every planet but Mercury and Saturn has at least one known Trojan asteroid, even a temporary one. Venus and Earth have one each; Mars has eight; Uranus has two; and Neptune has at least 18.

Astronomer Scott S. Sheppard of the Carnegie Institution for Science and the co-discoverer of four Neptune Trojans believes that Neptune actually has a Trojan swarm larger than Jupiter's. Two of Saturn's moons are also accompanied by Trojan asteroids. Several researchers have offered evidence that both the dwarf planet Ceres and the asteroid Vesta have at least one temporary Trojan each.

Despite extensive searching, no Trojan objects have been found at the Earth-Moon L4 and L5 Lagrangian points, nor at the Mercury or Saturn Lagrangian points. — **J.D.**

VENUS

Name	Location	Discoverer	Diameter (m)	Notes
2013 ND_{15}	L4	WISE	~40–100	Temporary; eccentric orbit crosses orbits of Mercury and Earth

EARTH

Name	Location	Discoverer	Diameter (m)	Notes
2010 TK_7	L4	WISE	~30	Temporary

MARS

Name	Location	Discoverer	Diameter	Notes
5261 Eureka	L5	D.H. Levy, H. Holt	~1.3 km	First known martian Trojan; discovered in 1990
1998 VF_{31}	L5	LINEAR	~800 m	
1999 UJ_7	L4	LINEAR	~1 km	Only known L4 martian Trojan
2001 DH_{47}	L5	Spacewatch	562 m	
2007 NS_2	L5	Observatorio Astronómico de La Sagra	800–1600 m	
2011 SC_{191}	L5	Mount Lemmon Survey	600 m	
2011 SL_{25}	L5	Alianza S4 Observatory	~550 m	
2011 UN_{63}	L5	Mount Lemmon Survey	560 m	

SATURN TROJAN MOONS

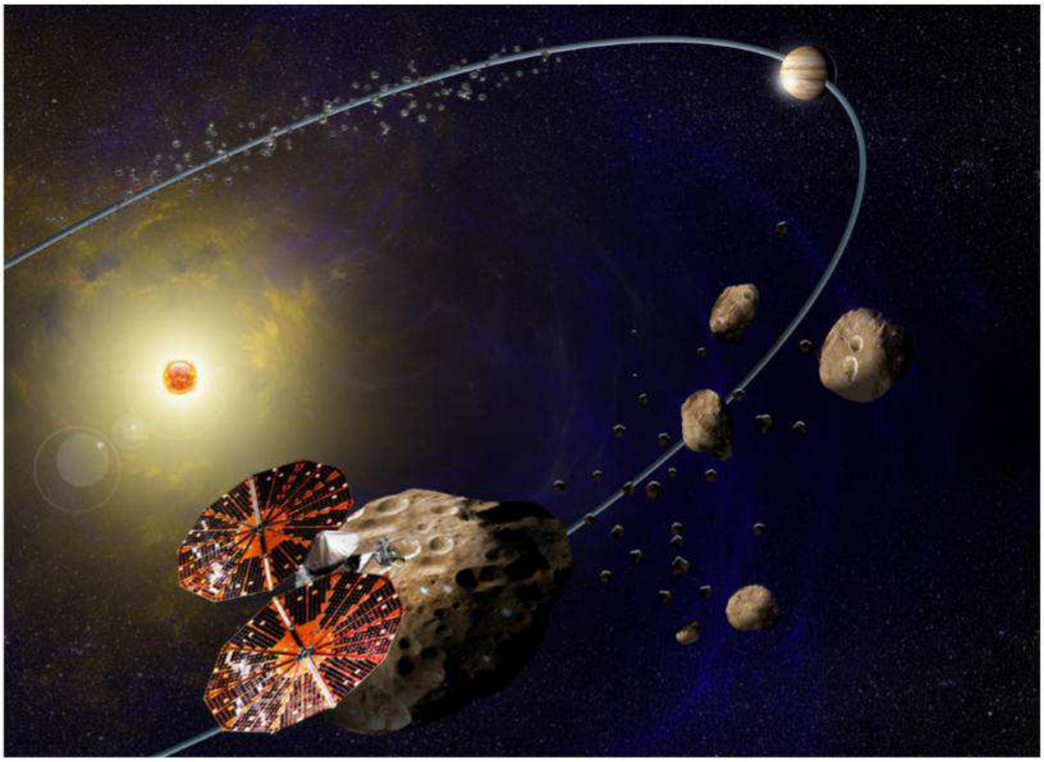
Name	Location	Discoverer	Diameter (km)	Notes
Telesto	Tethys, L4	B.A. Smith, H. Reitsema, S.M. Larson, J.W. Fountain	~24.8	Discovered in 1980; Trojan status determined in 1981
Calypso	Tethys, L5	D. Pascu, P.K. Seidelmann, W.A. Baum, D.G. Currie	~21.4	Discovered in 1980; Trojan status determined in 1981
Helene	Dione, L4	P. Laques, J. Lecacheux	~35.2	Discovered in 1980 during Earth ring-plane crossing
Polydeuces	Dione, L5	Cassini Imaging Science Team	~2.6	Discovered in 2004; first Trojan discovered by a space probe

URANUS

Name	Location	Discoverer	Diameter (km)	Notes
2011 QF_{99}	L4	M. Alexandersen, J. Kavelaars S.M. Larson, J.W. Fountain	~60	First discovered uranian Trojan; centaur in temporary Trojan orbit
2014 YX_{49}	L4	B. Gibson, T. Goggia, N. Primak, A. Schultz, M. Willman	40–120	Centaur in temporary Trojan orbit

NEPTUNE

Name	Location	Discoverer	Diameter (km)	Notes
2001 QR_{322}	L4	Deep Ecliptic Survey	~140	First Neptune Trojan discovered
2004 KV_{18}	L5		56	Temporary (~100,000 year)
2005 TN_{53}	L4	S.S. Sheppard, C. Trujillo	~80	First high-inclination Trojan discovered
2005 TO_{74}	L4	S.S. Sheppard, C. Trujillo	~100	Possibly unstable orbit
2006 RJ_{103}	L4	Sloan Digital Sky Survey	~180	
2007 VL_{305}	L4	Sloan Digital Sky Survey	~160	High (28.1°) inclination
2008 LC_{18}	L5	S.S. Sheppard, C. Trujillo	~100	First L5 Trojan discovered; high (27.5°) inclination
2010 EN_{65}	L4*	D. L. Rabinowitz, S.W. Tourtellotte	~200	*Jumping Trojan, moving from L4 to L5 via L3
2010 TS_{191}	L4	Hsing Wen Lin et al.	~120	Pan-STARRS 1 (PS1) survey
2010 TT_{191}	L4	Hsing Wen Lin et al.	~130	Pan-STARRS 1 (PS1) survey
2011 HM_{102}	L5	New Horizons KBO Search Survey	90–180	High (29.4°) inclination; second Trojan discovered by a spacecraft
2011 SO_{277}	L4	Hsing Wen Lin et al.	~140	Pan-STARRS 1 (PS1) survey
2011 WG_{157}	L4	Hsing Wen Lin et al.	~170	Pan-STARRS 1 (PS1) survey
2012 UV_{177}	L4		~80	
2013 KY_{18}	L5	Hsing Wen Lin et al.	~200	Pan-STARRS 1 (PS1) survey
2014 QO_{441}	L4	Dark Energy Survey Collaboration	~130	Most eccentric stable Neptune Trojan
2014 QP_{441}	L4	Dark Energy Survey Collaboration	~90	
385571 Otrera	L4	S.S. Sheppard, C. Trujillo	~100	First named Trojan



In this artist's concept (not to scale), the Lucy spacecraft flies by Eurybates, one of six notable Trojans that it will encounter between 2027 and 2033. Lucy will also fly by 52246 Donaldjohanson, a main belt asteroid named after the discoverer of a fossil hominin coincidentally nicknamed "Lucy."

April 2028, the spacecraft will visit Leucus, which is 21 miles (34 km) wide and very dark. The last L4 Trojan Lucy will visit is Orus in October 2028. Orus is about 32 miles (51.5 km) wide.

Lucy's orbit will bring it back to Earth for another gravity-assist flyby in December 2030. Then it will again coast out to Jupiter's realm and pass through the L5 swarm for a final Trojan encounter in March 2033. Patroclus, the second Trojan to be discovered, is a binary asteroid with a mean diameter of 70 miles (113 km), and its companion, Menoetius, is roughly 65 miles (104 km) wide. They orbit one another at a distance of 422.5 miles (680 km).

"That's going to be a great encounter, my favorite!" exclaims Levison. "It's at the end of the mission. We will have to wait, but it will be the highlight!"

The science team had two objects of particular interest for the Lucy mission, Levison says. Eurybates, the first Trojan Lucy will encounter, is the only one on the team's "must-visit" list. The other is Patroclus. "The fact that Patroclus is still a binary means that it is probably pretty pristine," says Levison. "If either of the objects in the binary had suffered a large collision, it would have completely disrupted the binary. That's why there are so few binaries in the inner part of the solar system.

"On the other hand, Eurybates is the largest member of a collisional family of objects," he says. "So we are visiting a binary that is probably pretty pristine, and a guy that we know got the crap kicked out of it. Comparing those will be interesting in and of itself."

The visit to Patroclus is a great example of the good fortune Levison's team has had. "This object has an orbital inclination of more than 20°, and it just so happens that it will be crossing the plane of the solar system just as Lucy goes by," he says. "It was pure luck. I've been studying celestial mechanics for 30 years, and the celestial mechanics gods are paying me back!"

With their low albedos and reddish spectra, most Jupiter Trojans appear similar to some outer main belt asteroids, centaurs, and Kuiper Belt objects. However, says Levison, many individual Trojans differ widely in spectral type, color, size, and collisional history. One possible explanation for this mystery is that these objects all originally formed in the outer reaches of the solar system and were later mixed together in the Trojan swarms. That could have occurred during planetary formation, or later as the giant planets migrated to their present-day orbits. But the only way to begin sorting it out is to study the diversity of the Trojans up close.

Fortunately, Levison and his team are confident that Lucy is the perfect mission to help shed new light on these dusky diamonds in the sky.

Joel Davis *has worked as a technical writer at Microsoft and WideOrbit. He blogs regularly at notjustminorplanets.blogspot.com.*

SPACECRAFT AT OTHER LAGRANGIAN POINTS

Lagrangian points provide unique vantage points for space research. The following operational spacecraft reside at or near two Sun-Earth Lagrangian locations:

Sun-Earth L1

- Solar and Heliospheric Observatory (SOHO), 1996–present
- Advance Composition Explorer (ACE), 1997–present
- GGS WIND, 2004–present
- Deep Space Climate Observatory (DSCOVR), 2015–present
- LISA Pathfinder, 2016–present

The International Sun–Earth Explorer 3 (ISEE-3) operated around the Sun-Earth L1 point for four years (1978–1982). After being moved to a heliocentric orbit and renamed the International Cometary Explorer (ICE) in 1985, it became the first spacecraft to visit a comet, 21P/Giacobini–Zinner.

Sun-Earth L2

- Gaia Space Observatory, 2014–present

Gaia is currently the only operational spacecraft at the Sun-Earth L2 point. GGS Wind and Chang'e 2 spent time at L2 and then moved on to other locations in the solar system. They are still operational. Three others — the Wilkinson Microwave Anisotropy Probe, the Herschel Space Telescope, and the Planck Space Observatory — successfully completed operations at the L2 point and were then moved into heliocentric parking orbits. — **J.D.**