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On a New Moon Far, Far Away

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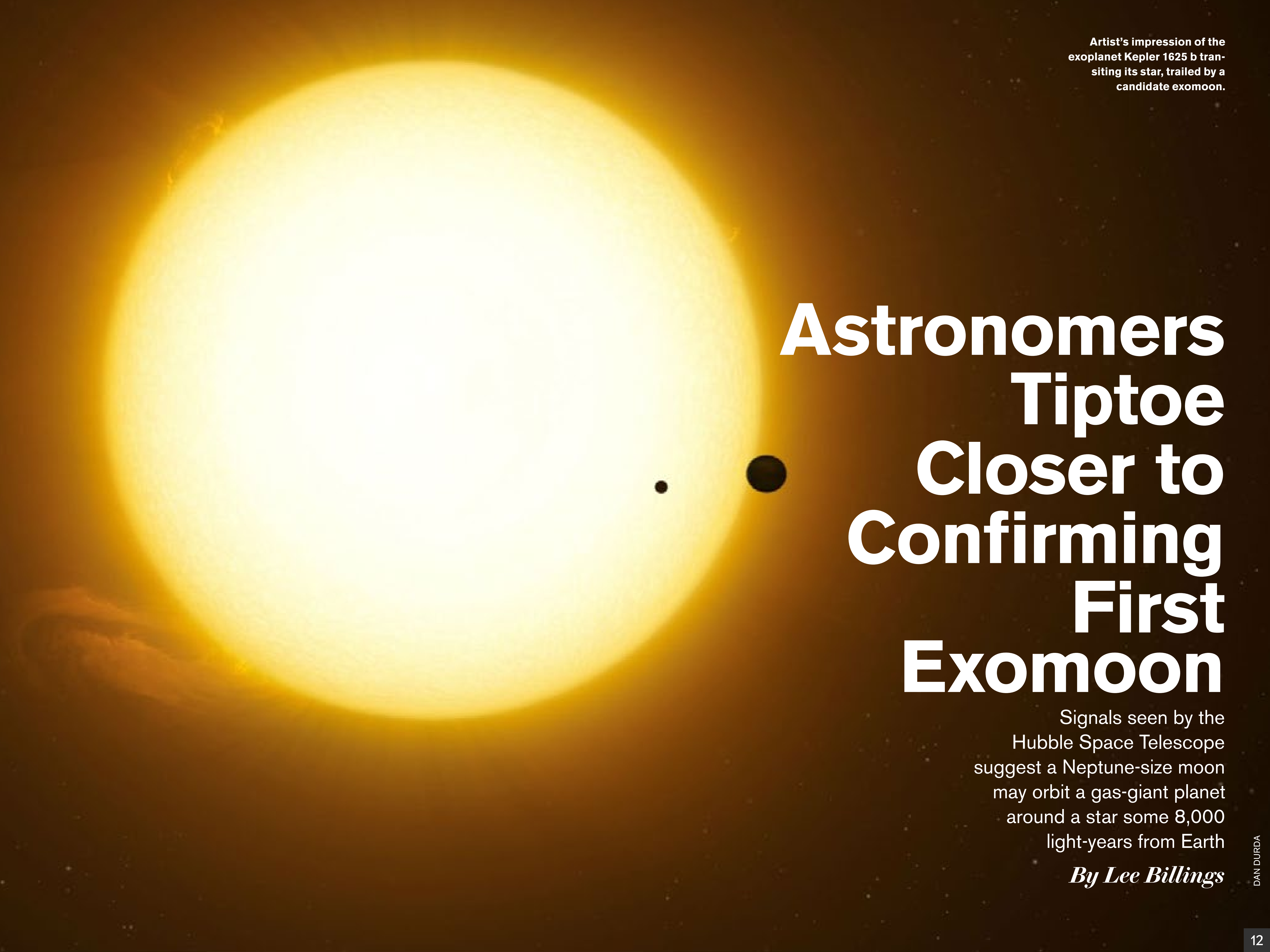

Artist's impression of the exoplanet Kepler 1625 b transiting its star, trailed by a candidate exomoon.

DAN DURDA

Astronomers Tiptoe Closer to Confirming First Exomoon

Signals seen by the Hubble Space Telescope suggest a Neptune-size moon may orbit a gas-giant planet around a star some 8,000 light-years from Earth

By Lee Billings

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HAVE ASTRONOMERS JUST FOUND THE FIRST-EVER exomoon, a lunar companion of a planet orbiting another star? Definitely maybe.

Using data from NASA's Kepler and Hubble space telescopes, Columbia University astronomers Alex Teachey and David Kipping report the potential signal of a Neptune-size moon around a planet three times heavier than Jupiter, all orbiting a nearly 10-billion-year-old sun-like star called Kepler 1625 b about 8,000 light-years from Earth. Such a large moon defies easy explanation based on prevailing theories. The findings appear in a study published October 3 in Science Advances, and follow from the duo's earlier work reported last year that first offered more tentative evidence of the moon.

If confirmed, this discovery would challenge scientists' current understanding of planet and moon formation while bearing potentially profound implications for the prevalence of life throughout the cosmos, revealing once again that when it comes to alien worlds, the universe is often stranger than anyone can suppose.

AN EXTRAORDINARY EXOMOON

IF OUR SOLAR SYSTEM IS any guide at all, moons should vastly outnumber planets in the universe, and could make up most of the habitable real estate in any given galaxy. Pinning down how—and how often—they form would thus give astrobiologists a leg up on finding life elsewhere in our galaxy. Already, Kipping and Teachey's statistics derived from Kepler data suggest moons are conspicuously absent around planets in temperate orbits around their stars—hinting that most large lunar companions must lurk farther out in colder climes, and that habitable moons akin to *Star Wars*' Endor or *Avatar*'s Pandora may be exceedingly rare.

Moons, it is thought, can form in three ways: coalescing from rings of gas and dust leftover from a planet's formation; from debris knocked into orbit around a planet from a giant impact; or by being gravitationally captured by a planet via rare close encounters with pairs of co-orbiting asteroids or comets. But this newly proposed exomoon fails to fit neatly in any of those origin stories. It appears to be too big to easily coalesce alongside its planet, which itself is too massive and gassy to readily eject debris from any conceivable impact. Capture via close encounter, although possible, would require an implausibly perfect concatenation of unlikely circumstances. "If valid, this would probably open up a new formation scenario for moons," says René Heller, a theorist at the Max Planck Institute for Solar System Research in Germany who was not part of the study. "Actually, the very existence of the proposed moon would call for a need to rethink our concepts of what a 'moon' actually is in the first place."

For perspective, consider that our solar system's largest moon, Jupiter's Ganymede, is less than half as massive as our sun's smallest planet, Mercury. Kepler 1625 b's moon, by contrast, would be about 10 times as massive as all the terrestrial planets and the hundreds of moons in our solar system combined. This suggests, Heller says, "that this moon would have formed in a completely different way than any moon in our solar system."

Even the study's authors agree their potentially historic claim should give pause—no one has ever conclusively discovered an exomoon before, let alone one so utterly bizarre. "This moon would have fairly surprising properties, which is a good reason for skepticism," says Kipping, an assistant professor at Columbia who has spent the last decade pioneering the hunt for exomoons. "If this was the 10th known object of its type, we would be calling it a 'discovery,' no question. But because it's the first of its kind, it demands a higher level of scrutiny.... I can't yet convince myself 100 percent this is definitely real."

"We are urging caution here—the first exomoon is obviously an extraordinary claim, and it requires extraordinary evidence," says Teachey, the study's lead author and a Ph.D. candidate under Kipping's wing at Columbia. "We are not cracking open champagne bottles just yet on this one."

Scarcely anything else is known about this potential satellite, save that its estimated size and three-million-kilometer separation from its planetary host would make it appear in that world's skies twice as large as Earth's own moon. Based on the planet-moon pair's 287-day orbit around its star, Teachey and Kipping have crudely calculated average temperatures there might approach that of boiling water—uncomfortably warm, to be sure, but easy enough for Earth's hardiest microbes to thrive in. Biology's bigger challenge would be the lack of surfaces on both the planet and its moon—expect no aliens there.

CAUGHT IN TRANSIT

CLAIMS OF EXOMOONS HAVE come and gone over the years, but a couple stand out as particularly plausible. In 2013 scientists reported the potential detection of what could have been either a Mars- to Neptune-mass exomoon circling a Jupiter-mass exoplanet floating freely through space—or a Jupiter-like gas giant orbiting a small, faint star. Whatever its nature, the system was only detected in the first place due to a phenomenon called gravitational microlensing that occurs just once and entirely by chance in any given instance, and thus could not be observed again. Then, in 2015, a separate analysis of a gargantuan ring system found around the "super-Saturn" exoplanet J1407 b revealed multiple gaps potentially cleared by what might be several Mars- to Earth-mass exomoons otherwise hidden in the rings. Yet beyond these circumstantial findings no credible candidates existed.

The first hints of a breakthrough discovery emerged last year, as part of a five-year hunt Kipping and Teachey conducted for exomoons around nearly 300 planets from Kepler's massive data set, which contains thousands of known worlds. Almost all of Kepler's planets transit, meaning they cross the faces of their suns as seen from Earth, casting a shadow toward us that astronomers measure as a star's brief dimming. If some of those planets harbor conspicuously large moons in wide orbits, the moons might detectably transit, too, imprinting their own much smaller diminution in a star's light either shortly before or after a planet's passage. Kipping and Teachey spied what looked to be just such a signal in three transits of Kepler 1625 b. This was enough to net them 40 hours of time using Hubble's Wide Field Camera 3 (WFC3) instrument for a follow-up observation of a single additional transit of the planet and its potential moon, predicted to take place on October 28 and 29, 2017. In addition to looking for a moon's transit, their Hubble program would also attempt to pin down the precise timing of Kepler 1625 b's transit, which could be altered by the gravitational tugging of a moon or a nearby nontransiting planet.

Reaching four times greater precision than Kepler's data, Hubble's observations revealed that, indeed, this transit of Kepler 1625 b was shifted in time, arriving about 75 minutes ahead of schedule—just as would be expected if the planet's motions were being perturbed by a massive accompanying moon. Additionally, 3.5 hours after the planet's transit concluded, Hubble picked up a second, far smaller dip as the star's brightness appeared to fade by just five hundredths of 1 percent. Stars dim more than that all the time due to starspots and convective patterns on their surfaces, but basic observational tests suggest such stellar activity was not the culprit here, Kipping says. Instead, he says, the minuscule signal was consistent with a Neptune-size moon "trailing the planet like a dog following its owner on a leash."

> **"A moon is the simplest, most elegant and self-consistent hypothesis—that's why we favor it."**
> ***—David Kipping***

Alas, Kipping and Teachey's allotted Hubble time expired before they could capture the conclusion of the smaller transit's conclusion, rendering their data set incomplete and leaving wide open the possibility that the apparent shadow of the moon had been something else entirely.

A TIME TO KILL

"I don't see any reason why it wouldn't be an exomoon," says Peter McCullough, an astronomer and expert on Hubble's instrumentation at Johns Hopkins University who was not involved in the research. "Alternatively, I don't see any reason why it would be. Either statement is justifiable."

Against the exomoon hypothesis, McCullough and other researchers familiar with the results note Hubble's WFC3 instrument is notorious for routinely exhibiting minor, hard-to-pin-down variations in its performance that could mimic the subtle signal of a moon. Furthermore, they point to the latest data release from the Kepler mission, in which new, state-of-the-art analytical methods caused the already borderline signs of the exomoon to fade to insignificance in the Kepler data. "I think this shows how fluid the interpretation can be, with so few observed transits [of Kepler 1625 b]," McCullough says. "The researchers are fully aware of that—they are the world's experts in this field. It's just the nature of the problem—it's hard."

Teachey and Kipping maintain that after spending almost a year being their own harshest critics and trying as best they can to explain away the evidence, their most extraordinary claim remains the most compelling. "As far as we can tell, there is no way to kill this signal—there really is a second dip in the star's light," Kipping says. And yes, the time shift in Kepler 1625 b's transit could alternatively be due to the influence of a very massive unseen planet—but no such planet has been found despite Kepler's and Hubble's combined scrutiny. "A moon is the simplest, most elegant and self-consistent hypothesis—that's why we favor it." Kipping says. "The time has come to let the community interrogate our findings."

There is only one way to truly settle the issue: more data. NASA's upcoming James Webb Space Telescope should be more than capable of definitively ruling for or against this hoped-for first exomoon, but it is not slated to launch until 2021 at the earliest. In the meantime Kipping and Teachey are awaiting approval of another Hubble observing proposal, which would use twice as much telescope time to catch complete transits of Kepler 1625 b and of its putative moon during the celestial pair's next predicted crossing in May 2019.

This time, they predict the moon will be on the opposite side of its orbit, with a transit preceding that of the planet itself. "We should see a separate, clean moonlike event," Kipping says. "If we see that, then I think we're done.... I think we'd have a very closed case on this system." Except, of course, on how it formed in the first place.