MORE THAN 400 LIGHT-YEARS away from Earth, the 16-million-year-old star J1407 (*upper left*) harbors a giant world wreathed by the largest planetary ring system ever seen. Nestled within a gap inthe planet's rings, a newborn Mars-sized moon (*foreground*) still glows from the heat of its formation.

Illustration by Ron Miller

PLANETARY SCIENCE

Rings of a Super Saturn

Astronomers have discovered a gargantuan planetary ring system and possibly a moon around another star

By Matthew Kenworthy

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MUCH ASTRONOMY TAKES PLACE IN THE OFFICES AND OBSERVATORIES WHERE scientists work. But if you want to find the most exciting theories, you need to go where guards are lowered and wilder ideas can roam free.

It is not by coincidence that one of the best bars in Tucson, Ariz. (called 1702, after its street address), nestles close to Steward Observatory at the University of Arizona. It was there that my colleague Eric Mamajek of the University of Rochester showed me something that sent us on a quest to find the first ringed planet beyond our solar system, a quest involving both the world's most modern telescopes and century-old astronomical observations. Along the way, we found not only a ring system larger than Saturn's but also what seems to be a newborn moon.

SPOTTING THE RINGS

THE STORY BEGINS in 2011, when Mamajek and his then graduate student Mark Pecaut at Rochester were assembling a catalog of very young stars near to Earth. To guess the ages of their candidates, Mamajek and Pecaut checked the stars' rotation rates. Younger stars spin faster than older ones, and their spins can be clocked by watching for star spots (darker, cooler regions on a star's surface) coming in and out of view.

One candidate for inclusion in the survey had no name, just a code based on the instruments that observed it and its position in the sky, in the constellation of Centaurus: 1SWASP J140747.93-394542.6. We now call it J1407 for short. It and the other stars under consideration were too far away for their spots to be seen directly, so Mamajek and Pecaut instead examined J1407's "light curve"—a plot of its brightness over time—looking for small dips when spots spun into view and reduced the starlight. Planets can also cause such dips when they "transit" across their stars as seen from Earth. Mamajek and Pecaut found J1407's curve in the database of a planet-hunting camera survey called SuperWASP, which to date has found more than 100 transiting planets by monitoring about 31 million stars.

The light curve did suggest that J1407 was a young, rapidly spinning star, but it also held other, more intriguing information. A casual glance at SuperWASP's light curve for J1407 showed that in 2007 the otherwise unremarkable star flickered in an unpredictable pattern for many nights, then repeatedly dimmed to near invisibility over a week, before finally returning to its usual brightness. Data from other years showed no such variability in the star. In 2007 the odd event did not make much of an impression, and the curve had then languished unnoticed in the archives. But after he saw it in 2011, Mamajek could not forget about it.

"I put a printout of the light curve on my office wall, and I looked at it for weeks," he recalled to me in the bar in Tucson. "The crazy structure and detail were unique. What could cause these rapid changes in the star's brightness?"

IN BRIEF

Researchers have discovered a ring system some 200 times larger than Saturn's around a giant planet orbiting a distant star in the Milky Way.

Using state-of-the-art observations and archival data, professional and amateur astronomers are joining forces to study the system in more detail.

Models of the rings suggest they harbor a Mars-sized moon. If confirmed, this moon would be the first detected beyond our solar system, suggesting more await discovery. Further studies of this unique system promise to reveal new, unprecedented details of how planets and moons form around other stars.

Soon after that discussion we began working together to solve the mystery. We quickly ruled out such obvious culprits as problems with the SuperWASP cameras or poor observing conditions. Whatever it was, the source of J1407's mysterious dimming was not located on Earth.

We soon concluded that something very fast and very big must be eclipsing J1407 and making it flicker. The speed of the brightness fluctuations suggested that the eclipsing object was racing in front of the star's face at 30 kilometers per second, and yet the eclipse itself lasted for 56 days! This long duration meant that the object was some 180 million kilometers in size.

There are only so many plausible explanations for what a structure so large could be. One by one, we considered and then dismissed them. Could it be a belt of dust orbiting close to the star? No, there was no telltale infrared glow around J1407 that you would expect from warm dust. Was this a binary system, with a giant red star eclipsing a smaller companion such as a white dwarf, neutron star or black hole? No, such systems tend to emit far more x-rays than we were seeing, and J1407 did not appear to be a giant star. Could the flickering be a coincidence caused by the shadow of something floating in deep interstellar space between Earth and the star, or could J1407 perhaps be a complex triple-star system, with an eclipsing 180-million-kilometer wide companion? No, neither of those possibilities matched the data, either. In the end, the simplest explanation consistent with all the observations was also something very strange: the dips in the light curve could be caused by a giant ring system some 200 times larger than Saturn's, orbiting an unseen planet that had passed between J1407 and Earth in 2007.

But why did we think it was a ring system? The most striking feature in the light curve was the level of detail that could be seen at all timescales—the eclipses lasted 56 days, but rapid changes could be seen to happen in as little as 20 minutes. These speeds hinted that the giant eclipsing object had large amounts of substructure, and the roughly symmetric shape of the light curve suggested that the object possessed a circular or elliptical geometry—much like the familiar ring system of Saturn. If we were right, the gargantuan planetary rings would be the first found outside our own solar system.

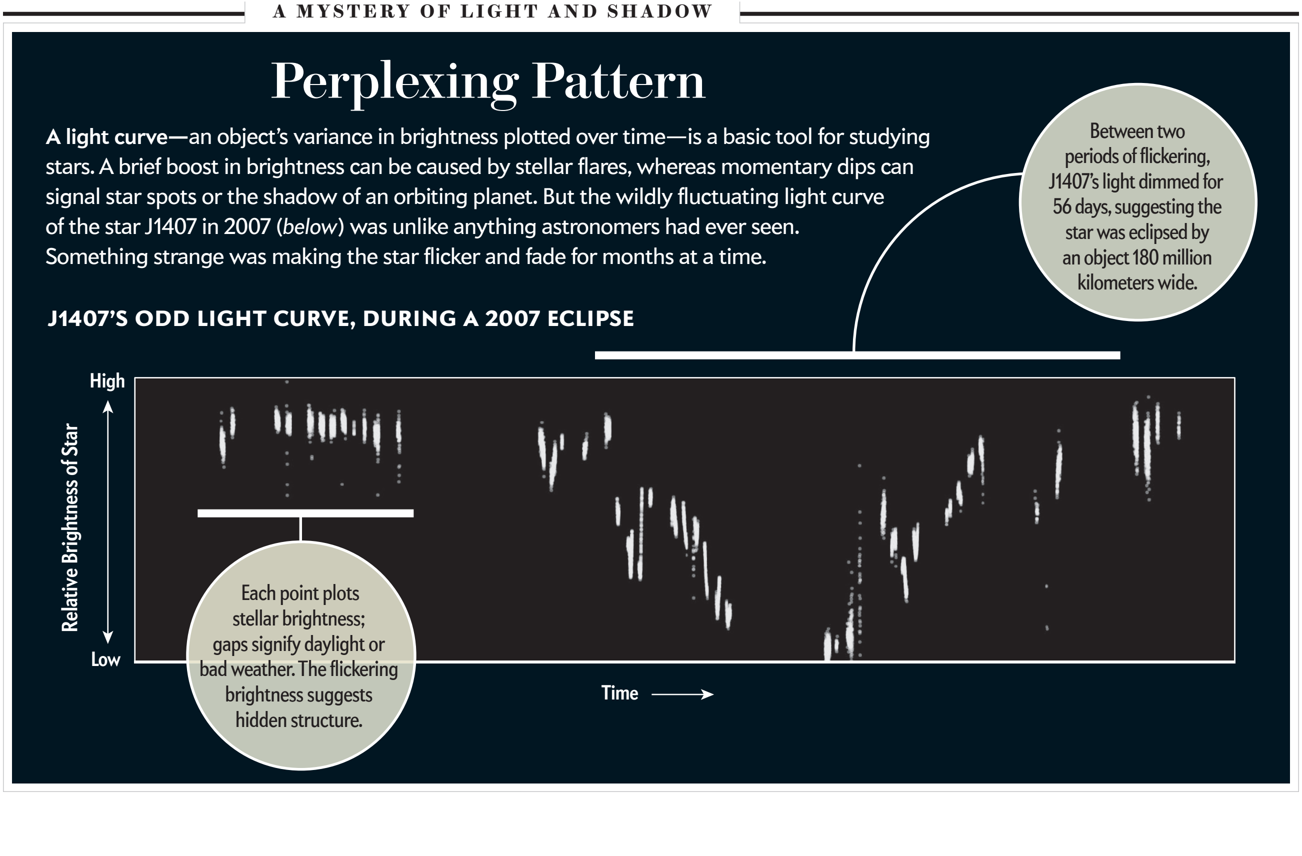
PLANET HUNTING

IF THIS TRULY was a giant ring system, then there had to be a giant planet around J1407 to bind the rings in place. So we went looking for the planet, which we call J1407b, using advanced instrumentation on two of the largest observatories on Earth: the 10-meter Keck II telescope in Hawaii and the 8.2-meter Very Large Telescope in Chile.

Even the biggest, brightest planets are far fainter and more difficult to see than their host stars. But J1407 is very young for a star. Given its estimated age—only 16 million years—any gas-giant planet around it would still be glowing brightly in infrared light from the heat of its formation. Based on J1407's distance from us, its predicted companion, when seen through a powerful telescope, would appear to be separated from the star by only about 50 milliarcseconds—equivalent to the distance between the goalposts of a football field seen on the surface of the moon. Though challenging, the observation was just within the realm of possibility.

For two years we sought to image the planet while looking for telltale periodic shifts in the star's motion caused by the to-

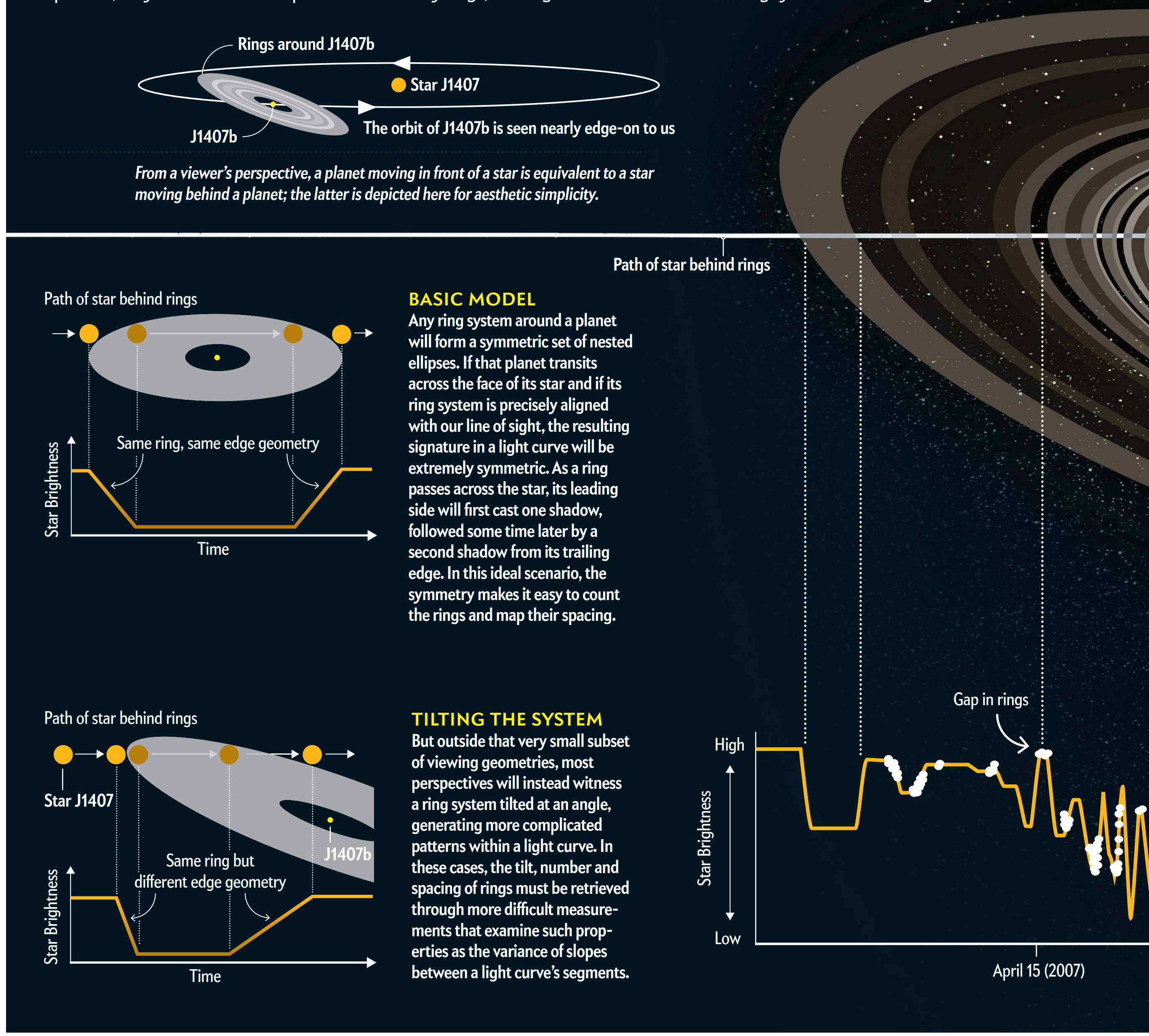
A MYSTERY OF LIGHT AND SHADOW



SOURCE: "ANALYSIS OF 1SWASP J140747.93–394542.6 ECLIPSE FINE-STRUCTURE: HINTS OF EXOMOONS," BY T.I.M. VAN WERKHOVEN, M. A. KENWORTHY AND E. E. MAMAJEK, IN *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY*, VOL. 441, NO. 4; JULY 11, 2014

How to Map a Ring System

After considering and dismissing a wide variety of other possible explanations for J1407's bizarre light curve, astronomers decided the star's flickering must be caused by shadows being cast by a giant ring system around an unseen orbiting planet. To prove it, they constructed a map of those shadowy rings, starting from a basic model of a ring system's idealized light curve.



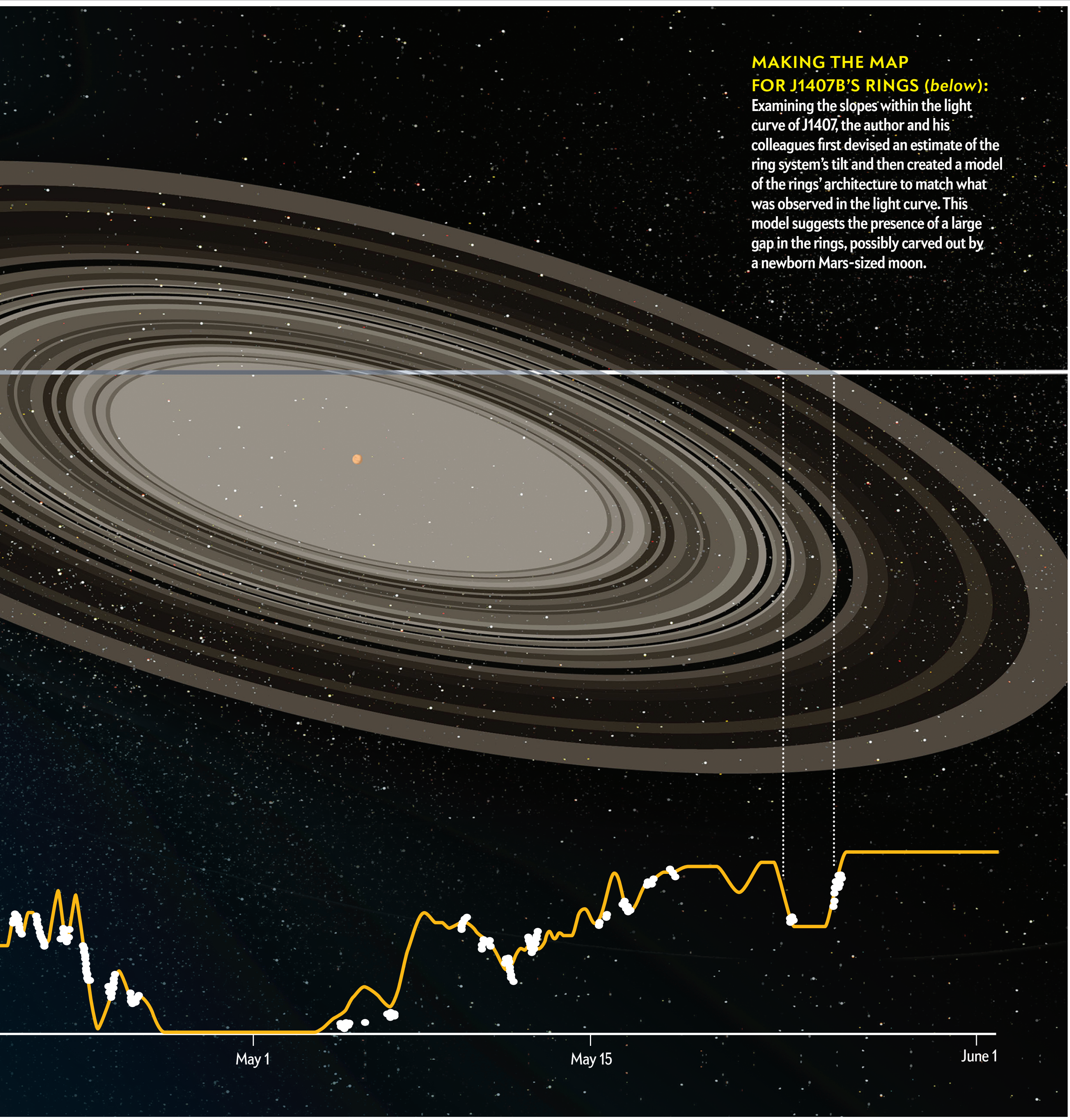
and-fro tugging of that unseen orbiting world. We also enlisted a network of professional and amateur astronomers (including the American Association of Variable Star Observers) to monitor J1407's brightness each night, looking for the dimming that would signal the onset of another eclipse.

We found nothing. This result did not mean that the planet was nonexistent; even if it was 12 times more massive than Jupiter, we would have easily missed it. We could also have looked at the wrong time, when the planet would have been behind its star and invisible to us. Even so, these null detections did allow us to rule out some varieties of low-mass companion stars as the causes of J1407's dimming.

THE RINGS, UNVEILED

DESPITE THE UNCERTAINTY, we forged ahead, trying to surmise the architecture of the rings we suspected were swirling around

Illustrations by Nigel Hawtin (schematics) and Ron Miller (J1407b ring system)

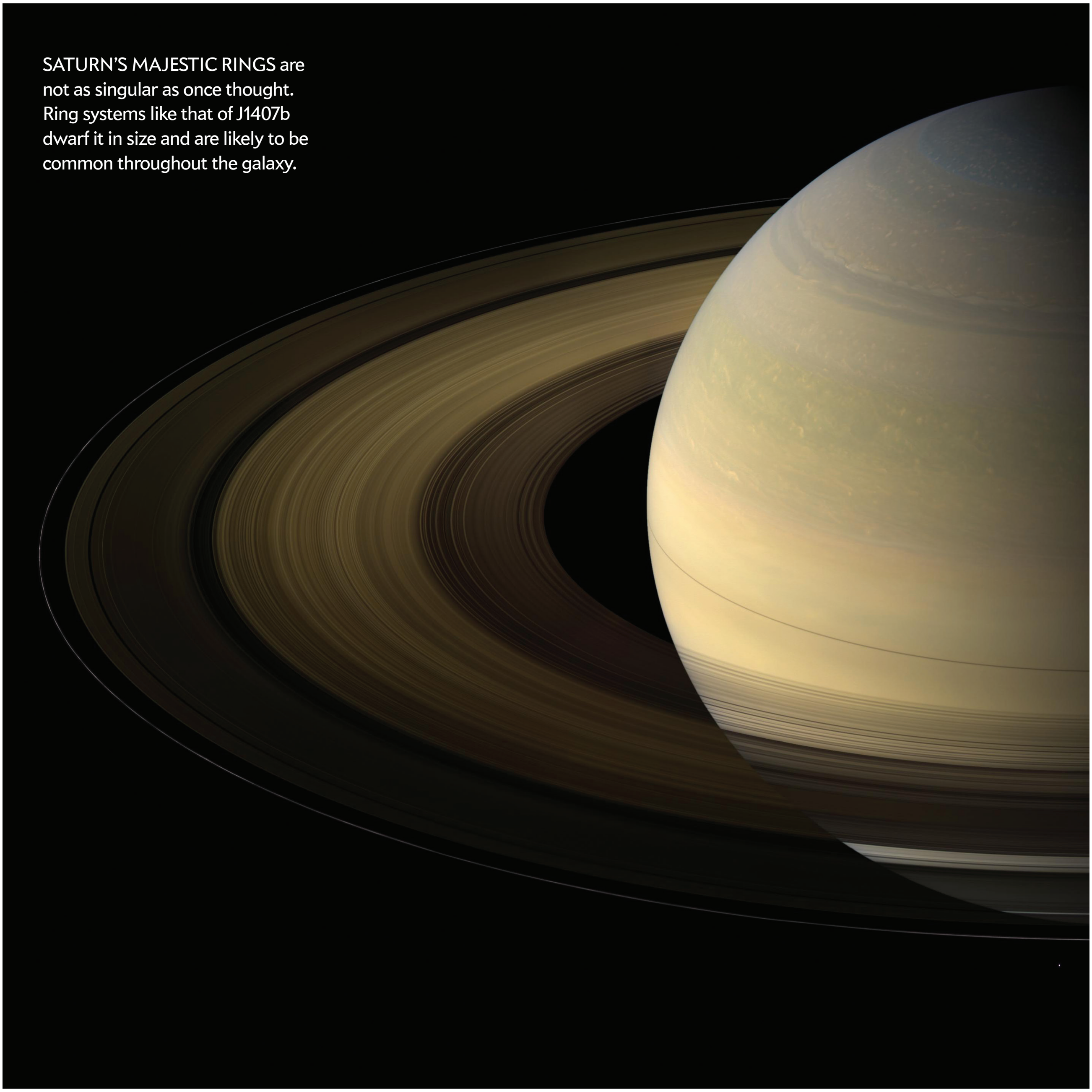


MAKING THE MAP FOR J1407B'S RINGS (*below*): Examining the slopes within the light curve of J1407, the author and his colleagues first devised an estimate of the ring system's tilt and then created a model of the rings' architecture to match what was observed in the light curve. This model suggests the presence of a large gap in the rings, possibly carved out by a newborn Mars-sized moon.

J1407b. For months our team developed computer models that would extract information about the makeup and three-dimensional structure of the rings from the J1407's light curve.

Standing and talking about the problem with several colleagues in front of a whiteboard, we suddenly had an insight: even though we did not know the exact number and placement of individual rings, the steepness of the light curve's sloping segments could give us clues to the ring system's overall geometry, such as its alignment with its star. Using this additional piece of information, we could now complete our computer model for the rings and generate synthetic light curves based on a number of different hypothesized tips and tilts for the rings. Sure enough, one configuration we tested matched the distinctive dips and jags we were seeing in the J1407 data!

Armed with this knowledge, we mapped the ring system, matching each part of the light curve to different ring distances



SATURN'S MAJESTIC RINGS are not as singular as once thought. Ring systems like that of J1407b dwarf it in size and are likely to be common throughout the galaxy.

COURTESY OF NASA, JPL AND SPACE SCIENCE INSTITUTE

from planet J1407b. Each time the light curve's slope changes, this switch marks the advent or the conclusion of a ring's transit. Counting up all these points in the light curve, we saw at least 24 rings—though considering gaps in the data created by occasional poor observing conditions, we estimated that the system is more likely to have at least 100 rings.

We are fortunate to see J1407b's ring system at this stage in its evolution. To understand why, consider our familiar Saturn and how its ring system has evolved over time. The solid appearance of its rings is actually an illusion. They consist of particles of ice that trace circular orbits around the planet. Those particles, in aggregate, are sculpted by tiny moons—moonlets—that orbit within and just past their outer edge. It is thought that Saturn once had larger rings, but the small particles at the system's outer edges clumped together through their mutual gravity in a runaway process that formed some of the Saturnian moons familiar to us now. This vista would have been as beautiful as it was fleeting—any observer would have been lucky to live in just the right slice of cosmic time to see it.

Like Saturn's ring system long ago, that of J1407b seems today to be in transition. Our model suggests that the system contains a large gap, probably formed by something astronomers have never seen before: a moon—a newborn exomoon—circling J1407b. Our calculations suggest that the moon takes almost two years to orbit J1407b and may have the mass of Mars. Although this large gap cannot by itself constitute a de-

SCIENTIFIC AMERICAN ONLINE Watch a video about the process of mapping rings at ScientificAmerican.com/jan2016/exorings

finitive exomoon detection, if the existence of J1407b and its ring system is confirmed, the gap will be the best evidence to date for the existence of these elusive, long-sought objects.

The emerging picture of this exotic, dynamic system is nothing short of spectacular. Flying in from interstellar space, you would see the glare of the primary star almost overpowering the dull glow of its cooler (but still red-hot) planet. Approaching the planet from above, one would see the rings as bright ripples spreading out against the dark backdrop of space. Wreathed with fans of debris produced by collisions, the ring plane would be awash with undulating waves of clumping material. Some of those waves would break at the great gap produced by the largest clump between two rings, the Mars-sized moon.

If the moon orbits slightly out of the ring plane, then by standing on its surface, you would see the surrounding rings arcing against the heavens all around you. And if the moon possesses an atmosphere, errant ring particles would burn from frictional heating as they passed through, filling the skies with majestic showers of sizzling meteors. Overhead, the planet J1407b would be set like a small jewel amid the glare of scattered light from its sprawling rings, crisscrossed with dark cloud bands and glowing like a burning coal.

This system offers astronomers much more, though, than the possibility of pretty scenery. Gas-giant planets orbiting close to their stars are among the easiest worlds to detect beyond our solar system, but lacking solid surfaces, they provide poor prospects for life as we know it. A large moon around such a planet would be a different matter entirely because it could provide a relatively life-friendly rocky, water-bearing surface. If our solar system is any guide, our galaxy could teem with trillions of large moons orbiting giant planets. Proving the existence of moons around extrasolar gas giants would greatly expand the possibilities for places where life could exist.

For years a small cadre of researchers has been ardently searching for exomoons, chiefly through the indirect effects they can have on the motions of their parent planets. Transiting planets provide a precise and periodic dimming of their parent star, but the mass of a large unseen exomoon causes an additional drift in the otherwise regular eclipse schedule. Astronomers such as David Kipping of Columbia University have carried out intensive searches for exomoons, looking for this signature within the light curves from transiting worlds found by NASA's planet-hunting Kepler satellite. To date, they have found no exomoons. But J1407b's possible moon suggests that these ongoing searches shall not remain fruitless for long.

For now, however, both the planet and its moon are only hypothetical. The largest telescopes and most sensitive instruments on Earth have not yet been able to find conclusive evidence irrefutably confirming their existence. Instead that evidence may come from archival data gathered by much cruder technology in years past—such as a collection at the Harvard-Smithsonian Center for Astrophysics.

BACK TO THE FUTURE

THE CENTER HOSTS many researchers, and its offices and corridors are busy with people poring over data from space telescopes, writing papers, running simulations and attending talks. Just a few meters away from this bustling building are the Harvard Plate Stacks, housed in a quiet, brick-walled annex where few people venture. Off in one wing, stacks of large paper envelopes on long shelves fill the walls of three floors all the way up to the ceiling. You might think that it is a secondhand record store, but instead of vinyl disks, these envelopes contain more than half a million photographic plates from various observatories—a quarter of all the astronomical photographic plates in the world. They record a century of night-sky observations.

These photographic plates are now being scanned by the Digital Access to a Sky Century @ Harvard project, which aims to digitize and upload all the data stored on these fragile glass slides. We have determined that J1407 appears on about 700 of these plates, in images taken from 1901 to 1984. With the data from these plates, we will be able to search for more eclipses so that we might learn when the next one will occur.

Right now our best guess is that it will happen sometime in the next decade. Meanwhile we are still hunting for definitive proof of the planet and its rings, and dedicated astronomers monitor J1407 almost every night. They are looking for the dip in starlight caused when the outermost ring begins to pass across the star. When that happens, many observations can be carried out to study the rings in much greater detail. When the rings move in front of the star, we can use spectrographs on the world's largest telescopes to collect some of the starlight shining through and around the rings to discern their chemical composition and how that composition changes with distance from J1407b. Most excitingly, J1407 is a relatively bright star visible from the Southern Hemisphere and is easily observable—astronomers with small telescopes can follow the brightness fluctuations of the star in real time to provide 24-hour continuous coverage from around the world.

Our deep dive into the giant rings of J1407b will be only the beginning of a broader series of investigations relating to how solar systems form. Newborn giant planets are thought to give rise to circumplanetary disks that condense into moons and rings, and we expect to soon detect more of these systems by the shadows they are surely casting far across the galaxy. Now that we know what we are looking for, the race is on to find more giant ring systems and exomoons like the ones thought to exist around J1407b. My colleagues and I are already scouring new databases for telltale signs of additional ring-bearing planets in other systems. Saturn's gorgeous system of rings may soon have stiff competition from those around other stars. SA

MORE TO EXPLORE

Planetary Construction Zones in Occultation: Discovery of an Extrasolar Ring System Transiting a Young Sun-like Star and Future Prospects for Detecting Eclipses by Circumsecondary and Circumplanetary Disks. Eric E. Mamajek et al. in *Astronomical Journal,* Vol. 143, No. 3, Article No. 72; March 2012.

Modeling Giant Extrasolar Ring Systems in Eclipse and the Case of J1407b: Sculpting by Exomoons? M. A. Kenworthy and E. E. Mamajek in *Astrophysical Journal,* Vol. 800, No. 2, Article No. 126; February 20, 2015.

Online resources related to mapping the rings: **https://github.com/mkenworthy/exorings**

FROM OUR ARCHIVES

The Search for Life on Faraway Moons. Lee Billings; January 2014.

Better Than Earth. René Heller; January 2015.

In Search of Alien Jupiters. Lee Billings; August 2015.

scientificamerican.com/magazine/sa