Amateurs Track a DISINTEGRATING Exoplanet

As we watch, a world that came too close to its dead star is falling to pieces.

If someone had told me 20 years ago that I, an amateur astronomer, would someday be on my roof watching the destruction of a small planet orbiting a 17th-magnitude star, I would have said they were nuts. Yet I and other amateur astronomers are now doing just that, and more.

WD1145+017, or "WD 1145" to its friends, is an obscure white dwarf star 570 light-years away in Virgo near the Leo border. It is pulling apart, grinding up, and devouring one or more of its planets as we watch. We are monitoring fast-changing clumps and streams of orbiting wreckage as they cross the star's face, dimming its light in ways both regular and irregular. Amid the debris is a solid object some 1,000 kilometers in diameter that continues shedding material.

We didn't discover this happening. For that, we can thank the ingenious and determined engineers who put together the K2 mission for the Kepler spacecraft after it lost its precision pointing ability in May 2013 (see box).

On March 21, 2015, Andrew Vanderburg, a graduate student at Harvard, was reviewing data from the K2 mission and noticed that faint little WD 1145, which happened to be in one of the K2 survey fields, showed some unusual brightness variations. He arranged to do follow-up spectroscopy with the 6.5-meter MMT telescope at Whipple Observatory in Arizona and to monitor the star's brightness with the 1.2-meter telescope at Whipple.

On April 11th, he found WD 1145 undergoing dimmings that looked similar to cases where a transiting planet sheds material if it orbits too close to a normal, much larger main-sequence star. Saul Rappaport (MIT) had been the first to report on those finds. Vanderburg wondered, could the same thing happen around a white dwarf? These stars are typically only a hundredth the diameter of the Sun. That's roughly the size of Earth, a smallish planet itself. How would that work?

Kepler's K2 Mission

Kepler detects worlds orbiting faraway stars by the tiny, periodic dimmings that a planet will cause if, by luck, it crosses the face of its star from our viewpoint. But after two of Kepler's four reaction wheels (gyroscopes) failed, leaving only two working, the spacecraft lost its ability to orient and point steadily. For that, it needs three different force vectors that it can twist itself around in 3-D space.

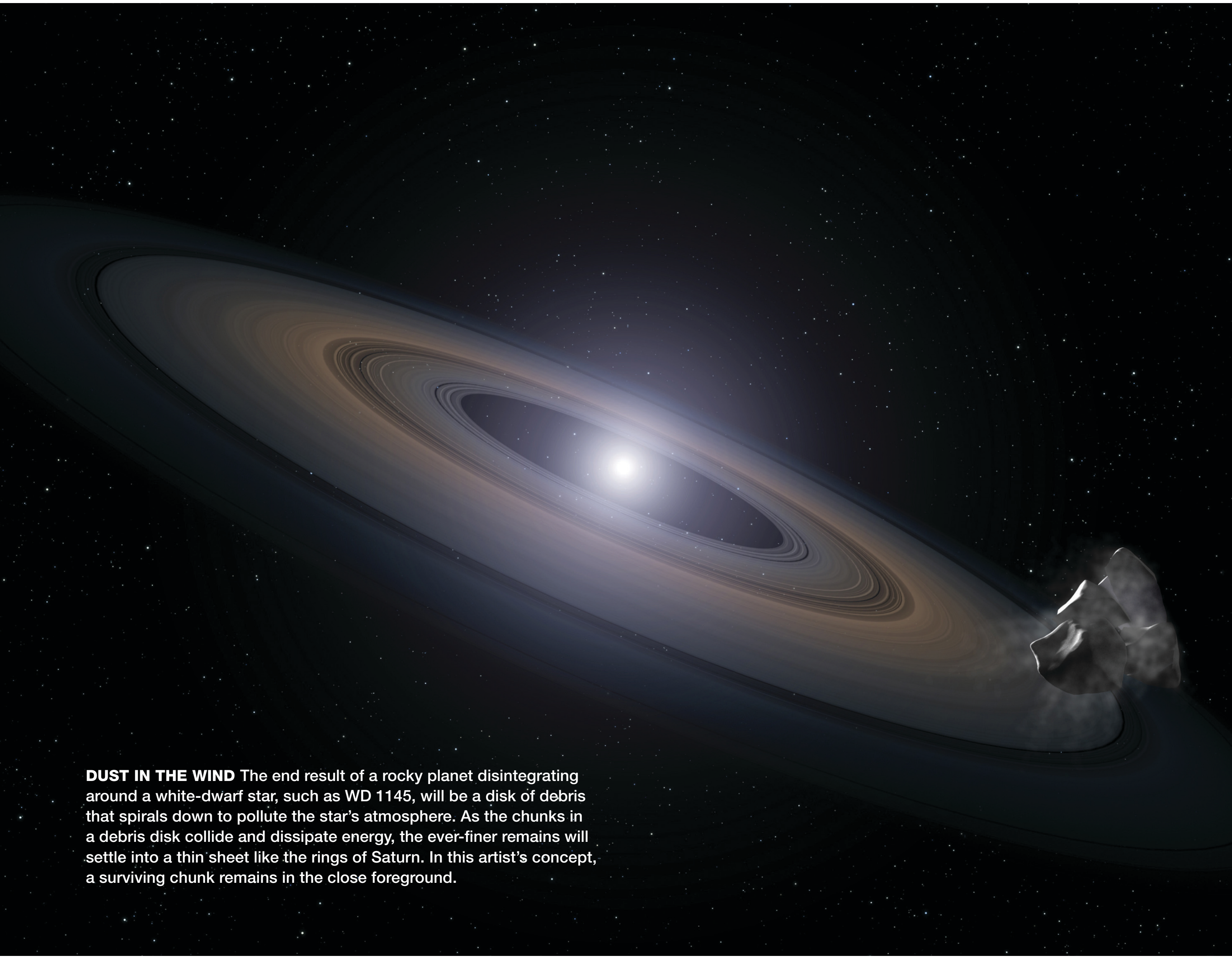
Kepler's handlers figured out how to balance the craft against the delicate radiation pressure of sunlight, so that it does not drift too far in its unconstrained third direction. Thus Kepler came back from the dead in November 2013. In its new role it is able to point to star fields along the ecliptic for a new, extended mission dubbed Kepler 2.

This mission continues today. Unavoidable slow drifts mean that Kepler cannot monitor stars' brightnesses with the same precision as it originally could. But even so, the K2 mission had found 178 new exoplanets as of January — some of them, like WD 1145, very interesting.

End-of-Life Drama

White dwarfs are the dense cores of dead stars that were once more or less Sun-like. They are what's left after a low- to medium-mass star comes to the end of its complex life of burning nuclear fuel. After evolving through a complex old age as a mass-losing red giant, the star goes through death spasms that throw off much more of its mass. The ejecta glow, for a relatively brief time, as an expanding planetary nebula. The star's exposed hot core, lacking any further source of energy, settles down to cool slowly forever.

The ejecta can amount to 30% to 75% of the star's mass. And that's bad news for any system of planets that may have



DUST IN THE WIND The end result of a rocky planet disintegrating around a white-dwarf star, such as WD 1145, will be a disk of debris that spirals down to pollute the star's atmosphere. As the chunks in a debris disk collide and dissipate energy, the ever-finer remains will settle into a thin sheet like the rings of Saturn. In this artist's concept, a surviving chunk remains in the close foreground.

NASA / ESA / GREG BACON (STSCI)

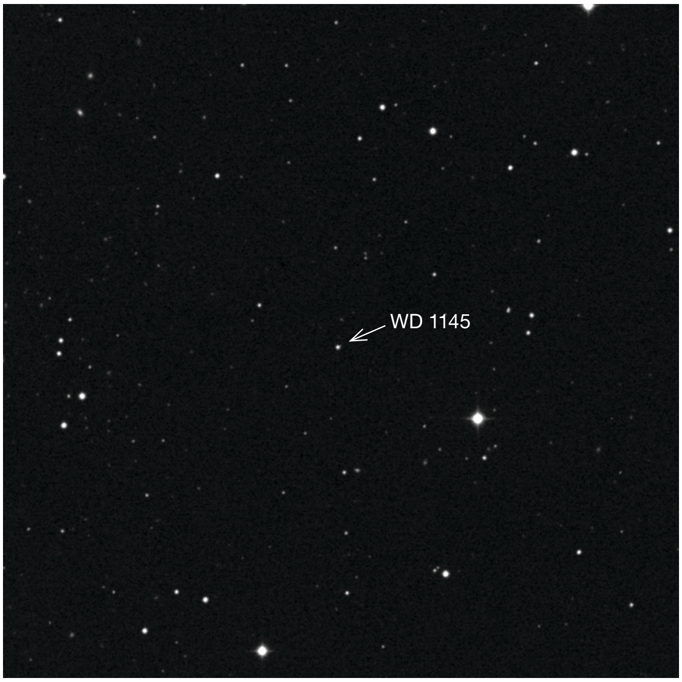
survived the previous stages of the star's late-life drama.

As a star loses mass, its gravity weakens, which means that any planets will migrate outward into larger, slower orbits. But the new planetary system will not just be a larger copy of the old one. The star's weaker gravity means that even though the planets orbit farther out, their influence on one another is more powerful. This spells trouble.

Our solar system, for instance, has remained stable for billions of years. That's because, early on, objects in unstable orbits were flung out by gravitational interactions or collided and merged. What was left were planets that don't seriously interfere with each other.

But the Sun will lose much of its mass in about 7 billion years, and when that happens the planets will drift outward from the Sun. The result can be a chaotic system where many strong gravitational interactions occur. At first, a planet may find itself gradually worked into a more elliptical orbit that eventually brings it close to another. Their first near miss is likely to throw at least one of the two into an even more elliptical orbit, setting it up to interfere with others. As the chaos spreads, some planets may be expelled

As an aging star loses mass, planets that orbited it stably for billions of years will drift outward and begin to interfere with each other. Chaos will grow.



▲ **PULLED FROM HIDING** Lurking ¼° from the ecliptic just behind the head of Virgo, the world-annihilating white dwarf WD1145+017 glimmers at an unassuming 17th magnitude. The events around it would have gone unnoticed were it not for the crippled Kepler spacecraft's K2 mission. This frame is ¼° square.

from the system, others may collide, and other encounters may send a planet inward toward the star. This last is what astronomers think happened in the case of WD 1145.

Astronomers already had evidence of the catastrophic end result. White dwarfs have intense surface gravities, so any heavy elements should sink below the hydrogen/helium surface in only a million years or so. Yet about a quarter to a half of white dwarfs show surfaces polluted with iron, silicon, magnesium, nickel, aluminum, calcium, and other rocky-planet material. The white dwarfs are old, but the heavy pollutants must be fresh.

And indeed, when Vanderburg's co-authors Warren Brown and Patrick Dufour took spectra of WD 1145 with the MMT telescope, it too showed such materials on its surface — despite estimates (from its temperature and expected rate of cooling) that it has been a white dwarf for 175 million years.

Now, with debris swarms apparently orbiting this star and obscuring its light, the Harvard group had found a "smoking gun" connecting polluted white dwarfs to a planet being destroyed in real time.

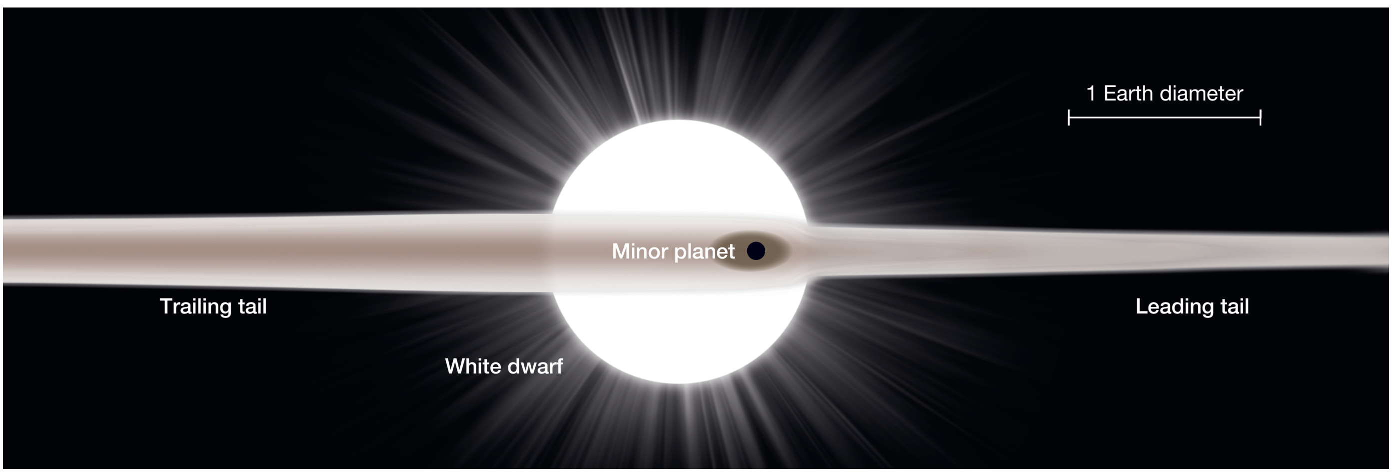
Fast Transits Nonstop

Again using Kepler and the MMT 1.2-meter, Vanderburg and the group found a distinct object whipping around WD 1145, transiting it every 4.5 hours. The star is 1.4 times the size of Earth, which makes the transiting object no larger than the dwarf planet Ceres. Wherever it originated, the object has worked its way down to orbit only 800,000 km above the star's surface: roughly twice the Earth-Moon separation, with one side roasting in the star's intense heat. At this distance the object has reached its expected Roche limit, where tides induced by the star should literally pull it apart.

Given the body's fast orbital speed and the star's small size, transits should last just a minute or so. What we see, however, are a great many transits happening continuously all around the orbit, differing in depth and duration. And they change from week to week! This implies that many clumps and clouds of debris are expanding like the coma around a comet nucleus. The fact that we see obscurations throughout the 4.5-hour "year" indicates a clumpy ring of debris all around the star.

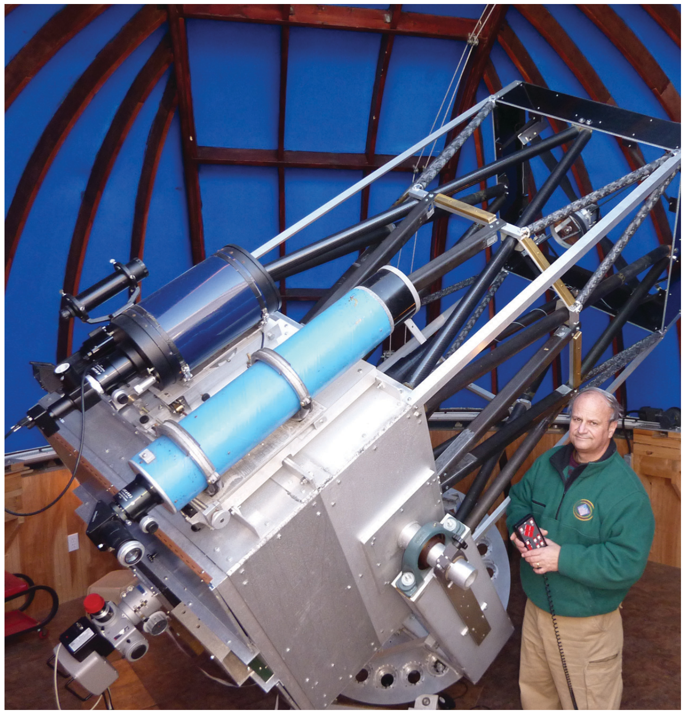
A Network of Observers

Vanderburg realized early on that, if he wanted to properly study this unusual and scientifically interesting system, he



▲ **STREAMER OF OBSCURATION** In this smoothed reconstruction from 5 minutes of data around a "primary" transit, the planetoid speeding around WD 1145 (black disk, drawn to scale) is surrounded by an opaque dust cloud with a thick extension orbiting behind it and a sparser, narrower extension ahead of it. The star itself is very typical for a white dwarf, with 1.4 times the diameter of Earth and 0.6 solar mass.

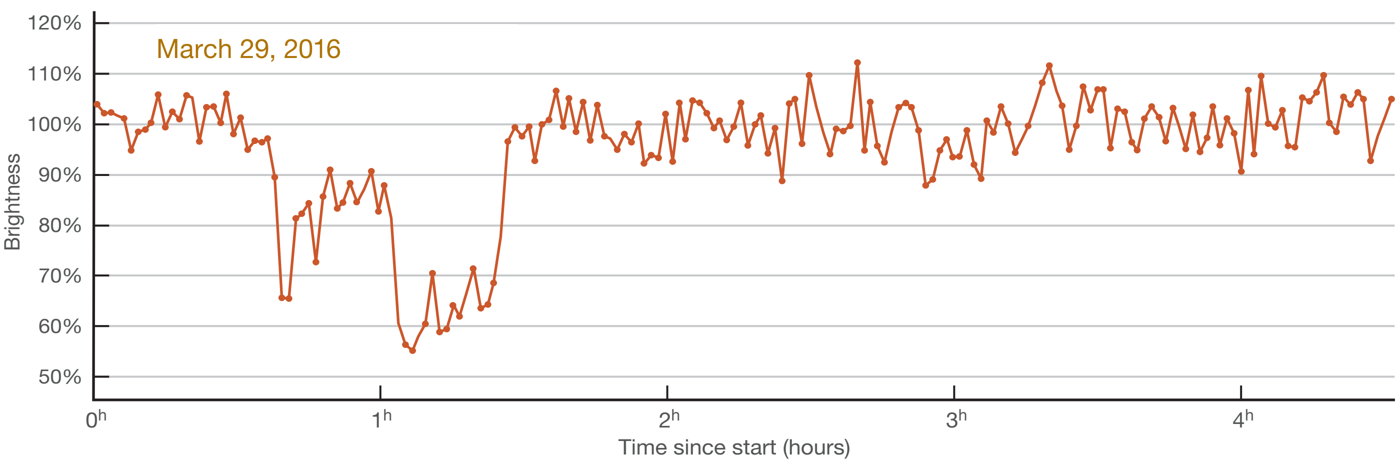
IMAGE: DIGITIZED SKY SURVEY, DIAGRAM: *S&T*: LEAH TISCIONE / DATA: ANDREW VANDERBURG ET AL. / *NATURE*



▲ **TROUBLE AHEAD** The Helix planetary nebula in Aquarius, as imaged by the author with his scope at right. The central star is a newborn white dwarf, the core of an expired star that recently expelled its outer layers. The reduction in its mass is bad news for any planetary system that may remain around it. **Right:** The author and his homebuilt 32-inch reflector. The observatory is on the roof of his house; the scope rests on a pier that goes down to bedrock. Faint stars beware; your secrets shall be revealed.

would need to enlist many observers to track its events as continuously as possible. Among those he recruited were Bryce Croll at Boston University and a few advanced amateurs such as Bruce Gary, Tom Kaye, and myself. He contacted me in the summer of 2015, then visited my home in Gloucester, Massachusetts, where I have a 32-inch (0.8-meter) homemade telescope in a rooftop observatory, seen above. We tested the capabilities of the telescope and its systems on some other stars with transiting exoplanets.

Considering the speed expected of objects circling WD 1145 at the Roche limit, Vanderburg wanted a fast, 1-minute cadence of brightness measurements to capture the details of the orbiting debris field. So, no long exposures! But with the star only 17th magnitude, would my scope and camera be up to that task? Although Kepler boasts a 1-meter telescope, it images on a 30-minute cadence, more appropriate for its work of looking for small planets around much larger main-sequence stars. The longer exposures allow the extremely

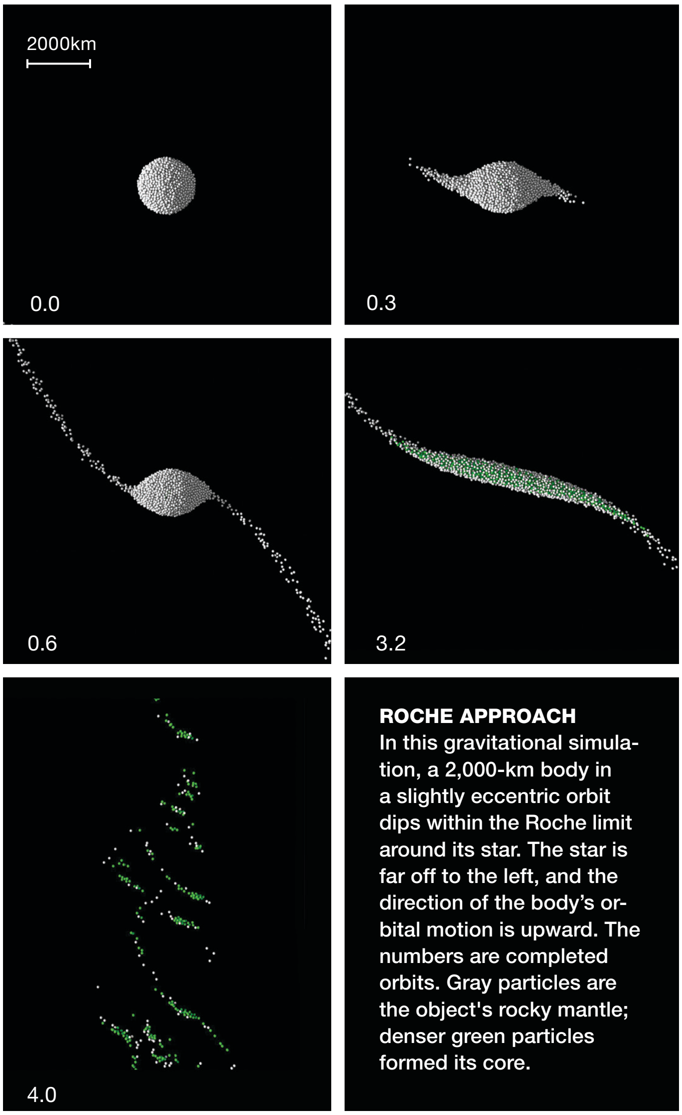


▲ **ONE ORBIT, SCORES OF TRANSITS!** Once a minute, the author's system shown above measured the brightness of WD 1145 against comparison stars in the same field. The comparison stars held steady in brightness to within 1%, but the white dwarf dimmed and recovered wildly from minute to minute as clumpy orbiting material crossed its face. This 4½-hour run spanned almost one complete orbit of the debris ring. The solid planet with its opaque surrounding cloud, which transited about 40 minutes into the run, has a smaller profile than the dusty swarms of stuff it has shed.

PHOTOS: MARIO MOTTA (2), LIGHT CURVE: *S&T* LEAH TISCIONE / SOURCE: MARIO MOTTA precise brightness measurements that are required for this.

Virgo wasn't observable from New England until winter, and as luck would have it, the winter of 2015-16 was so cloudy that I could not start collecting data until March. Fortunately, advanced amateurs in other parts of the world started taking data in December. One was Bruce Gary, a leader in the amateur exoplanet-transit world. His early and influential book *Exoplanet Observing for Amateurs* had inspired me to get started in this exciting field.

In December 2015 Gary and Tom Kaye confirmed that the star is undergoing multiple chaotic transits. I took the light curve on the previous page on March 29, 2016. It showed that by then the system had evolved into a new state. The brief, initial sharp fade for 1 or 2 minutes likely corresponds to the planet itself, but it was much deeper than expected for such a small body. Apparently an opaque or semi-opaque cloud of material surrounded it. Following this "primary" transit came a clearer spell and then an even deeper dimming lasting some 25 minutes: a large cloud of debris,



ROCHE APPROACH In this gravitational simulation, a 2,000-km body in a slightly eccentric orbit dips within the Roche limit around its star. The star is far off to the left, and the direction of the body's orbital motion is upward. The numbers are completed orbits. Gray particles are the object's rocky mantle; denser green particles formed its core.

DIMITRI VERAS *ET AL.* / *MONTHLY NOTICES OF THE RAS*, OCT. 25, 2016

> Next year the TESS satellite should start revealing a flood of nearby exoplanets. Some will be especially ripe for pro-am followups.

which later expanded in size and thinned out. The rest of the orbit showed smaller rapid obscurations, indicating that an irregular, dusty debris field completely rings WD 1145. Broken-off chunks of the main body seem to be shedding debris and dust of their own, in a cascading process. Some of the objects seem to have slightly longer orbital periods of up to 4.9 hours.

Meanwhile, the comparison stars in my imaging field held very steady: to about 0.01 magnitude from frame to frame, or 1% of their brightnesses. So the seemingly "noisy" fluctuations you see from minute to minute in the light curves are mostly real — not instrumental noise or atmospheric effects.

By comparison, in a recording I made of a normal exoplanet crossing the star HAT-P-26 last April, the smooth, steady dimming of only 7 millimagnitudes (a 0.7% percent brightness change) stands out clearly from my system's noise. That planet is roughly Neptune-size and crosses a main-sequence star of spectral type *K*1. This was one of the observations that Dennis Conti of the American Association of Variable Star Observers (AAVSO) is coordinating among amateurs to support a major Hubble study of 15 exoplanets.

Compare that to the wild fluctuations of WD 1145 and you see what drew Andrew's initial attention to this object. Instead of the typical transit drop of just a few millimagnitudes, we have seen WD 1145 being obscured by up to 40%!

The light curves at right show five more of my observing runs from the following two months. Most span a large part of the system's 4.5-hour "year." No two are alike, indicating the debris field's fast evolution. We are watching the end of a world in real time.

Given the planet's small size, this situation is not likely to continue much longer. Eventually everything should grind itself down to small particles, settle into flat rings like Saturn's, and gradually spiral into the star via "friction" with the star's brilliant radiation, as in the artist's portrayal on page 67. Indeed, the last observation on May 31st showed reduced activity. Was the show winding down?

Nope! When Virgo came back into view in December 2016, Bruce Gary was the first to find that new debris was causing big dips again, which I subsequently confirmed.

We will collect many more observations over time to follow the continuing evolution of the WD 1145 system. It's possible that more than one initial body has broken up, or is breaking up, or is about to.

Join Us!

Scientists like Vanderburg, Croll, and Rappaport depend on close professional-amateur collaborations. Pro-am partnerships are proving essential as astronomers find ever more exoplanets and need followup observations. As of January, 3,440 planets of other stars were considered "confirmed," and more than 2,000 additional "candidates" awaited verification. This is an area where diligent, well-equipped amateurs can contribute greatly to science.

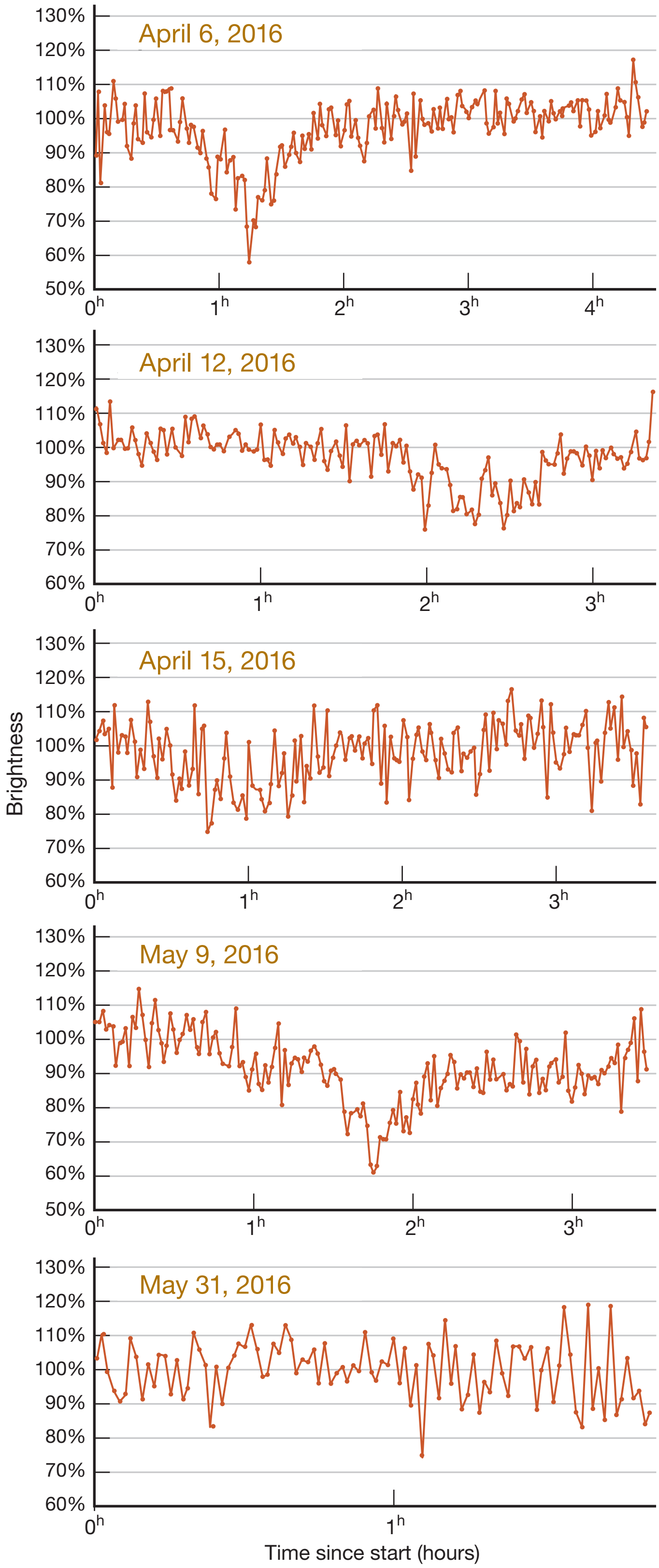
A useful way to start is to join the AAVSO's exoplanet section, headed by Dennis Conti. Find it at **aavso.org/exoplanet-section**. You can download the current edition of his *Practical Guide to Exoplanet Observing* from **astrodennis.com**. See also Bruce Gary's book mentioned earlier. Finally, get the powerful, free data-reduction program *AstroimageJ* at **astro.louisville.edu/software/astroimagej**. Karen Collins designed it with amateurs in mind for following up transit discoveries made by the KELT survey. It reduces the large volumes of data that your camera acquires, organizes it into a scientifically useful Excel spreadsheet, and can draw light curves like the ones on these pages.

Any amateur with imaging and variable-star experience has the skillset to contribute incredibly useful data. And you don't need access to a 32-inch scope! Many stars of interest are much brighter than my 17th-magnitude pet project. For instance, high-school student Alana Gudinas, a beginner at Phillips Academy in Andover, Massachusetts, obtained useful data on WASP–39 b using the school's 16-inch scope and high-end CCD camera. That planet is a puffed-up Jupiter closely orbiting a G8 star of magnitude 12.1. Much smaller scopes can be appropriate for selected systems. In particular, long-term monitoring can reveal slight *transit timing variations* (TTVs). These reveal the gravitational influence of additional bodies or other interesting things happening.

The K2 mission continues searching, and so do ground-based professional and amateur transit hunts. And in the spring of 2018 the TESS satellite should launch. It will watch 200,000 relatively bright stars all around the sky, most of them much closer to us than the bulk of Kepler's targets. TESS will be the first all-sky transit survey conducted from space. Its principal goal is to find small planets around relatively nearby main-sequence stars, so that astronomers will have prime Earth-size worlds for further study. But TESS will also identify planets of all sizes up to the largest gas giants, orbiting stars of a wide variety of types. Many in the expected flood of discoveries will be ripe for extended followups by pro-am collaborations.

It's an exciting new field. You may not find something as bizarre as a planet that's disintegrating, but you will be in on many new discoveries and the satisfaction of helping to find and characterize new worlds. Happy hunting.

■ **MARIO MOTTA**, MD, FACC, is a cardiologist, a clinical professor at Tufts Medical School, past president of the Massachusetts Medical Society, past president of the AAVSO, and telescope maker extraordinaire. He has received several national awards for his years of work in advanced amateur astronomy.



▲ **NO TWO ALIKE** The author took these further observing runs on WD 1145 over the course of two months. Again, typical comparison-star noise was only about 1%, much less than the rapid changes being recorded. The activity seemed to quiet down a bit by the end of May, but as of December 2016 the long, deep dips had picked back up.

S&T LEAH TISCIONE / SOURCE: MARIO MOTTA (5)