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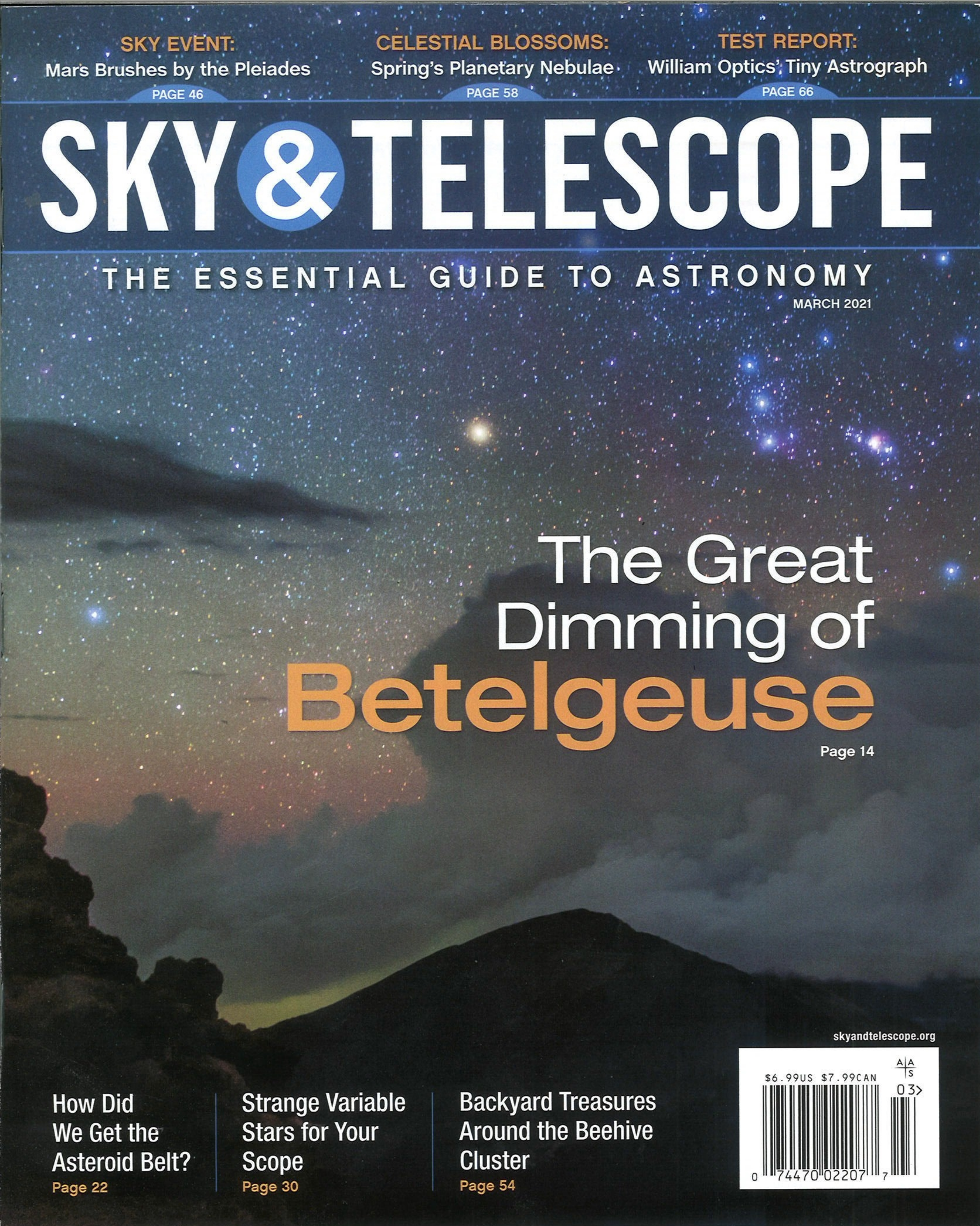
MARCH 2021



The Great Dimming of Betelgeuse

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Professional and amateur astronomers are working to understand why the famed red supergiant faded so dramatically.

THE GREAT DIMMING

Betelgeuse has become a star — a media star, that is. Never in modern times has so much public attention been paid to a distant sun that *hasn't* exploded. Astronomers have been keenly interested in Orion's alpha star for some time (for example, *S&T:* May 2019, p. 34), but now it's a subject for the newspapers.

Betelgeuse is a *red supergiant* (RSG), a swollen, puffy star nearing the end of its life. These gigantic stars produce an abundance of dust, seeding interstellar space with various atomic elements. We still don't understand exactly how they disperse their chemical bounty. This is partly because red supergiants are so few, and so many of them are so far away. Betelgeuse, being nearby, is our backyard RSG laboratory.

But that's not what brought Betelgeuse into the spotlight. Between October and December 2019, the star's ruddy glow plummeted, then kept on fading. Popular speculation abounded that it was about to go supernova.

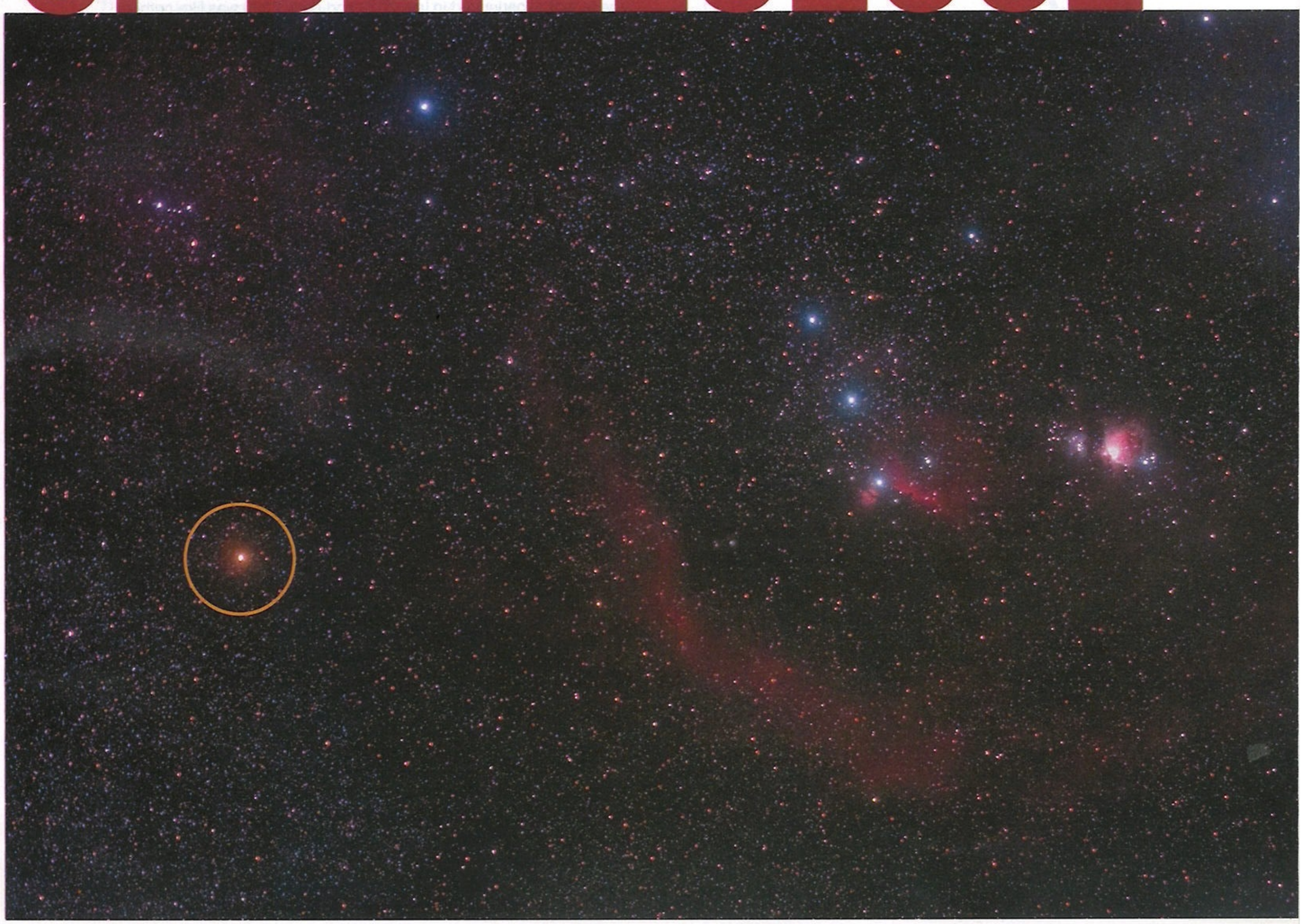
BABAK TAFRESHI (2)

UNUSUAL FADE Betelgeuse was around magnitude 0.5 in 2013 as it approached a regular minimum *(left)*. But it was a magnitude fainter in January 2020 during a mysteriously pronounced dimming.

The "Great Dimming" electrified both amateur and professional astronomers. Members of the American Association of Variable Star Observers (AAVSO) have followed the star for decades, and professionals regularly refer to AAVSO's data to add context to their own investigations. With such instruments as Hubble, ALMA, and the Very Large Telescope (VLT) at their disposal, the pros can probe slivers of the Betelgeuse spectrum in exquisite detail. But for overall measures of brightness, they often depend on the modest tools of amateurs, whose instruments are not saturated by the star's intense light.

I lead an AAVSO observer group that was in on a campaign called the Months Of Betelgeuse, coordinated by Andrea Dupree (Center for Astrophysics, Harvard & Smithsonian). Known as the MOB, they are a loose association of professional astronomers in the Americas and Europe. Our group provided the MOB with precise brightness measurements throughout Betelgeuse's strange episode, using a technique known as *photoelectric photometry*. Together, the pros and amateurs saw the supergiant dim and recover, watching from vantage points on Earth and in space.

OF BETELGEUSE



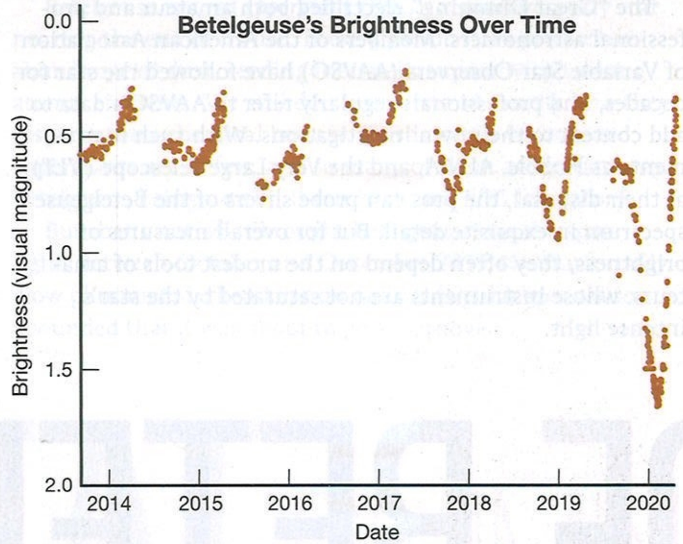
Inherently Inconstant

A red supergiant starts out with a mass about 8 to 40 times that of the Sun. On the main sequence, it furiously fuses hydrogen to helium for perhaps 1 to 10 million years. The core finally fills up with helium, and hydrogen fusion stops. No longer supported by an outward flow of energy, the core contracts and heats up dramatically.

Around the outer core, the temperature rises high enough to restart hydrogen fusion in a surrounding shell. Within the core, the temperature will rise even higher, beginning the fusion of helium into carbon and then oxygen. As the core shrinks, the outer envelope expands to incredible proportions, a process — not fully understood — called the *mirror effect*.

We think Betelgeuse is in this helium-fusing stage. After its central supply of helium is exhausted, the core will go through a series of flameouts, contractions, and re-ignitions that finally create a nickel-iron center that can produce no more energy. A collapse will follow, and likely a fantastic explosion, treating earthlings to a spectacular sky show (see box below).

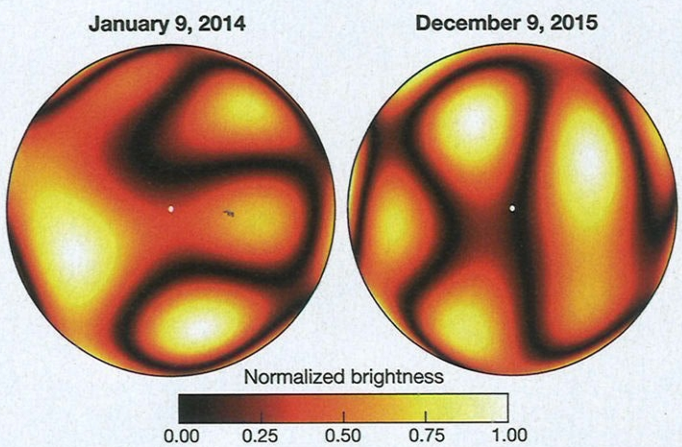
Almost all red supergiants are variable stars, changing in brightness over time. Some of them literally pulsate, expanding and shrinking over periods typically lasting hundreds of days.



▲ **ABNORMAL MINIMUM** Betelgeuse's brightness varies on multiple time scales, and its dips every 420 days or so are fairly predictable. But the fade it experienced in late 2019 and early 2020 was like nothing astronomers have seen from the star. These data from AAVSO observer Wolfgang Vollmann show about seven years' worth of photometric data.

Betelgeuse currently pulsates over about 420 days, but its brightness also varies on a cycle of 2,000 days (5½ years). Many RSGs exhibit such a *long secondary period* (LSP), the cause of which is unclear. Repeated upwellings of hot material from deep inside the star may drive this slow variation. Giant, hot convection cells rise to the top, each one covering so much area that they collectively change the surface's temperature distribution.

Astronomers have indirectly detected convective cells on Betelgeuse. Using the 2-meter Bernard Lyot telescope in the French Pyrenees, Arturo López Ariste (University of Toulouse, France) and others studied Betelgeuse from 2013 to 2018. With specialized equipment, the researchers inferred the presence of huge regions of upwelling bright material edged by sinking, cooler material, and they mapped out these hotspots. Further evidence from Doppler shifts enabled them to also estimate the velocities of the updrafts and downdrafts — about 20 km/s (45,000 mph). The cells may take a few years to finish rising, much longer than the day-long time scales of similar motions in the Sun.



▲ **GIANT CELLS** Based on polarization patterns in Betelgeuse's light, these simulated images show the star's slowly overturning surface in January 2014 and December 2015.

WILL BETELGEUSE EVER GO SUPERNOVA?

It might seem a silly question, but astronomers aren't certain Orion's red supergiant will have a spectacular demise. Observations haven't turned up clear examples of supernovae from red supergiants born with more than about 20 solar masses. (Betelgeuse is potentially below that limit, but astronomers don't know for sure.) It's possible stars above the limit instead implode directly into a black hole, perhaps due to how the star burns its carbon. Alternatively, the larger stars might lose enough material as they age that they evolve into hotter yellow or blue supergiants before exploding.

—CAMILLE M. CARLISLE

CONVECTIVE CELLS: A. LÓPEZ ARISTE ET AL. / *ASTRONOMY & ASTROPHYSICS* 2018; BRIGHTNESS GRAPH: *S&T* DIAGRAM, SOURCE: WOLFGANG VOLLMANN / AAVSO

The Data

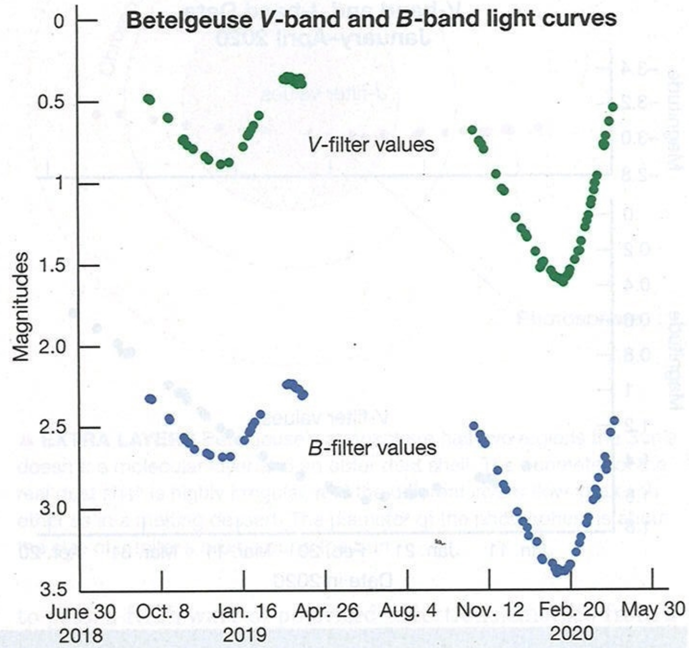
Between pulsation and convection, Betelgeuse has a long history of brightness variation. But the Great Dimming and the minimum it reached in February 2020 before rebrightening was extraordinary, causing much excitement in the scientific community.

The 2018 minimum of the 420-day cycle occurred near Christmas, so observers expected the next minimum about mid-February of 2020. But by the end of November 2019, the star had already broken through the 2018 low and was clearly headed lower. In early December, MOBster Ed Guinan (Villanova University) sent out an Astronomical Telegram to alert those scientists who had not already noticed.

The buzz grew. The American Astronomical Society (AAS) annually stages its big meeting for professional astronomers in early January. As attendees began gathering in Honolulu in 2020, I was getting urgent emails from the MOB: *Tom . . . What's it doing? . . . What's it doing?* The AAS conference held a special session to discuss the latest developments, and soon after, Betelgeuse was featured in the *New York Times*.

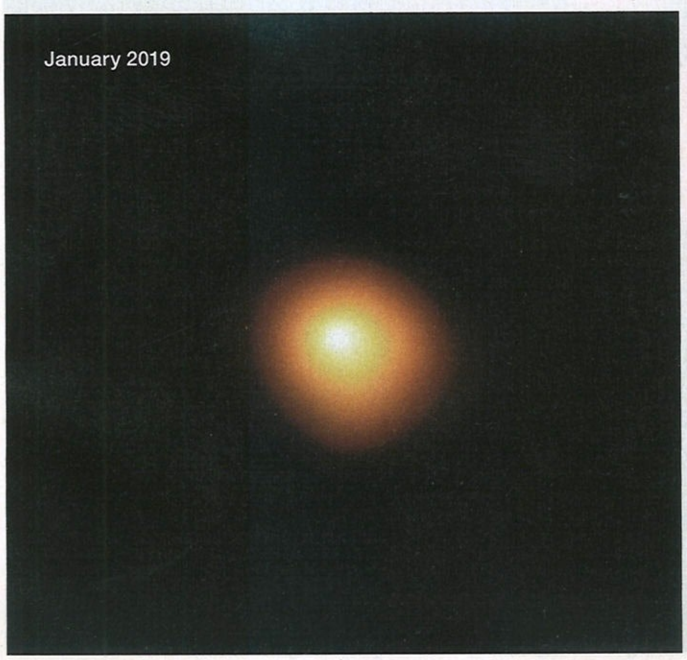
The iconic image of the Great Dimming was provided by Miguel Montargès (then of KU Leuven, Belgium) and others using the VLT. Taken in December 2019, it shows the southeast of Betelgeuse starkly fainter than the rest of the star. A similar picture from January 2019, when Betelgeuse was near its prior minimum, showed no such contrast.

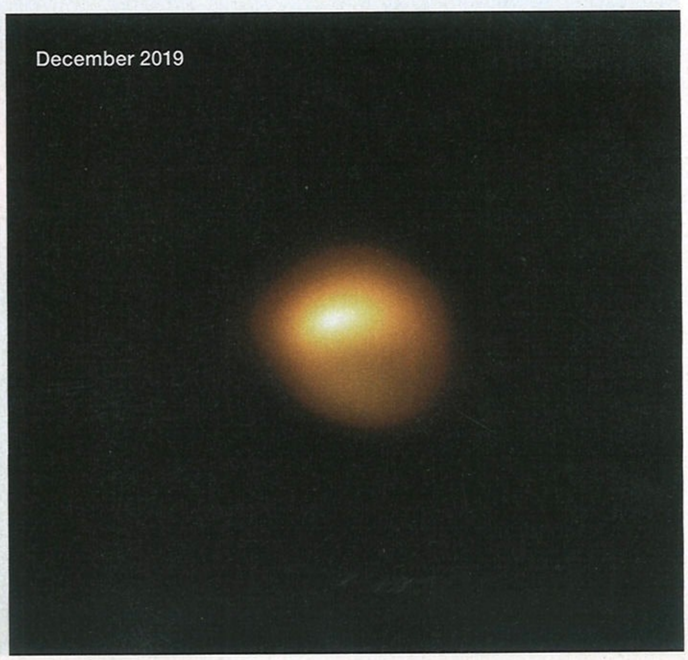
But the Great Dimming is best summed up in a *light curve*, a graph showing the brightness of the star over time. Astronomers work with light curves taken through standard color filters that reveal how the star looks at different wavelengths. Here are *V* (green) and *B* (blue) light curves that I gathered with a photometer during 2018–2020. The *V* filter approximates the sensitivity of the human eye. In 2018, Betelgeuse dimmed to a *V* magnitude of 0.88, whereas in 2020, it bottomed out at 1.61 — an additional 50% drop in brightness.



Why take data in different colors (known as *bands*)? Because the star's behavior may manifest differently at one wavelength compared to another, potentially revealing interesting information. For example, my group has photometers

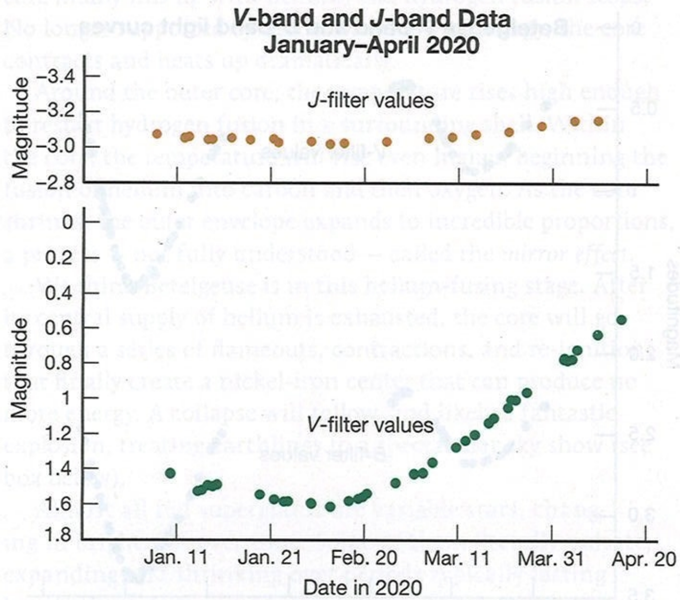
▼ **PIECEMEAL DIMMING** These VLT images show Betelgeuse as it looked shortly after its 2018 minimum *(left)* and partway through its abnormal minimum in 2019–20 *(right)*.





LIGHT CURVES GRAPH: GREGG DINDERMAN / *S&T*, SOURCE: THE AUTHOR; BETELGEUSE BEFORE AND AFTER: ESO / M. MONTARGÈS ET AL.

that take data in the near-infrared (NIR). Compare the shape of the two light curves below, starting in January 2020 when we first began observing in the *J* band (1.25 microns) of the NIR. AAVSO member Jerry Persha took the *J*-band data.



While *V*-band brightness changed dramatically, the *J*-band data scarcely budged. Whatever affected the visible light had little effect on the infrared radiation, and that's a clue to the physics at work.

Based on the professional and amateur data in hand, two main theories are competing to explain the fade of Betelgeuse: a burst of new dust that partially obscured the star, or an unusual drop in its surface temperature.

Peeling the Onion

Before we explore these theories, let's have a look at the outside layers of Betelgeuse. The visible surface of a star is called its *photosphere*. In truth, it's not a surface at all (nothing could rest upon it). The photosphere is where the atmosphere of the star becomes opaque to our vision. It looks like a surface because we cannot see through it.

The photosphere of the Sun is about 5800 kelvin, so hot that barely any molecules can survive there. Betelgeuse, on the other hand, has swollen up so large — spreading its heat over so much area — that its surface is only about 3650K. The low temperature permits an assortment of compounds, such as titanium oxide (TiO), to exist in gaseous form.

Above the photosphere of our own Sun lies the *chromosphere*, a shell of very hot, very thin gas. But the chromo-

DUST SHROUD This infrared image shows the dust surrounding Betelgeuse in December 2019. The black disk at center obscures the star so that its brightness doesn't overwhelm the instrument. The dot in the middle is Betelgeuse, to scale.

V- AND J-BAND DATA: GREGG DINDERMAN / S&T, SOURCE: THE AUTHOR; DUST SHROUD: ESO / P. KERVELLA / M. MONTARGÈS ET AL.

sphere of Betelgeuse is sandwiched between two layers the Sun lacks: a *molecular sphere* (or MOLsphere) below, and a dust shell above.

The MOLsphere is a recently discovered oddity of Betelgeuse, a region richer in gaseous molecules than the photosphere, which is how it gets its name. In our own Sun, it's a puzzle how the chromosphere becomes hotter than the photosphere below it. But in Betelgeuse the mystery is compounded, for the MOLsphere separating the photosphere and chromosphere is cooler than both of them.

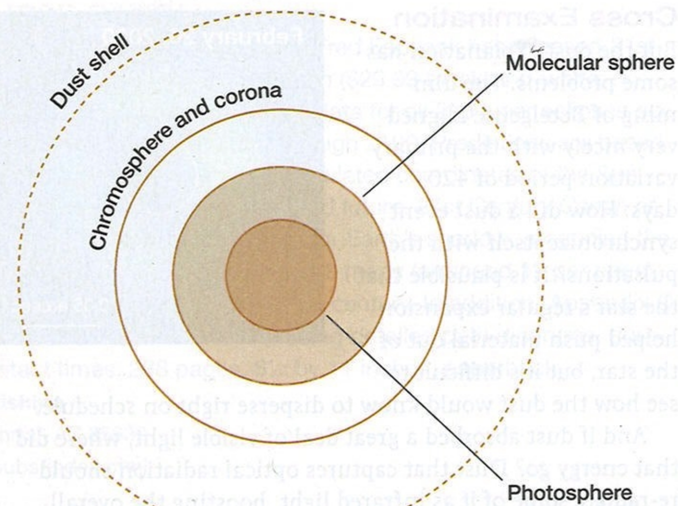
The dust shell is the end-product of mass loss in an RSG. Astronomical dust is not the fluff under your couch. It consists of tiny solids that have condensed from material that has escaped from a star. Within the star, all material is gaseous, even metallic elements like aluminum and magnesium. On the surface of a cool star like Betelgeuse, the molecules, too, are in the form of gases. But if the atoms and molecules can leap off and migrate to a cooler area, they then have the chance to stick together and form grains such as silicon monoxide (SiO) or aluminum oxide (Al_2O_3). These grains are accelerated by unknown means and fly out to enrich the composition of interstellar space (*S&T:* Dec. 2020, p. 34).

Witnesses for Dust

In the temperature versus dust debate over the cause of the Great Dimming, Emily Levesque (University of Washington) and Philip Massey (Lowell Observatory) staked the first claim. Using a spectrograph on the 4.3-meter Lowell Discovery Telescope, they determined that the surface temperature in February 2020 was not much lower than it had been in March 2004, when the star was of normal brightness.

Earthbound astronomers cannot, of course, stick a thermometer into a distant star — the measurement was indirect. Levesque and Massey examined absorption features caused by titanium oxide (TiO) in Betelgeuse's atmosphere. TiO molecules start forming at about 3800K, and they become more prevalent as the star gets cooler, absorbing ever more light. The researchers didn't see big changes in the TiO lines compared to 2004, suggesting that the temperature had changed little since then.

Professional astronomers also found evidence in support of dust by studying polarized light coming from the envelope around Betelgeuse. When sunlight reflects off the surface of a lake or the hood of your car, it becomes partially polarized, with the light waves vibrating at only certain angles. This is why polarized sunglasses are so helpful when driving or boating on a sunny day. Starlight reflecting off dust also becomes partially polarized. A team led by Boris Safonov (Lomosonov Moscow State University, Russia) imaged Betelgeuse with an instrument that picks out polarized light from an unpolarized background — sort of like sunglasses in reverse. Their data showed a big increase in polarized light as Betelgeuse recovered from its minimum. The interpretation was that, first, dense dust had formed, blocking light and causing the star to fade. Then, as the grains spread out enough for light to pass, a fresh wave of polarized reflections emerged from a newly enriched dust zone.



▲ **EXTRA LAYERS** Betelgeuse's atmosphere has two regions the Sun's doesn't: a molecular layer and an outer dust shell. The perimeter of the real dust shell is highly irregular, and the different layers flow into each other as in a melting dessert. The diameter of the photosphere is about the size of Jupiter's orbit around the Sun.

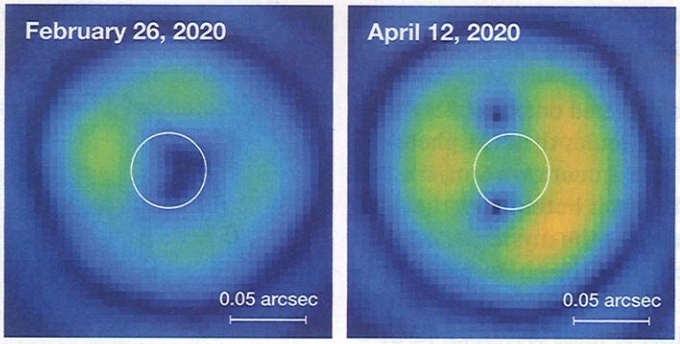
GREGG DINDERMAN / S&T

Observations suggest an ejection of material happened around the same time, which might be a source of dust. Betelgeuse has been shedding mass for eons, as we can see from the great cloud of dust that surrounds it. Dupree and others discovered signs of a recent expulsion by using Hubble's Space Telescope Imaging Spectrograph (STIS) to take ultraviolet spectroscopy of the chromosphere. The Hubble team scanned across Betelgeuse with the STIS, sampling narrow rectangles to build a kind of map of the star in UV. The spectra indicate that the southeast chromosphere experienced a shock throughout its levels during the fall of 2019. This is consistent with a burst of material passing through the chromosphere, material that could have condensed upon emerging and cooling.

But the ultraviolet data cannot reveal fresh dust, if any actually formed. And since we don't know how fast the material was moving through the chromosphere, we don't know when it would have reached a zone cool enough for condensation to occur.

Research is now turning toward *rogue cells*: unusually strong upwellings that could have the energy to push material off the photosphere. Rather than create a uniform circumstellar envelope, the result would be a kind of Swiss cheese, with pockets of new, hot gas injected into a generally cooler environment. The chromosphere does, in fact, appear to have regions of high temperature that occupy only a fraction of that layer. Dupree speculates that Hubble caught an outflow caused by a particularly powerful cell surfacing just as an outward pulsation peaked.

Cross Examination



◀ **POLARIZATION** Images reconstructed from polarized light data show that the amount of polarized light from Betelgeuse's dust-laden wind increased after the star's minimum in February 2020. The polarization intensity indicates how much light is scattering off dust. The change could be due to a change in the amount of dust, or in the illumination. The white ring shows the size of Betelgeuse.

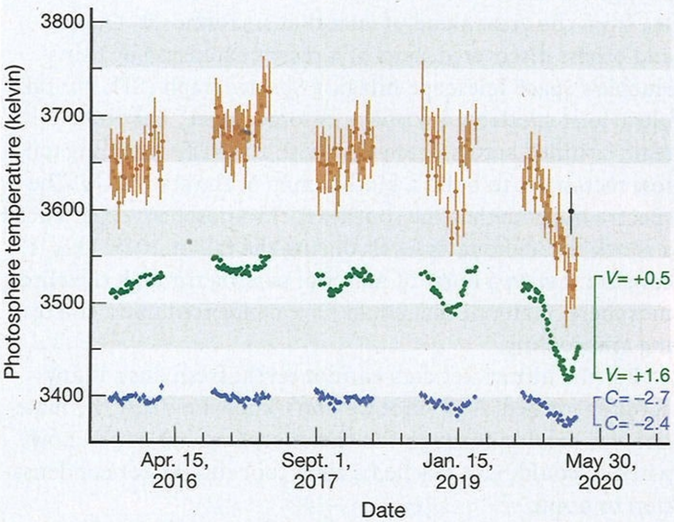
But the dust explanation has some problems. The dimming of Betelgeuse aligned very nicely with the primary variation period of 420 days. How did a dust event synchronize itself with the pulsations? It is plausible that the star's regular expansion helped push material out of the star, but it's difficult to see how the dust would know to disperse right on schedule.

And if dust absorbed a great deal of visible light, where did that energy go? Dust that captures optical radiation should re-radiate some of it as infrared light, boosting the overall infrared brightness. Yet the near-infrared AAVSO data do not show this, nor do broader infrared data from the O'Brien Observatory of the University of Minnesota, taken by Robert Gehrz and others.

Lastly, Thavisha Dharmawardena (Max Planck Institute for Astronomy, Germany) and others observed Betelgeuse in submillimeter-band radio. That radiation would not be affected by dust and should stay fairly constant if the stellar temperature were stable. But they saw the brightness drop by about 20% compared to the pre-dimmed level.

These data raise the question of whether the near-constant temperature inferred from the spectrum is correct. The 2020 spectrum largely matches a computer-modeled spectrum for 3600K. This model assumes a uniform temperature across the disc. But what if the temperature distribution is uneven? Hot regions would be less affected by TiO absorption, filling the TiO bands of the whole-disc spectrum with light that would wash out deeper absorption features in the cool areas. Cool zones, by contrast, would radiate less total light than the average temperature would indicate.

Such a "dilution" of the light is the conclusion of Graham Harper (University of Colorado, Boulder) and others. Graham's team studied the TiO absorption using a different method. The average temperature of Betelgeuse they calculate is lower than that inferred by Levesque and Massey. Given that Levesque and Massey did detect emission characteristic of gas at about 3600K, a significant fraction of the surface must be substantially cooler — about 3300K. That would be sufficient to explain the dimming.



▲ **TEMPERATURE FLUCTUATIONS** The amount of light absorbed by titanium oxide in a red supergiant's atmosphere is a good indicator of the photosphere's average temperature. Using a combination of near-infrared filters, Graham Harper and others measured TiO absorption (brown) in Betelgeuse's light over several years and found that the star's temperature dropped notably during the Great Dimming. Light curves in *V*-band (green) and an infrared band (blue) are also shown for reference, with the magnitude extremes for the 2019–20 event. (The TiO and infrared data are averaged into 7-day bins.) A study by Levesque and Massey used TiO absorption at shorter wavelengths to estimate a higher temperature (black dot). Perhaps regional temperature changes are at work.

We can visualize the competing models by returning to the strange December 2019 image of Betelgeuse. In the dust model, the southeast is partly obscured by dust, while in the temperature-drop model, the southeast has cooled off. The results of Harper's team imply that the analysis of Levesque and Massey applies only to hot, bright areas of the surface, not the whole star.

The Jury Is Out

The verdict on the Great Dimming remains under deliberation. Data from the last observing season are still under analysis, with more scientific papers in the publication pipeline.

Betelgeuse is a complex beast, and I have only scratched the surface of the story. The contention between various researchers using different instruments (more than are mentioned here) can feel like the story of the Blind Men and the Elephant. But although the men are always seen as comical characters, keep in mind that none of them is actually *wrong*. Each draws a conclusion based upon the best information he has. Their collective challenge is to synthesize a common explanation from everyone's data. That's how difficult science gets done.

■ **TOM CALDERWOOD** leads the AAVSO's photoelectric photometry ("PEP") section from the high desert of central Oregon. He can be reached at **pep@cantordust.net**.

POLARIZATION: STERNBERG ASTRONOMICAL INSTITUTE OF LOMONOSOV MOSCOW STATE UNIVERSITY; TEMPERATURE GRAPH: G. HARPER ET AL. / ARXIV: 2011.05982