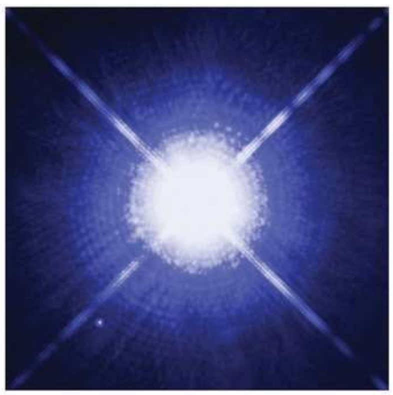
The First White Dwarf

The road to discovering a new type of star was long and winding.

A white dwarf is an extraordinary object. If you could stand on its surface and drop a pebble, the stone would smash into the star a split second later at thousands of miles per hour. The tiny star's immense surface gravity arises because the typical white dwarf packs 60% of the Sun's mass into a sphere that's only slightly larger than Earth. Its gravity, therefore, pulls that pebble down *hard*.

Yet these extraordinary objects are common, making up 6% of the stellar population of the Milky Way. They represent the eventual fates of most stars, including our Sun, after they run out of fuel. Since white dwarfs abound, many shine nearby. The closest is just 8.6 light-years from Earth, orbiting brilliant Sirius in Canis Major. Designated Sirius B, this near neighbor has an apparent magnitude of 8.4, making it the brightest white dwarf of all. But in backyard telescopes, it's difficult to see, lost in the glare of its dazzling mate.



▲ **SUPER DENSE** Smaller than Earth but as massive as the Sun, the white dwarf Sirius B (7 o'clock position) is so dense that a spoonful of its material would weigh tons. With a surface temperature of 25,000 K, Sirius B is also one of the hottest stars in our vicinity and much hotter than its brilliant mate, which it orbits every 50 years.

NASA / ESA / H. BOND (STSCI) AND M. BARSTOW (UNIV. OF LEICESTER)

Astronomers first suspected the presence of Sirius B long before they actually observed it. In 1844, in Prussia, Friedrich Wilhelm Bessel reported that Sirius wobbled as it traveled through space. He correctly attributed this wobble to the gravitational pull of an invisible partner orbiting the bright star. On January 31, 1862, American astronomer Alvan Graham Clark spotted the elusive companion, which is 10 magnitudes dimmer than Sirius A (*S&T:* Feb. 2008, p. 30). However, no one then knew that Sirius B was a white dwarf. In fact, that term didn't exist until 60 years later.

Today, of course, Sirius B is the best-known white dwarf of all, leading to the claim that it was the first white dwarf ever found. In fact, at least two NASA websites say so. But that honor actually belongs to another stellar neighbor of ours — one that's a lot easier to see.

The Story of 40 Eridani

West of Orion's Rigel, in the northern reaches of the meandering constellation Eridanus, shines a triple-star system named 40 Eridani. It lies 16.3 light-years from Earth, about twice as far as Sirius. The brightest member of this stellar trio is an *orange dwarf* — a *K*-type main-sequence star that, like the Sun, converts hydrogen into helium in its core. Orange dwarfs are less luminous than the Sun because they are less massive. Although common, most are too faint to be visible to the naked eye, but 40 Eridani's proximity makes it an exception.

In 1783, on January 31st — exactly 79 years before the first sighting of Sirius B — the great German-born English astronomer William Herschel, who two years earlier had discovered the planet Uranus, aimed his telescope at 40 Eridani. He saw that the naked-eye star had two faint companions. The tight, dim pair was about $1\frac{1}{3}$ arcminutes east of the orange dwarf, 40 Eridani A.

Herschel recorded the separation and position angle of the companion stars, but he never observed them again. Of course, he didn't know 40 Eridani was special. Neither did anyone else.

The first sign that 40 Eridani stood out from the stellar pack came two decades later when Italian astronomer Giuseppe Piazzi (best remembered for discovering the first asteroid, Ceres) observed that the star had a large proper motion. *Proper motion* is the apparent movement, year after year, of a star across the night sky (*S&T:* June 2022, p. 30). The nearer a star is to us and the faster it dashes across our line of sight, the larger its proper motion.

At that time, however, astronomers had yet to ascertain the distance to any star but the Sun. They had long sought to do so by measuring *stellar parallax*, the apparent shift that occurs when we view a star from different vantage points as Earth circles the Sun. Mistakenly assuming that brightness indicated nearness, astronomers concentrated their parallax efforts on the very brightest stars, expecting them to be the closest. But Piazzi recognized that a large proper motion was a more reliable sign of proximity.

However, the Italian astronomer faced a problem. "They are going to think I am a fool because I have deduced the proper motions of a few stars on the observations of only ten years, and in some cases less than that," he wrote to Barnaba Oriani, director of the Observatory of Brera in Milan. Piazzi therefore confirmed the movements by comparing the stellar positions he had measured with those recorded in the 1600s and 1700s.

"I have found some movements that deserve full attention from astronomers, especially in the constellations of Cetus and Eridanus," he wrote in 1804, mentioning 40 Eridani, correctly suspecting that it was one of our closest neighbors.

That same year, Piazzi discovered the large proper motion of an even fainter star, 61 Cygni. In 1838, using the parallax method, Bessel successfully measured 61 Cygni's distance — a first for any star besides the Sun — thus propelling it to fame. However, 40 Eridani would keep its secrets a little longer.

In the 1880s astronomers on two different continents finally succeeded in measuring 40 Eridani's distance. One was Scottish-born David Gill, who observed 40 Eridani A from South Africa. "This is the principal star of one of the most remarkable systems in the heavens," he wrote from the Cape of Good Hope. Between July 11, 1881, and February 19, 1883, he measured the star's position and derived its parallax.

Meanwhile, American astronomer Asaph Hall, of the U.S. Naval Observatory, learned of the star's importance from a Russian astronomer. Otto Wilhelm von Struve, head of the Pulkovo Astronomical Observatory near Saint Petersburg, Russia, had tracked the motion of 40 Eridani B and C around each other.

"During one of his visits to the Naval Observatory, Director Otto Struve called my attention to this interesting stellar system, and advised me to undertake a determination of its annual parallax, since its position made it a difficult object to observe in Europe," Hall wrote in the German journal *Astronomische Nachrichten* (*Astronomical Notes*). Using the same 26-inch refractor with which he had discovered the Martian moons Phobos and Deimos in 1877, Hall observed 40 Eridani 30 times between February 23, 1883, and March 4, 1884. "These observations were tedious, and took much time," he added. But he succeeded in detecting the star's parallax.

Both Gill and Hall published their work in 1885. Gill's parallax indicated that the star was about 3 light-years farther than the modern figure of 16.3 light-years, whereas Hall's work put the star about 2 light-years closer than it actually is. Either way, the measurements showed that the 40 Eridani system was nearby, which meant that the stars also had to be intrinsically faint. In particular, 9.5-magnitude 40 Eridani B and 11.2-magnitude 40 Eridani C emit much less light than the Sun, which would shine at 3rd magnitude if viewed from the same distance. It takes 40 Eridani B nearly a year to emit as much visible light as the Sun does in a 24-hour day. And 40 Eridani C is even dimmer.

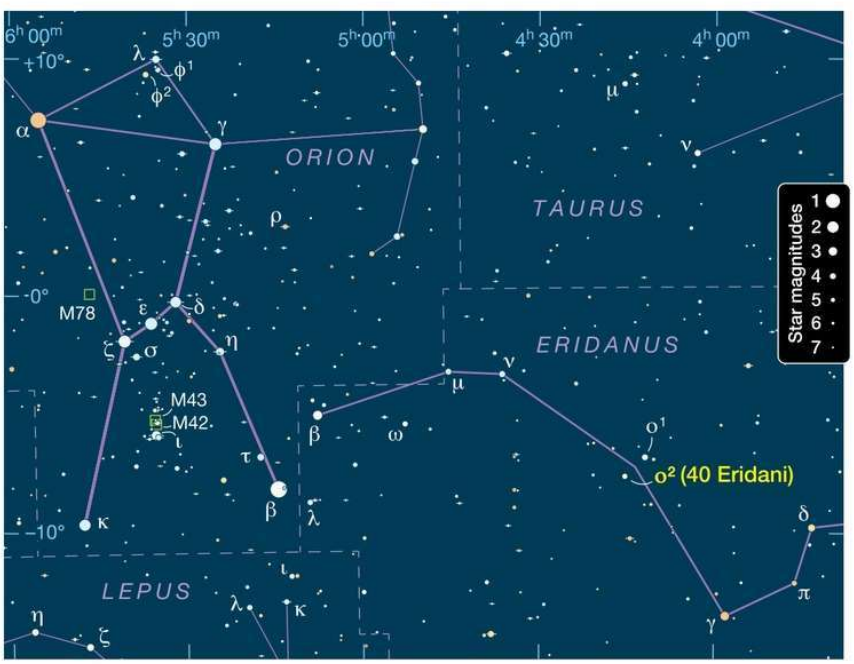
By the late 19th century, however, astronomers were starting to realize that many of the Sun's stellar neighbors were faint and red — what we now call *red dwarfs*. For example, astronomers had previously found that 7.5-magnitude Lalande 21185, a red dwarf in Ursa Major, was closer than any other star then known except the Sun and Alpha Centauri (*S&T:* June 1995, p. 68), and in the 1880s Gill himself measured the parallax of Lacaille 9352, a 7.3-magnitude star in Piscis Austrinus that also turned out to be a nearby red dwarf.

The preponderance of dim red stars seemed to have a clear implication for the nature of the star orbiting Sirius. Although no one could see it well, Sirius B was surely just another red dwarf — one that happened to accompany the brightest star in the night sky.

A White-Hot Discovery

With every new hard-won parallax measurement, astronomers could calculate a star's intrinsic brightness because they now knew its distance. Patterns were starting to emerge. Red stars, now classified as spectral type *M*, came in two varieties. A few, like Antares and Betelgeuse, were luminous, but most, like Lalande 21185 and Lacaille 9352, were much dimmer than the Sun. In contrast, all the blue and white stars (spectral types *B* and *A*) outshone the Sun.

Harvard astronomers had developed these spectral types to classify the stars. Observatory director Edward Pickering led the effort, but his assistants — especially Williamina Fleming and Annie Jump Cannon — actually performed most of the classifications. The discovery of the first white dwarf resulted from combining two pieces of



A GEM IN THE RIVER The easiest white dwarf to see in backyard telescopes is unquestionably 9.5-magnitude 40 Eridani B, which lies 83″ east-southeast of 4.4-magnitude 40 Eridani A, also known as Omicron^2 (o^2) Eridani.

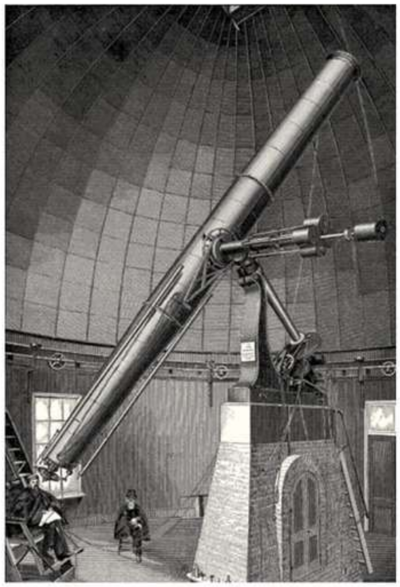
knowledge: spectral type and luminosity, the latter revealed by parallax.

Princeton astronomer Henry Norris Russell was quite interested in this work. In 1910 while visiting Pickering, Russell commented that he didn't think most of the stars with measured parallaxes had known spectral types. Pickering asked for an example of such a star, and Russell cited 40 Eridani B. If the dim star was a red dwarf, it would be spectral type *M*.

Pickering responded, "Well, we make rather a specialty of being able to answer questions like that." As Russell recalled:

> *. . . we telephoned down to the office of Mrs. Fleming and Mrs. Fleming said, "yes", she'd look it up. In half an hour she came up and said "I've got it here, unquestionably spectral type A". I knew enough, even then, to know what that meant. I was flabbergasted. I was really baffled trying to make out what it meant. Then Pickering thought for a moment and then said with a kindly smile, "I wouldn't worry. It's just these things which we can't explain that lead to advances in our knowledge." Well, at that moment, Pickering, Mrs. Fleming and I were the only people in the world who knew of the existence of white dwarfs.*

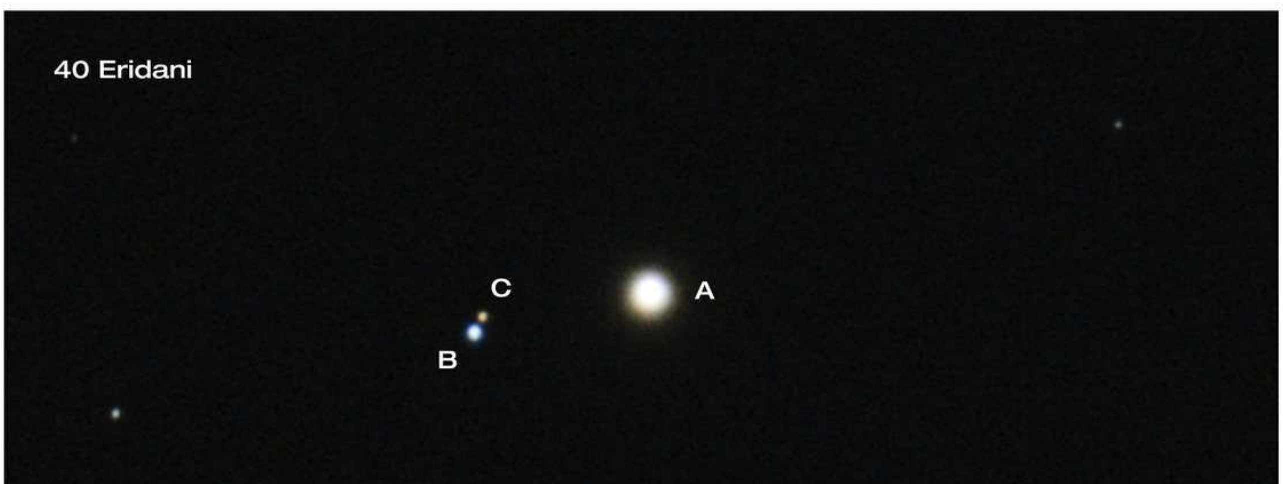
However, Russell gave this account at a Princeton colloquium that occurred four decades after the discovery of 40 Eridani B's white dwarf status. Initially he had been much more skeptical. On June 13, 1913, he addressed the Royal Astronomical Society in England, displaying what we now call a Hertzsprung-Russell diagram — a plot of stars by luminosity and spectral type that Russell and European astronomer Ejnar Hertzsprung had independently conceived.



MACHINERY OF DISCOVERY The U.S. Naval Observatory's 26-inch refractor revealed the moons of Mars, the parallax of 40 Eridani, and more recently the orbital period of the white and red dwarfs 40 Eridani B and C around each other.

Russell pointed out the nearly empty quadrant on the Hertzsprung-Russell diagram where intrinsically dim blue and white stars would be, referring to 40 Eridani B without actually naming it: "It is immediately conspicuous that one corner of the diagram is vacant (except for one star whose spectrum is very doubtful). There do not seem to be any faint white stars." Russell couldn't object to 40 Eridani B's low luminosity since both its apparent magnitude and its distance were known, but he did doubt its type *A* classification.

Russell knew that the star's spectral type carried radical implications for its true nature. First, it meant the dim star was hotter than our *G*-type Sun. And that meant every square inch of 40 Eridani B's surface had to emit much more light than every square inch of the Sun's surface. But how could that be if the star shone so dimly? The answer: *40 Eridani B's*



THREE FOR THE SHOW
For backyard scopes, 40 Eridani is an attractive triple star. The separation between A and the B-C pair is 82.7″, while B and C are 7.8″ apart.

26-INCH USNO REFRACTOR: M&N / ALAMY STOCK PHOTO; 40 ERIDANI: STEVE SMITH *surface must have very few square inches*. In other words, the star was tiny. In 1914 Walter Adams at Mount Wilson Observatory in California observed the star and confirmed that it was indeed spectral type *A*.

The next year, Adams took aim at a more difficult target: Sirius B, the presumed red dwarf orbiting Sirius A. On October 18, 1915, "under exceptionally good conditions of seeing," Adams succeeded in obtaining the dim star's spectrum. The "red" dwarf wasn't spectral type *M* at all; rather, it was the same type *A* as Sirius itself. Like 40 Eridani B, Sirius B was therefore hot, which in turn meant that every square inch of its surface radiated profuse amounts of light. But because the star was so dim, it had to be tiny. And that led to another radical revelation: Sirius B was incredibly dense. Astronomers had already used the gravitational tug on its brilliant partner to find that it was half as massive as Sirius A. Divide Sirius B's mass by its minuscule volume, and you end up with an extraordinarily dense star.

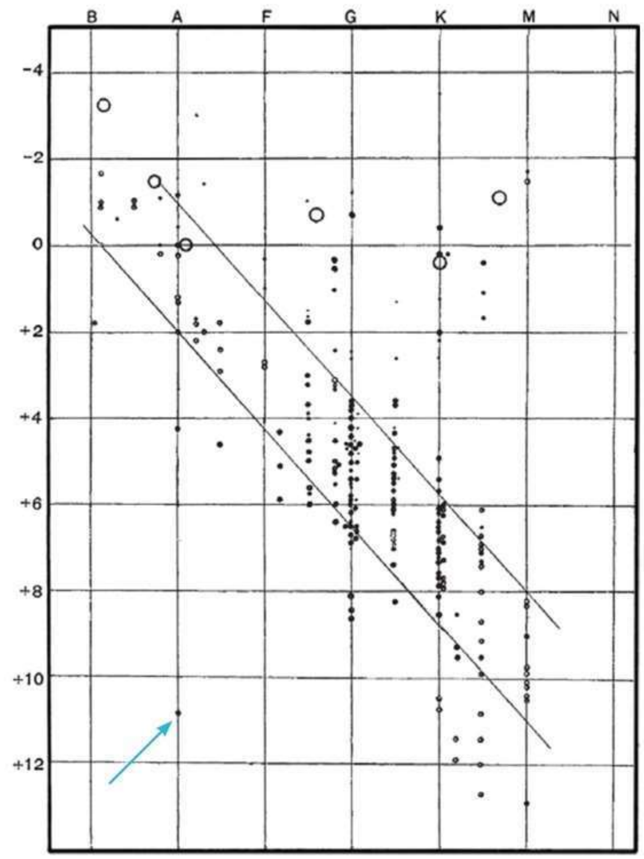
Several astronomers questioned the result, however, claiming that light from Sirius A had contaminated the fainter star's spectrum. But Adams pointed out that one other feeble *A*-type star was already known: 40 Eridani B.

Soon there was another member of the class. In September 1917 Mount Wilson Observatory astronomer Adriaan van Maanen was searching for a companion to a star in Pisces named Lalande 1299, which had a fairly large proper motion. He noticed on his photographic plates that an unrelated dim star had an even larger proper motion. Now named Van Maanen's Star, it's the nearest solitary white dwarf to Earth, lying just 14 light-years away.

Meanwhile, observations of 40 Eridani continued. In October 1921 Frederick Leonard (Lick Observatory) identified 40 Eridani C to be of spectral type *M*. The 40 Eridani system therefore consists of an orange dwarf, a white dwarf, and a red dwarf.

Hertzsprung recognized the implication of three dim, white stars (40 Eridani B, Sirius B, and Van Maanen's Star) in our immediate vicinity. Despite their bizarre nature, statistically such stars must be common. In a 1922 article that appeared in the *Bulletin of the Astronomical Institutes of the Netherlands*, he wrote, "The absolutely faint white stars seem to be even more frequent per unit volume than the absolutely bright yellow stars" (by which he meant giants like Arcturus).

Even with three known examples, this class of stars still had no name. That changed later in 1922 when Willem Jacob



▲ **EARLY CLUES** Henry Norris Russell's original H-R diagram shows the main sequence (diagonal band from upper left to lower right), giant stars at the upper right, and one stellar outcast at lower left: the first white dwarf, 40 Eridani B (indicated), which possessed two seemingly incompatible qualities: high temperature and low luminosity.

The Omicron Variant

The star 40 Eridani also goes by the name Omicron[2] Eridani. Look for it about a degree southeast of Omicron[1] Eridani, an unrelated star that is slightly brighter and a good deal farther from Earth. Because 40 Eridani A shines at magnitude 4.4, you can see it in a dark sky without optical aid.

40 Eridani is about 16.3 light-years away, which means the separation of the orange dwarf from the white and red dwarfs is at least 410 a.u. — more than 10 times the Sun-Pluto distance — while the mean separation between the white and red dwarfs is at least 34.5 a.u.

The 40 Eridani Star System

	40 A	40 B	40 C
Type of star	Orange Dwarf	White Dwarf	Red Dwarf
Spectral type	*K*0.5 *V*	*DA*2.9	*M*4.5 *V*
Apparent magnitude	4.43	9.52	11.24
Absolute magnitude	5.94	11.03	12.75
Visible-light output*	36%	0.33%	0.068%
Mass*	85%	57%	20%

*Compared with the Sun

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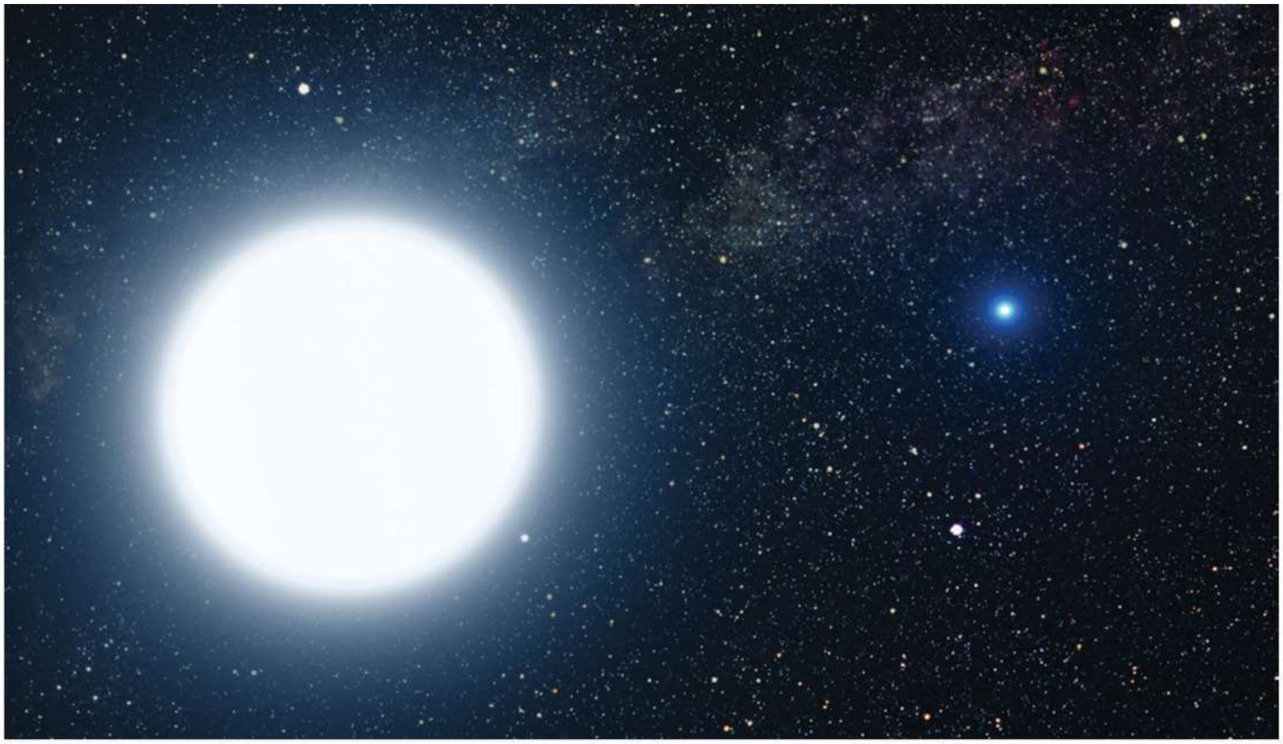

▲ **DOG AND PUP SHOW** This illustration shows the star Sirius A (the dominant star at left) and its white-dwarf companion, Sirius B (pictured at center right) — sometimes called the "Pup." Although some sources list Sirius B as the first white dwarf discovered, that distinction actually goes to 40 Eridani B. In backyard telescopes, Sirius B is a challenging target, while 40 Eridani B is relatively easy to spot.

NASA / ESA / G. BACON (STSCI)

Luyten, who had earned his doctorate under Hertzsprung the year before, coined the term "white dwarf." Although Luyten went on to discover many additional white dwarfs, their numbers grew so slowly that by 1940 *The Sky* (a forerunner of this magazine) reported that only 25 were known.

The Modern Era

Today astronomers have cataloged many thousands of white dwarfs. As it turns out, the stars come in a range of colors, from blue to red. That's because white dwarfs cool and fade with age — blue ones are the hottest and youngest, whereas red ones are the coolest and oldest. Both Sirius B and 40 Eridani B are as hot as blue main-sequence stars of spectral type *B*. Sirius B's surface temperature is 25,000 kelvin and 40 Eridani B is also hot, with a surface at 17,000K — nearly three times the Sun's temperature of 5800K.

In 2017 Brian D. Mason (U.S. Naval Observatory) and his colleagues observed 40 Eridani B and C with the same 26-inch refractor Asaph Hall had earlier employed. This work revealed that the orbital period of the B and C components is about 230 years, a bit shorter than indicated by older observations. The shorter period means that the two stars must be more massive than previously thought to have enough gravity to dance around each other faster than originally believed. Furthermore, the newly calculated masses resolved a long-standing puzzle regarding 40 Eridani B.

When a star possesses extreme surface gravity, photons lose energy as they're emitted from the star. This stretches the photons' wavelengths toward the red part of the spectrum, a process known as *gravitational redshift*.

Gravitational redshift helps astronomers determine a white dwarf's mass: The more massive a white dwarf, the stronger its surface gravity (both because the greater mass exerts more force and because gravity squeezes the star, reducing its diameter). The gravitational redshift of 40 Eridani B is about 26 km per second — far greater than the Sun's gravitational redshift of only 0.6 km per second. The old orbital period for the pair of stars implied a mass too low and a size too large to produce so great a redshift for 40 Eridani B. However, the new orbital measurements yield a white dwarf mass that's about 57% that of the Sun, which agrees well with the 53% figure derived from the gravitational redshift.

This new mass estimate also means that 40 Eridani B is quite average for its class, because the typical white dwarf is about 60% as massive as the Sun. In contrast, Sirius B is unusually heavy — estimates place it at one solar mass.

Compared with Sirius B, 40 Eridani B is much easier to see. Although it's a magnitude fainter, the Eridanus white dwarf doesn't have to compete with the brilliance of a star like Sirius. In his monumental *Celestial Handbook*, Robert Burnham, Jr., notes that 40 Eridani B is "the only white dwarf star which can honestly be called an easy object for the small telescope."

A century ago this easy-to-see star made astronomical history as the first white dwarf ever found — a star that foretells the destiny of our own Sun.

■ **KEN CROSWELL** has long been interested in the nearest stars. He earned his PhD at Harvard University and is the author of *The Alchemy of the Heavens* and *Magnificent Universe*.