-TREME STARS of the cosmos

Get to know the galaxy's biggest, hottest, and most distant stars. /// BY C. RENÉE JAMES AND HOWIE MARION

Whether stars are tiny and cool or massive and unstable, they tell us a lot about the way our universe works. Sure, it's important to understand average stars, like the Sun. But watching the extremes, whether they be on Earth, in the solar system, or the galaxy, tells us something deeper about the universe. Moreover, extreme stars are laboratories where astronomers can test what they think they know under the weirdest, most outrageous circumstances. If astronomers ever decide to compile a *Cosmic Book of Stellar Records*, these stars will be in it.

Less than 1 percent of the stars within 100 light-years rank as high-mass stars, those more than 10 times heavier than the Sun, but they produce most of the light nearby. Our Sun is more massive than about 90 percent of the stars around it. Astronomers estimate the most common objects in the Milky Way's disk aren't bona fide stars, but brown dwarfs. These objects cannot fuse hydrogen — the hallmark of star-hood — yet they may outnumber stars 2 to 1.

STARS RANGE in size from bloated blue and red supergiants to tiny red dwarfs a fraction of our Sun's mass. When Sun-like stars end their energy-producing lives, they form Earth-size remnants called white dwarfs, which cool slowly over time. LYNETTE COOK FOR ASTRONOMY

In the beginning

Stars first lit up our universe a few hundred million years after the Big Bang. They formed from the raw materials of hydrogen (75 percent by mass), helium (24 percent), and a pinch of lithium and beryllium (less than 1 percent). These high-mass stars then took on the task of creating the rest of the periodic table.

Boiled down to its essence, the recipe for stars throughout the universe's history is much the same as it is today. A large cloud of gas falls in on itself and *voilà* — a stellar hatchery forms. Some members will be high-mass stars, which will self-destruct in a cosmic heartbeat. Others, of more moderate mass, will survive for billions of years. Low-mass stars, by far the most common, make up for their stature with numbers and longevity. They'll fuse hydrogen fuel into helium for trillions of years.

Missing massives

The composition of the early universe was different than it is today. In just a few hundred thousand years, the first stars enriched their environs with elements heavier than helium, which astronomers refer to as metals. This modest change profoundly affected the lives of subsequent stellar generations.

Stars from the earliest epoch provide the light we see in the most distant galaxies, but the stellar demographics of these systems probably don't mirror what we find in our neighborhood. Astronomers think star-forming clouds containing low amounts of metals have difficulty creating low-mass stars. As a star is born, gravity pulls it together, but its own heat tends to puff it out and slow the process. Metals channel this heat outward efficiently, allowing the birth of low-mass stars. Without metals,

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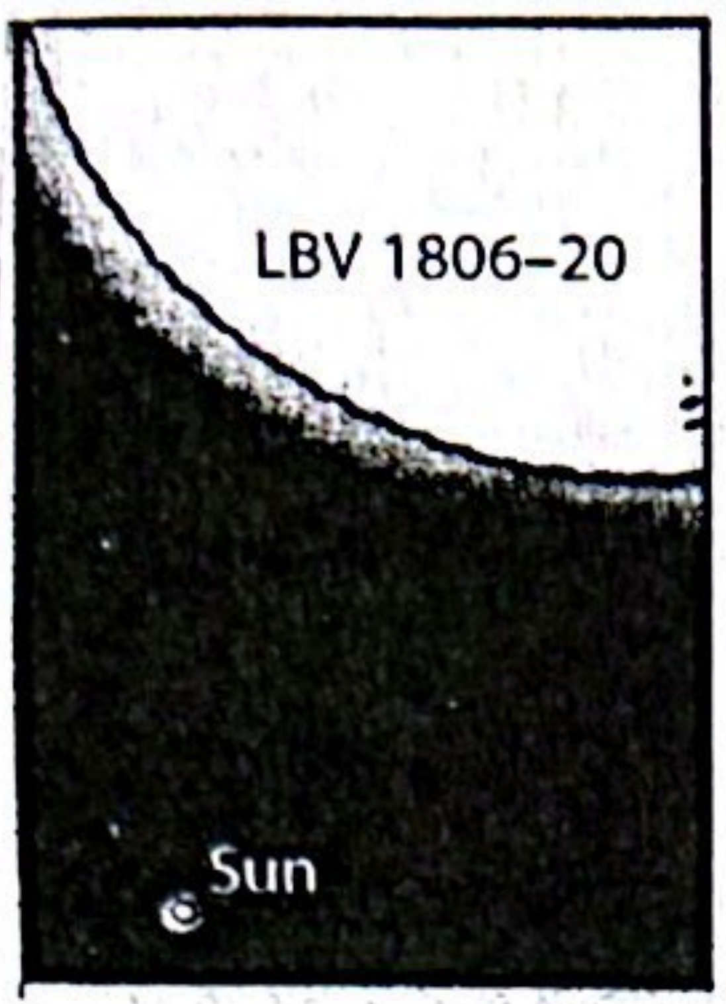
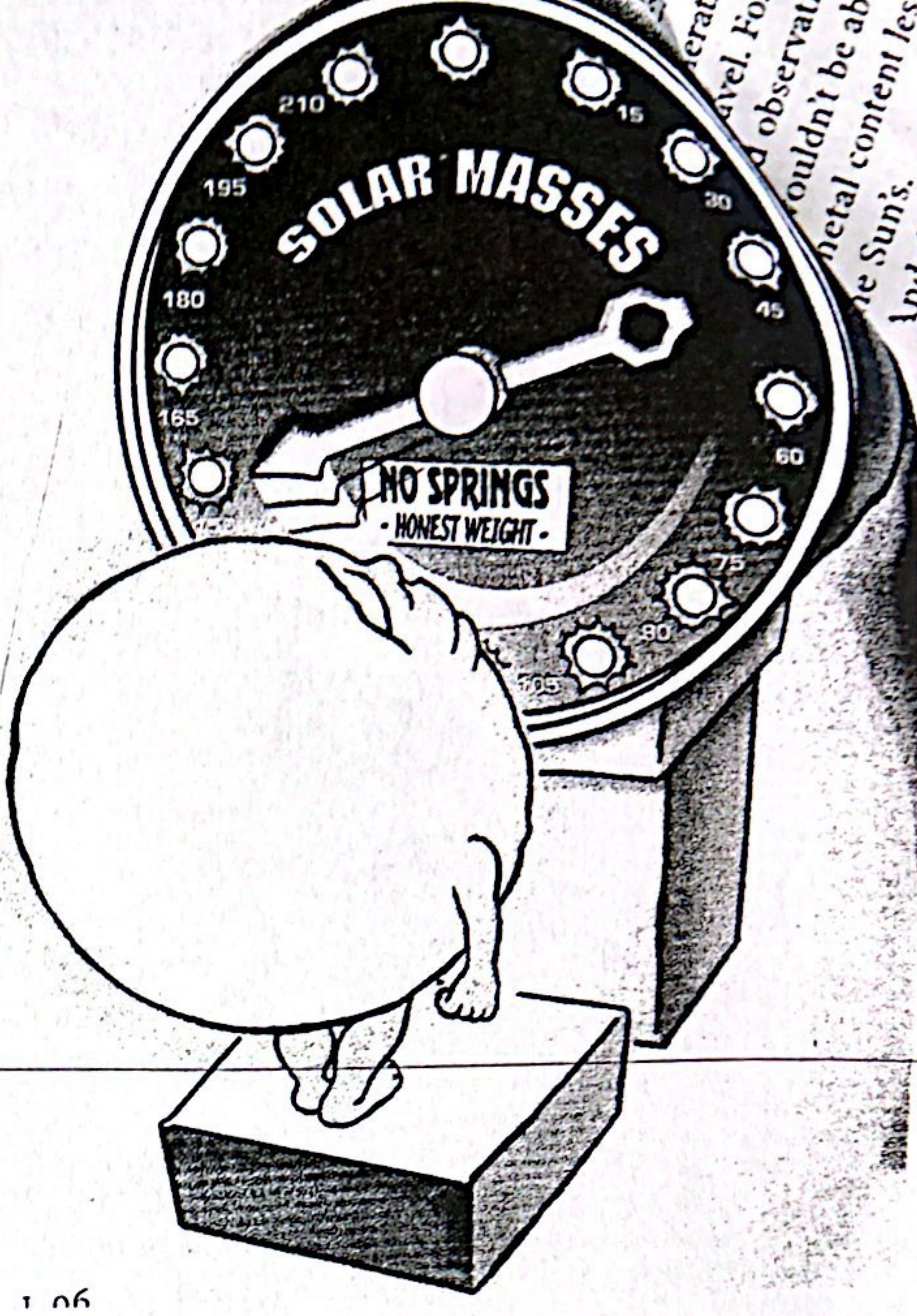
X-TREME MASS

MOST MASSIVE STAR KNOWN

Name: LBV 1806–20
Right ascension (R.A.): 18h08m40s
Declination (Dec.): –20°24'39"
Distance: 45,000 light-years
Surface temperature: At least 12,300 K (21,600° F) — more than twice the Sun's
Mass: 150 to 200 Suns
Radius: Approximately 500 times the Sun's
Luminosity: 5 million Suns
Discovered: 1995, by Varsha P. Kulkarni and colleagues, initially noted as a counterpart to a soft-gamma-ray repeater
Caveat: May be a binary system or tight cluster. If so, then the Pistol Star, which is in the same mass range, wins the title.



LBV 1806–20, more than 150 times the Sun's mass, holds the title for most massive star.



THE PISTOL STAR, thought to weigh between 150 and 200 Suns, is a contender for the most massive star known. Named for the pistol-shape nebula it erupted, the Pistol Star unleashes as much energy in 6 seconds as our Sun does in a year. It's so big that, if placed at the center of our solar system, its surface would extend to Earth's orbit. The Pistol Star lies 25,000 light-years from Earth near the Milky Way's center. NASA/D. FIGER, UCLA

astronomers believe, most of the Sun's neighbors couldn't have formed.

The early universe's lack of metals figured in the birth of massive stars, too. A massive protostar could gain weight more rapidly in that environment than it can today. Astronomers think that, back then, stars could grow to masses 1,000 times greater than the Sun's before they tore apart. These supermassive stars eventually collapsed into black holes, taking virtually all of their synthesized elements along for the ride. Although these supermassive stars dominated the light output of the first galaxies, their role in the early universe's evolution is unclear. Moreover, astronomers aren't sure what kind of stars they're seeing when they look this far back in time. Does most of this light come from just a few supermassive stars? Or is a crowd of less extraordinary stars responsible?

Current telescopes can't resolve individual stars within those ancient galaxies, so astronomers must examine closer stars. Stars with masses above about 150 solar masses don't seem to exist locally. Why? Do supermassive stars die too quickly, so that the odds of seeing one close by are essentially zero? Does our galaxy's metal content allow star-forming clouds to fragment into many low-mass stars at the expense of massive ones? Do the metals in massive protostars interact so strongly with radiation that the stars shred themselves?

"Right now we don't know whether the observed mass limit is an intrinsic property of stars or the star-formation process, or whether it is imposed by the environment," says astronomer Sally Oey of the University of Michigan at Ann Arbor, whose team has completed a statistical analysis confirming the observed upper limit. Theorists, however, must still grapple with those numbers. "Understanding the basic parameters of the massive star population is essential," Oey says, because stars have always been the universe's consumers, producers, and recyclers.

Low-mass stars — those with less than the mass of our Sun — make up the other extreme. Stars born with 60 to 80 percent of the Sun's mass in the first stellar generation would still be shining today. Despite their small masses, such stars are extremely fuel-efficient and can last tens of billions of years. The oldest ones would be the stellar equivalent of living fossils. Trouble is, astronomers don't think stars of such low mass could form in the extremely metal-poor environment of the early universe.

About 2.5 percent of the Sun's material is neither hydrogen nor helium, which indicates our star formed from gas processed by at least two earlier generations of stars. Astronomers have observed stars with metal abundances as low as 0.1 percent of the Sun's for decades. Most likely, such stars represent the second stellar generation. But with contributions from many

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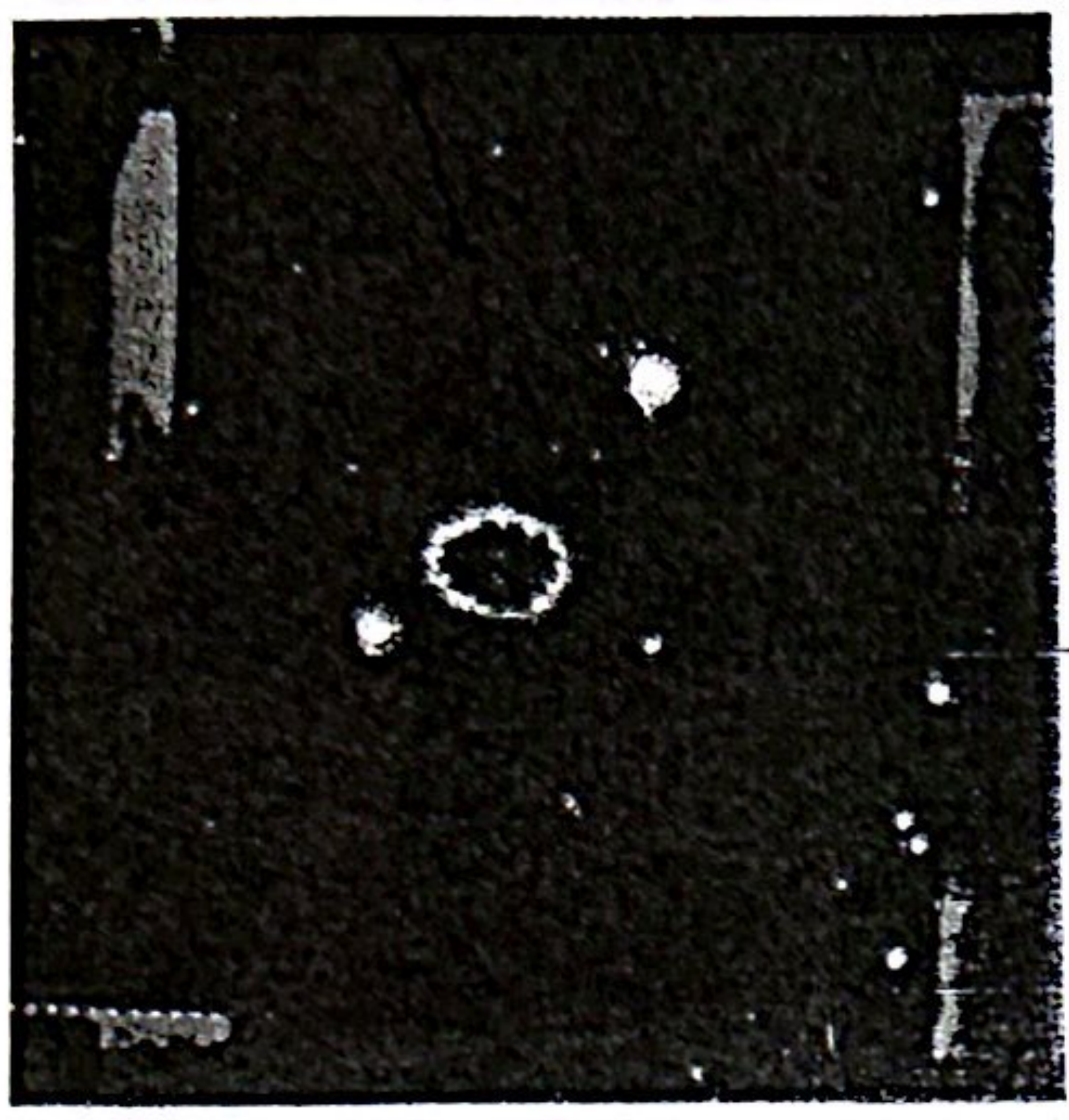
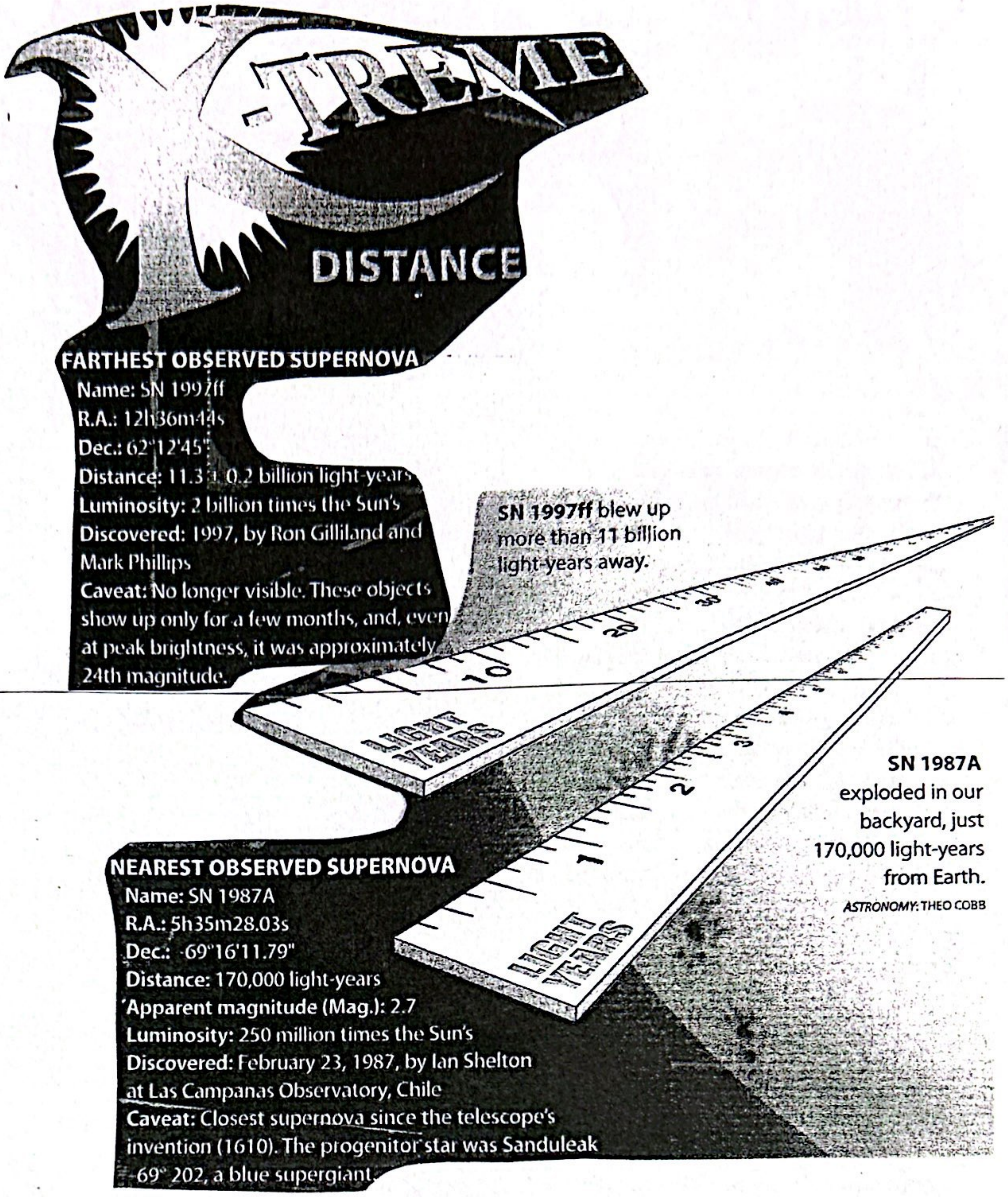
exact demographics neration have been difavel. For a long time, both d observation suggested astronwouldn't be able to find any stars metal content less than 1/10,000 that he Sun's.

\nd then they did.



SN 1987A still puts on a show for astronomers. Its blast wave is interacting with ring of debris the star shed before it exploded. As the wave heats the mateial, million-degree knots set the ring aglow. NASA/STScI/CfA/P. CHALLIS



X-TREME DISTANCE

FARTHEST OBSERVED SUPERNOVA
Name: SN 1997ff
R.A.: 12h36m44s
Dec.: 62°12'45"
Distance: 11.3 ± 0.2 billion light-years
Luminosity: 2 billion times the Sun's
Discovered: 1997, by Ron Gilliland and Mark Phillips
Caveat: No longer visible. These objects show up only for a few months, and, even at peak brightness, it was approximately 24th magnitude.

SN 1997ff blew up more than 11 billion light-years away.

NEAREST OBSERVED SUPERNOVA
Name: SN 1987A
R.A.: 5h35m28.03s
Dec.: -69°16'11.79"
Distance: 170,000 light-years
Apparent magnitude (Mag.): 2.7
Luminosity: 250 million times the Sun's
Discovered: February 23, 1987, by Ian Shelton at Las Campanas Observatory, Chile
Caveat: Closest supernova since the telescope's invention (1610). The progenitor star was Sanduleak -69° 202, a blue supergiant.

SN 1987A exploded in our backyard, just 170,000 light-years from Earth.

ASTRONOMY: THEO COBB

llar surprise

2002 discovery of HE 0107–5240, preted astronomers with clear evidence that -mass stars can form in metal-poor ds. In just 4 years, HE 0107–5240 has been the subject of nearly 40 journal articles. They address everything from the mass range of the first stars, to the chemistry of the Milky Way's first supernova explosions, to how low-mass stars could form in the young universe. Since 2002, astronomers have found stars with even lower metal fractions (see "X-treme chemistry," above).

But if these stars formed, they also died. In doing so, they puffed out their gaseous envelopes, and their cores turned into white dwarfs. Pair up a white dwarf and a normal star, and you have a time bomb. As the normal star evolves, it will swell and donate material to its white-dwarf companion. This transfer of matter sets the stage for one of the most powerful explosions in the cosmos: a type Ia supernova.

Type Ia supernovae are brilliant beacons — astronomers can spot them billions of light-years away. Observations of type Ia supernovae have driven the recent acceptance of an accelerating cosmic expansion. But, from the perspective of extreme stars, spectra of these supernovae tell astronomers about the composition of the exploding white dwarfs and their companions. Of significance to cosmologists: Does composition affect the supernova's peak brightness and fade-out time? Could early type Ia supernovae be different from today's?

White dwarfs also help us trace our galaxy's history. Once blazing hot at more than 100,300 K (180,000° Fahrenheit), white dwarfs themselves have no additional power source, no ability to compress and heat any further (at least without help from a partner), and nothing left to do but cool off forever.

Don Winget at the University of Texas, Austin, is drawn to this research. "There is a straightforward relation between the age of a white dwarf and its luminosity," he says. Compared to other stars, white dwarfs are simple, Winget explains.

For the past decade or so, astronomers have searched for the coolest white dwarfs as clues to the ages of different galactic populations. Applying relatively basic astrophysical principles, astronomers find that white dwarfs in the Milky Way have been cooling down for the past 8 or 9 billion years. The current record holder is SDSS J1403, which glows faintly at a mere 4,300 K (7,200° F).

"Finding SDSS J1403 is like unearthing the oldest known fossilized bone of a prehistoric dinosaur," says the University of Chicago's Evalyn Gates, who discovered the star. "We have much to learn from these relics from the ancient universe as we seek to refine the picture they sketch out for us of the early galaxy."

Migrating worlds

Meanwhile, stars are born, live, and die. They scatter their elemental ashes into the galaxy, eventually enriching gas clouds enough that planets, and even life, become possible. The idea that stars like the Sun have planets was mere speculation 16 years

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ago. Then, in 1995, Michel Mayor and Didier Queloz of Switzerland's Geneva Observatory confirmed the first extrasolar planet around 51 Pegasi, a star with essentially the same mass and temperature as our Sun. A team led by Geoff Marcy at the University of California, Berkeley, followed up with precise information about the planet: It's a gas giant with a Jupiter-like mass, and it orbits every 4 days.

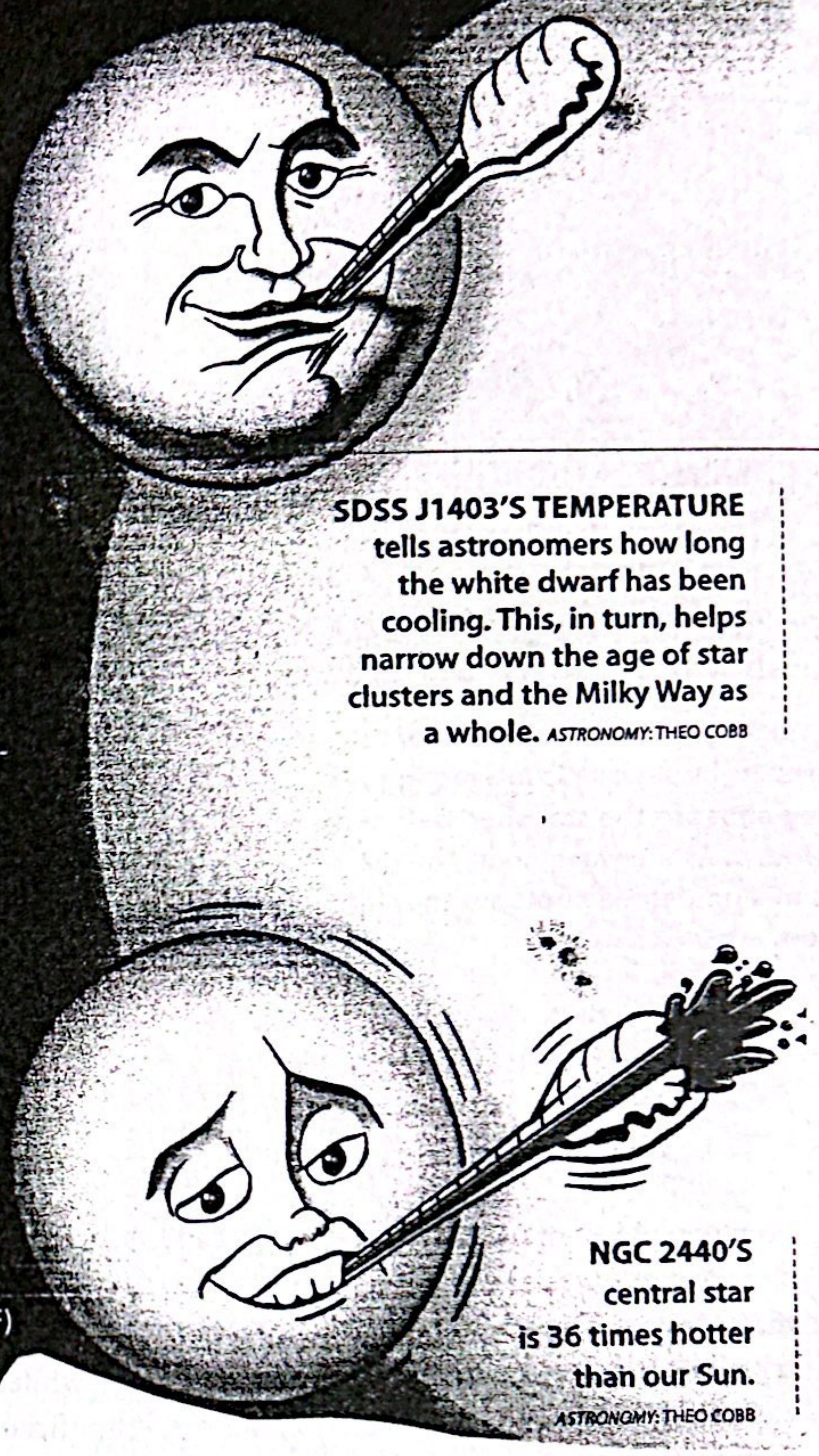
How can a gas giant lie so close to its parent star? This made no sense with what we thought we knew about the formation and evolution of planetary systems. Dozens of subsequent discoveries confirmed the seemingly common existence of Jupiter-size planets practically skimming the surfaces of the stars they orbit. These planets spurred new theories of planetary migration to explain their locations and sizes.

Astronomers wonder if perhaps some condition within the star's natal cloud drives the process that allows giant planets to form so close to their stars. Metal-rich clouds seem to encourage not only the formation of lightweight stars, but also the development of close-in giant planets. Recent research suggests that, for the most part, stars with close-in giants also have metal concentrations some 60 percent higher than the Sun's.

And here we sit, on a planet orbiting the Sun — a star that is neither the most nor the least massive, neither the hottest nor the coolest. Our Sun is far from being the oldest star, and nearly as far from being the youngest. It holds a modest supply of goods manufactured by other stars, and its gas-giant planets haven't migrated far enough to disrupt the orbits of smaller, rocky worlds like Earth.

All in all, we should be thankful any *Cosmic Book of Stellar Records* lacks an entry for our Sun. ◘

X-TREME TEMPERATURE



COOLEST WHITE DWARF KNOWN

Name: SDSS J1403
R.A.: 14h03m24.7s
Dec.: 45°33'33"
Mag.: 20
Distance: 145 light-years
Temperature: Possibly less than 4,300 K (7,200° F)
Mass: Approximately 0.6 Sun
Radius: Approximately 1/100 the Sun's
Luminosity: 0.00002 Sun
Discovered: 2004, Evalyn Gates and colleagues
Caveat: Don Winget and colleagues warn that current models cannot reproduce the spectra of these ultra-cool white dwarfs. Mukremin Kilic (University of Texas) warns, "We are clueless on the temperatures of these objects."

SDSS J1403'S TEMPERATURE tells astronomers how long the white dwarf has been cooling. This, in turn, helps narrow down the age of star clusters and the Milky Way as a whole. ASTRONOMY: THEO COBB

HOTTEST WHITE DWARF KNOWN

Name: Central star of NGC 2440
R.A.: 7h41m54.9s
Dec.: –18°12'29.7"
Mag.: 17.6
Distance: 7,100 light-years
Temperature: 211,000 K (380,000° F)
Mass: Approximately 0.6 Sun
Radius: 0.028 Sun
Luminosity: 1,100 Suns
Discovered: The planetary nebula, known since the 1800s, was included in the *New General Catalogue*. A team led by Michael J. Wolff at the Space Science Institute in Boulder, Colorado, used Hubble Space Telescope data to make the latest contributions in understanding the central star.

NGC 2440'S central star is 36 times hotter than our Sun. ASTRONOMY: THEO COBB

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