Astronomy magazine

ALL YOU NEED TO KNOW ABOUT OUR HOME GALAXY

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THE Milky Way INSIDE AND OUT

Inside the Orion Nebula

SPECTACULAR GALAXY FOLDOUT!

How the Milky Way works

+

The search for Earth-like worlds

+

Meet the stars next door

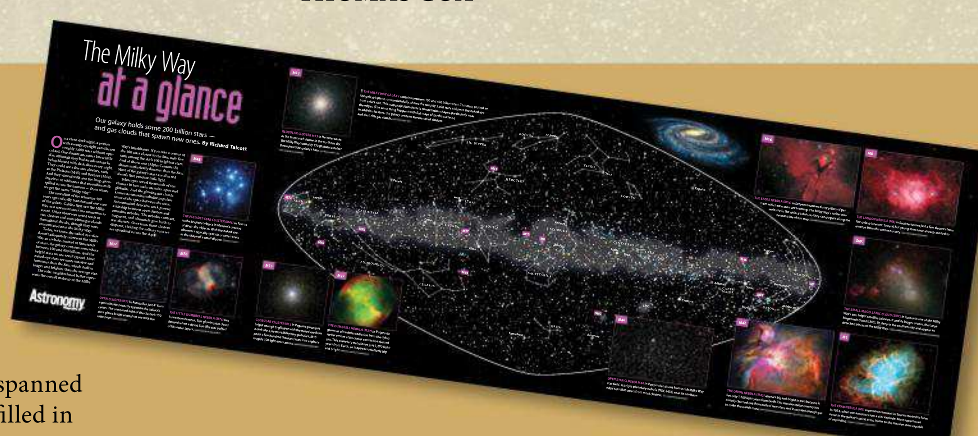
+

What makes stars explode?

YOU ARE HERE

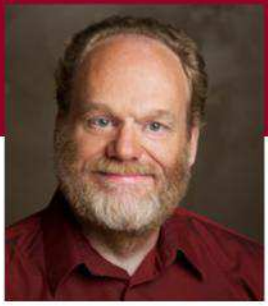
"BRIDGE TO THE STARS" is a photograph by Tony Hallas. It shows the summer Milky Way in the constellation Cygnus the Swan rising behind the Foresthill Bridge, which is California's highest. The structure, some 35 miles northeast of Sacramento, rises 730 feet (223 meters) above the North Fork of the American River. Notice how the Milky Way's colors reflect off the river's rushing water. Tony Hallas

Contents



The Milky Way
at a glance
Our galaxy holds some 200 billion stars — and gas clouds that spawn new ones. By Richard Talcott
Astronomy

Our city of stars



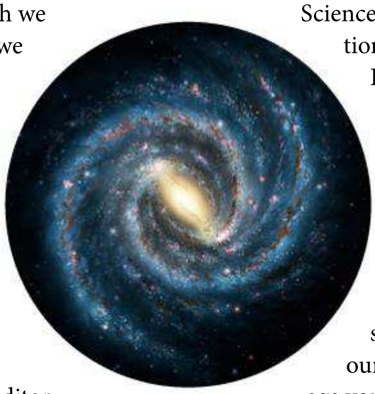
From a dark site on a clear summer night, you'll see a band of light arching across the sky. Thousands of years ago, people imagined the milk of a goddess had spilled across the heavens. They called the region *Via Lactea* (the Milky Way).

But it was Galileo Galilei who first looked at the Milky Way "close-up," more than 400 years ago. He aimed his simple refracting telescope toward this band of light and wrote that he could resolve many more stars than he could see with his naked eye. This simple observation started subsequent astronomers on a quest to understand our galaxy's structure.

We now know the Milky Way is a barred spiral galaxy. Four curved stellar arms — regions where a great deal of star formation occurs — radiate outward from the bar. Our solar system lies in the Orion Spur, a minor arm between the larger Perseus and Scutum-Centaurus arms.

Astronomers believe the Milky Way's vast bulk of visible and unseen dark matter may total more than 2 trillion solar masses. Within its gravitational influence lie more than 200 billion stars. Light, which travels at the fastest speed possible, takes 120,000 years to traverse our galaxy's diameter.

Among all that matter and all those stars, we know of only one inhabited planet: Earth. It's our home in space. By this analogy, our solar system, then, would be the neighborhood where that house resides. And the Milky Way? It's the city of stars within which we live, and around whose center we orbit.



Astronomy's editors gathered the most important information about the Milky Way in this special edition. We're proud to have an impressive lineup of contributors. They represent the best science writers and leading researchers.

Former *Astronomy* Senior Editor Francis Reddy, now a senior writer at NASA's Goddard Space Flight Center, starts things off with an overview of the Milky Way. (By the way, the idea for this issue sprang from Reddy's fertile mind.)

Following this overview, James B. Kaler, professor emeritus of astronomy at the University of Illinois at Urbana-Champaign, introduces us to our solar system's nearest stellar neighbors. Science writer and artist Michael Carroll then describes the search for planets slightly larger than Earth. And Robert Benjamin of the University of Wisconsin-Whitewater explains how our galaxy works.

Astronomy Contributing Editor Raymond Shubinski then takes us into the heart of the Orion Nebula. Yaël Nazé of the University of Liège discusses 10 things we don't know about massive stars, though some may be close to a solution. Next up, Francis Reddy's second story deals with what triggers supernovae. Robert Benjamin follows by explaining how astronomers determined the Milky Way's shape.

For this issue's center, I team with *Astronomy* magazine's illustrator Roen Kelly to provide a Milky Way tour. Contributing Editor Steve Nadis next leads a search for our galaxy's most magnetic stars. Then astronomer and geologist John Dvorak dissects the supermassive black hole lurking in the Milky Way's heart.

Contributing Editor Ray Jayawardhana of York University explains that some of the Milky Way's growth has come at the expense (death) of smaller galaxies. Next, science writer Marcia Bartusiak introduces us to our galaxy's 150 globular clusters. Francis Reddy's third and final story compares and contrasts open and globular clusters. Ray Villard of the Space Telescope Science Institute describes the collection of galaxies that make up the Local Group. And to wrap things up, Abraham Loeb and Thomas Cox of the Harvard-Smithsonian Center for Astrophysics describe the Milky Way's future collision with the Andromeda Galaxy.

As you turn the page and start exploring how and why our Milky Way works, I encourage you to venture out to a dark site and examine our wondrous galaxy for yourself.

Yours truly,

Richard Talcott, Editor

Cover illustration: Lynette Cook for *Astronomy*

THE Milky Way INSIDE AND OUT

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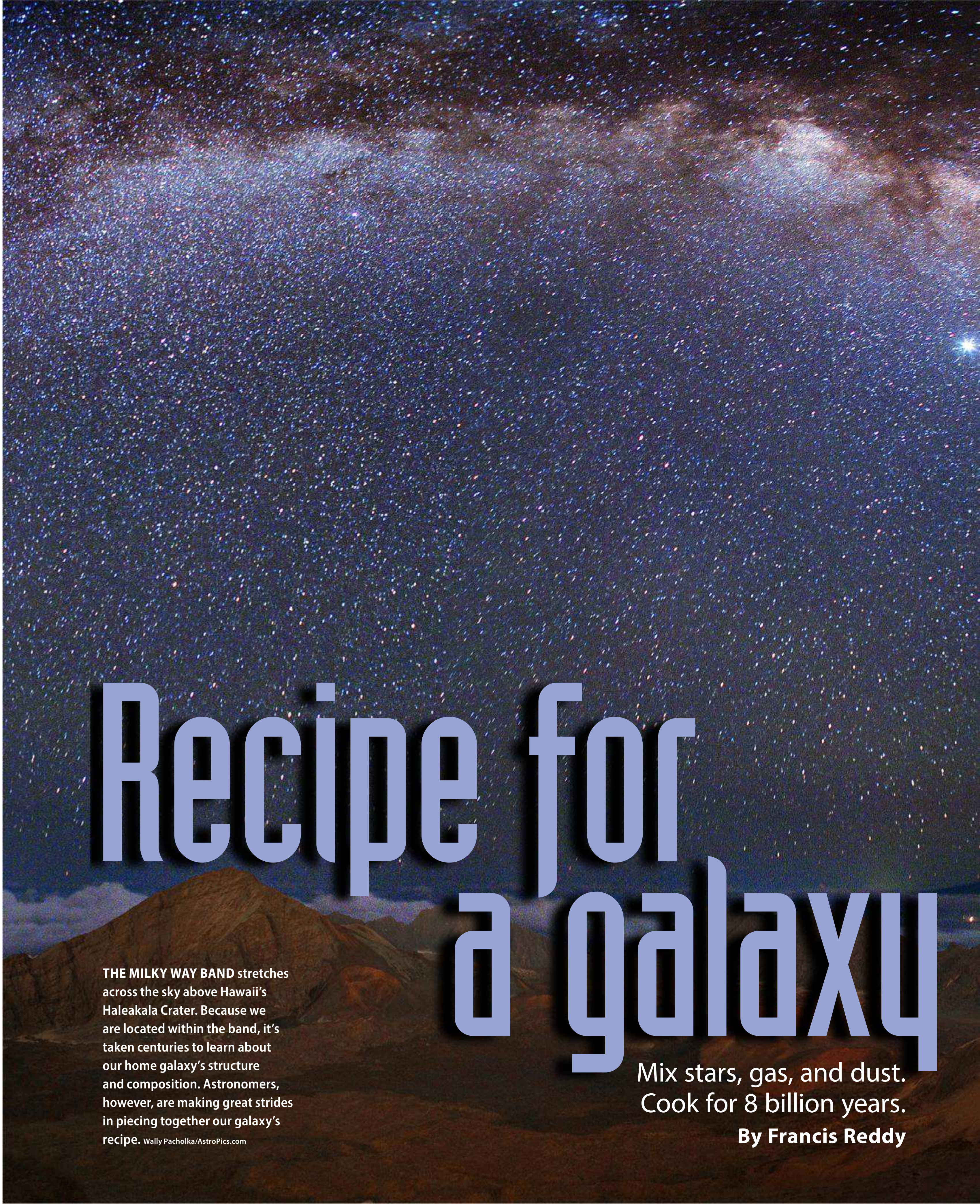


Recipe for a galaxy

Mix stars, gas, and dust. Cook for 8 billion years.

By Francis Reddy

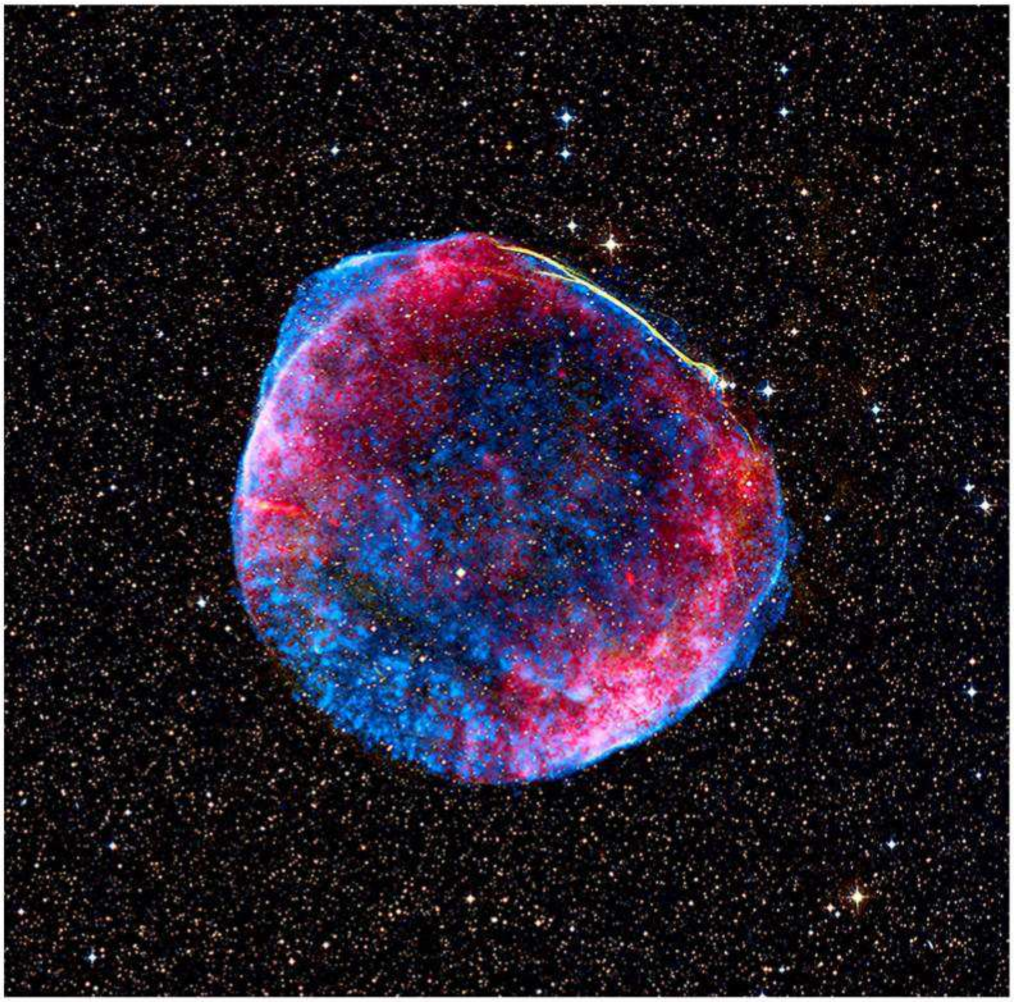
THE MILKY WAY BAND stretches across the sky above Hawaii's Haleakala Crater. Because we are located within the band, it's taken centuries to learn about our home galaxy's structure and composition. Astronomers, however, are making great strides in piecing together our galaxy's recipe. Wally Pacholka/AstroPics.com

Spend some time under the stars on any clear, dark night away from city lights, and you'll notice a misty lane arching overhead across the sky. Recognized since antiquity, this luminous glow was associated with a heavenly path or celestial stream by most ancient peoples.

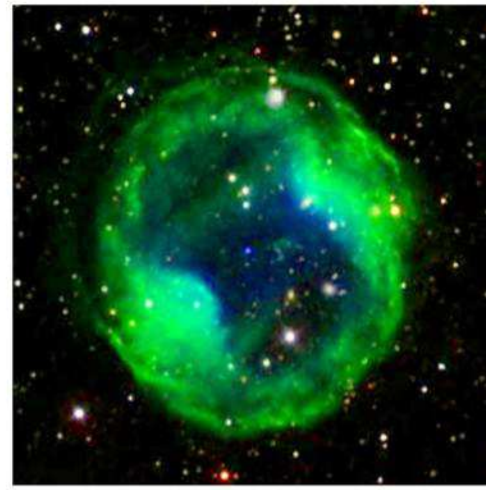
The Romans called it *Via Lactea*, or the Milky Way. But a name used by a tribe in South Africa's Kalahari Desert better hints at this glowing lane's true nature: "The Backbone of the Night." For the Milky Way is nothing less than the full structure of our galaxy seen edgewise. As 18th-century scientists began to realize this, the Roman name for a cosmic highway became our galaxy's name.

When Galileo Galilei turned his spyglass to the Milky Way in 1610, he revealed for the first time that its glow was individual stars "so numerous as almost to surpass belief." For centuries after that, astronomers suffered from a forest-for-the-trees problem: Because they were in the galaxy, they couldn't easily map it.

That changed in the 1920s when a new generation of large telescopes, coupled with photography, revealed that some "nebulae" were galaxies in their own right. Decades later, the first surveys at radio wavelengths tracked how the galaxy's gas moved and mapped the winding arms that classify the Milky Way as a spiral galaxy.



THE REMNANT OF SUPERNOVA 1006, located about 7,000 light-years from our Sun, glows in X-rays (blue) as well as radio waves (red) and optical light (yellow). When this star died just over a thousand years ago, it was the brightest supernova ever recorded. The resulting explosion spewed material into space that was forged within its core. X-ray: NASA/CXC/Rutgers/G. Cassam-Chenaï, J. Hughes, et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena, and Cornwell; Optical: Middlebury College/F. Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS



PLANETARY NEBULAE are the last evolutionary stage of stars similar to our Sun. In the center of this planetary nebula, G164.8+311, lies the star's core, now a remnant white dwarf. The circular gas shell is the star's outer layers, which have puffed away from the core. SDSS

During the past 15 years, NASA's Spitzer Space Telescope has produced the best picture yet. Using infrared wavelengths that penetrate all but the thickest dust clouds, Spitzer can see clear though the Milky Way. Its survey reveals that the central portion of our galaxy contains a vast elliptical star cloud that makes the Milky Way a barred spiral galaxy.

Star stuff

The visible galaxy principally contains stars and the massive clouds of gas and dust that form them. Astronomers estimate that the Milky Way contains 200 billion stars or more. Most are small red dwarfs that shine only feebly but will far outlast our Sun. A few are behemoths 100 times the Sun's mass that burn so bright they make nearby gas clouds glow. Long before our Sun's fires subside, these stars will end their days in spectacular supernova explosions.

Some stars barely shine at all. They never generate energy in their cores through true hydrogen fusion, the power source that heats stars most of their lives. But when young, they can produce energy by fusing a rare form of hydrogen called deuterium. These objects, called brown dwarfs, measure between 1.2 and 7 percent of the Sun's mass. With surface temperatures as cool as one-tenth of the Sun's, brown dwarfs are marginal stars — yet they may be as numerous as "the real thing."

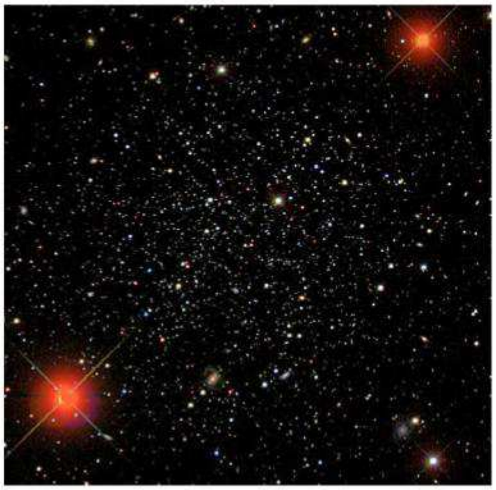
Although stars shine for a long time by human standards, they do not last forever. Stars born with less than eight times the Sun's mass meet their ends relatively quietly. Such a star casts off its outer layers until only the star's crushed core — called a white dwarf — remains. The concentric shells of glowing gas form an expanding bubble called a planetary nebula, so named for its planetlike appearance in a telescope. Common examples include the Helix Nebula (NGC 7293) and the Ring Nebula (M57). After about 10,000 years, the gas is too faint and diffuse to see, which is why astronomers list only about 3,000 planetary nebulae in the Milky Way.

Stars born with eight or more times the Sun's mass don't have such a peaceful ending: They explode. The blast shatters the star into a superhot, rapidly expanding shell of gas that peppers the galaxy with the heavy elements only massive stars can forge. Supernova remnants may be identifiable for more than 50,000 years, but fewer than 300 are known in the Milky Way. Astronomers believe supernovae occur only about once or twice each century in the galaxy.

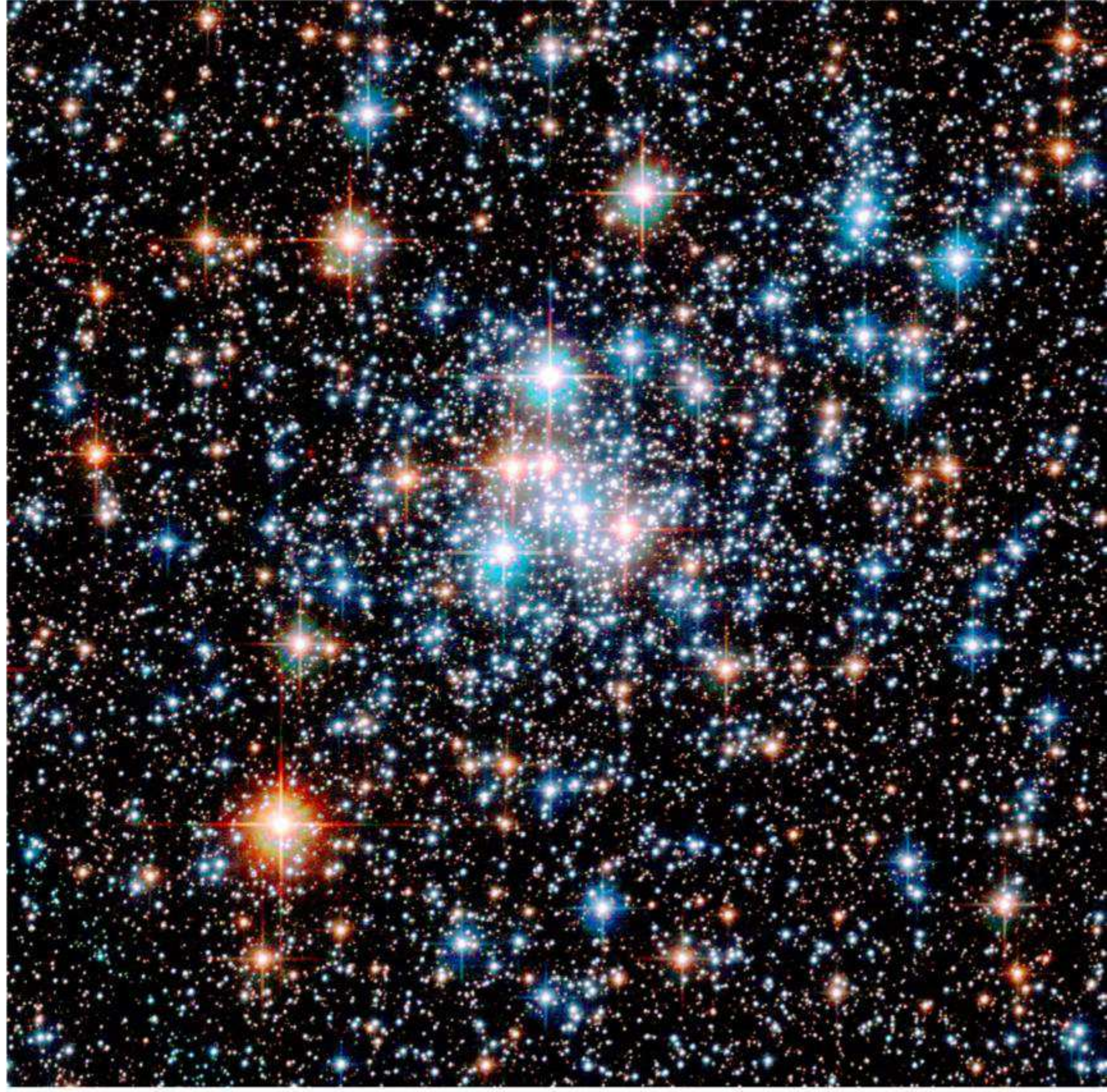
Hot young stars initially gather together, often near their natal gas clouds. Because the stars in these groups gradually disperse, astronomers call them open clusters. The Pleiades (M45) and the Beehive (M44) clusters, both plainly visible to the naked eye, are open clusters observers have known about since antiquity. Astronomers have cataloged more than 1,100 open clusters in the Milky Way, and our galaxy may contain as many as 100,000.

Another kind of star cluster is radically different. Tens of thousands to perhaps a million old stars congregate in giant balls called globular clusters. These stars are gravitationally bound into densely packed spheres no

Francis Reddy *is the senior science writer for the Astrophysics Science Division at NASA's Goddard Space Flight Center in Greenbelt, Maryland.*



PALOMAR 5, **a globular cluster, is being pulled apart by the Milky Way Galaxy. Streams of stars — called tidal tails — trail the globular cluster as it orbits the galactic core. Pal 5 orbits some 75,000 light-years from the Sun.** SDSS



OPEN STAR CLUSTER NGC 290 **contains hundreds of hot young stars. NGC 290 lies about 200,000 light-years away in the Small Magellanic Cloud.** ESA/NASA/E. Olszewski (University of Arizona)

GLOBULAR CLUSTER M15 **contains hundreds of thousands of stars. If our solar system were at the center of M15, our sky would always be ablaze from the light of tens of thousands of stars. These stars are much older than those of open clusters. The stars in M15 are an estimated 12 billion years old.** NASA and The Hubble Heritage Team (STScI/AURA)

bigger than 200 light-years across. With ages greater than 10 billion years, the stars in these clusters are nearly as old as the universe itself. While some other galaxies harbor thousands of globular clusters, fewer than 200 such clusters orbit in the Milky Way.

Big picture

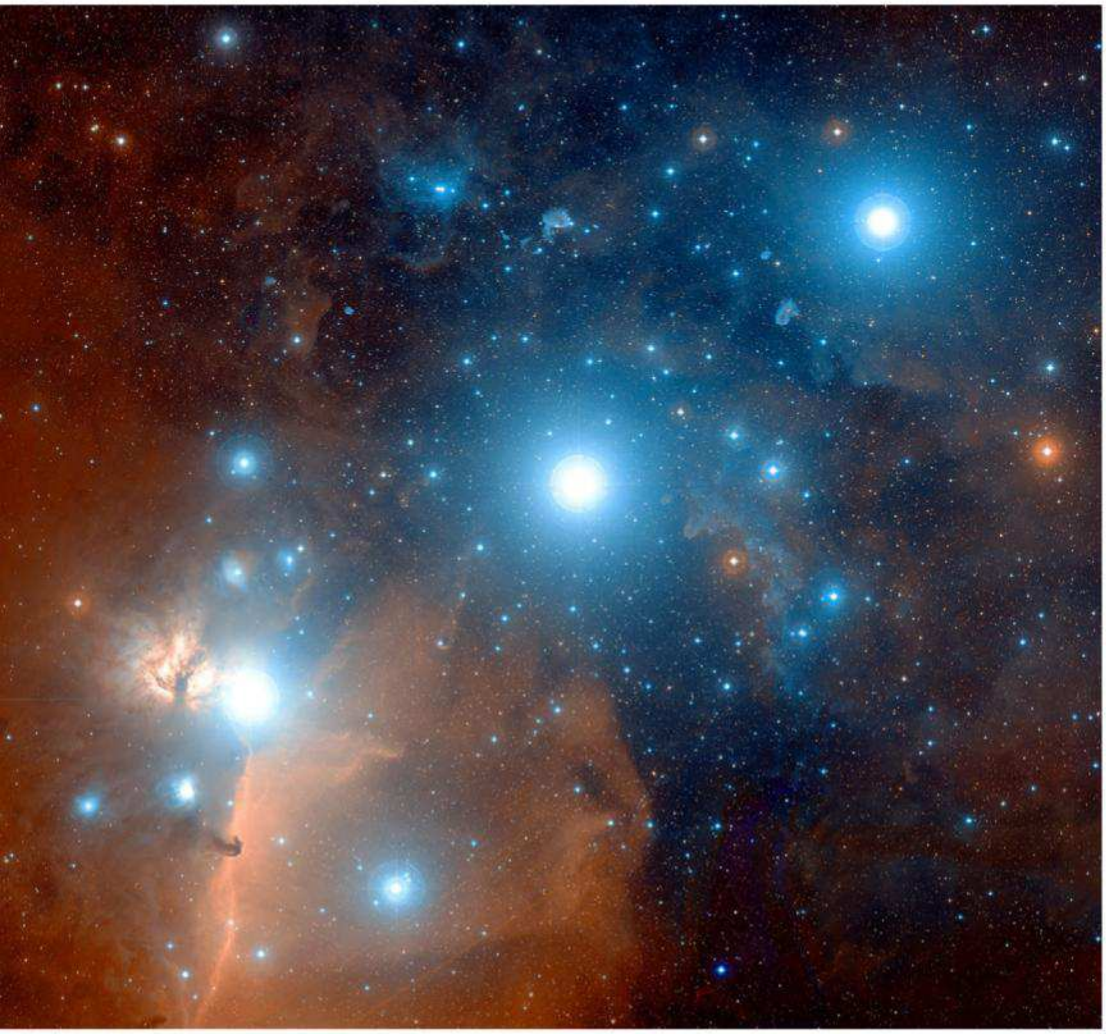
Early in the last century, the differences between these open clusters and globular clusters guided astronomers to an overview of the Milky Way. Open clusters orbit in a disk-shaped volume that also contains nearly all of the galaxy's gas and dust, the seed for new stars. This disk is about 1,000 light-years thick and has a radius of roughly 60,000 light-years. The Sun lies about halfway from the center to the disk's edge.

Sitting in the center of this disk is a roughly spherical "bulge" about 12,000 light-years across. Astronomers believe a supermassive black hole weighing about 4 million times the Sun's mass lies at the bulge's center. Most of the bulge stars are old, but, perhaps surprisingly, a few massive young clusters have formed near the galaxy's center. Gas clouds colliding in the crowded environs a few hundred light-years from the black hole may have enabled these clusters to form.

Globular clusters orbit the same central mass as objects in the disk, but they do so in wildly inclined paths. Because their orbits often take them through the disk, globular clusters are subjected to forces that can knock some of their stars loose. Over time, these clusters can dissolve. Some, such as Palomar 5, have been imaged displaying tails of escaped stars that lead and follow the cluster in their orbits. The Milky Way once may have sported hundreds of globular clusters — all we see today are the survivors.

Astronomers refer to the Milky Way's halo as the "realm of the globular clusters." The halo component is a spherical volume a little wider than the disk. Here, there is no star-forming gas to make new stars because as the galaxy developed, the gas gradually flattened into the disk. The quick rush of star formation that formed the halo globular clusters was followed by billions of years in which they gradually dissolved, their stars cast throughout the Milky Way's halo. Astronomers estimate that over the next 10 billion years, half of the galaxy's remaining globular clusters similarly will fall apart.

Astronomers know the halo stars are old because they contain stars with the lowest proportion of heavier elements. As every star



THE ORION BELT shows two different types of nebulae. In the bottom left lies the familiar Horsehead Nebula, a dark object too dim to be visible to the human eye. Just above the Horsehead in this image lies the Flame Nebula (an emission nebula). The dark lane in the Flame Nebula is a result of dust blocking starlight. The three stars, from bottom left to top right, are Alnitak, Alnilam, and Mintaka.

Digitized Sky Survey, ESA/ESO/NASA FITS Liberator, Color Composite: Davide De Martin (Skyfactory)

grows older, it manufactures heavier elements and — through explosion, eruptions, or outflows — casts them into the galaxy. Each new stellar generation tilts the galaxy's chemical balance toward heavier elements, such as carbon, nitrogen, and oxygen. Forged within stars, these elements make planets — as well as life on Earth — possible.

There's more going on in the halo than dissolving globular clusters. Tides from the Milky Way's massive bulk shred dwarf galaxies as they pass near or through the disk. Our galaxy — indeed, most galaxies — may have been built by gobbling up many smaller galaxies.

The evidence is hard to ignore. The Milky Way appears to have appropriated at least three globular clusters from the Sagittarius Dwarf Galaxy, which is now being torn apart on the far side of our galaxy. And astronomers believe that Omega Centauri, the largest and brightest globular cluster, is actually the leftover bulge of a dwarf galaxy long ago shredded by our own.

Most of the Milky Way's mass remains unseen. Beginning in the 1930s, astronomers began to recognize that galactic motions could not be completely accounted for by the combined gravity of visible stars, gas, and dust. By the 1970s, it was clear that galaxies like our own also possessed large amounts of mass far beyond the spans of their disks.

Astronomers called this stuff "dark matter" because they couldn't see it and didn't know what it was. They still don't. Nevertheless, studies show that the Milky Way resides in a roughly spherical dark-matter halo about 600,000 light-years across — some five times the disk's diameter — and that this volume contains roughly 90 percent of the galaxy's total mass.

Close to home

Back in the Milky Way's disk, massive, cold gas clouds provide plentiful raw material for making stars. As knots deep within these clouds gravitationally collapse, spin up, and grow hotter, new stars are born. Computer models of the process predict that collapsing and rotating clouds may fragment, and these fragments may produce stars themselves. This could explain why most stars in the galaxy occur in gravitationally bound groups of two or more. In this regard, our lone Sun is in the galactic minority.

Once a star ignites its nuclear fuel, outflows clear away the remaining gas. In any young cluster, a few massive, hot stars grow so large and burn so hot that they can dramatically reshape — and even burrow through — their birth cloud. The complex interplay of creation and destruction results in some of the sky's loveliest sights, such as the Rosette Nebula (NGC 2244) and the Eagle Nebula (M16). These so-called emission nebulae, which number in the thousands, can contain enough material to build 100,000 stars like the Sun.

The Orion Nebula (M42), a stellar nursery just 1,350 light-years away, is one of the nearest and best-studied star-forming regions. Outflows from the hot stars at its center have blown away gas and dust from the surface of the massive cloud that formed them. Emission nebulae glow because intense ultraviolet radiation from the hottest, most massive stars energizes the gas to emit visible light in different colors. In fact, a single star produces 95 percent of the energy responsible for lighting up M42.

Other nebulae simply shine by reflecting starlight. Reflection nebulae such as the Witch Head Nebula (IC 2118) and Merope

Milky Way Galaxy stats

Sun's distance from the center	26,000 light-years
Diameter of the disk	120,000 light-years
Sun's orbital period	225 million years
Mass of the central black hole	about 4 million Suns
Sun's age	4.5 billion years
Galaxy's oldest known star (HE 1523–0901)	13.2 billion years
Number of stars	200 billion or more
Estimated number of planets	1 trillion
Galaxy's total mass (includes dark matter)	1 trillion Suns

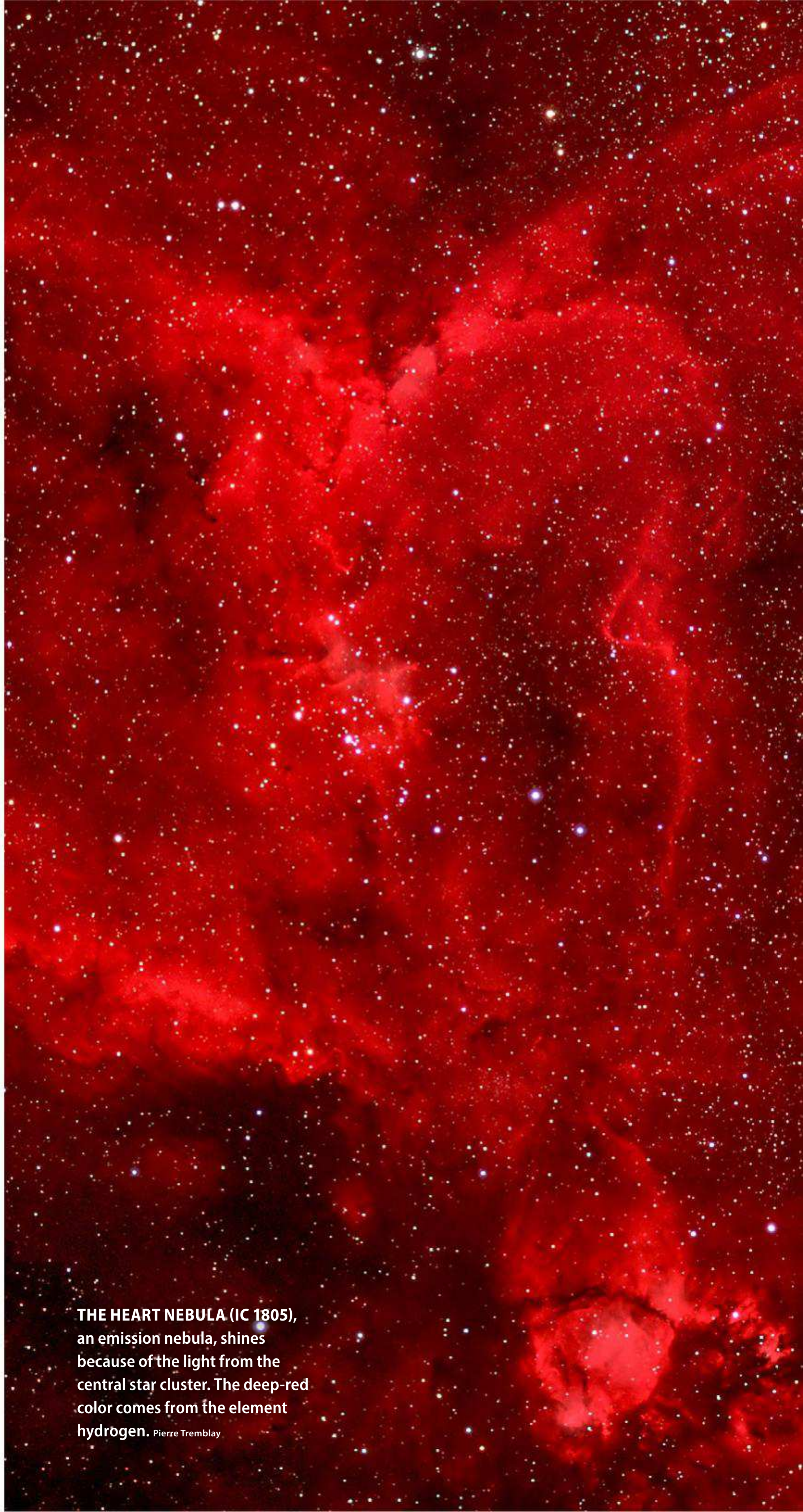
SHARPLESS 2-82 showcases both a small emission nebula and a surrounding bluish reflection nebula. This nebulosity mix is located in Sagitta. Don Goldman

Nebula (NGC 1435) contain dust grains that preferentially scatter short-wavelength light, so they always cast a blue glow.

Some of the material around a newborn star may form solid bodies, like asteroids, comets, and even planets. Since 1995, astronomers have identified more than 3,700 worlds around other stars. Based on this discovery rate, astronomers believe the number of planets in the Milky Way could top a trillion.

Many of the initial planets discovered were supersized versions of gas giants — worlds like Jupiter and Saturn that have no solid surface. But since then, astronomers have found planets with masses similar to Earth's and even smaller, and they estimate that up to 60 percent of nearby Sun-like stars could have Earth-like worlds. If so, direct imaging of such planets may be possible within a decade.

Astronomers are planning the next phase of galactic exploration with a new generation of space-borne and ground-based telescopes. We have already found dissolving globular clusters, shredded mini-galaxies, new Milky Way satellites, and a form of matter that remains unidentified. What this new assault on understanding the home galaxy will reveal, we can only guess.

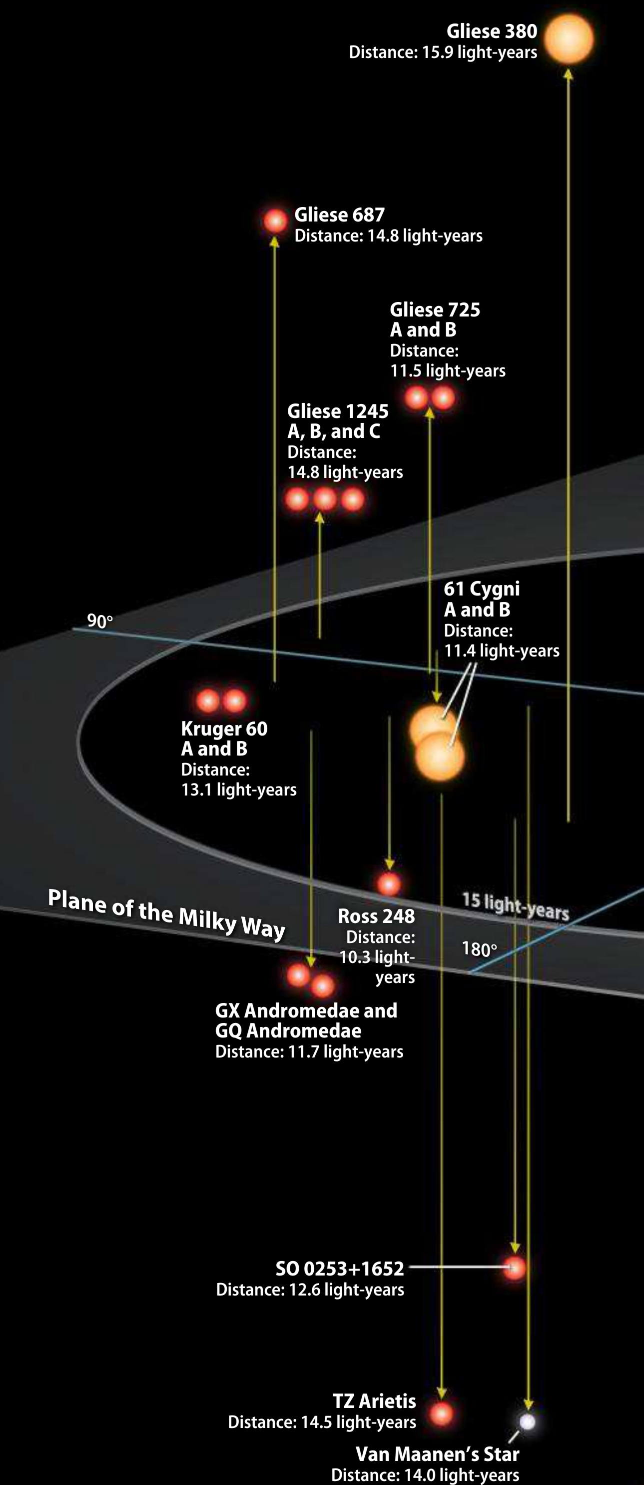


THE HEART NEBULA (IC 1805), an emission nebula, shines because of the light from the central star cluster. The deep-red color comes from the element hydrogen. Pierre Tremblay

Meet the stars next door

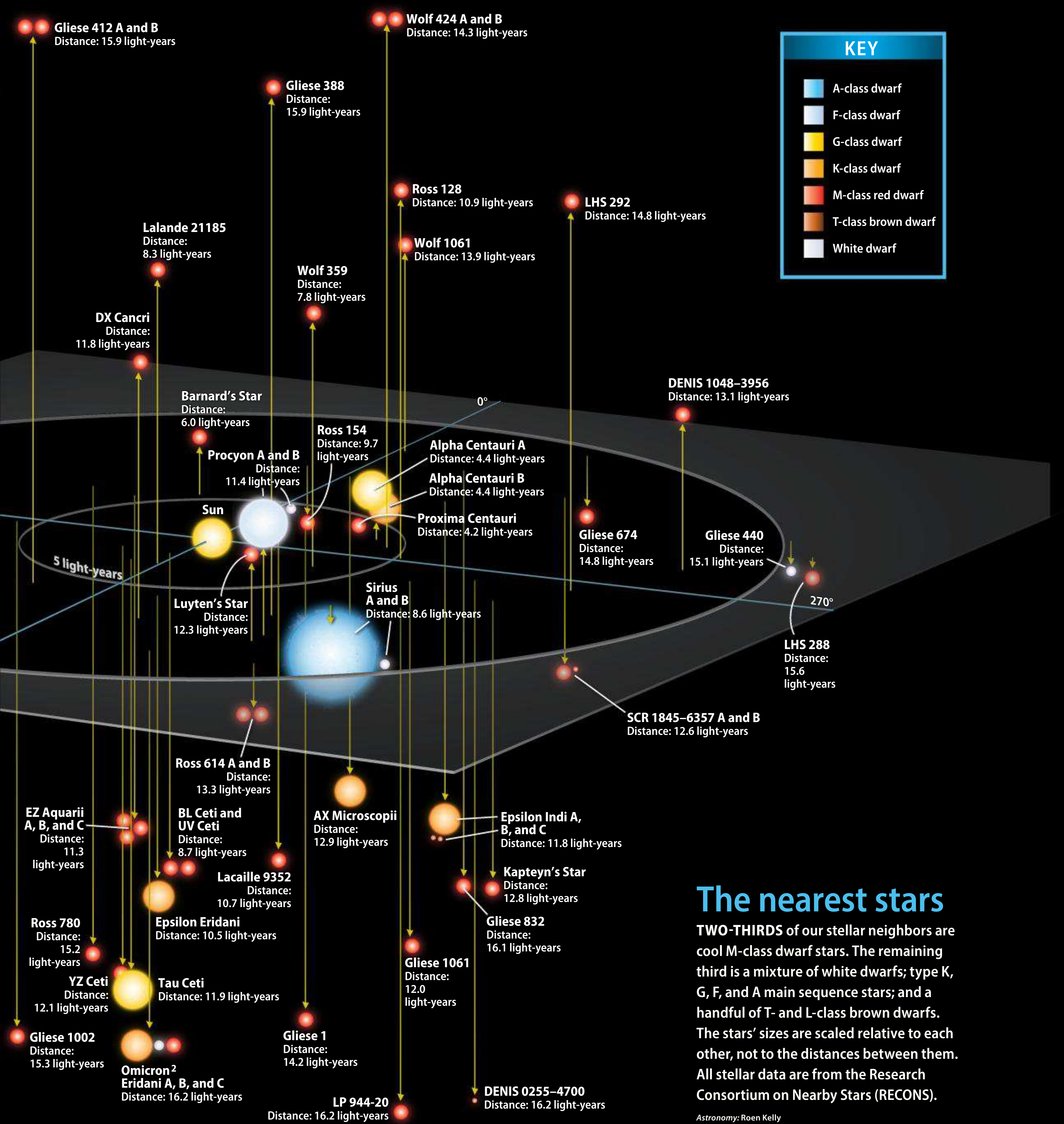
The Sun's neighbors hide secrets that could help astronomers learn more about our place in the galaxy.

By James B. Kaler



Most of the space in the Milky Way Galaxy can be pretty lonely — a dull, dark void. But our own neighborhood stands out as among the more intriguing places in the universe. Recently, with new telescopic technologies, astronomers have made big strides toward finding all our stellar neighbors. Knowing the stellar cast, they can then project this information into the galaxy at large to help us learn how stars, and even planets, are born and live out their lives. As a

James B. Kaler *is a professor emeritus of astronomy at the University of Illinois, Urbana-Champaign. He is the author of* From the Sun to the Stars *(World Scientific, 2016).*

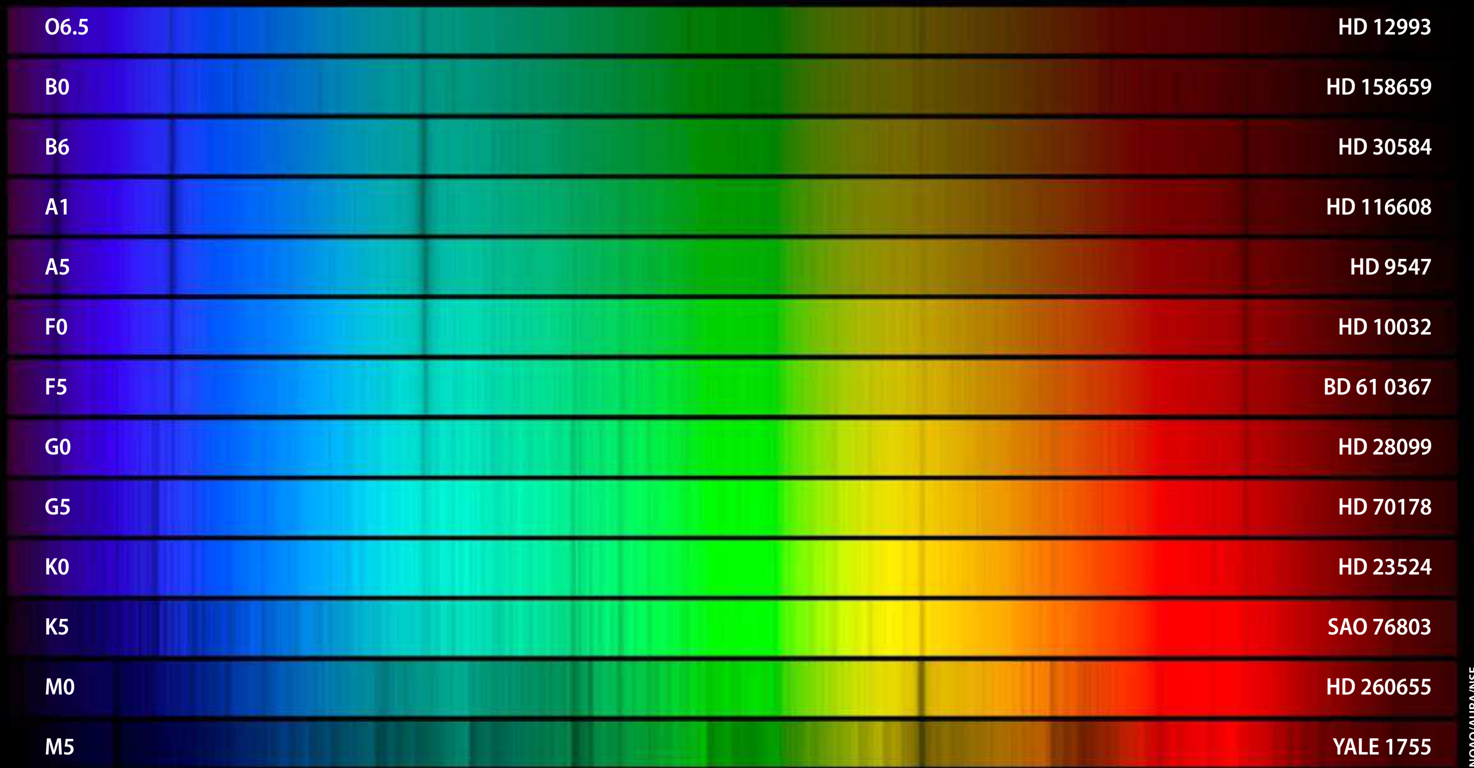


The nearest stars

TWO-THIRDS of our stellar neighbors are cool M-class dwarf stars. The remaining third is a mixture of white dwarfs; type K, G, F, and A main sequence stars; and a handful of T- and L-class brown dwarfs. The stars' sizes are scaled relative to each other, not to the distances between them. All stellar data are from the Research Consortium on Nearby Stars (RECONS).

Astronomy: Roen Kelly

Spectra — one of astronomy's greatest tools



ONE WAY to classify stars is by their absorption spectra. Each element absorbs light at wavelengths specific to that element and its atomic composition. The result is black lines on a continuous spectrum. Here are examples of spectral types, each associated with a specific star.

Organizing stars

If you spread starlight into a rainbow — a spectrum — from violet through red, you will see absorption lines cutting out narrow bands of color. Each line is produced by a specific atom or ion.

More than a century ago, stars were organized into classes O, B, A, F, G, K, and M according to the lines present in their spectra. Astronomers later realized this scheme corresponds to a temperature scale that runs from 50,000 kelvins (90,000 degrees Fahrenheit) at the top (class O) to a bit above 2,000 K (3,100 F) at the bottom (class M). In the past few years, astronomers have added cooler classes (L and T) with surface temperatures down to hundreds of kelvins.

Each class is divided into 10 parts from warm to cool; the Sun is in the middle at class G2.

Astronomers also organize stars by their current state in their life cycles. Ordinary "dwarfs" like the Sun — which are supported by the internal fusion of hydrogen into helium — lie on the main sequence line. Their masses range from more than 100 times a solar mass in spectral class O to just under one-tenth in class M. The energy emitted from main sequence stars ranges from millions of times more luminous than the Sun — in class O — to 10,000 times less — in class M.

Beneath stellar class M on the Hertzsprung-Russell classification diagram are "substars." These low-luminosity class L and T brown dwarfs cannot fuse hydrogen and have masses close to those of planets. In general, the lower a star's mass, the longer its life as a dwarf. Life spans of dwarf stars range from a few million years to trillions of years.

When the hydrogen fuel runs out, stars begin to die. Lower-mass stars, up to about 10 times that of the Sun, expand to become luminous "giants" — with radii comparable in size to the orbits of the inner planets — as they burn their helium into carbon and oxygen. They then lose most of their mass through winds. Their remains are dim white dwarfs, dead balls of carbon and oxygen with the mass of a star but a diameter similar to Earth.

High-mass stars become ultraluminous supergiants with radii similar to Jupiter's orbit. They fuse their cores into iron and collapse to create supernovae. Their cores are left as either neutron stars with densities a million times those of white dwarfs or even black holes so dense that light cannot escape. — *J.K.*

result of these studies, astronomers are now learning how our own Sun fits into the overall picture.

Neighborhood cliques

If we define our galactic neighborhood as a sphere just over 30 light-years across and centered on the Sun, it encompasses several planetary systems. Within this sphere lie 71 stars (including our Sun), which means our neighborhood has a density of 0.0039 star per cubic light-year.

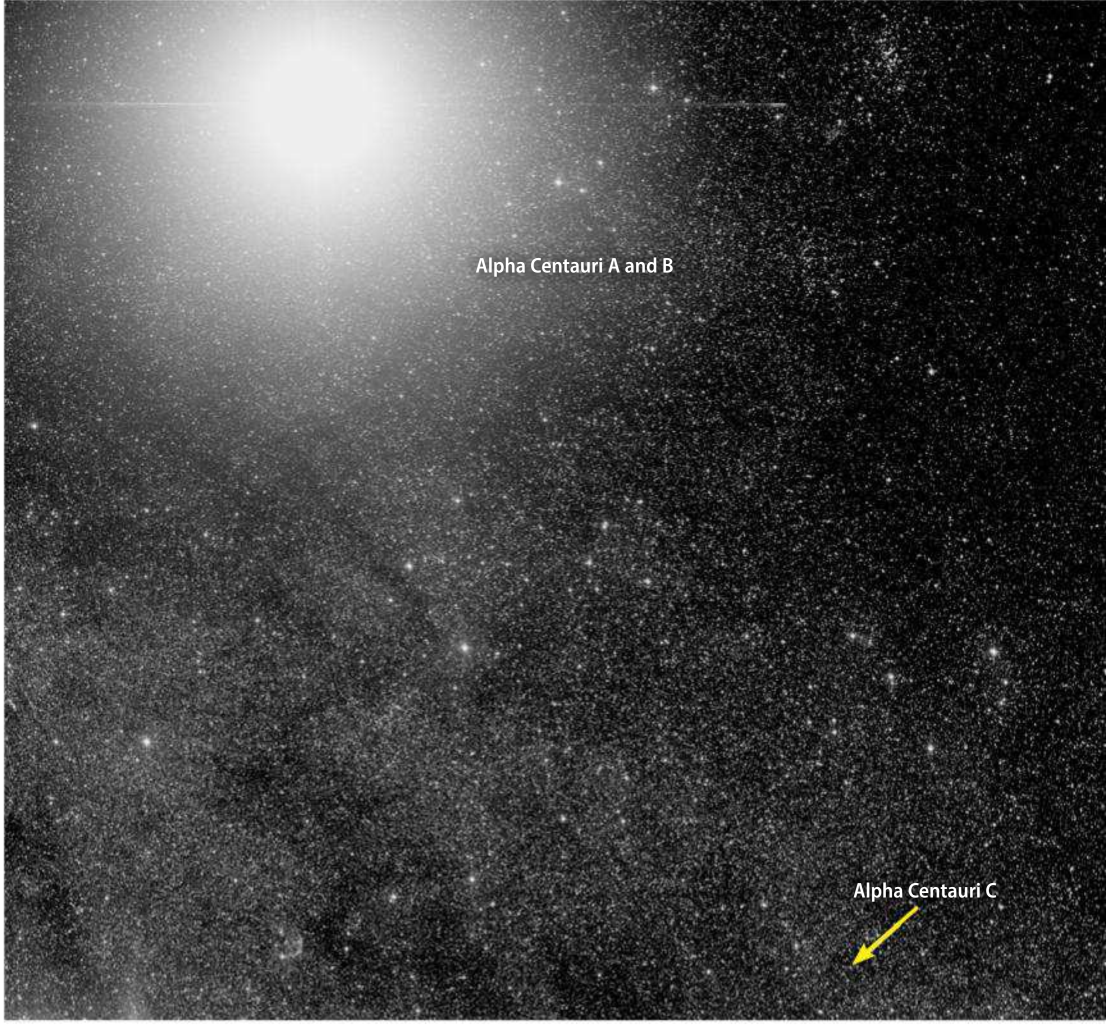
Nature, however, likes to make doubles and multiples. While there may be 71 stars, there are only 49 star systems: 22 of these suns are in double stars (binaries) and 15 are in triples, which leaves only 34 in single-star systems. After accounting for the multiple-star systems, the density drops to 0.0027 system per cubic light-year.

Double stars are important astronomical objects — analyzing their stars' orbits reveals stellar masses. Fifty percent of local stars have companions, similar to the proportion observed over greater distances. In reality, the figure probably is higher because some dim companions surely are hiding in the glare of their mates. Quadruple and higher systems are rare, the nearest lying 19 light-years away.

Local star systems each have some 370 cubic light-years to roam around in and, thus, are on average very far apart. (Note: All distances mentioned in this article are from the European Space Agency's [ESA] Hipparcos satellite.) The closest member of the Alpha Centauri triple, the nearest system to us, is 4.2 light-years away. For a sense of scale, 4 light-years is 27 million solar diameters, or 6,400 times the distance between the Sun and Pluto. If you put a marble on the ground to represent the Sun, the three stars of Alpha Centauri would comprise two marbles and a ball bearing 250 miles away. Stars in our neighborhood have a lot of empty space between them; they will not collide.

But that's not the astonishing part. Within 15 light-years, *no* high-mass class O or B stars exist. The closest B star — Regulus — is 79 light-years away, and the nearest O star is nearly 400. Neither does our designated sphere contain giants or supergiants. At 34 light-years, the nearest giant is Pollux. The closest supergiant, Betelgeuse, lies at an uncertain 400 light-years. Every star within 15 light-years from the Sun is a dwarf!

We do, however, see a run-of-the-mill A star, Sirius, the brightest star in the night sky. It lies 8.6 light-years away and has 22 times the visual solar luminosity. One cooler F star, Procyon, is 11.4 light-years away and is at least on its way to becoming a giant.



THE SUN'S NEXT-DOOR NEIGHBOR, the Alpha Centauri triple system, lies 4.2 light-years away. It contains two Sun-like stars and a red dwarf. Alpha Centauri A and B are overexposed in this image so the third member, Proxima Centauri (Alpha Centauri C), is visible. European Southern Observatory

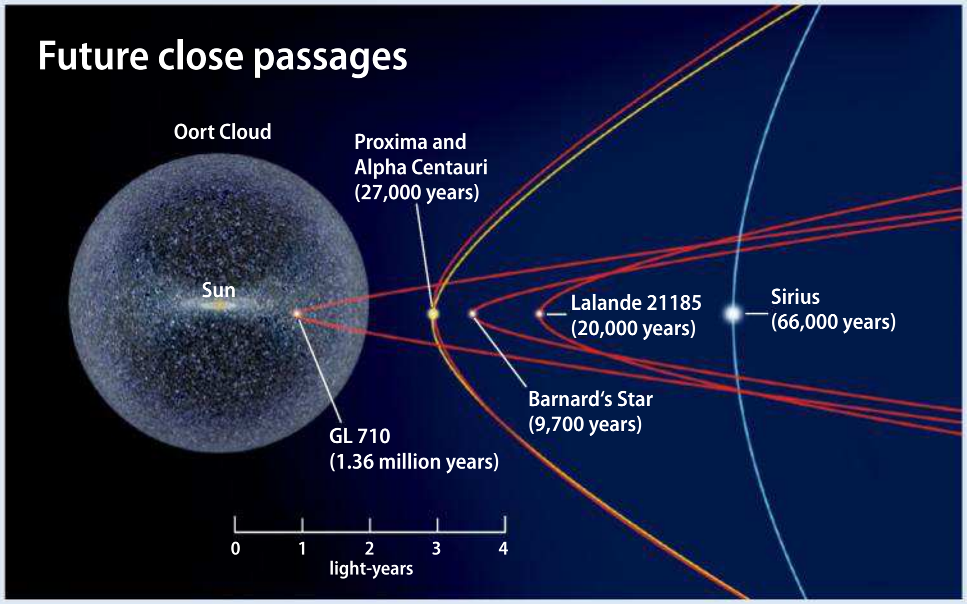
The cooler the stars we look at, the higher the numbers. Our neighborhood has three G-class stars: the Sun, the brightest member of the Alpha Centauri system, and Tau Ceti (11.9 light-years). Next cooler is the K class, which contains eight stars. This group includes the second-brightest member of the Alpha Centauri system and the 61 Cygni double — the first stars whose distances (11.4 light-years) were known. In fact, the 61 Cygni system contains the coolest main sequence stars bright enough to be seen with the naked eye (you still need a telescope to resolve them from each other).

About two-thirds of nearby stars — 49 of them — are cool M-class red dwarfs with masses under half the Sun's. Not one of these stellar microbes is visible to the naked eye: The brightest glows at 7th magnitude. The nearest star to us belongs to this class: 11th-magnitude Proxima Centauri, the third

Spectral classes

Spectral type	Color	Temperature* (kelvins)	Spectral lines
O	Blue	31,000–49,000	Ionized and neutral helium, weaker hydrogen
B	Blue-white	10,000–31,000	Neutral helium, hydrogen
A	White	7,400–10,000	Strong hydrogen, some ionized metals
F	White-yellow	6,000–7,400	Weaker hydrogen, ionized calcium and iron
G	Yellow	5,300–6,000	Weak hydrogen, neutral and ionized metals, especially calcium
K	Orange	3,900–5,300	Neutral metals, sodium, weak hydrogen
M	Red	2,200–3,900	Neutral metals, molecules, little hydrogen
L	Red-infrared	1,200–2,200	Hydrides, water, alkali metals
T	Infrared	Less than 1,200	Methane, water, alkali metals

*Temperatures are for main sequence dwarf stars; the temperatures of giants and supergiants of the same spectral type may differ.

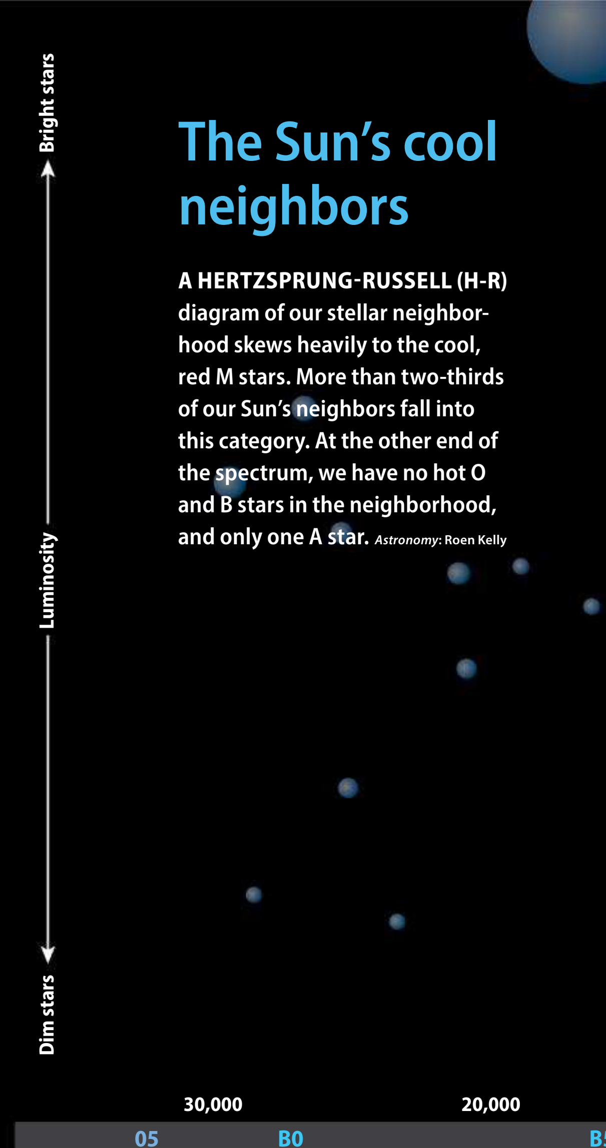


MANY NEARBY STARS will pass close to the Oort Cloud, but only one will move through it. In 1.36 million years, Gliese 710 likely will gravitationally perturb millions of comets, sending a sizable number on a potential collision course with Earth. *Astronomy*: Roen Kelly

Close stellar encounters

Our galaxy is in constant transition, and nearby stars present a few possible dangers. As stars orbit the galaxy, they constantly change positions relative to each other. Someday, a supergiant will invade our neighborhood, and, at Alpha Centauri's distance, it could shine with the light of 20 Full Moons. Even at 30 light-years, were it to explode, the results could severely damage Earth's atmosphere and alter life processes. Radioactive isotopes in Earth's ocean beds confirm that such an event actually has happened.

And don't discount the potential effects of red dwarfs. Trillions of comets, ejected from the early solar system, surround the Sun. They form the Oort Cloud, which extends a good part of the way to Alpha Centauri. While local stars don't collide, they still can come close to each other. In a million years or so, Gliese 710 (now 63 light-years away) will come within a light-year of us. Such a close passage could gravitationally affect the Oort Cloud and cause a rain of comets that could impact Earth. — *J.K.*



The Sun's cool neighbors

A HERTZSPRUNG-RUSSELL (H-R) diagram of our stellar neighborhood skews heavily to the cool, red M stars. More than two-thirds of our Sun's neighbors fall into this category. At the other end of the spectrum, we have no hot O and B stars in the neighborhood, and only one A star. *Astronomy*: Roen Kelly

member of the Alpha Centauri triple. This star is on the sunward side of its million-year orbit about the inner pair, and is, thus, about 10,000 astronomical units (AU; the distance between the Sun and Earth) closer to us, or 250 times the Sun-Pluto distance, than the brighter pair.

Four of the locals in our neighborhood are even cooler brown dwarfs. These objects exist on the fuzzy boundary between stars and planets — they form like stars, but they don't have enough mass to sustain hydrogen fusion in their cores.

Astronomers have found one L-class brown dwarf and three even-cooler T-class brown dwarfs in the solar neighborhood. Two of the latter belong to the Epsilon Indi system (11.8 light-years). They are so cool — barely warmer than a self-cleaning oven — that they radiate mostly infrared light. We still do not know exactly how many brown dwarfs exist. We have found them only in the past several years because of greatly improved infrared detectors.

Five other neighbors are, not surprisingly, white dwarfs — the slowly cooling cinders of Sun-like stars. Each of the two brightest stars in the solar neighborhood, Sirius and Procyon, has a dim white dwarf companion.

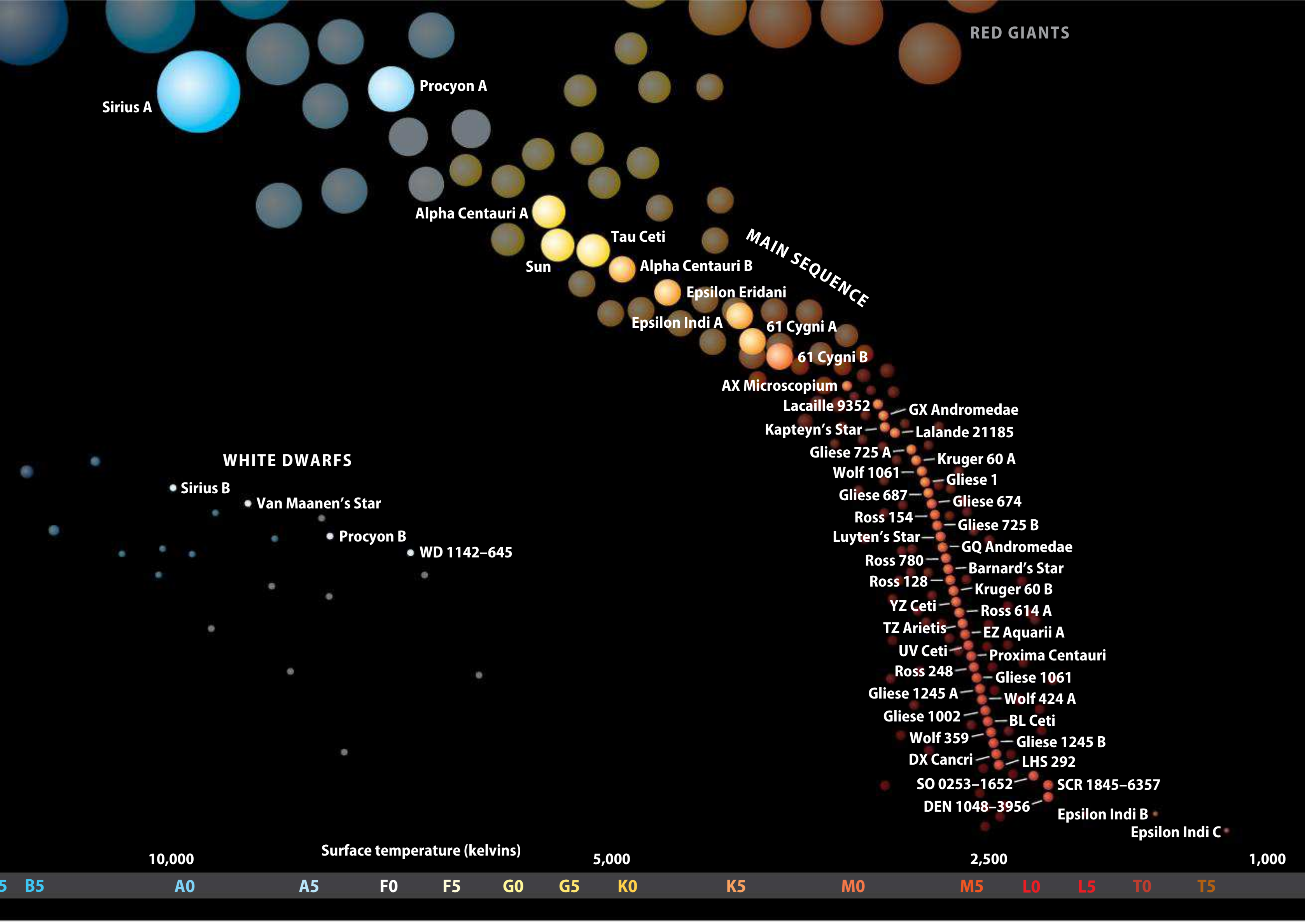
It pays to keep in mind that all these numbers are in flux. Undoubtedly, more nearby stars and brown dwarfs will turn up as techniques improve, particularly with infrared surveys that will find our coolest neighbors. And ESA's current Gaia spacecraft will nail down the distances to these suns even better than Hipparcos did.

Roll call

The individual members of these groups have their own characteristics. Sirius is the closest "metallic" star (one with odd metal patterns, usually low in calcium and scandium and high in copper, zinc, and other heavier elements). This unusual chemistry is caused by diffusion of chemical elements. Some elements settle in the star's core under gravity; others move upward by radiation. Sirius B, the accompanying white dwarf to A-class Sirius, used to be the dominant star, but it's 10,000 times fainter now and difficult to see (as is Procyon's companion).

When astronomers study the neighbors, Alpha Centauri usually takes center stage, and we neglect the second closest, Barnard's Star. Only 6 light-years away, this red dwarf holds the record for highest proper motion: It zips across the sky at 10" per year. The star's proper motion, combined with the 67 miles per second (108 kilometers per second) velocity toward us (deduced from Barnard Star's spectrum), gives the star a total speed of 87 miles/s (140 km/s) relative to the Sun. That's 10 times the speed of a normal star.

And this speed is slow compared with Kapteyn's Star, another red dwarf 12.8 light-



years away. It moves twice as fast as Barnard's Star. Most local stars, including the Sun, revolve around the galaxy's center in circular orbits. Both Barnard's and Kapteyn's, however, are tourists from the Milky Way's halo that are just passing through. Their high relative speeds are caused by strikingly different galactic orbits.

Many red dwarfs have powerful magnetic fields that, like the Sun's, collapse to produce bright, localized stellar flares. Unlike the Sun's version, however, red dwarf flares can temporarily double the star's brightness. Among the best known are Proxima Centauri and UV Ceti, the latter lying in a binary system 8.7 light-years away. Such flares are visible across the electromagnetic spectrum, from X-ray to radio, and can be fun for patient observers to spot.

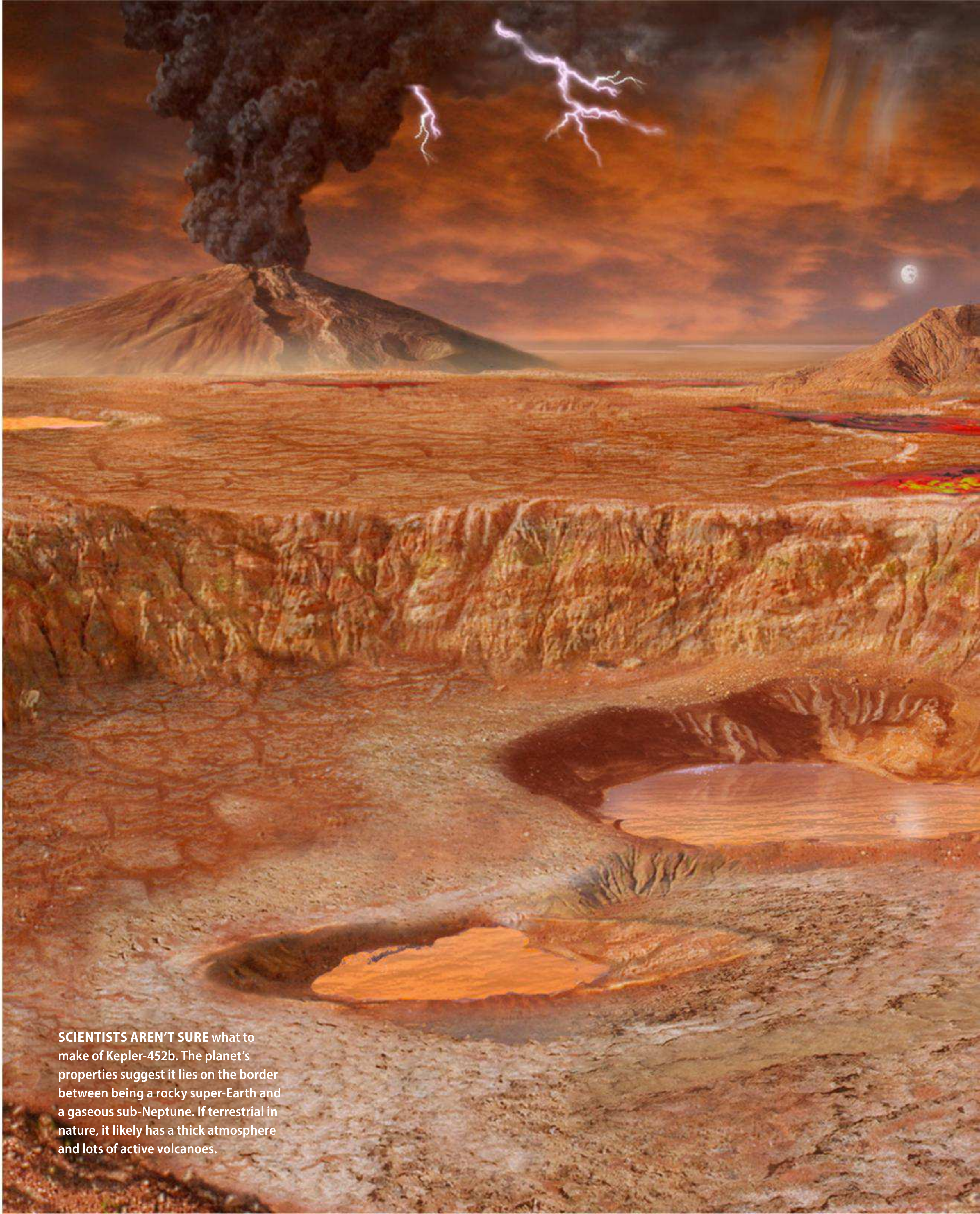
Fifty years ago, astronomer Frank Drake thought we might find intelligent signals from possible planets belonging to G-class Tau Ceti. Although Drake had no clue at the time, at least four planets orbit Tau Ceti. These range in size from about 1.8 to 3.9 Earth masses. Unfortunately, none of them lies within the star's habitable zone — the region where liquid water could exist on a rocky surface — and thus none has conditions conducive to life as we know it.

But these four are just the tip of the exoplanet iceberg. To date, astronomers have found some 30 planets orbiting the stars in our neighborhood, not counting the eight officially logged in our solar system. The only other star in our collection with four known planets is distant Ross 780 (Gliese 876), located 15.2 light-years away. Both YZ Ceti (12.1 light-years) and Wolf 1061 (13.9 light-years) have three planets.

But perhaps the most intriguing planet found to date orbits the Sun's nearest neighbor, Proxima Centauri. This world, which weighs 1.3 Earths, circles its star in just 11.2 days at a distance of 0.0485 AU. But because Proxima is a cool red dwarf, its planet lies within the star's habitable zone, and it's not inconceivable that life could exist there. Still, Proxima's stellar flares make advanced life unlikely on such a planet. But who knows? We can't help but wonder if the Sun's nearest stellar neighbors harbor hospitable planetary neighbors as well, some perhaps like Earth. ■

Defining distances

Astronomers could measure the distances to stars in miles, but the numbers get big. Instead, they use the light-year, the distance light travels in a year. The universe's top speed is the speed of light: 186,282 miles per second. The 31.56 million seconds in one year means one light-year stretches for 5.87 trillion miles (roughly the distance the U.S. population drives annually). The fundamental unit in astronomy, the astronomical unit (AU), is the average distance between Earth and the Sun: 93.2 million miles. This makes the light-year 63,240 AU long, just a bit short of the number of inches in a mile. — *J.K.*



SCIENTISTS AREN'T SURE what to make of Kepler-452b. The planet's properties suggest it lies on the border between being a rocky super-Earth and a gaseous sub-Neptune. If terrestrial in nature, it likely has a thick atmosphere and lots of active volcanoes.

The hunt for Earth's BIGGER COUSINS

Larger than Earth but smaller than Neptune, these in-between worlds harbor some surprisingly terrestrial environments.

Text and illustrations by Michael Carroll

Somewhere between the gas giants and the terrestrial Earth-like worlds that populate our galaxy lies a twilight zone, a region where planets defy easy classification. It is a dimension between gaseous and rocky, a territory where planet size straddles Earth and Neptune.

Several of these recently discovered hybrid planets offer the most exciting possibilities for Earth-like conditions on other worlds. And wherever such environments exist, the chance that life might gain a foothold can't be ruled out.

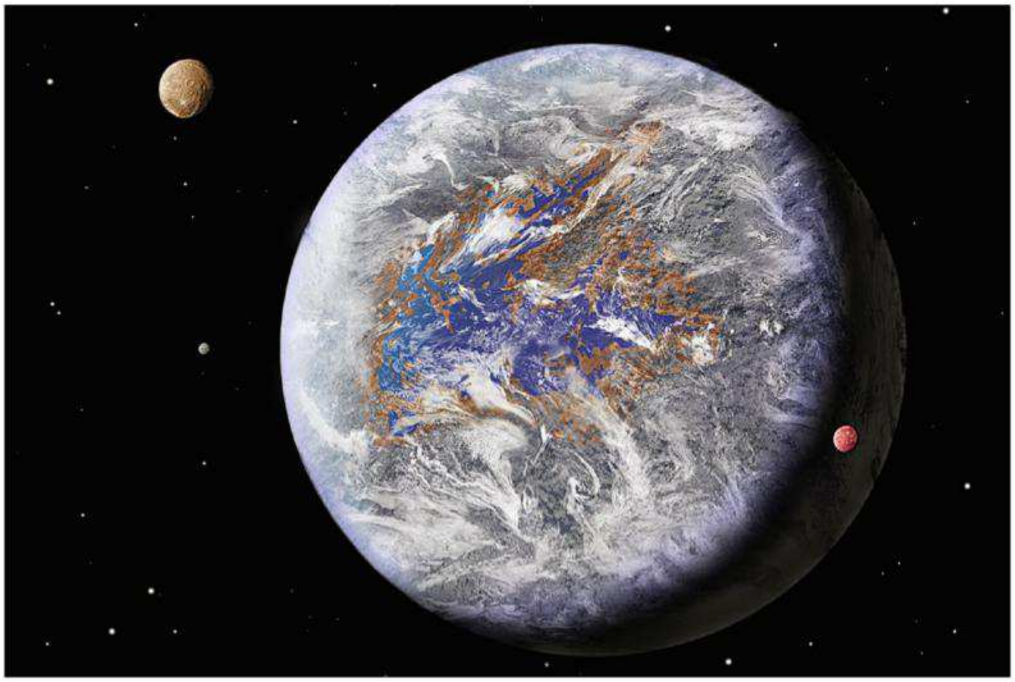
In search of Earth 2.0

Finding exoplanets isn't easy. It's hard to image a planet at interstellar distances because it gets lost in the glow of its host star. But astronomers are adept at teasing out planets by scrutinizing the light from distant suns. When a world passes directly in front of its star from our perspective (a transit), the star dims, and the amount of dimming depends on the planet's physical size. The Kepler planet-hunting spacecraft used this technique to find thousands of exoworlds.

A second method, called radial velocity, measures a star's movement as an orbiting body pulls on it. The planet's gravity causes its sun to wobble. When the planet tugs the star away from us, the light becomes redder; on the opposite side of the orbit, the star gets yanked toward us, and its light becomes bluer. Astronomers can detect this shift in a star's light. And the bigger the shift, the more massive the planet must be.

By combining these two techniques, scientists gain insights into the nature of exoplanets. If a planet has twice the mass of Earth but the same volume, for example, it must be very dense and thus rocky. But if a planet with Earth's mass has 10 times our planet's volume, it must be a low-density world like a small gas or ice giant.

Frequent contributor **Michael Carroll** *is a science writer and astronomical artist. His latest book is* Earths of Distant Suns *(Springer, 2017).*



GLIESE 581g COULD BE ONE OF THE MORE EARTH-LIKE WORLDS in our galaxy. Its tightly wound orbit around a red dwarf sun places the exoplanet within the star's habitable zone. Models indicate that under the right conditions, a large ocean would spread across this super-Earth's star-facing hemisphere.

Astronomers have charted a wide range of planets orbiting in their host star's habitable zone — the region where liquid water could exist on a world's surface — from small terrestrials akin to Mercury to rocky or gaseous worlds the size of Neptune. Our galaxy may hold 10 billion worlds with sizes comparable to our own. Among known exoplanets, however, Neptune- and sub-Neptune-sized worlds are most common. Many of these relatively small giants qualify as super-Earths.

Super-Earths and sub-Neptunes

Broadly speaking, the term *super-Earth* applies to planets that are larger than Earth but still have a rocky surface and a thin atmosphere. The term *sub-Neptune* refers to a small gaseous giant. But uncertainties in the data mean that the boundary between these two classes is more blurry than clear-cut.

Super-Earths seem to be the most common type of exoplanet. Roughly three out of every 10 worlds now known fall into this category. These worlds have no analog in our solar system. Scientists classify super-Earths strictly by mass without considering their composition, nature, or distance from their host star. Most of those discovered so far orbit close to their suns — simply because those are the easiest to detect. The masses of these worlds range from a low of about 1.5 to 2 Earth masses up to a high of 10 Earths.

Astronomers sort super-Earths into four categories. Low-density planets contain large amounts of hydrogen and helium and are referred to as dwarf or sub-Neptunes. Medium-density super-Earths probably are ocean worlds where water is a major component. A third type has a denser core than a sub-Neptune but still possesses a sub-Neptune's extended atmosphere. The extent of that atmosphere depends on the planet's distance from its star — the farther away it orbits, the cooler it will be, and the more atmosphere it will retain. Finally, larger, high-density super-Earths, sometimes called mega-Earths, probably include major components of rock and/or metal.

Not quite like Neptune

The ubiquitous sub-Neptunes join the exoplanet menagerie with masses ranging up to slightly less than our system's Uranus and Neptune. (Uranus contains 14.5 Earth masses; Neptune holds 17.1.) These worlds likely come with a wide variety of personalities.

Research scientist Mark Marley models exoplanet atmospheres at NASA's Ames Research Center in Moffett Field, California. He believes that sub-Neptunes may turn out to be the most varied of any size worlds. "You get bigger than a Saturn or so, and [planets] all tend to be about the same size because they are dominated by their hydrogen-helium atmospheres. When you get down closer to 1 Earth mass, they're probably all rocky worlds with a little bit of atmosphere. But [in this region between Neptune and Earth], there's probably a huge range of what these planets could be like. Every one is going to be unique," he says. Their natures depend on many factors, including their mass, the amount of water they possess, and the size of their core.

Like Neptune, most sub-Neptunes are gaseous. Unlike Neptune, however, many of these worlds orbit near their host star. This provides astronomers with a mystery: How did sub-Neptunes end up close to their star when they had to form in the outer regions of their planetary system? Such worlds can be born only beyond the so-called snow line, where cool temperatures enable them to collect large quantities of ices and gases.

Planets, it seems, are slippery things, capable of forming in one place and shuffling off to another. Our solar system's arrangement of

KEPLER-22b LIKELY IS A ROCKY PLANET with a radius about 2.4 times that of Earth. It orbits its host star near the inner edge of the habitable zone, so it may resemble Venus more closely than Earth.

gas and ice giants beyond smaller terrestrial worlds apparently is not the norm across the galaxy. Astronomers developed the Grand Tack model to explain the solar system's early evolution. The theory proposes that Jupiter and Saturn marched toward the Sun, but Saturn was able to pull Jupiter back from the brink of death. Similar migrations may be common in other systems, where sub-Neptunes could form at a large distance and drift starward later. An Earth-like world that develops close to its sun would have a much higher density because it lacks the water content of a planet originating in a system's cooler outer region.

Elisa Quintana of Ames Research Center has been working with a team trying to figure out when a planet transitions from being Earth-like to being a gaseous sub-Neptune. "Before we knew of any exoplanets, we had a basic mass-radius relationship based on our solar system. Now, we've had to throw that away," she says. "Theoretical models tell us that the transition from rocky super-Earth to gaseous sub-Neptune is about 1.5 or 1.6 Earth radii. Once a planet reaches 2 Earth radii, it will be more like a sub-Neptune." Researchers hope to pin down the transition point as they study more super-Earths.

How much like home?

Although the discovery of planets with terrestrial dimensions is exciting, it takes more than size to make an Earth. Even among worlds close to Earth's size and mass, the "Earth-like" pickings appear to be slim. Most orbit outside the host star's habitable zone.

Typical of these is the nasty Earth-sized planet circling Gliese 1132. Astronomers calculate that Gliese 1132b spans 1.2 Earth radii and has a mass about 1.6 times bigger than our planet, putting it on the border between being rocky or sub-Neptunian. As Earth-like planets go, so far, so good. But scientists estimate that its surface broils at the temperature of an oven, around 460 degrees Fahrenheit (225 degrees Celsius).

Just how Earth-like is a super-Earth? Features that contribute to our own world's uniqueness offer a good yardstick. First, Earth orbits in the Sun's habitable zone. Although some super-Earths orbit within the habitable zone of their own star, studies show this may not be enough to beget Earth-like environments. Plate tectonics is another critical attribute of our home world because it recirculates the minerals that wash into the seas and recycles elements of the atmosphere that have been chemically locked into rocks.

TWO SUPER-EARTHS ORBIT KEPLER-62. Both worlds likely have deep oceans of water, though Kepler-62f (bottom) orbits farther from its star than Kepler-62e (top) and thus may be covered with ice.

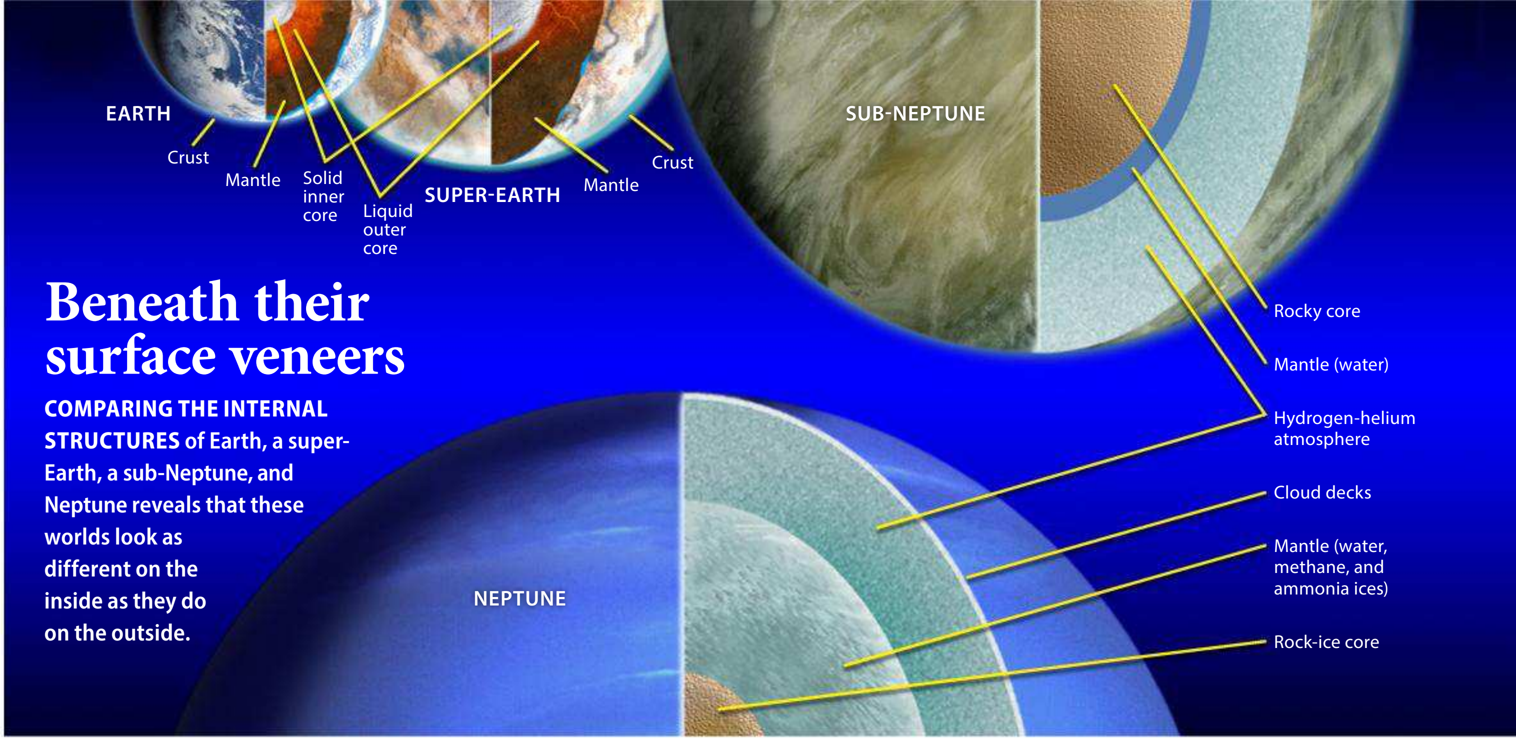
But recent models contend that super-Earths may not enjoy the benefits of plate tectonics. First, it takes the right mineral smorgasbord to create the jigsaw pattern of shifting plates. On Earth, as one plate slides under another, increasing pressure rearranges the atoms within it, making the rock denser. Without this alteration, plates would stall out and cease sliding past each other. Planets with mineralogically different crusts may not be able to maintain a conveyor belt of plates.

Second, a super-Earth's crust may be too thick for tectonics. Simulations of giant Earths reveal that most of these worlds have thick crusts, putting up a physical barrier to plate tectonics. Still, some researchers suggest that the increased heat within a super-Earth might be enough to drive the process.

Another factor that would contribute to a super-Earth's earthiness is a magnetic field. Earth's rotating molten core generates a field that protects us from energetic charged particles. To be Earth-like, a super-Earth needs to have such a field.

A survey of super-Earths

Out of the thousands of exoplanets known, astronomers have found only



a few super-Earths with the right characteristics to be potentially Earth-like. One of the closest matches appears to be Kepler-452b.

The first roughly Earth-sized planet found in the habitable zone of a star similar to the Sun, Kepler-452b is roughly 1.5 times larger than Earth. Although it lies slightly farther from its star (Kepler-452) than Earth does from the Sun, its star shines slightly brighter than ours, so the planet gets just a bit more energy than Earth does.

That is, *if* Kepler-452b has a solid surface. The planet's size hovers right on the edge between a rocky super-Earth and a gaseous sub-Neptune. Columbia University astronomers Jingjing Chen and David Kipping give the planet only a 13 percent chance of being terrestrial rather than gaseous. Models suggest that if Kepler-452b is rocky, it probably has a thicker atmosphere than Earth's and likely would be volcanically active.

Kepler-452b takes 385 days to orbit its sun, a year quite similar to Earth's. But all may not be well on this world. Its star is 1.5 billion years older than the Sun and radiates more energy than it used to. The planet once was in the center of the habitable zone, but as the aging parent star has warmed, its habitable zone has migrated outward, stranding the planet on the inner edge. Any oceans it once had likely are evaporating into a thick atmosphere.

Other possible matches may circle Gliese 581, a red dwarf star that lies 20 light-years from Earth. Up to five planets may orbit this star, and three of them may be super-Earths in the star's habitable zone. Gliese 581c orbits near the zone's inner edge. It may circle close enough to the star that it suffers from a runaway greenhouse effect like that found on Venus.

The other two planets — Gliese 581d and Gliese 581g — may be more Earth-like, but astronomers aren't even sure they exist. Both worlds have been detected by multiple teams, but other researchers have failed to confirm them. If real, they would be on the shortlist for most Earth-like planets.

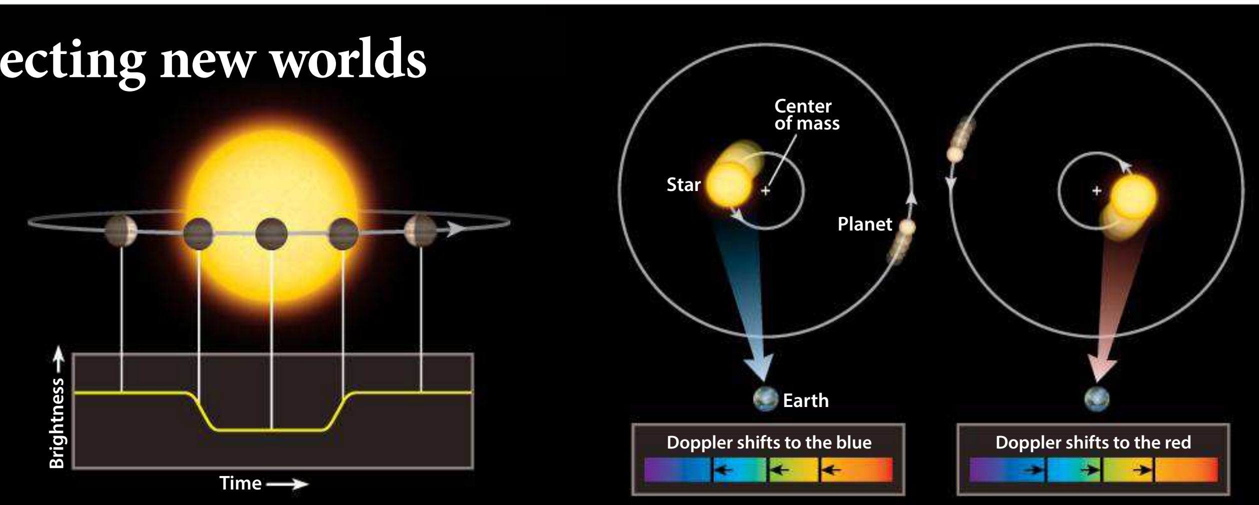
Gliese 581g appears to orbit just 0.13 astronomical unit (AU; 1 AU is the average Earth-Sun distance) from the star. But because the red dwarf is dim, the planet receives roughly the same amount of energy as Earth does from the Sun. Its mass may be no larger than 2.2 Earths, barely qualifying it for super-Earth status. The planet orbits close enough to its sun that it should be tidally locked, always keeping the same face toward the star. Depending on its atmospheric composition and surface, it might be a barren, Venus-like world, or one with an abundance of water.

If it has an atmospheric pressure similar to Earth's, the globe might be blanketed in a thick ice crust. But if the air contains enough greenhouse gases like carbon dioxide, temperatures could be substantially warmer. The tidally locked world could develop a permanent ocean on the hemisphere facing the star, where temperatures would be similar to those in Earth's tropics.

Gliese 581d appears to be much heavier, perhaps with as much as 7 Earth masses. This purported planet's size caused astronomers to add a new class to exoplanets: the

SUPER-EARTH GLIESE 667Cc, seen here from the surface of a hypothetical nearby moon, may be a sub-Neptune, with windy cloudscapes rather than rocky vistas. The planet lies so close to its red dwarf host that it probably is tidally locked, a situation that may wreak havoc with its banded cloud formations.

Dissecting new worlds



ASTRONOMERS KNOW THE MOST about exoplanets observed with both the transit and radial velocity methods. When a planet passes in front of (transits) its parent star (left), it causes a dip in the star's light. The wobbles induced by a planet's gravity alter the host star's radial velocity and show up as shifts in the stellar spectrum (right). In the rare cases when scientists can view a planet with both methods, they get valuable information on the world's size, mass, and density.

mega-Earth. The world apparently orbits its star with a period of 67 days, placing it near the outer edge of the habitable zone.

Kepler's reign of glory

At a distance of 620 light-years, the Sun-like star Kepler-22 hosts Kepler-22b. The planet was the first habitable-zone world discovered by the Kepler spacecraft.

With a diameter about 2.4 times that of Earth, it has a density similar to rock, which means that it may be terrestrial. Kepler-22b also might have a fairly dense atmosphere and, because it orbits in the inner region of its star's habitable zone, the climate may resemble Venus more closely than Earth. But the planet's rotation and cloud cover could moderate conditions there. Some recent models point to a surface temperature hovering around a comfortable 72 F (22 C).

Farther out in the galaxy, at a distance of about 1,200 light-years, Kepler-62 boasts five confirmed planets. Two of these reside in the habitable zone of the host orange dwarf star. Both are roughly 1.5 times larger than Earth, putting them at the border between Earth-like and super-Earth.

Studies indicate that water likely covers Kepler-62e in a deep global ocean. And although sibling Kepler-62f also may have a large component of water, it lies far enough out in the habitable zone that the surface might be frozen, at least at the poles. The latter world may have an atmosphere denser than Earth's, perhaps similar to — but cooler than — that of Venus.

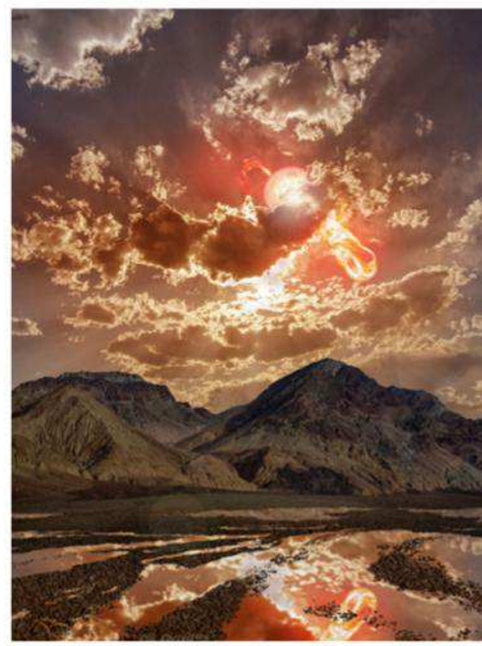
Some 22 light-years from Earth lies the triple-star system Gliese 667. Two of the members are K-type orange dwarfs somewhat cooler than the Sun, while the third is an even cooler red dwarf. The two K-type stars orbit each other; the red dwarf, Gliese 667C, circles them both at a distant 230 AU. Gliese 667C appears to have at least three planets in the vicinity of its habitable zone.

Perhaps the most intriguing of these is Gliese 667Cc, which has a mass less than four times that of Earth. This alien planet may be a rocky terrestrial, though some researchers think it may be a sub-Neptune. The world circles its sun at breakneck speed, completing a circuit in just 28 days.

But because Gliese 667C is a red dwarf, the world lies far enough out that liquid water could exist on its surface. Gliese 667Cc collects about 90 percent of the light and heat that Earth receives from the Sun. And as with any large planet in a habitable zone, it may have moons with quite Earth-like environments.

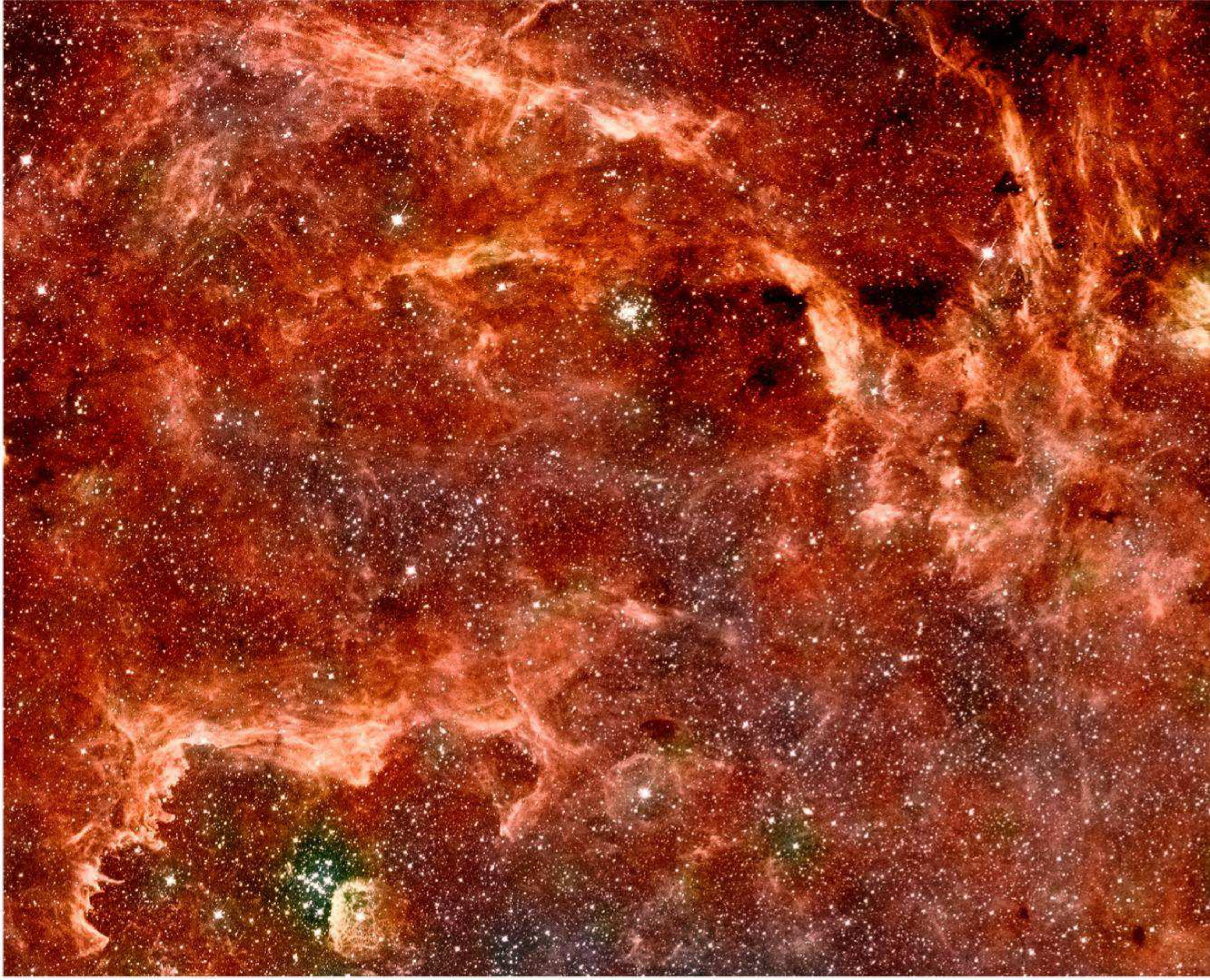
One of the most Earth-like planets yet discovered is a world with a radius 12 percent larger than our own. Kepler-438b orbits within the habitable zone of a red dwarf, making a circuit every 35 days. If Kepler-438b is terrestrial in nature, its mass would be about 1.4 times Earth's. Surface temperatures on this world likely would range from 32 to 140 F (0 to 60 C).

The planet suffers from the disadvantage of orbiting close enough to its parent star to feel the fallout from any of the stellar flares that are so common to red dwarfs. In fact, observers have seen Kepler-438 unleashing radiation and plasma every few hundred days. But if Kepler-438b has a strong magnetic field, its surface still might be hospitable.



CLOUDS IN THE SKY OF KEPLER-438B hide its red dwarf host. The planet lies close enough to its active star to be exposed to massive stellar flares. If it does not have a magnetic field, Kepler-438b likely experiences deadly levels of radiation.

Astronomers have discovered a variety of exoplanets within their host star's habitable zone. The field seems ripe for the discovery of worlds with thriving biomes beyond our own. The search for life-forms on Earths of distant suns will be a difficult one, but the detection of a new living world would forever change our views of biology, planetary development, and the frequency of life in the universe.



HOW the Milky Way works

Fundamental forces shape our galaxy and transform gas into stars. **By Robert Benjamin**

If you sit down with a photo album of galaxies, it doesn't take long to see that they are like snowflakes: No two are alike, and they are hard to study at a distance.

Happily, we have a close-up view of one galaxy — our own Milky Way. We can see its individual stars and determine their motions, map its interstellar gas and dust, and make all sorts of measurements that observers of other galaxies could only dream about.

But there is one major drawback. We are stuck in the middle of the galaxy's dusty disk, so it has been difficult to determine what the Milky Way looks like from the outside.

Thanks to decades of research and major advances in telescope technology, some of

HOT GAS swirls amid massive young stars in this infrared portrait of the Milky Way's central region. The galaxy's star-making engine converts gas into new suns.
NASA/ESA/JPL/Q.D. Wang (UM Amherst)/S. Stolovy (SSC/Caltech)

the Milky Way Galaxy's basic characteristics are now clear. We have a provisional map of its spiral arms, evidence for a pronounced galactic bar, and observations of a dense, gaseous star-forming region surrounding a supermassive black hole. But how do these pieces fit together? How does the Milky Way's star-making machine work?

What does the Milky Way do?

Typically, astronomers think of our galaxy as a stellar island, a collection of 200 billion or more stars orbiting a common center of mass. But stars make up only 10 percent of the Milky Way's total mass. About 1 percent consists of gas and dust drifting between the stars — the so-called interstellar medium. The rest appears to be dark matter. This mysterious substance — unlike visible, or "baryonic," matter — betrays its presence only by its gravitational pull on its surroundings.

The galaxy's relatively small reservoir of interstellar gas may not sound like much at a mere 1 percent of the total. However, it represents enormous potential for star birth. The galaxy's gas could make enough stars to equal about 1 billion times the Sun's mass.

Gas is central to the galaxy's inner workings. A star is a self-gravitating ball of gas whose "job" is to fuse hydrogen. This, in turn, releases energy and makes heavier elements. Similarly, think of a galaxy as a self-gravitating assembly of dark matter, stars, and gas whose function is to convert gas into new suns.

A few key factors regulate the location and rate of star formation in spiral galaxies. Influential work in 1989 by Rob Kennicutt, now at the University of Cambridge, proved that the star formation rate in spiral galaxies is related to the density of gas in the galactic disk. This relation is called the Kennicutt-Schmidt Law because it builds on an earlier idea proposed by Dutch astronomer Maarten Schmidt.

In their efforts to understand how the Milky Way and other galaxies work, astronomers must deal with some complications. One is that galaxies do not evolve in isolation after they form. They interact with their environments, and this shapes their fates.

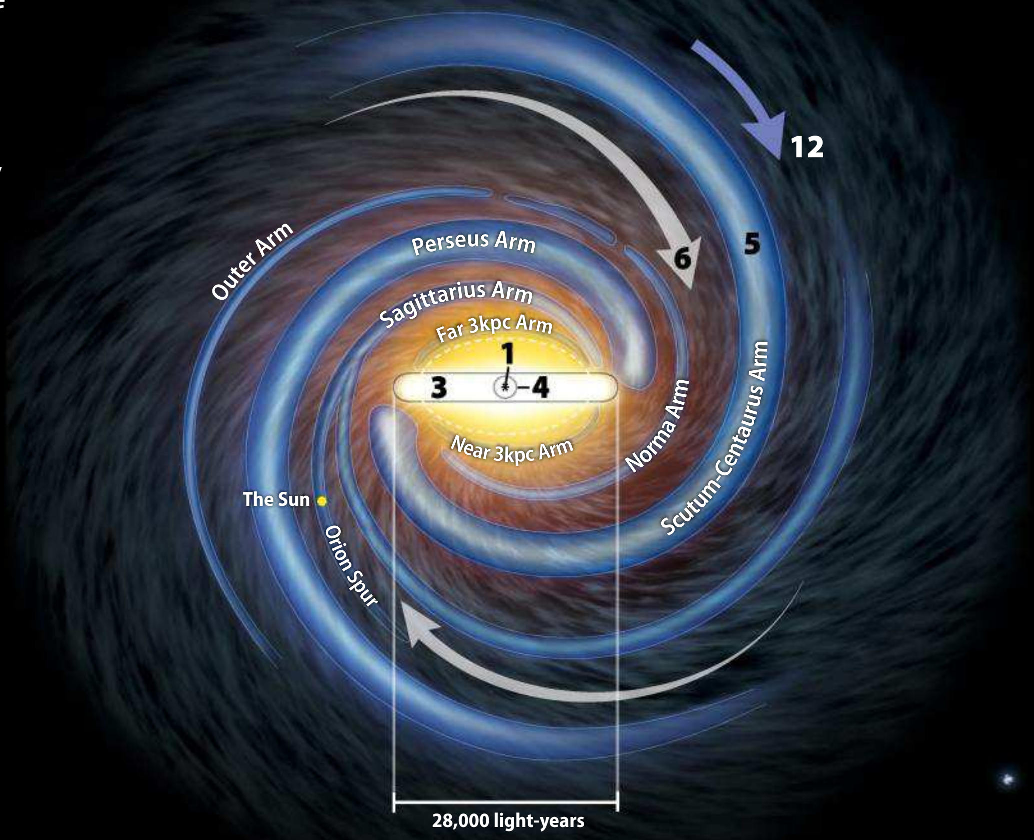
For example, astronomers using the massive Sloan Digital Sky Survey have discovered

Inside the Milky Way's star factory

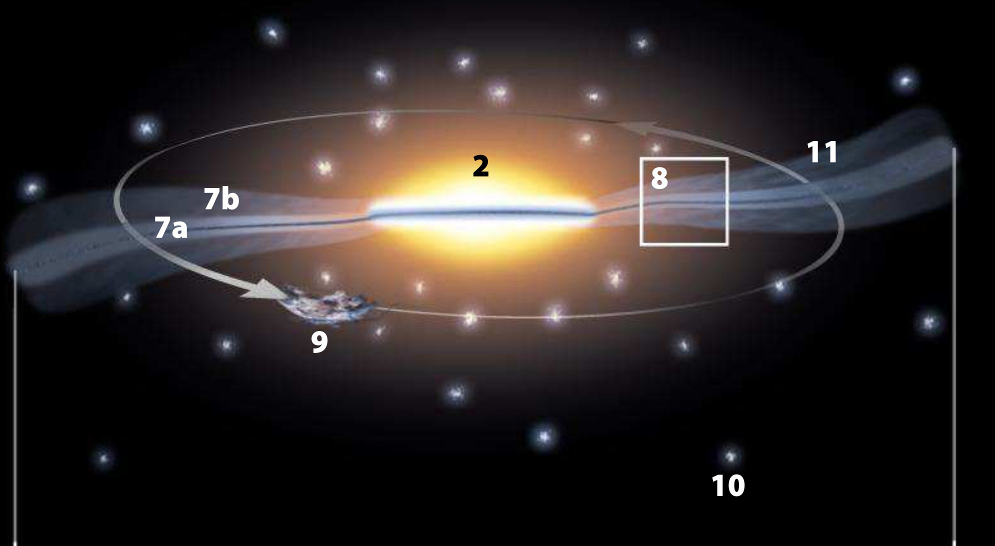
By Daniel Pendick

Galaxies make stars — that's their "job." The Milky Way is no different. Our home galaxy contains 200 billion or more stars. Each was born in a collapsing gas cloud. Various forces in the Milky Way Galaxy maintain its spiral structure, ignite new suns, and supply raw materials. Here are the major structures in the Milky Way and some important processes at work within it.

Top view



Side view



1. GALACTIC CENTER

The galactic center is the rotational center of the galaxy, lying about 26,000 light-years from Earth. A supermassive black hole sits at the center, containing about 4 million times the Sun's mass.

2. GALACTIC BULGE

The galactic bulge is a spherical population of stars orbiting the galactic center.

3. GALACTIC BAR

The galactic bar is a region in which stars orbit in elliptical instead of circular paths. The bar is about 28,000 light-years long. It helps to funnel gas toward the Central Molecular Zone.

4. CENTRAL MOLECULAR ZONE

The Central Molecular Zone contains dense, turbulent gas. It gives rise to new stars at a higher rate than more outlying regions of the disk. It measures about 2,400 light-years across.

5. SPIRAL ARM

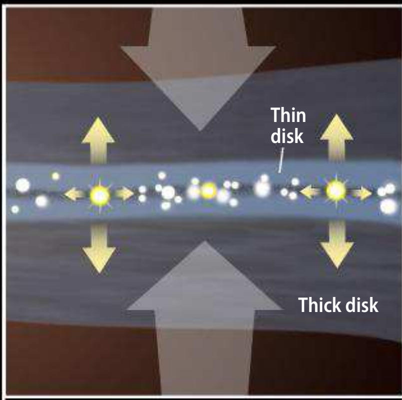
The spiral arms represent zones of above-average density. As stars and gas orbiting the galactic center enter the arms, they slow down slightly. This causes them to bunch up like cars in a traffic jam. Increased star density lights up the arms; compression of gas within the arms triggers star birth.

6. GAS FLOW

As gas slows upon entering a spiral arm, its path is deflected slightly toward the galactic center. The result is gradual migration of gas toward the center, where it fuels star birth.

7. GALACTIC DISK

The thin, wide galactic disk contains most of the galaxy's stars. A central stripe called the thin disk (7a), about 1,300 light-years thick, contains most of the stars. It lies within a more diffuse, gaseous zone called the thick disk (7b). It is five times thicker, or about 6,500 light-years.



Astronomy: Roen Kelly

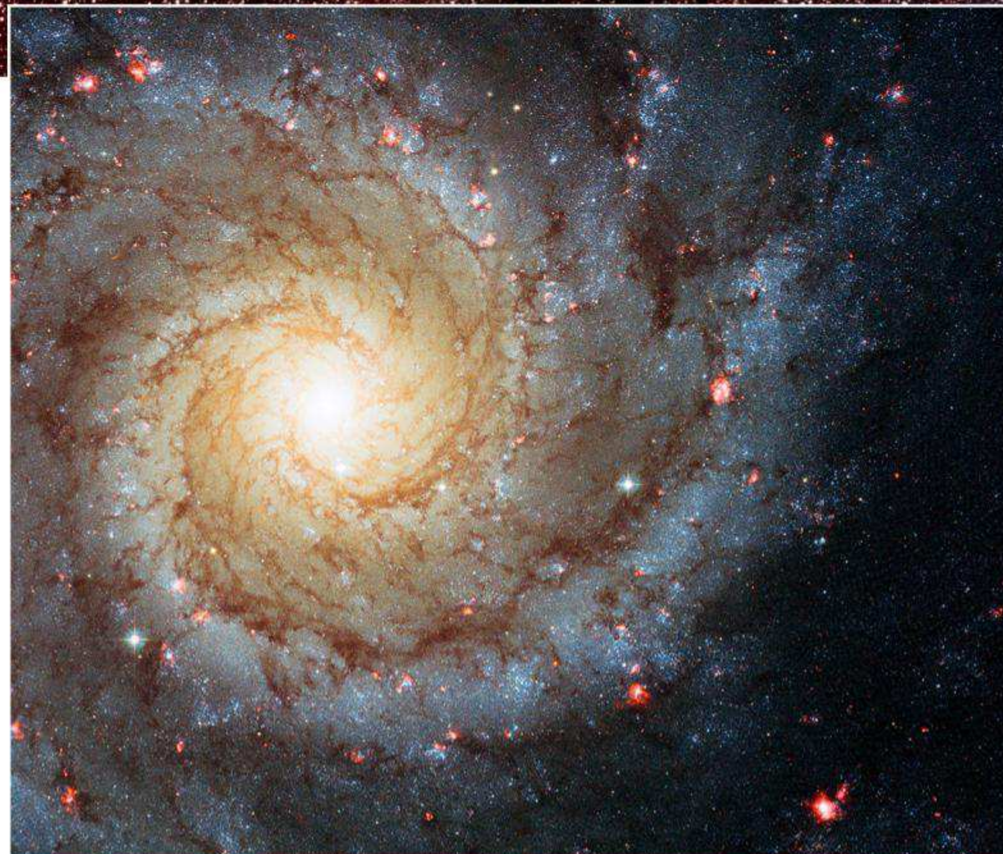
8. DISK STRUCTURE
As stars form in the galactic disk, they emit radiation and heat the surrounding gas. Turbulence and other processes create an outward pressure that helps prevent the disk from collapsing under its own gravity.

9. GAS CLOUDS
At least two dozen large gas clouds and hundreds of smaller ones orbit the Milky Way within the extended galactic stellar halo. Clouds eventually subsumed by the galactic disk during collisions provide fuel for star formation.

10. GLOBULAR CLUSTERS
At least 158 dense balls of stars called globular clusters orbit within the galaxy's extended galactic halo. Some clusters may have been captured by the Milky Way's gravity.

11. DISK ASYMMETRIES
The Milky Way's disk is not perfectly round and flat. The gas layer in the galactic disk has a flare: It gets thicker with distance from the center. The disk warps into a shape resembling a potato chip. The disk appears to be slightly oval in shape, too.

12. ROTATION
The rotation of gas and dust helps maintain the galaxy's disk shape. The tendency of a spinning object to continue doing so is called angular momentum. No star or gas cloud orbiting the galactic center can move inward or outward from its starting position without shedding or gaining angular momentum.



GLOWING KNOTS OF GAS provide an environment rich in star birth, decorating the arms of M74 (also known as NGC 628). The galaxy's arms trail from a bright central nucleus. NASA/ESA/STScI/AURA

several new nearby "dwarf" galaxies surrounding the Milky Way. These faint stellar structures, all much closer to us than the Andromeda Galaxy, frequently appear stretched across the sky. This indicates their disruption by the Milky Way's powerful gravitational field. Our galaxy has already absorbed the remains of many dwarfs.

Intergalactic clouds, typically containing a few million solar masses of hydrogen, also interact with and become part of our galaxy. Just to cite one notable example, a vast mass of hydrogen, Smith's Cloud, orbits the Milky Way. It contains enough gas to build an entire dwarf galaxy. The evidence suggests Smith's Cloud will eventually merge with the Milky Way, depositing raw material for future star creation. Astronomers have located at least two dozen large clouds and hundreds of smaller ones orbiting the galaxy.

Much of the gas brought in by intergalactic clouds serves to refuel the galaxy's star formation engine. But collisions between the Milky Way and dwarf galaxies or gas clouds can trigger bursts of star formation on their own. When the mass and frequency of this constant intergalactic bombardment is high enough — and presumably this would change over time — it could affect or even determine how the galaxy evolves.

Robert Benjamin *is a physics professor at the University of Wisconsin-Whitewater. He is the principal investigator of GLIMPSE 3D, a research project on the inner Milky Way's structure.*

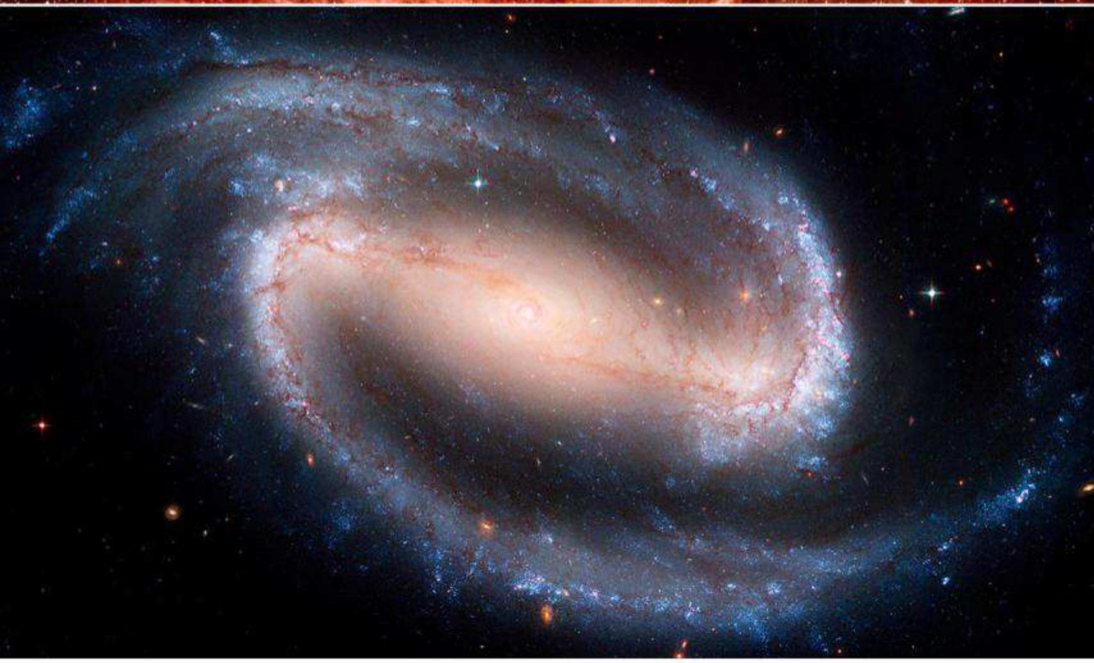
Galactic laws

Any engine, particularly one as complex as our galaxy, has many moving parts. Here are the fundamental physical principles and processes that help drive the whole system.

The galaxy is trying to collapse to a central point.

The Milky Way Galaxy is a self-gravitating system. All self-gravitating systems have a tendency to collapse in on themselves. And they would if it weren't for other forces counteracting or slowing the collapse.

In galaxies, one of the forces that opposes gravity is star formation. As gas clouds collapse within the Milky Way's disk, some of them grow dense enough to ignite into new stars. The galaxy's rotation also puts up a



IN THE BARRED spiral galaxy NGC 1300, the swirling arms extend from an elongated bar crossing the galactic center. The bar develops when stars orbiting the galactic center assume elliptical pathways. The Milky Way also has a bar, although we can't see the feature from our location. NASA/ESA/STScI/AURA

fight. In the outward (radial) direction, the Milky Way resists gravitational collapse by rotating. (Its extended spherical halo of stars also appears to rotate, but much more slowly.) Absent these forces, the galaxy would contract until its gravity warped space-time inward to form a black hole.

One place where this ultimate act of gravitational collapse has occurred is at the Milky Way's center, home to Sagittarius A* (pronounced "A star"). It's a giant black hole containing about 4 million solar masses. The process by which the Milky Way and other galaxies form such "supermassive" black holes is still poorly understood. Fortunately, only a paltry amount of the galaxy's total bulk ended up in the central black hole.

Galactic evolution increases the total disorder of the universe.

In physics, the term *entropy* describes the amount of randomness or disorder in a self-contained ("closed") system. Frank Shu of the University of California, San Diego, has emphasized in his writing that a fundamental tension in astrophysics is the battle between gravity, the great organizer, and the second law of thermodynamics, the great disorganizer. The second law states that physical systems tend to move irreversibly toward a state of disorder, or increased entropy.

Nature always seems to find a way to slow or prevent self-gravitating systems from collapsing to a state of infinite density. Stars, for example, generate photons via nuclear fusion. The resulting release of heat and radiation pressure holds up a star against gravity. The outward flow of photons into space adds to the overall entropy of the universe.

A galaxy's interstellar gas also engages in a battle with gravity. In the direction perpendicular to the galactic plane, the gas in a disk-shaped galaxy supports itself against gravity by forming stars. Since the gas is diluted, radiation from the stars provides very little push on it. Most of the interstellar pressure comes from turbulent gas motions, cosmic rays, and magnetic fields generated by the energy input from the stars.

A galaxy's angular momentum must always be conserved.

Angular momentum is the tendency of a rotating mass to continue doing so unless some outside force intervenes. In other words, because the Milky Way's disk was born spinning, it continues to spin. The galaxy's total angular momentum cannot change without some inflow or outflow of material from outside the system.

Much of the stellar mass of the Milky Way lies within a thin disk, which lies within a lower-density thick disk and the extended, diffuse stellar halo. Within the galaxy, the only way stars or gas can change position is by redistribution of angular momentum. For example, a cloud of interstellar gas can move toward the galaxy's center only by shedding some angular momentum.

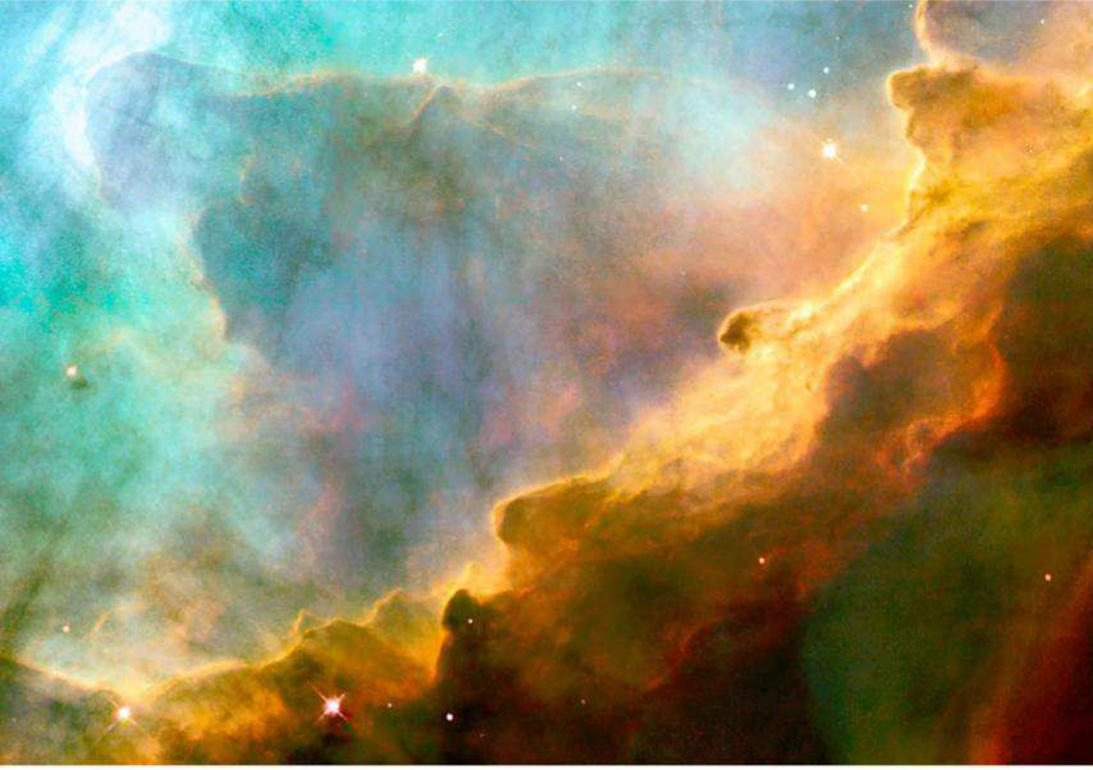
The Milky Way and other spiral galaxies have two prominent features that allow gas to lose angular momentum and migrate toward the center: bars and spiral arms. More than 60 percent of galaxies may have bars.

It is not clear what triggers a galaxy to form a bar. For some reason, stars in the galaxy's interior interact with each other so that their circular orbits become more stretched out, or elliptical. These stars then perturb other stars, which further reinforces the bar structure. The Milky Way has a prominent galactic bar approximately 28,000 light-years long, but there is still debate as to its vertical thickness along that length.

The bar's gravitational field diverts interstellar gas from its normally circular motion around the galaxy. The gas streams collide with each other, triggering large-scale compression and heating. In fact, the presence of compressed, or "shocked," gas toward the galactic center tipped off astronomers to the likely presence of a galactic bar even before they could actually see it.

In 1957, Dutch astronomer Hugo van Woerden discovered a structure called the Three-Kiloparsec Arm. Located in the galaxy's dense central region, the structure consists of

A MASS OF GAS called Smith's Cloud, imaged above in radio wavelengths, is heading for the Milky Way in an ever-tightening orbit. When it collides sometime in the next 40 million years, it may ignite a burst of star formation. Many such clouds contribute fuel to star formation in the galaxy. Smith's Cloud is 11,000 light-years long. Bill Saxton/NRAO/AUI/NSF



AN OCEAN of hydrogen in the Omega Nebula (M17) seethes with star formation. The Milky Way's star output comes from regions like this, where compression and heating ignites new suns. In this false-color image, radiation from young stars causes the gas to glow orange and red. NASA/ESA/J. Hester (ASU)

STARS BLAZE TO LIFE in a nebula within the Small Magellanic Cloud (SMC), a satellite galaxy of the Milky Way 200,000 light-years from Earth. The SMC is visible to the naked eye in the southern constellation Tucana. NASA/ESA/A. Nota (STScI)

shocked gas. Astronomers hypothesized that a central bar was causing the gas to pile up.

In 2008, Thomas Dame and Patrick Thaddeus of the Harvard-Smithsonian Center for Astrophysics discovered a remarkably similar counterpart to the Three-Kiloparsec structure, presumably located parallel to the bar on the far side of the galactic center. We now call these features the Near and Far Three-Kiloparsec arms.

In the center of the Milky Way's bar lies the Central Molecular Zone. The entire area is about 2,400 light-years across. The bar helps funnel gas into this star-forming zone of highly shocked gas. Outside the central bar, the Milky Way's spiral arms also help move gas inward. The details of how spiral arms form and propagate are still unsettled despite decades of research, but their basic features are now fairly clear.

The spiral arms are zones within the galactic disk where the density of stars is higher. The zones don't rotate along with the disk. Instead, stars and gas pass through the zones as they orbit the galactic center. The situation resembles the effect of a traffic snarl on the highway: As stars and gas clouds hit the region of high density, they begin to slow down and bunch up. As the stars and gas exit the snarl, they spread out and resume normal speed.

During the slowdown, gas passing through the arms has a tendency to deflect slightly inward. The net effect is for gas to flow toward the galactic center. This feeds the most active star-forming regions.

Galaxies try to remain symmetrical, but usually fail.

The rotating disks of galaxies should be symmetric around the rotation axis, like a spinning DVD. But the best many can do is remain bisymmetrical, meaning they tend to look the same on opposite sides.

Bisymmetry means that astronomers expect structures in the Milky Way to come in pairs. The existence of twin Three-Kiloparsec arms certainly meets this expectation. The same rule may also apply to the spiral arms outside the bar. A survey with the Spitzer Space Telescope suggests two of the spiral arms (Norma and Sagittarius) may represent bunching up of the interstellar gas alone. The other two spiral arms (Scutum-Centaurus and Perseus) appear to contain both interstellar gas and stars and connect to the ends of the central galactic bar.

The galaxy's outer regions seem more prone to deviate from bisymmetry. Looking toward the outer edges of the galaxy with our backs to the galactic center, gas does not rotate exclusively from right to left. Part of the gas motion is toward or away from us. This could be evidence that the galaxy's overall shape is somewhat oval rather than perfectly round, as proposed by Leo Blitz of the University of California, Berkeley, and David Spergel of Princeton University.

The Milky Way is imperfectly shaped in other ways. The gas layer in the galactic disk has a flare — it gets thicker with distance from the center. The disk is also warped, forming a shape similar to a potato chip. The cause of these irregularities could be the effect of gravitational interactions with neighboring dwarf galaxies, infalling intergalactic gas, or the galaxy's dark matter halo.

The galaxy in a nutshell

Simply put, the Milky Way is a gravitating system that converts gas into stars. It attempts to funnel gas toward the galactic center. However, the collapse of gas into stars and the difficulty in getting rid of the angular momentum of the gas hampers the flow. The Milky Way's bar and spiral arms help speed the inward movement of gas. Overlaid on these processes are disruptive outside influences, such as collisions with other galaxies and infalling clouds of gas.

Right now, the various observations and insights astronomers have gathered about the Milky Way lie unassembled, like pieces of a jigsaw puzzle. In the 20th century, astronomers knitted many different insights on stars into a physical theory for star formation and evolution. Perhaps next scientists will assemble a unifying theory for understanding galaxies — particularly our own Milky Way.

Inside the Orion Nebula

Astronomers are starting to figure out what's going on in this colossal stellar nursery. **By Raymond Shubinski**

The Orion Nebula (M42) is so named because it lies within Orion the Hunter, a constellation that dominates the winter sky. To find the nebula, look below Orion's Belt where his sword hangs. Your eyes alone will see the center star as fuzzy. Binoculars help, but also reveal more fuzz. Look through a telescope, however, and you'll never forget it. For here lies one of the showpiece celestial objects — a stellar nursery that, after being observed for hundreds of years, still has a lot to reveal.

HUBBLE'S Wide Field Planetary Camera 2 imaged this region of the Orion Nebula (M42). The nebula's gas clouds form a stellar nursery, a region of ongoing star formation. The bright plume of gas in the upper left in this picture results from the ejection of material by a recently formed star. The diagonal length of this image is 1.6 light-years. Red light shows emission from nitrogen atoms, green is from hydrogen, and blue originates from oxygen.

C.R. O'Dell/Rice University, NASA

Stellar neighborhood

The Orion Nebula's position in our galaxy is well-known. If we could view the Milky Way from above, it would appear as a pinwheel with four spiral arms. The galaxy contains hundreds of billions of stars and massive amounts of gas and dust. Our solar system resides in the Orion Spur, which sits between the Perseus and Sagittarius arms, about halfway out from the galactic center.

Our earthbound view is different. On a clear summer night in the Northern Hemisphere, the Milky Way's glow stretches from Cassiopeia in the northeast to Scorpius in the south. From this vantage point, we're looking along the galaxy's rim. Toward Scorpius is the central part of the Milky Way. Rather than seeing a field of blazing stars, our view is obscured by huge clouds of dust and gas.

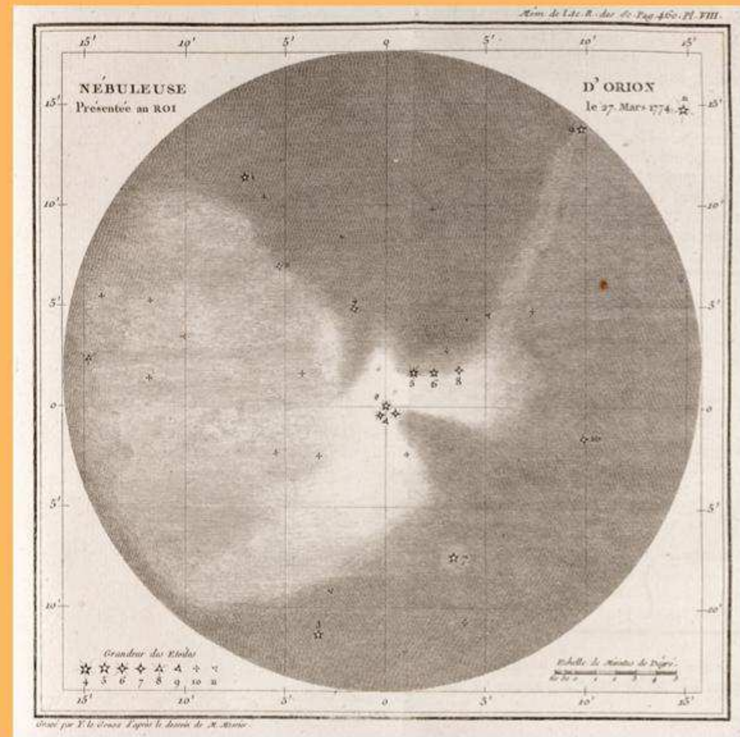
In the winter, we see the sky opposite the stellar traffic jam found toward the galaxy's center. The winter Milky Way is there, but you need a dark sky to see it with unaided eyes. The winter sky is the brightest of the seasonal skies — it contains the highest concentration of bright stars — and its most famous representative is Orion.

Although the background sky is fainter here than in summer, this area still contains much of the gas and dust that's so prevalent throughout the galaxy. In fact, the Orion Nebula represents only the tip of the proverbial iceberg. M42 is a small part of a huge complex called the Orion Molecular Cloud

Raymond Shubinski, *a contributing editor for* Astronomy, *lives in Las Vegas.*

AMATEUR ASTRONOMERS find the Orion Nebula irresistible. It's large, bright, and detailed. Las Vegas astrophotographer George Greaney shot this image with his 6-inch Astro-Physics EDF apochromatic refractor at f/7. This image is a digital composite of two 45-minute exposures on hypered 120-format Kodak PPF Pro 400 film.

THE FIRST PRINTED REPRESENTATION of the Orion Nebula appeared in 1659 in Christiaan Huygens' *Systema Saturnium*. This book is famous, however, because in it, Huygens correctly explains the nature of Saturn's rings. Linda Hall Library of Science, Engineering, and Technology



THE DESIGNATION M42 comes from French astronomer Charles Messier, who made a list of 109 objects that looked cometlike through his small telescope. Messier's sketch of his 42nd object appeared in *Mémoires de l'Académie Royale*, 1771. Linda Hall Library of Science, Engineering, and Technology

Who saw it first?

The credit for the first telescopic identification of the Orion Nebula should go to Italian astronomer Nicholas Peiresc (1580–1637), who made notes in 1610. They remained unpublished for many years, and Jesuit priest Johann Baptist Cysat "rediscovered" the fuzzy patch in 1618.

Scientists give most of the credit to Dutch astronomer Christiaan Huygens (1629–1695). Huygens' list of accomplishments is breathtaking: He developed the pendulum clock, invented the balance wheel for mechanical watches, and formulated a wave theory of light.

He was also an avid observer. Huygens built and used several long-focal-length refracting telescopes. In his 1659 book, *Systema Saturnium* (in which he correctly identified the nature of Saturn's rings), Huygens published the first drawing of the Orion Nebula.

Near the end of the 18th century, English astronomer William Herschel turned one of his first telescopes on this cosmic wonder. Herschel continued to build bigger telescopes, which culminated with a scope containing a 48-inch mirror. This instrument gave bright, detailed views of celestial objects but was hard to maneuver. The Orion Nebula was the last object Herschel viewed through this telescope before he retired the ungainly beast.

French comet hunter Charles Messier (1730–1817) was the one who really put the Orion Nebula on the map. In 1758, Messier spotted what would become known as the Crab Nebula. He made it the first entry — M1 — in his now-famous catalog of deep-sky objects. By 1769, Messier had developed a list of 41 objects he wanted to publish.

To wrap up the project, Messier added four objects: the Orion Nebula (M42), a separate part of the Orion Nebula (M43), the Beehive open cluster (M44), and the Pleiades (M45). Messier's list eventually totaled 109 objects, but few capture observers' interest like No. 42. — *R.S.*

(OMC). Actually, this complex is divided into OMC-1 and OMC-2. OMC-1 lies only 1' northwest of the Trapezium — a small cluster of newly formed stars at the Orion Nebula's heart — and contains all the visible nebulae. OMC-2 is an infrared and molecular emission source centered approximately 12' northeast of the Trapezium. The OMC is a great star-forming region that envelops all of the constellation Orion and more.

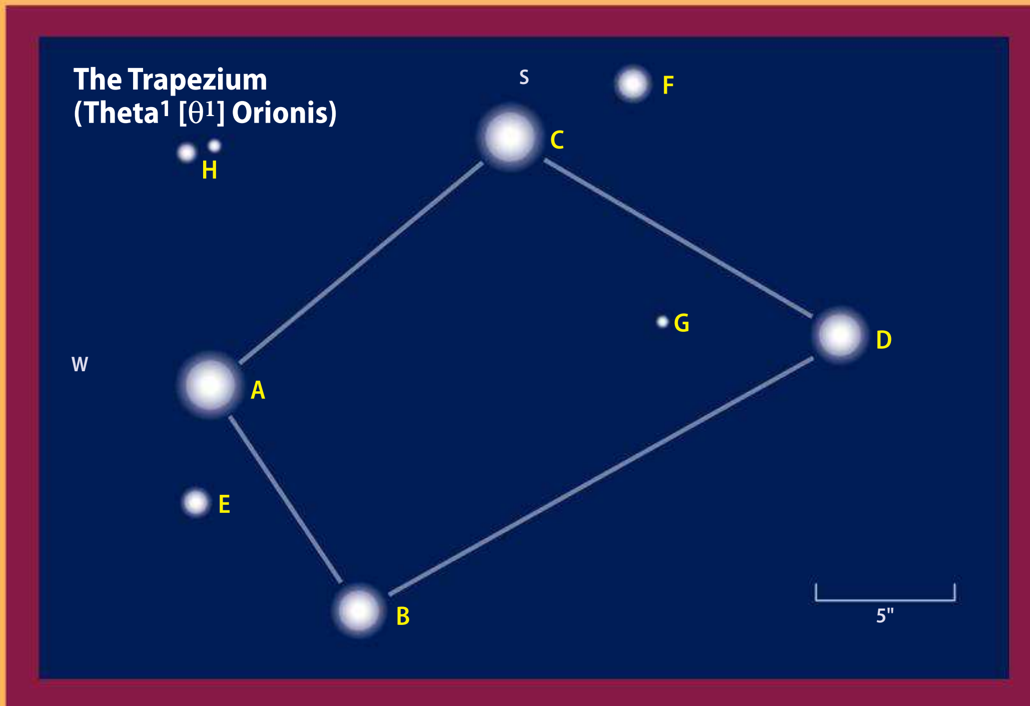
Observing M42

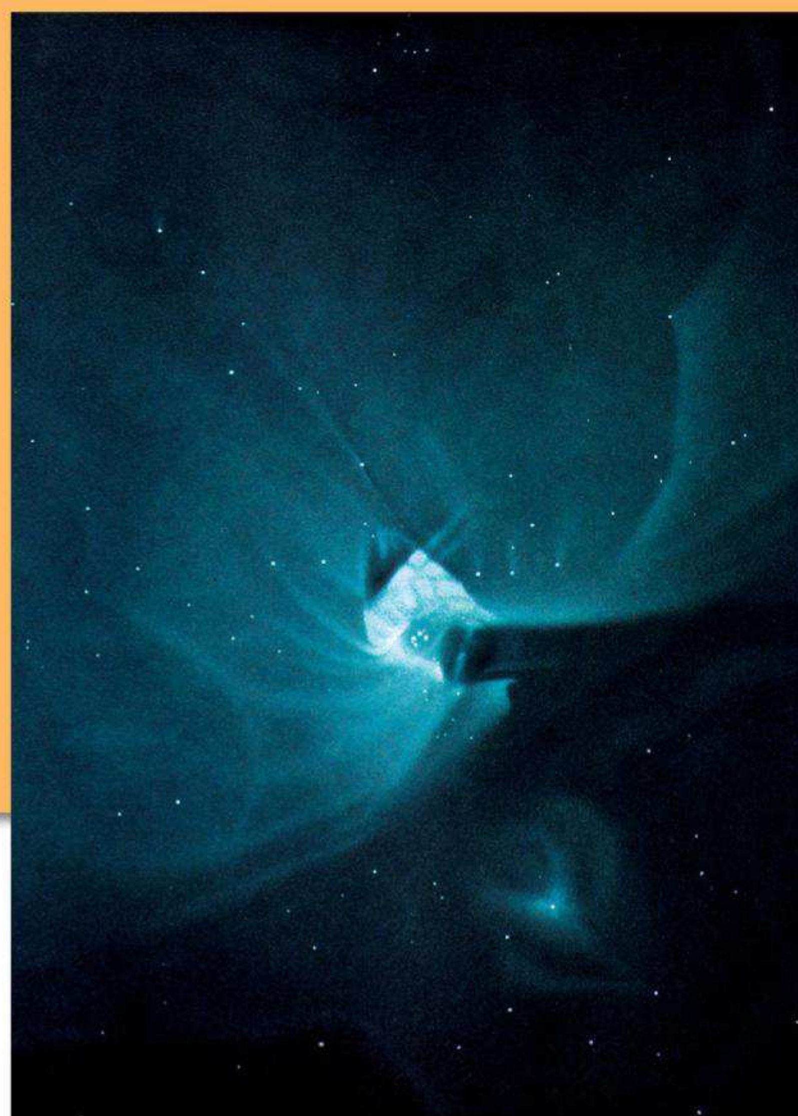
Today, just as in the time of William Herschel (1738–1822), getting a new telescope means taking a look at the Orion Nebula. It represents a benchmark to which we can compare other deep-sky objects.

Nineteenth-century astronomy popularizer Garrett P. Serviss noted the middle star in the sword — Theta^1 (θ^1) Orionis — resolves into the famous Trapezium even through the smallest of telescopes. He described it as an "irregular square shining in a black gap in the nebula."

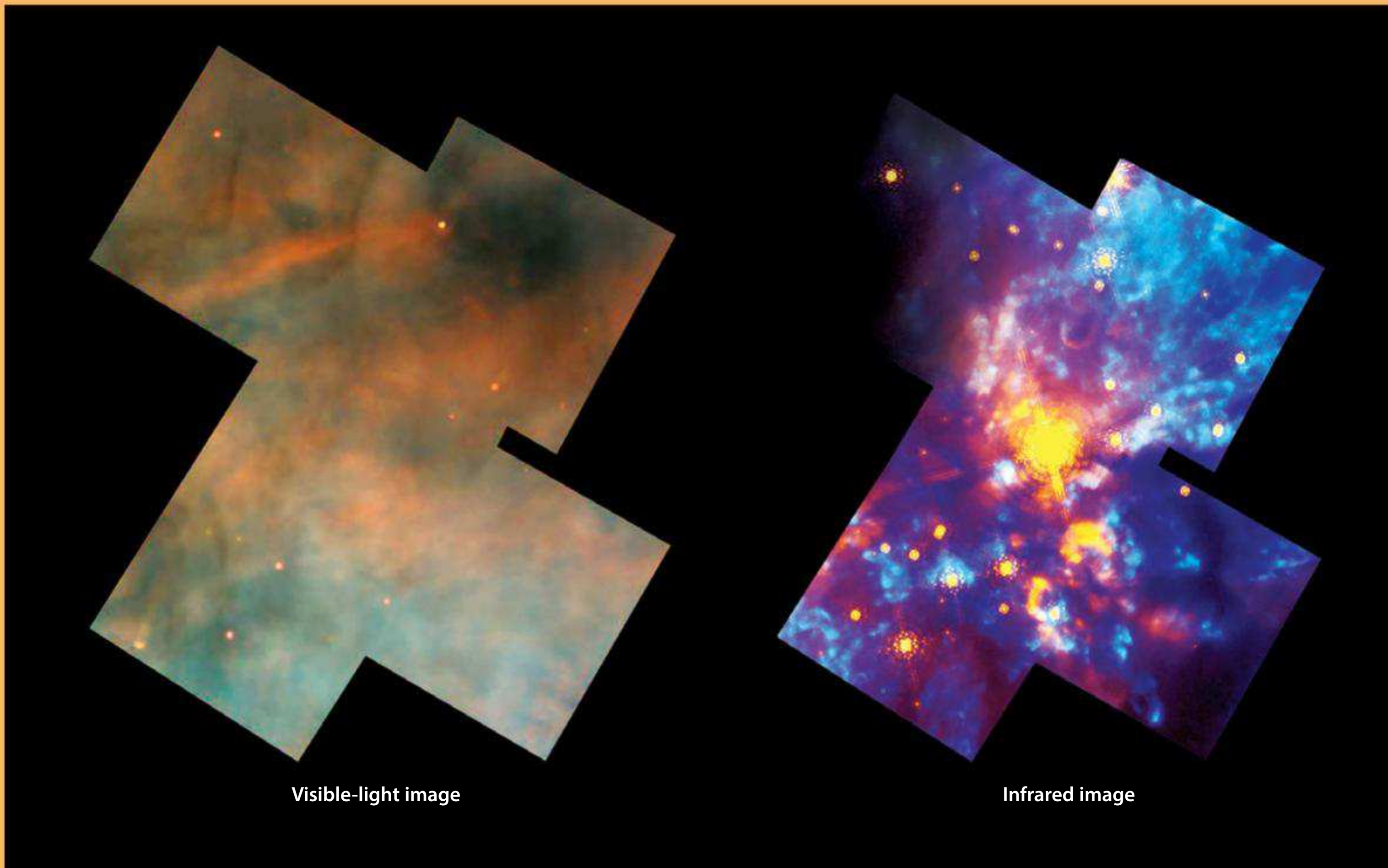
To the unaided eye, the Trapezium appears as a single star. When viewed through a telescope at low power, the "star" splits into four — designated, from west to east, as A, B, C, and D, with C being the brightest. A larger telescope with higher magnification reveals two more (E and F), and

THETA^1 (θ^1) ORIONIS, the middle star in Orion's Sword, shines at magnitude 4.2. When seen through a small telescope, however, it resolves into four stars called the Trapezium. The stars A, B, C, and D received their designations according to their right ascensions, not their brightnesses. Star A shines at magnitude 6.7, B at magnitude 8.0, C at magnitude 5.1, and D at magnitude 6.7. If your sky is steady, an 8-inch scope may reveal 11th-magnitude E and F. You probably will need a 14-inch telescope to find G and H, which both glow faintly at 15th magnitude. *Astronomy*: Roen Kelly





THIS PAIR OF SKETCHES of the Orion Nebula appeared in *Account of the Great Nebula in Orion*, Harvard College Observatory Annals, vol. 5, 1867. The volume's author, William Cranch Bond (1789–1859), sketched the nebula (above), emphasizing its extent and contrasting areas. The author's son, George Phillips Bond (1825–1865), created the frontispiece (right) based on numerous observations. Michael E. Bakich collection



TWO VIEWS OF THE ORION NEBULA show why astronomers image celestial objects in different wavelengths. The Wide Field and Planetary Camera 2 aboard the Hubble Space Telescope created the visible-light image on the left. Hubble's Near Infrared Camera and Multi-Object Spectrometer made the one on the right through infrared filters. The right image reveals the Orion Nebula as an active star-formation region where stars and dust glow yellow-orange and hydrogen clouds appear blue. The diagonal extent of each image spans about 0.4 light-year. STScI/NASA

Galileo and the Orion Nebula

Why didn't Galileo, who made so many telescopic discoveries, record the Great Nebula in Orion? We might understand how he could overlook a faint outer planet like Neptune, but how could he have missed a fuzzy patch visible to the naked eye?

As always, reality is more complex than it seems at first glance. Flandrau Planetarium in Tucson, Arizona, has displayed an exact replica of one of Galileo's telescopes for many years. One look through this primitive instrument (mounted so visitors can view with it), and you'll realize just how incredible his discoveries were.

Galileo made his first telescopes while living in Venice. The "figure" of the glass lenses was done by trial and error, and the glass may have been full of air bubbles. Perhaps Galileo thought the fuzzy nature of the region in Orion's Sword had more to do with his instrument than with the true nature of the object. — *R.S.*

the largest amateur scopes may show G and H (which constitute a double star).

English observer William Henry Smyth (1788–1865) in his famous *Cycle of Celestial Objects* (1844) referred to the nebulosity that surrounded the Trapezium as the Fish's Head. Other early observers also noticed this aquatic similarity. Sir John Herschel (1792–1871), son of William, compared the nebulosity "to a curdling liquid or a surface strewn over with flocks of wool."

Despite what high-resolution Hubble Space Telescope images or even photographs taken by amateur astronomers show, it is difficult to see colors in the nebula. Through telescopes, some observers have reported a hint of green or purple in the clouds surrounding the central stars.

Before photography, capturing an image of the Orion Nebula depended on a skilled observer with a keen eye and an artistic hand. Dutch astronomer Christiaan Huygens' (1629–1695) early drawing shows only a smudge with an indentation and three stars. M42 drawn by French comet-hunter Charles Messier is detailed and clearly shows the visual impression left by the nebula.

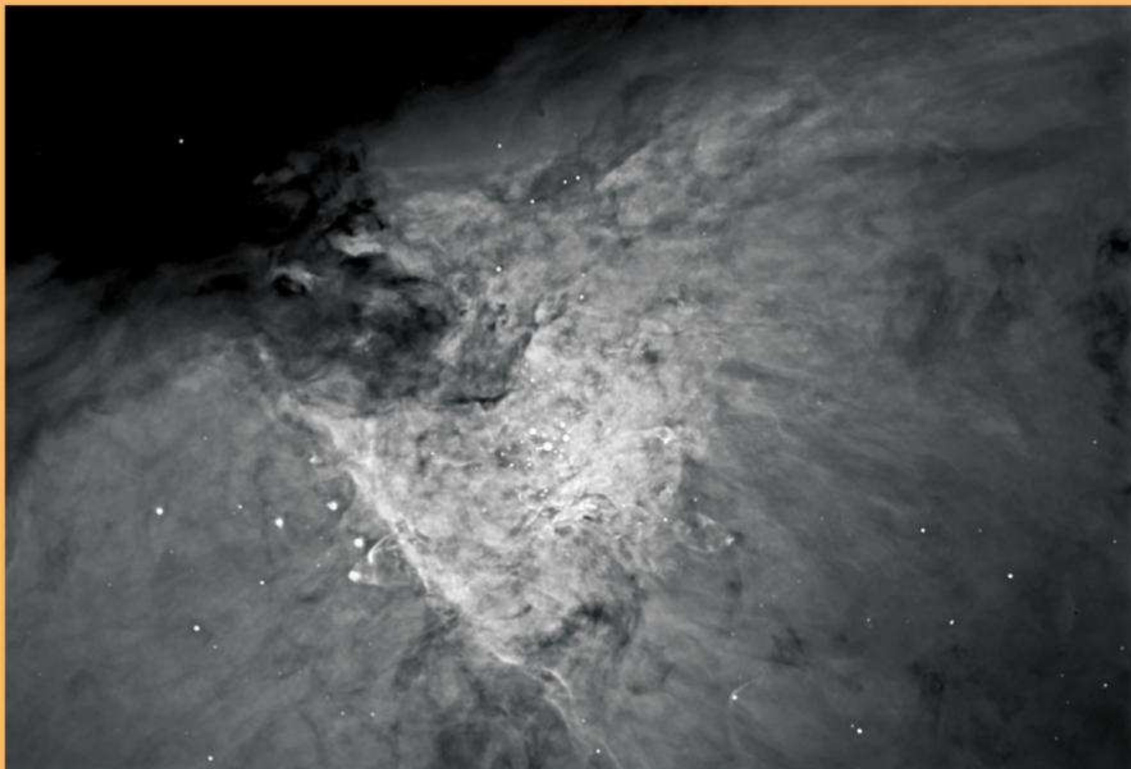
THE TWO MICRON ALL SKY SURVEY provides a different view of the Orion Nebula. The nebula is a gaseous bubble formed on the front side of the Orion Molecular Cloud-1 (OMC-1). In this 10-minute exposure, some of the light from the bright nebulosity comes from scattered starlight, some is due to various hydrogen emission lines, and some comes from shocked molecular hydrogen, which glows at 2 microns. At a distance of just 1,350 light-years, the Orion Nebula is the closest site of high-mass star formation to the Sun. 2MASS/mosaic image construction by E. Kopan

Photography began in the 1830s but was cumbersome. Before the first photographic image of M42, American astronomer George Phillips Bond (1825–1865) produced a drawing of M42 that ranks as the most beautiful and detailed ever made. Bond was the director of the Harvard College Observatory during the American Civil War and used observations of the Orion Nebula through a 15-inch refractor over many years to render this detailed image. The original drawing still hangs at Harvard University.

American astronomer Henry Draper (1837–1882) captured the first photographic image of the Orion Nebula on September 30, 1880. Draper used an 11-inch Alvan Clark refractor with a triplet objective. He also used a new "dry-plate" photographic technique to make his images. The exposure lasted 50 minutes. Since that night in 1880, astronomers have scrutinized M42 through every size telescope and in every available band of the electromagnetic spectrum.

Inner turmoil

The Orion Nebula is about 1,350 light-years away and more than 10 light-years across. Yet



M42 LOOKS STRANGE when imaged through a Hydrogen-alpha (Hα) filter. Hα is red light with a wavelength of 656.28 nanometers created when a hydrogen atom absorbs energy and re-emits it. Common Hα images show solar flares and prominences on the Sun. But, as this image shows, nebulae also emit Hα light. This Hα image (a single 105-minute exposure) was taken through a 20-inch RC Optical Systems Ritchey-Chrétien reflector at f/8.4 using an SBIG ST-10XME CCD camera. Adam Block/NOAO/AURA/NSF

THE FAMILIAR CONSTELLATION ORION looks different in infrared wavelengths. This false-color image was constructed from data collected by the Infrared Astronomical Satellite (IRAS) and covers 30° by 24°. The bright yellow region to the lower right is Orion's Sword, which contains the Orion Nebula. Betelgeuse (Alpha [α] Orionis) shines at the upper center. Infrared Processing and Analysis Center, Caltech/JPL

M43 IS PART of the much larger Orion Nebula complex, and it lies roughly 10' north of M42. This section features a hot, bright star (center) that is ionizing the gas near it. The ionization creates a sphere of glowing hydrogen, which appears pink. This image was shot through a 20-inch RC Optical Systems Ritchey-Chrétien telescope at f/8.4 with an SBIG ST-10XME CCD camera. Three 20-minute exposures through red, green, and blue filters were combined to produce the final image. Pat and Chris Lee/Adam Block/NOAO/AURA/NSF

it represents only a small part of the great Orion Molecular Cloud. The cloud contains a mixture of cold hydrogen and dust grains. M42 is known as an emission nebula. The hydrogen is excited by the hot stars buried within. Excitation is a process by which hydrogen atoms absorb energy (from nearby stars). The atoms can't hold the energy for long, however, and quickly release it as light.

The Orion Nebula is a hotbed of star formation. The stars in and near the Trapezium are young — possibly only 300,000 years old. Theta^1 C Orionis contains 40 times the Sun's mass and has a surface temperature of 40,000 kelvin (72,000 degrees Fahrenheit). Because of its size and mass, Theta^1 C produces tremendous amounts of ultraviolet radiation, which causes nearby gas clouds to fluoresce. Theta^1 C is 210,000 times brighter than the Sun, and it produces a stellar wind that blows at 5.7 million mph (9.2 million km/h). This tremendous wind blows planet-forming dust particles away from the surrounding stars, making it impossible for planets to form.

Conditions within the Orion Nebula are incredible. In *The Perfect Storm* by Sebastian Junger, two massive atmospheric fronts

Mythic surroundings

Greek mythology provides many stories about Orion the Hunter. One myth says that the gods placed Orion in the sky as a punishment for his arrogance. Another declares Orion was in love with the beautiful goddess Diana. Diana's brother, Apollo, was enraged by this relationship and tricked Diana into killing Orion with one of her arrows.

Another story claims Orion threatened to kill all animal life on Earth. To prevent this, the Earth goddess, Gaia, sent a scorpion that stung Orion on the heel, killing him. Regretting her actions, Gaia placed Orion opposite Scorpius the Scorpion in the sky so Orion could never be harmed again. Any star chart shows this arrangement.

The ancient Egyptians saw Orion as the god Osiris, the husband of Isis. Seth killed his brother Osiris in an ancient rivalry. To make certain the job was complete, Seth chopped Osiris into 14 pieces and scattered them throughout Egypt.

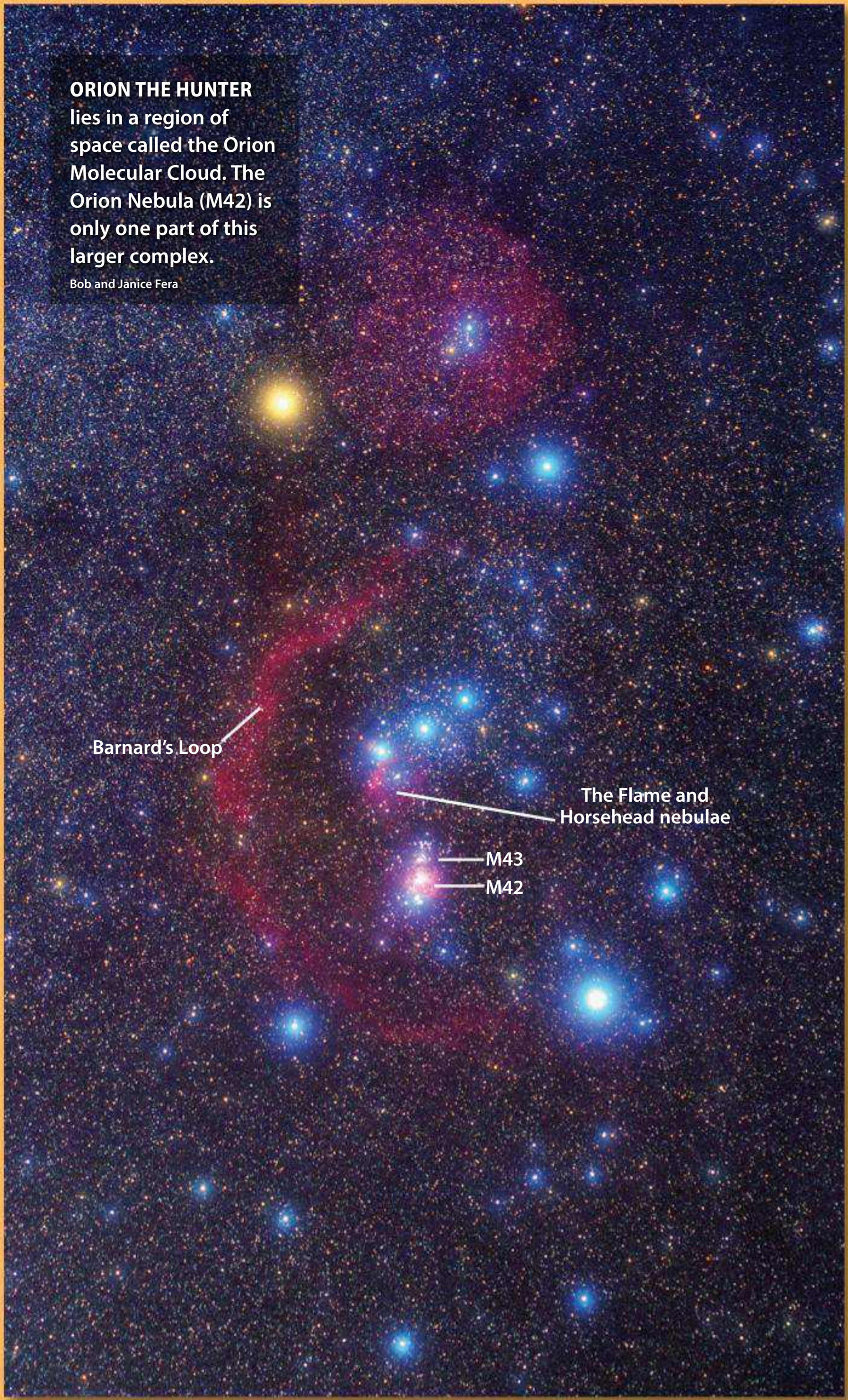
Isis recovered all but one part and placed Osiris in the sky (as the constellation Orion), where he could be seen by all. Osiris became a pre-Christian symbol of death and resurrection because Orion sets in the springtime when crops are being planted and reappears when the crops have been harvested.

The Greeks told similar stories emphasizing Orion's timekeeping nature. The poet Aratus wrote a book, *Phaenomena*, around 200 B.C. The long poem is really a calendar guide that gives directions about nature and the passage of the year.

Even T.H. White captures Orion's calendric use in his book *The Sword in the Stone* when he has the young Wart — the future King Arthur — looking through a castle window at Orion, hoping spring will arrive soon. Perhaps Wart looked at the giant's gleaming sword and thought of Excalibur.

As the civilizations of Greece and then Rome eventually collapsed, the growing power of Islam flowed from the deserts to fill the void. Muslim scholars collected Greek manuscripts and translated them into Arabic. This preserved a great part of ancient literature and science.

To these scholars, Orion became Al Jabbar, the mighty giant. From a contemporary view, this gives a good idea as to what heights basketball superstar Kareem Abdul-Jabbar must have aspired. — *R.S.*



ORION THE HUNTER lies in a region of space called the Orion Molecular Cloud. The Orion Nebula (M42) is only one part of this larger complex. Bob and Janice Fera

collide over the Atlantic Ocean to create killer waves. A perfect storm of cosmic proportions is taking place in M42. Disks of dust and gas surround small, low-mass stars that produce stellar winds. The supersonic stellar wind of Theta[1] C collides with the stars' winds, producing the perfect cosmic storm. This storm will continue as long as the supermassive star continues to produce energy. If we could run time forward even a million years, we'd see Theta[1] C obliterate itself in a supernova.

No matter how much we know about the physical nature of this complex region, the Orion Nebula never fails to delight when seen for the first time or after many years. When first shown Orion, children relate the shape of this constellation to a bow tie, an hourglass, or even a butterfly. In the latter case, the great nebula marks one of the colorful spots on its wing.

However you see this giant constellation, it's filled with wonders beyond imagination. Nearby and just above M42, one can find M43. Above M43 is the Running Man Nebula (NGC 1973–5–7). Still, the complexity of the Orion Nebula and the surrounding area only hints at the beauty and drama of our galaxy.

10 things we don't know about massive stars

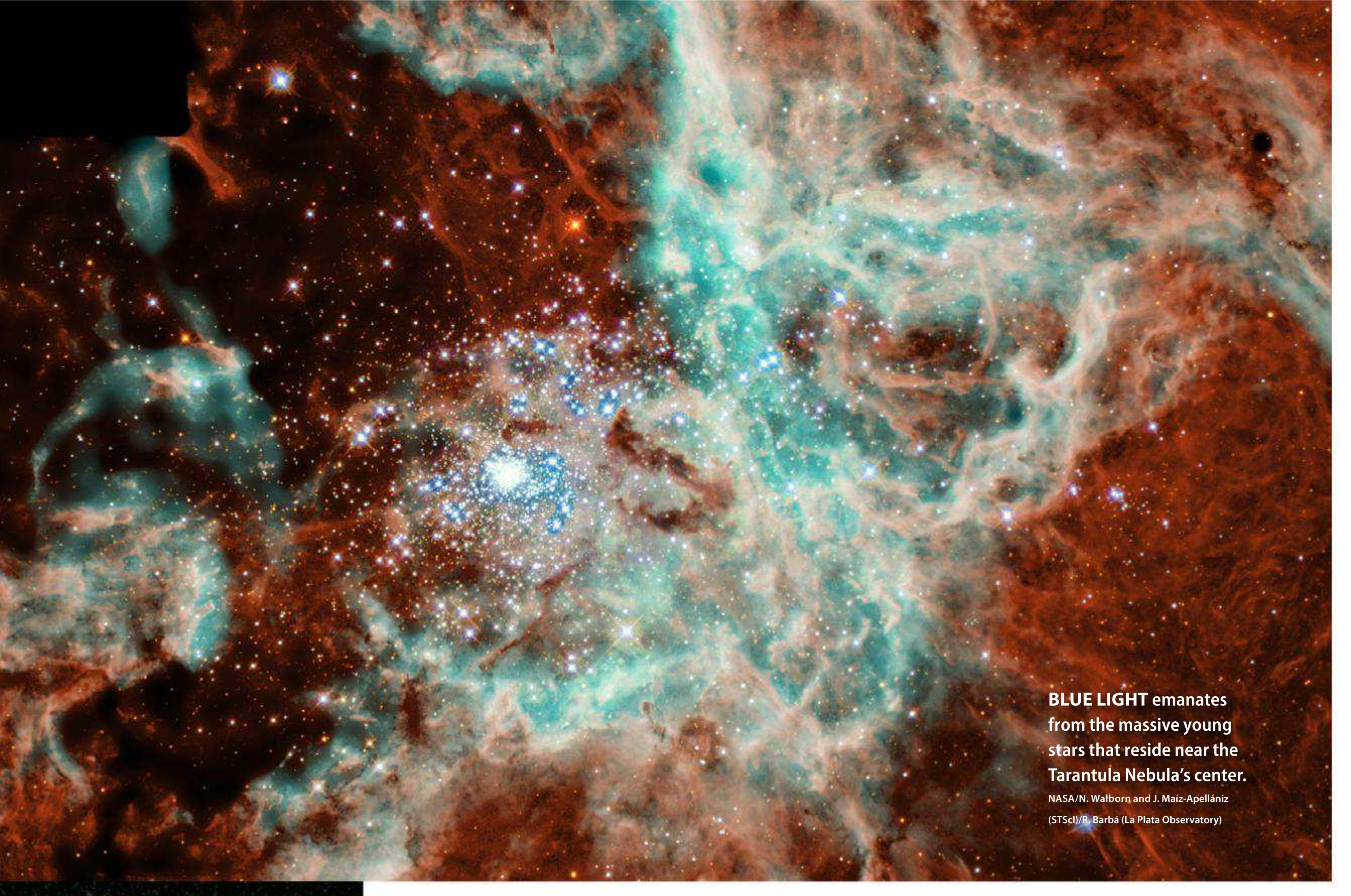
These rare beasts are essential to the universe but often misunderstood. Here are the most important questions facing astronomers. **By Yaël Nazé**

The universe continues to baffle the great minds of our age. Yet, ask most people where the deepest mysteries lie, and you're apt to hear discussions on the origin and fate of the cosmos, the nature of dark matter, and the existence of extraterrestrial life. Astronomers must have figured out all there is to know about mundane objects like stars, right?

Not so. These ubiquitous building blocks of galaxies still hold many secrets. The greatest questions surround the stars with the most mass. On a cosmic scale, these rare behemoths last only for the blink of an eye. Yet, in their short lives, they forge heavy elements — the raw material for future generations of stars, planets, and perhaps life — and then eject them into the cosmos in titanic explosions.

A decade ago, Cássio Barbosa of Brazil's University of São Paulo and Donald Figer of the Rochester Institute of Technology surveyed their fellow researchers to find out the most pressing questions facing theorists and observers. Here are 10 topics that still keep their minds busy.

Yaël Nazé *studies massive stars and their relationship to the environment using wavelengths from gamma rays through infrared. She's also deeply involved in science popularization activities.*



BLUE LIGHT emanates from the massive young stars that reside near the Tarantula Nebula's center. NASA/N. Walborn and J. Maíz-Apellániz (STScI)/R. Barbá (La Plata Observatory)

THE GAIA spacecraft will measure precise distances to a billion stars, including — for the first time — high-mass stars. ESA

1 How far away are massive stars?

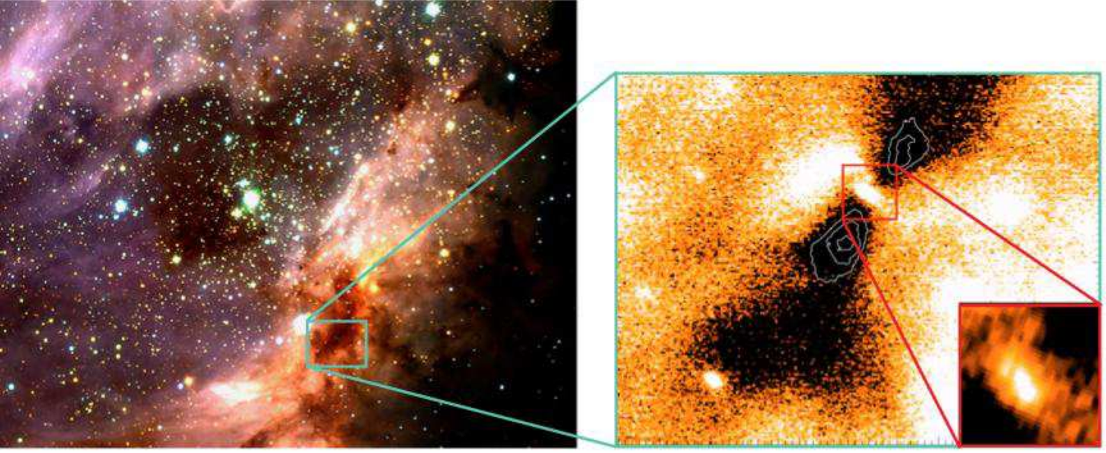
It's so simple a question, it seems extraordinary we don't yet know the answer. After all, astronomers have accurate distances to a host of low-mass and midsize stars. The best method for getting reliable distances involves measuring the position of a nearby star relative to more distant objects from opposite sides of Earth's orbit. Simple trigonometry then converts the star's observed angular displacement into a distance.

Unfortunately, these angles are so small, the method can be applied only to the Sun's close neighbors. Before 1989, this technique had yielded just a few hundred precise distances. Things changed that year with the launch of the European Space Agency's (ESA) Hipparcos satellite. Thanks to its 3.5-year mission, astronomers had reliable distances — meaning an uncertainty of less than 10 percent — to nearly 120,000 stars out to some 300 light-years.

Yet, this seemingly large sample of solar neighbors does not contain a single massive star. So rare are these heavyweights that the nearest one lies well over 300 light-years away. Astronomers can only estimate the distances to these stars: The closest O-type star, Zeta (ζ) Ophiuchi, lies roughly 370 light-years away; the nearest Wolf-Rayet star belongs to the binary system Gamma^2 (γ^2) Velorum, and it checks in at a distance of more than 1,000 light-years.

Without a precise distance, it's impossible to know a star's real properties, like luminosity, and this leads to uncertainty in theoretical models. Massive stars easily rank as the most luminous in the cosmos — the brightest outshine the Sun by a million times. And these are the only stars bright enough for us to see in distant galaxies. So, understanding massive stars better will improve our knowledge of extragalactic astronomy.

This first problem should be solved quickest. ESA launched Gaia, a successor to Hipparcos, in 2013. This satellite, which lies nearly a million miles beyond the Moon, should get accurate distances to a billion stars out to a distance of 30,000 light-years. That's far enough to pinpoint a significant fraction of all the Milky Way's massive stars.



◄◄ **A CLUSTER OF MASSIVE STARS** forms from the gas and dust of the Omega Nebula (M17) in Sagittarius. Protostars lie embedded in a huge molecular gas cloud near the nebula's southwestern edge (box). ESO

◄ **A MASSIVE PROTOSTAR** inside the vast cloud grows as it accretes matter from a surrounding disk. The developing star currently contains about 20 solar masses, and the disk weighs more than 110 solar masses. ESO

2 How do massive stars form?

The birth of monster stars provokes heated quarrels among specialists. Two theories confront each other. In the first, massive stars form like their low-mass cousins. Gravity causes an interstellar gas cloud to collapse and fragment, with both big and small stars forming in the process.

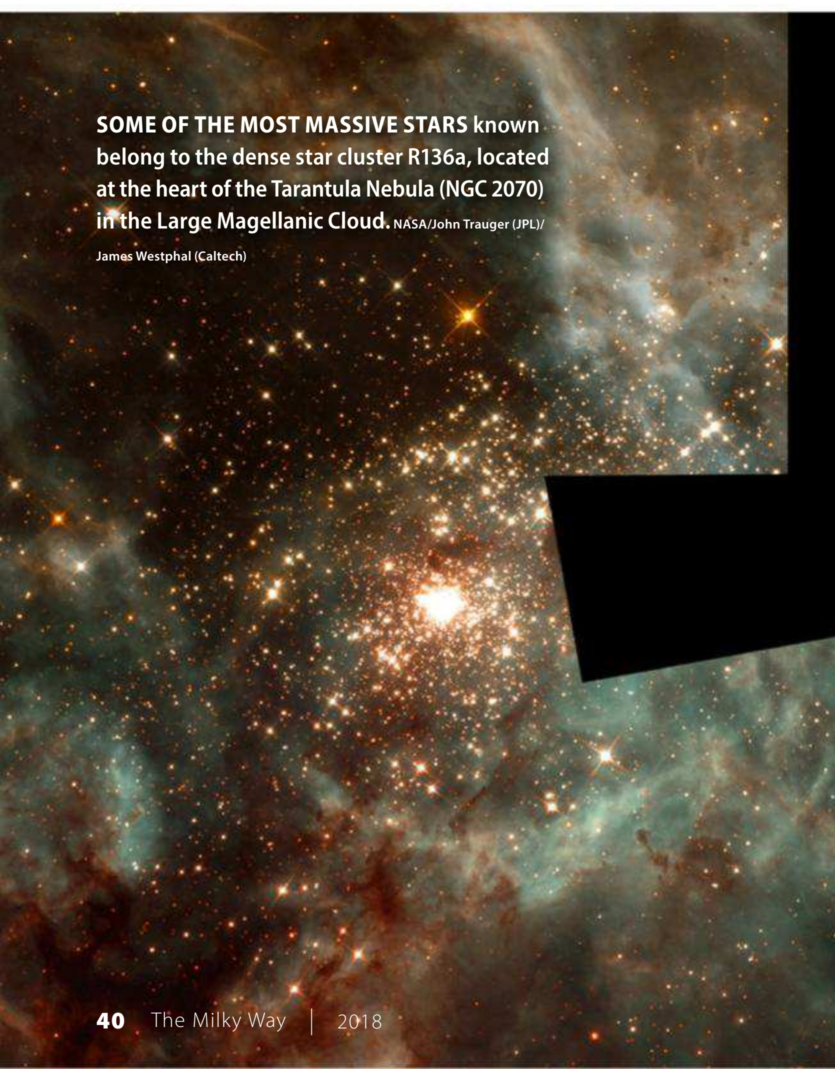
The problem: Massive objects should start nuclear reactions long before they reach final form. The reactions emit intense radiation that should stop more matter from falling in. A slight alteration may save this idea. Scientists now suggest the largest fragments become midsize protostars, each surrounded by an accretion disk. The growing stars gain weight by feeding off their disks. Observations have found at least one massive star, located in the Omega Nebula (M17), forming as this model predicts.

Another group has performed simulations that show instabilities in the formation process create channels to funnel out the radiation while allowing the gas to accrete.

Other observations imply massive stars are born when smaller objects collide — the second theory of high-mass star formation. Most big stars live in clusters, and the more stars a cluster contains, the more massive the largest stars are. X-ray observations reveal lots of low-mass stars near the massive objects. Could they be a food reservoir?

Computer simulations show collisions can be an effective method of creating massive stars. Nevertheless, not all massive stars belong to clusters. Were these solitary gems born in a different way, or were they violently ejected from their birthplaces?

For the moment, astronomers have yet to reach a consensus. Some scientists think both processes could act simultaneously.



SOME OF THE MOST MASSIVE STARS known belong to the dense star cluster R136a, located at the heart of the Tarantula Nebula (NGC 2070) in the Large Magellanic Cloud. NASA/John Trauger (JPL)/ James Westphal (Caltech)

3 What is a star's maximum mass?

At the beginning of this century, some researchers claimed they had discovered stars with extraordinary masses. For example, R136a — the central region of the star-forming Tarantula Nebula in the Large Magellanic Cloud (LMC) — was thought to be a single star containing 2,500 solar masses. However, the illusion has passed. Most of these mass estimates were done by indirect means. Better observations showed the apparently ultramassive stars are dense clusters of smaller stars possessing more reasonable masses.

Still, determining how much massive stars weigh proves difficult. Statistical surveys of big clusters have shown that no star with a mass larger than 150 to 200 solar masses exist. The only reliable method involves studying binary-star orbits. An orbit's size and period depend on the stellar masses. To date, two binary pairs appear most promising. One of those pairs, the Milky Way's WR 20a contains two stars that each weigh about 80 solar masses.

However, more massive stars may be out there. For example, the star HD 15558 may contain 152 solar masses — plus or minus 46 solar masses; the star WR 25 may contain 75 solar masses.

Apart from direct observation, astronomers also wonder if a physical limit exists beyond which no star can form. If so, does the limit depend on the content of heavy elements in the gas from which the star formed, instabilities in the protostar's structure, dynamical processes within the cluster, or accretion problems?

4 What role did massive stars play after the Big Bang?

In the minutes following the Big Bang, the universe synthesized only a few light elements: hydrogen, helium, and lithium. From this mixture, the first stars were born.

Astronomers call this initial stellar generation "Population III." These peculiar, early stars played a crucial role in cosmic evolution because they sowed the universe with heavier elements and, thanks to their ionizing radiation, made the cosmos transparent again. These missing links between the Big Bang and today will help scientists understand the current face of the universe.

Theoretical models indicate these stars were born 100 to 250 million years after the Big Bang and each contained several hundred times the Sun's mass. These enormous objects died in gigantic supernova explosions that ejected all the elements these stellar "nuclear factories" had synthesized. If our bones contain calcium, our computers silicon, and our power plants uranium, thank these stars and their massive descendants. Nobody knows how such large objects formed, or even what properties they possessed. Of all the mysteries facing astrophysicists, the lives of Population III stars may be the hardest to solve because none of their kind survives.

THE FIRST STARS in the universe were massive ones that formed about 180 million years after the Big Bang. This computer simulation shows a central density concentration that will grow into one of these heavyweights. Matthew Turk and Tom Abel (KIPAC, Stanford)/Greg Bryan (Columbia)

5 How do massive binary stars form?

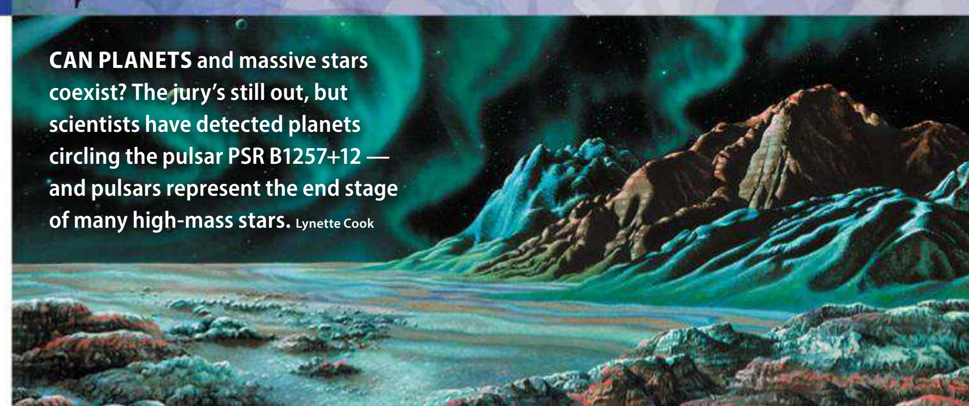
Massive stars often turn up in pairs, just like stars with lower masses. If theorists already have a hard time determining how single massive stars formed, the problem becomes more acute with binaries.

Astronomers have developed several scenarios. "Capture" almost certainly plays a role. In a cluster, stars continually move around and occasionally graze each other. When stars meet, a couple can form, although astronomers debate how frequently it occurs.

A second process involves "fission." A star that rotates rapidly bulges at the equator. Crank the rotational speed high enough, and it can break in two. Unfortunately, only close binaries can form by fission, and some massive binaries have wide separations.

The final idea is "fragmentation" — a protostellar cloud breaks into several pieces that remain near one another. Or, a protostar might be surrounded by a massive accretion disk that coalesces into another star.

Although astronomers have yet to explain how massive binaries form, nature has found a way to create them. Massive pairs populate the galaxy, and some are true behemoths — each component of WR 20a contains approximately 80 times the Sun's mass.



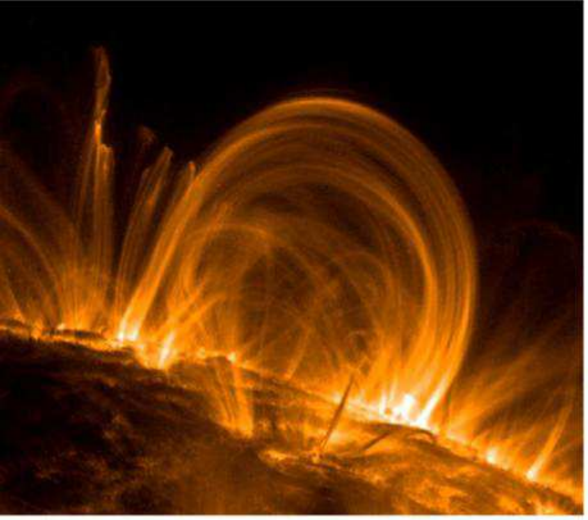
CAN PLANETS and massive stars coexist? The jury's still out, but scientists have detected planets circling the pulsar PSR B1257+12 — and pulsars represent the end stage of many high-mass stars. Lynette Cook

6 Can planets form around massive stars?

No planet has been found orbiting a massive star. But absence of evidence is not evidence of absence — particularly in this instance, because most planet searches have been conducted on Sun-like stars.

Planets form from circumstellar disks of gas and dust. But how long can such disks survive around massive stars? Plus, heavy stars exhaust their nuclear fuel in a few million years. Can planets form that fast?

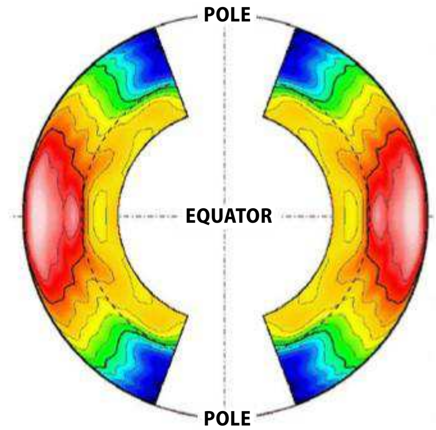
Finally, conditions near a massive star are not friendly. These hot suns emit large amounts of ultraviolet radiation and ionized particles. The stellar winds carry away up to 10 billion times as much material as the solar wind at speeds of thousands of miles per second. So, even if planets do form around massive stars, they don't survive for long.



◄ **MAGNETIC FIELDS** must be an important factor in how massive stars work, but how? As with rotation, detailed observations of stellar magnetic fields exist only for the Sun. Here, loops of hot gas in the Sun's corona follow magnetic field lines. TRACE

► **ALL STARS ROTATE,** but how do their interiors spin? Solar physicists have started probing the Sun's insides with helioseismology (in this illustration, red indicates fast rotation and blue, slow), but no one knows the role of rotation in massive stars.

Michael Thompson (University of Sheffield)



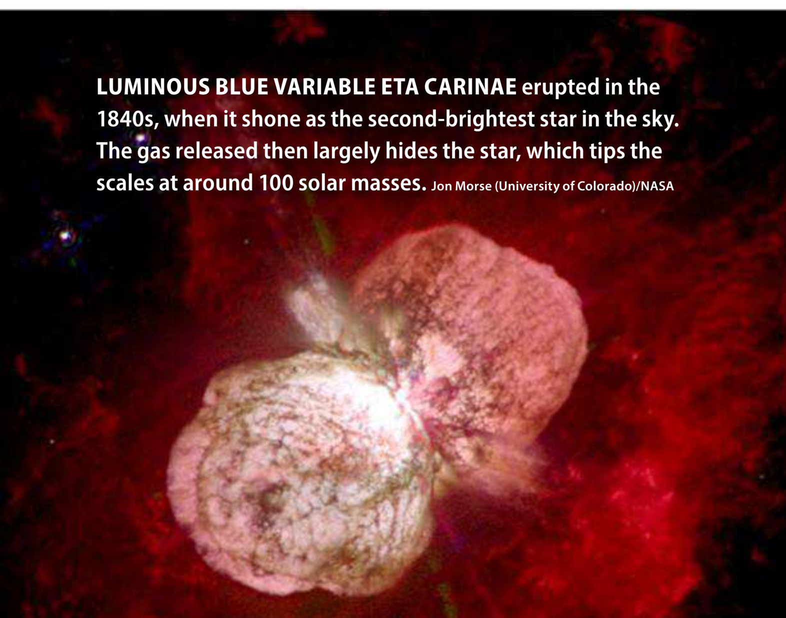
7 What role do rotation and magnetic fields play in massive stars?

Astronomers didn't develop the current stellar models in a single day. These complex models already include a large number of parameters, but scientists have only begun to include two crucial factors: rotation and magnetic fields.

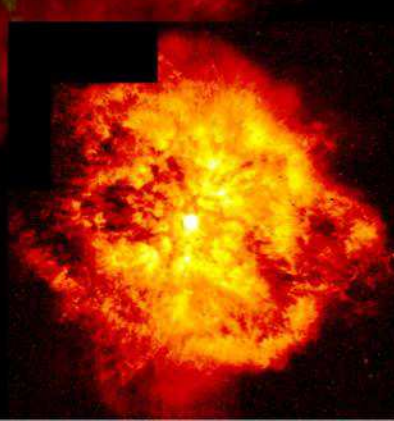
Astronomers see rotation everywhere in the universe. Planets and stars spin, galaxies rotate, and even galaxy clusters conduct their own celestial ballets. Researchers haven't been lazy by neglecting this factor in their stellar models; it's just that rotation creates theoretical and practical problems.

Although advanced computing power is starting to overcome the numerical obstacles, other problems still will exist. For example, how do the interiors of massive stars rotate? Current research in astroseismology only begins to answer this question. The first measurement of the internal rotation of a star other than the Sun was made in 2003, and that was for a lower-mass object. Moreover, although astronomers agree rotation is a vital parameter, no one knows exactly how it influences the birth and evolution of massive stars.

Magnetic fields fall in the same category. They seem to be ubiquitous, showing up on Earth, Jupiter, the Sun, pulsars, and even in the interstellar medium. They likely exist in massive stars (and astronomers even have detected a few cases). As with rotation, however, including this parameter in stellar models is a tricky business, and the first attempts have only recently been made. Will adding rotation and magnetic fields alter our ideas about massive stars?



LUMINOUS BLUE VARIABLE ETA CARINAE erupted in the 1840s, when it shone as the second-brightest star in the sky. The gas released then largely hides the star, which tips the scales at around 100 solar masses. Jon Morse (University of Colorado)/NASA



GALELIKE WINDS blow at more than 100,000 mph from the surface of the massive Wolf-Rayet star WR 124, located 15,000 light-years from Earth. Yves Grosdidier and Anthony Moffat (University of Montreal)/Gilles Joncas (Laval University)/Agnes Acker (Strasbourg University)/NASA

8 How do single massive stars evolve?

The lives of massive stars, although short, fuel intense debate. In broad outline, astronomers use the so-called Conti scenario to describe these objects' evolution. A massive star spends its adult life as an O-type star, emitting a fast and fairly dense stellar wind.

When the nuclear fuel starts to dwindle, the star evolves into either a red supergiant or a luminous blue variable (LBV) depending on its initial mass. During this stage, the star's stellar wind increases in density and slows dramatically — to only a few miles per second compared with thousands of miles per second for the adult star. LBVs even experience gigantic eruptions.

Next, the star becomes a Wolf-Rayet star — the mass loss goes down, but the wind picks up. Throughout the star's life, the wind ejects matter and effectively peels the star. Layers with heavy elements gradually come to the surface. A Wolf-Rayet star becomes enriched first in nitrogen (a WN type), then in carbon (a WC type).

The Conti scenario may seem clear, but many details remain vague. The most contentious area concerns the LBV phase: What starts and stops LBV eruptions? Does the star's metal content play a role at the eruption's start? The most famous LBVs — Eta Carinae and HD 5980 — are binary systems; is this a necessity? What is the lowest stellar mass that can create such an event? Can we see a signature of this phase once the star evolves into a Wolf-Rayet?

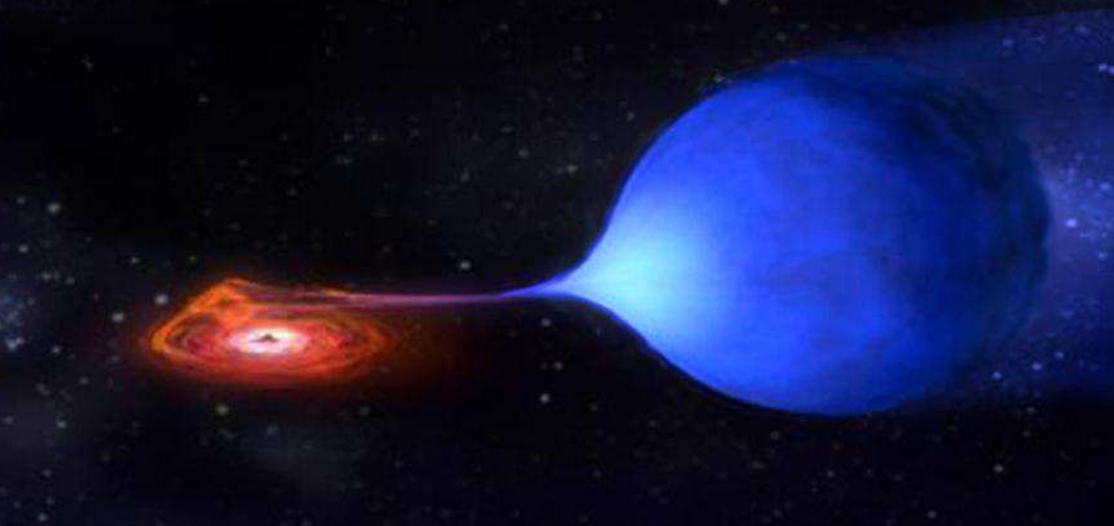
9 How do massive binaries evolve?

Massive binaries evolve in even more complex ways than single objects because the components interact throughout their lives. A companion's presence affects many stellar properties. For example, a massive companion can tidally deform a star so it's not spherical anymore. The neighbor's presence also changes each star's rotation. In a binary system, the stars' rotation periods often equal their orbital periods, so each star shows the same face to its companion throughout the orbit.

Even more complex phenomena take place. In massive binaries, the dual stellar winds collide, generating intense X-ray emission and changes in the system's optical spectrum. Astronomers are just beginning to study these effects. The space mates likely also exchange matter, with the cannibal partner sucking up its companion's wind or perhaps even part of its surface. What would happen if the more massive and evolved star suddenly became the less massive?

Even if nothing much happens to the system during the stars' lives, what if one of the partners suddenly dies? Can the system survive a supernova explosion? And, if so, how would a binary system composed of a normal massive star and either a neutron star or black hole evolve? Studies show that a compact object can spiral toward its companion and might even venture inside the other star. How would that situation change the other star's evolution?

Astronomers have found binary systems comprising two pulsars, so we know massive binaries can survive. But there's still a long way to go before we understand how systems reach such an end.



MATTER FLOWS from a massive blue star to a neutron star — the collapsed remnant of another heavy star. Material transfer in massive binaries affects the two stars' evolutions in ways still not understood. NASA illustration

10 How do massive stars die?

If Sun-like stars die rather quietly, massive stars end in cataclysm — a supernova explosion announces the death to the entire galaxy and beyond. Yet, forensic astronomers have questions about this process.

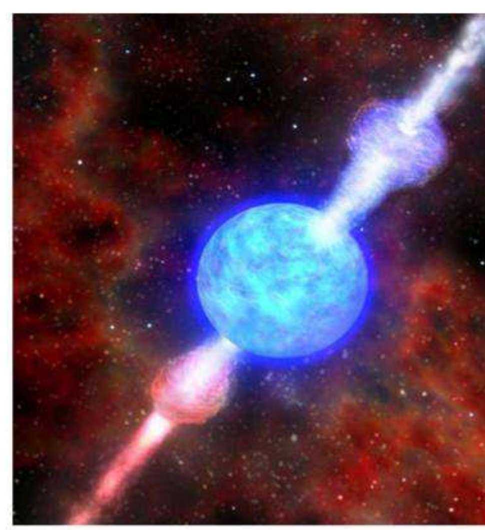
A massive star explodes after it exhausts the nuclear fuel in its core and no longer generates energy to support the weight of the star's outer layers. The core collapses and generates a shock wave that should blow apart the star's outer layers. Despite years of theorists' efforts, however, computer simulations still can't reliably convert the collapse into an explosion.

Gamma-ray bursts — the most powerful cosmic explosions — raise another question. Astronomers have shown that some of these bursts are linked to the deaths of massive stars. But no one knows how this happens or what differentiates a star that ends with a gamma-ray burst instead of a supernova.

After the supernova, two things remain: hot gas in the form of an expanding supernova remnant, and a compact object. Is the mass of the pre-supernova stellar core the only factor that determines whether the compact object is a black hole or a neutron star? And is it possible the explosion can totally rip apart the core so that no corpse is left behind? ■

NASA/ESA/The Hubble Heritage Team (STScI/AURA)

◄ **A CHAOTIC MESS** of gas and dust expands in supernova remnant N63A in the Large Magellanic Cloud. Most massive stars die in supernova explosions, although the exact mechanism remains murky.



▲ **A DYING MASSIVE STAR** ejects a powerful burst of gamma rays. Astronomers are trying to figure out what differentiates a gamma-ray burst from its more common counterpart: a supernova explosion. NRAO/AUI/Dana Berry (SkyWorks Digital)

What makes stars

Sound waves in collapsing stars may produce supernova explosions. **By Francis Reddy**

No event in nature surpasses a supernova's raw power. The flood of neutrinos accompanying the explosion of a single massive star releases as much instantaneous power as the rest of the visible universe combined. Such blasts stir interstellar gas and dust, helping new stars form. More importantly, supernovae disperse most of the elements heavier than carbon — such as the iron in our blood — and create neutron stars and black holes.

After decades of debate, astrophysicists still aren't sure how a star turns into nature's grandest firecracker. Even the most complex supercomputer simulations haven't solved the problem, but they have served up some surprises. For instance, sound waves in a collapsing star's heart could help kick-start a stalled explosion, while a white dwarf's detonation may arise when the star's gravity turns a thermonuclear conflagration back on itself.

The big picture

By the 1930s, it was clear that some stellar flare-ups, called novae, were in a class by themselves. In 1933, astronomers Walter Baade at Mount Wilson Observatory and Caltech's Fritz Zwicky began referring to the most luminous events as supernovae. They suggested the explosions occurred when a massive star collapsed and created a neutron star. Bear in mind this was more than three decades before pulsed radio signals from the Crab Nebula supernova remnant proved that neutron stars exist at all.

In 1941, Mount Wilson's Rudolph Minkowski proposed supernovae come in two flavors based on the absence (type I) or presence (type II) of strong hydrogen spectral lines at peak brightness. Since then, the observational picture has become more complex as astronomers recognized new subclasses of both types. Nevertheless, astronomers generally agree that two scenarios likely account for most supernovae.

Type Ia supernovae occur in all galaxies among an older stellar population. All others — type II, plus types Ib and Ic associated with gamma-ray bursts — prefer galaxies sparkling with star-forming regions, which contain many hot, young, massive stars. Such stars explode when they use up their nuclear fuel and collapse.

Core collapse

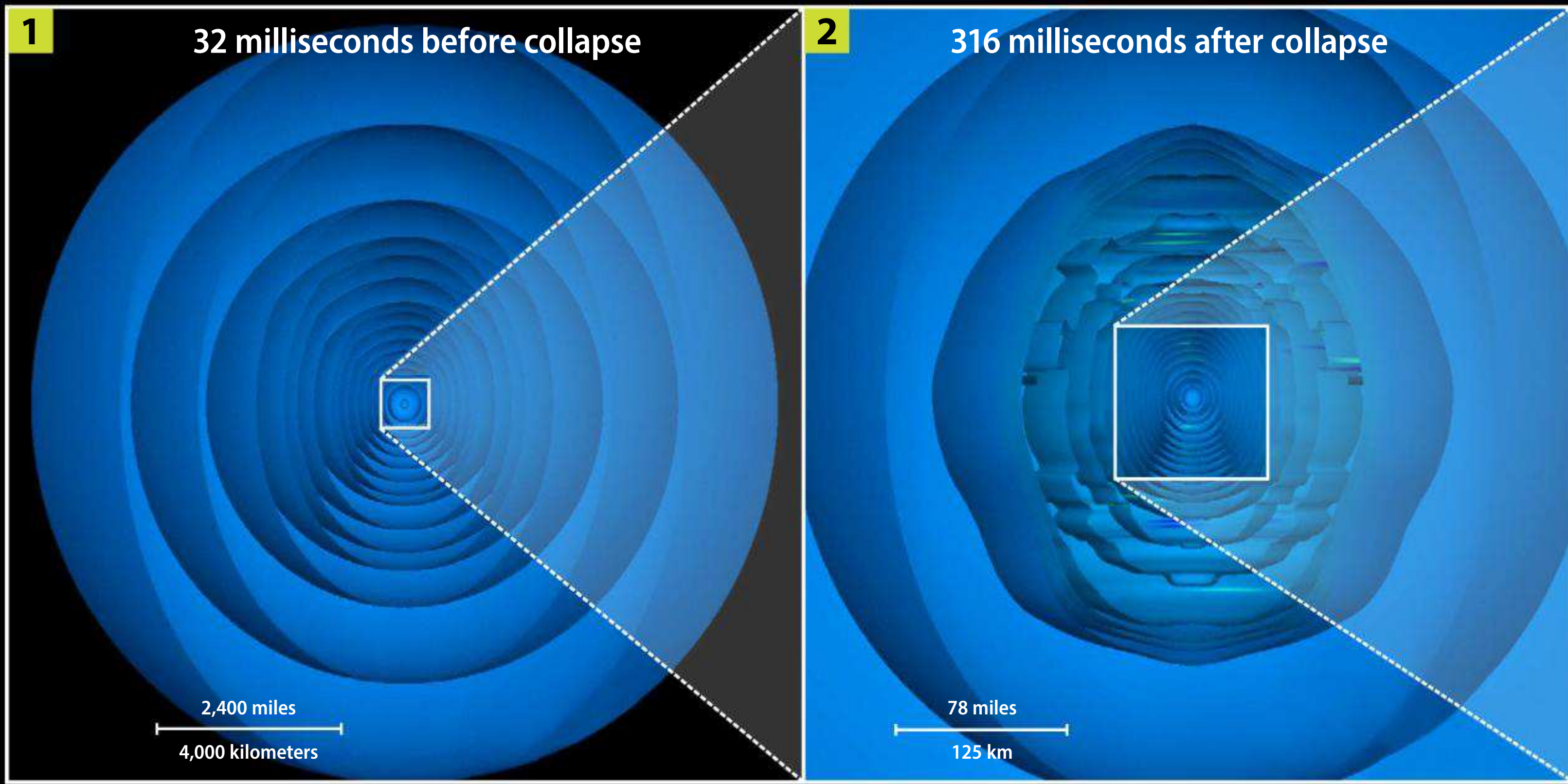
Stars weighing more than about eight times the Sun's mass burn through their hydrogen fuel quickly, but as a massive star runs low on one fuel, it taps into another. Its core contracts, growing hotter and denser until the previous nuclear reaction's "ash" — helium, at first — undergoes fusion itself. As each fuel runs out, the star's core responds in the same way, running through a succession of fuels: hydrogen, helium, carbon, neon, oxygen, and silicon.

But this is a game of diminishing returns. Each new fuel releases less energy, so the star burns through it even faster. Moreover,

A SUPERNOVA DETONATES in a spiral galaxy in this illustration. These titanic explosions create and distribute most of the elements, stir up galactic gas and dust, and give astronomers beacons that shine across billions of light-years. Adolf Schaller for *Astronomy*

explode?

SINGING SUPERNOVA



A STAR STANDS on the brink of collapse in Adam Burrows' computer simulation. After a few weeks of fusing silicon, the star has created an iron core slightly larger than Earth but more massive than the Sun. This simulation shows the star's iron core as shells of equal density.

THE CORE COLLAPSES, then rebounds as it compresses to densities higher than an atom's nucleus. This launches an outward-moving shock wave that's stalled by infalling gas. Even after a third of a second, neutrino heating fails to get the shock moving again.

once carbon ignites and the core's temperature approaches a billion degrees, neutrinos form and escape in greater numbers. Formed in many nuclear reactions, neutrinos don't interact easily with other matter and quickly exit the star. To compensate for the energy loss, the core burns its nuclear fuel even faster.

While such a star may take 10 million years or more to run through its "first course" of hydrogen fuel, it consumes its helium in 2 million years and its carbon in just 2,000 years. The last phase, when the core fuses silicon, lasts less than three weeks.

As silicon fusion ends, an Earth-sized iron-nickel core about 1.5 times the Sun's mass resides in the star's center. But iron-group elements have nature's most tightly bound nuclei, so the core can't resort to its old trick — fusing iron actually consumes energy. Neutrinos stream from the core. The core's central density is so high that it forces electrons — the star's main pressure source — inside nuclei. The electrons transform some protons into neutrons. Both processes — streaming neutrinos and squeezing protons and electrons together — remove pressure that supports the star. With pressure losses mounting and no new energy source to tap, the star's battle with gravity is over.

The iron core collapses at about ¼ light-speed. In half a second or less, it transforms from an Earth-sized stellar core to a hot, dense proto-neutron star just 19 miles (30 kilometers) across. When the central density reaches about twice that of an atomic nucleus, the core stiffens and rebounds thanks to a repulsive component in the strong nuclear force. This core "bounce" acts like a spherical piston that drives into the star's infalling gas.

"It was hoped this piston would generate a shock that would be the supernova in its infancy," says Adam Burrows, who models supernovae at Princeton University. "That was sweet, and it made some sort of sense, but it doesn't work." As the shock moves out, it radiates lots of neutrinos, which saps its energy. "In addition, it's trying to overcome all that stuff that's still falling in, and it fails."

The shock stalls a few milliseconds after it starts and simply sits there, heating the infalling gas. If nothing changed during the next second, the nascent neutron star would accrete a few tenths of a solar mass of matter and then become crushed into a black hole. No supernova.

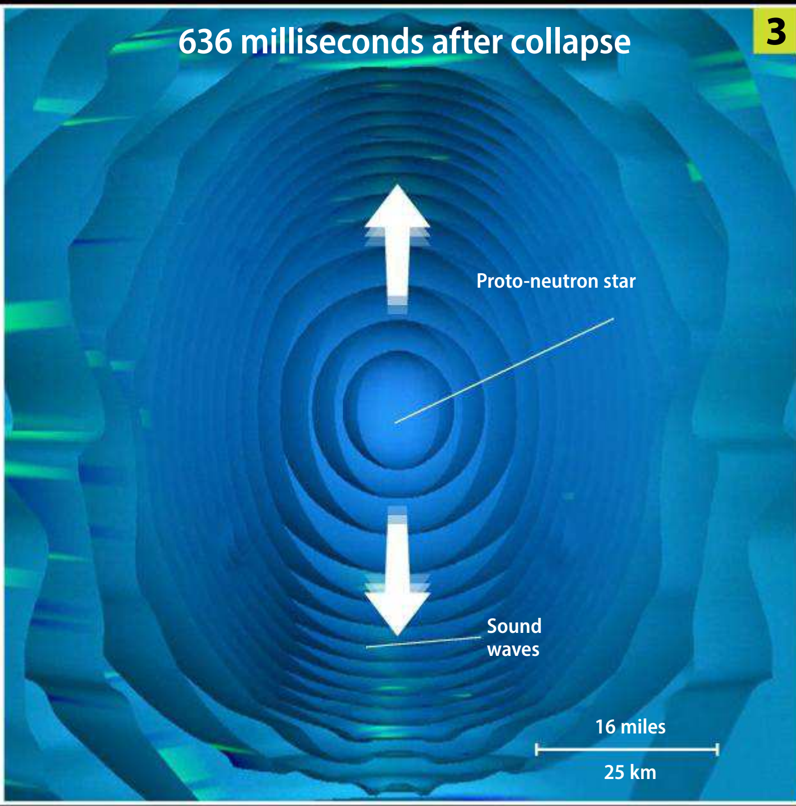
The pause that refreshes

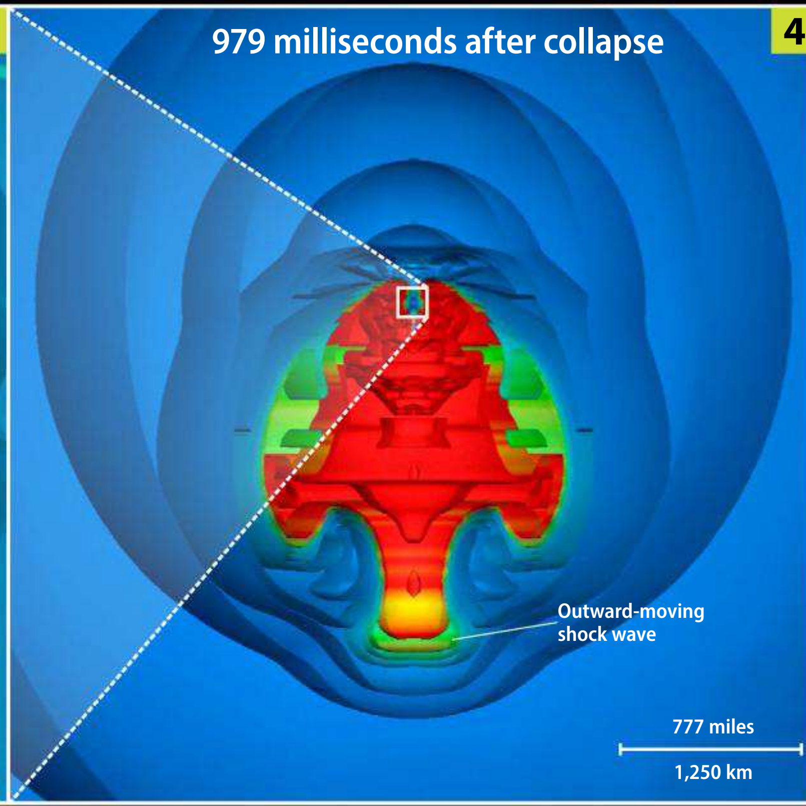
The central mystery of core-collapse supernovae is how this situation ever can turn itself around. "What people had suggested was, you wait a while, and neutrinos eventually heat up the material behind the shock enough that you relaunch an explosion," says Burrows. He calls this happening "the pause that refreshes."

The large number of neutrinos departing the core makes up for the low odds that a single neutrino will interact with the star's matter as it leaves. The action pauses for just a few hundred milliseconds, but "that's a long time in this game because things happen fast," says Burrows.

In early computer simulations, which assumed the collapsing star was spherically

Francis Reddy *is a senior science writer at NASA's Goddard Space Flight Center in Greenbelt, Maryland.*





Adam Burrows (University of Arizona)

TURBULENT GAS falling onto the proto-neutron star causes it to oscillate about 300 times a second, a frequency that corresponds to the musical note F above middle C. Sound waves expand into the gas and force the shock to wobble.

SOUND WAVES deposit nearly all their energy into the gas. This forces infalling streams to one side of the neutron star and clears a path on the other. Acoustic energy revitalizes the shock wave, which now moves outward. A supernova is born.

symmetric, even this process didn't work. Such 1-D calculations gave way to more demanding 2-D models, which assume symmetry around the star's spin axis. They revealed fluid instabilities and turbulence that promised to aid the stalled shock.

"For a while, that was the prevailing view," Burrows explains. "But with the best neutrino physics, it doesn't look like this works in 2-D." Will new effects in 3-D simulations help neutrinos deposit energy more efficiently? "That's still the hope," he says.

In 2005, Burrows and his colleagues discovered a potentially important alternative energy source in collapsing stars: sound waves. In the team's 2-D model, the stalled shock starts to wobble top-to-bottom along the star's spin axis. "People hadn't seen this

ARE TYPE IA SUPERNOVAE REALLY ALL ALIKE?

Similarities in the spectra and light outputs of type Ia supernovae outweigh their differences, a fact that makes these explosions our most important beacons in the far universe. Evidence from type Ia supernovae fuels astronomers' ideas about dark energy and the expanding universe's acceleration.

"The peak luminosities and kinetic energies of type Ia supernovae span a range of roughly a factor of 10, so there may well be several different mechanisms at work," says the University of Chicago's Don Lamb.

SN 2003fg is a case in point. Andrew Howell, then at the University of Toronto, led an international team that studied the event, which occurred in a galaxy 4 billion light-years away.

In September 2006, the researchers published their conclusion that the explosion's progenitor star was more massive than theory allows a solitary white dwarf to be.

Either SN 2003fg was spinning so fast its rotation supported a mass above the Chandrasekhar limit or, the group suggests, a pair of orbiting white dwarfs merged. Team member Richard Ellis of Caltech says the find illustrates how much more astronomers need to learn about supernovae to extend current studies.

White-dwarf-merger scenarios are "particularly challenging" for large-scale numerical simulations, says Lamb. No detailed simulations have been completed so far. — *F.R.*

TYPE IA SUPERNOVA 1994D outshines its spiral galaxy, NGC 4526. NASA/ESA/Hubble Key Project/High-Z Supernova Search Team before because they had waited for maybe 200 milliseconds after bounce," Burrows explains. "And the shock just went up, it stalled, and it went back down." Nothing more happened, so supernova modelers ended their expensive computer runs.

As matter streams onto the proto-neutron star, turbulence around the core sets it oscillating at around 300 hertz — musically, about F above middle C. Acoustic waves radiate back into the collapsing envelope. While the energy from neutrinos is far greater, only a fraction of it becomes deposited in the stalled shock, whereas matter absorbs sound almost completely. There's enough acoustic power to blow the star apart half a second after core bounce in Burrows' simulation.

How important this process is remains an open question. It's the accreting material that keeps a lid on the explosion, preventing neutrinos from moving the shock out. "If the neutrino mechanism worked, we would have seen it in our model," Burrows says.

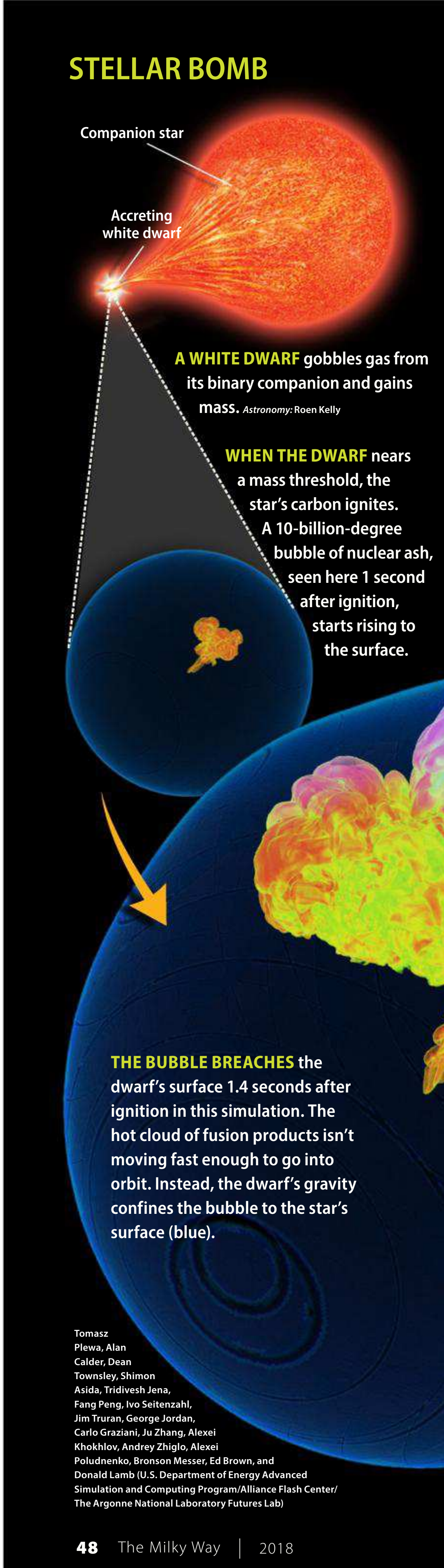
The sound waves push streams of accreting matter to one side of the core while energizing the shock on the opposite side. So, by creating a path of least resistance, sound may help neutrinos revitalize a stalled shock. "It's unproven," he says, "but very interesting." Moreover, the oscillating core could be a prominent source of gravitational radiation.

Shattered dwarfs

Large-scale computer simulations are also providing new insights into how white dwarfs, the end state of low-mass stars, destroy themselves as type Ia supernovae. Brighter and more uniform than core-collapse explosions, type Ia events are important probes of the distant universe. The discoveries of dark energy and cosmic acceleration add urgency to deciphering how they work.

A star similar to the Sun ends its days as a white dwarf, with the star's carbon-oxygen-rich core crushed to Earth's size. Most shine for billions of years, gradually cooling until they fade into dark stellar cinders. Electron

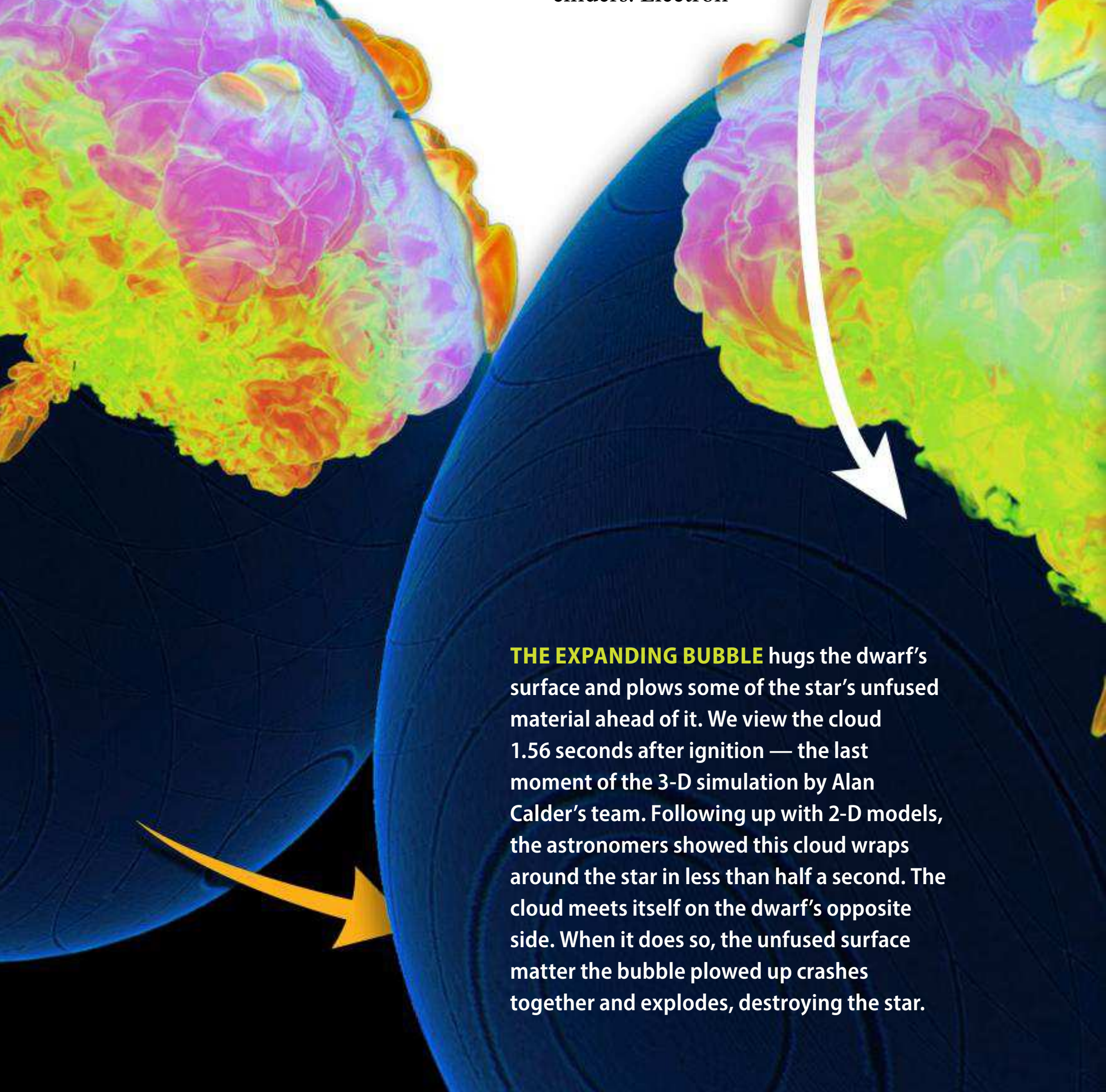
STELLAR BOMB



A WHITE DWARF gobbles gas from its binary companion and gains mass. *Astronomy:* Roen Kelly

WHEN THE DWARF nears a mass threshold, the star's carbon ignites. A 10-billion-degree bubble of nuclear ash, seen here 1 second after ignition, starts rising to the surface.

THE BUBBLE BREACHES the dwarf's surface 1.4 seconds after ignition in this simulation. The hot cloud of fusion products isn't moving fast enough to go into orbit. Instead, the dwarf's gravity confines the bubble to the star's surface (blue).



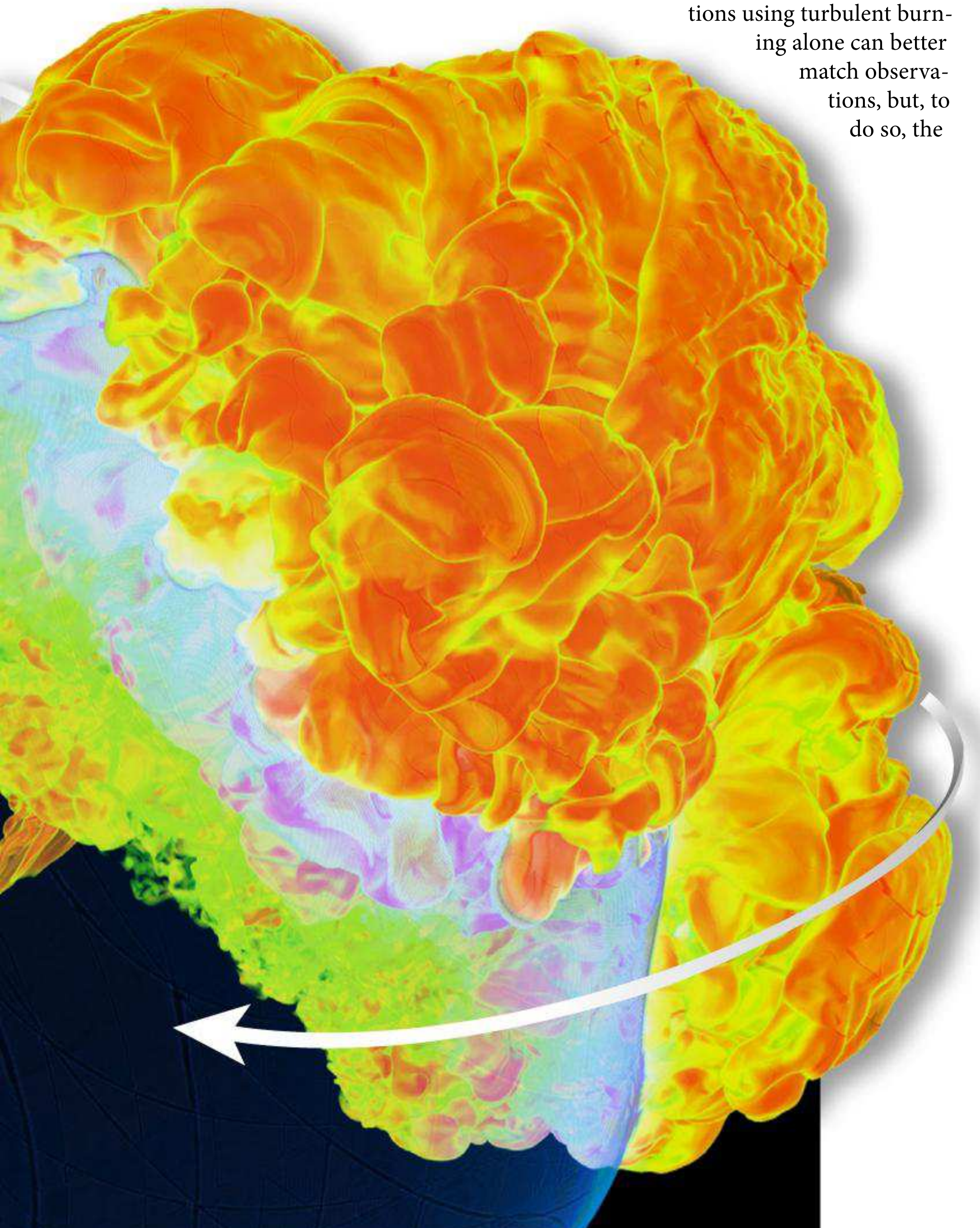
THE EXPANDING BUBBLE hugs the dwarf's surface and plows some of the star's unfused material ahead of it. We view the cloud 1.56 seconds after ignition — the last moment of the 3-D simulation by Alan Calder's team. Following up with 2-D models, the astronomers showed this cloud wraps around the star in less than half a second. The cloud meets itself on the dwarf's opposite side. When it does so, the unfused surface matter the bubble plowed up crashes together and explodes, destroying the star.

Tomasz Plewa, Alan Calder, Dean Townsley, Shimon Asida, Tridivesh Jena, Fang Peng, Ivo Seitenzahl, Jim Truran, George Jordan, Carlo Graziani, Ju Zhang, Alexei Khokhlov, Andrey Zhiglo, Alexei Poludnenko, Bronson Messer, Ed Brown, and Donald Lamb (U.S. Department of Energy Advanced Simulation and Computing Program/Alliance Flash Center/The Argonne National Laboratory Futures Lab) pressure prevents further collapse, but it works only if the dwarf weighs less than 1.44 Suns — the so-called Chandrasekhar limit. Exceed that, and collapse resumes until the dwarf becomes a neutron star.

In 1960, University of Cambridge astronomer Fred Hoyle and Caltech's William Fowler realized a white dwarf near this limit could be a giant thermonuclear bomb. Place a white dwarf in close proximity to a normal star, and the dwarf can gain mass until it nears the 1.44-Sun threshold and explodes. The dwarf gobbles up hydrogen gas from its partner at a probable rate of about 1/30 of an Earth mass per year. If it's much slower than this number, the dwarf's stellar wind prevents the gas from reaching the surface; if it's any faster, the gas will flash-fuse rather than accumulate.

As a white dwarf tips the scale toward 1.44 Suns, its carbon ignites somewhere inside. Before 2004, no one could figure out how to make a carbon-oxygen star detonate, so theorists first invoked turbulent thermonuclear fusion. These simulations failed to match the energy and element mix of type Ia blasts. Models that followed a period of turbulent burning with a detonation better matched reality, but theorists simply decided where and when the explosion would occur and inserted it into the simulation. "I sometimes refer to this as the 'Here, a miracle occurs' mechanism," says the University of Chicago's Don Lamb.

For this reason, Wolfgang Hillebrandt and his group at the Max Planck Institute for Astrophysics in Munich, Germany, tried a different direction. They found that simulations using turbulent burning alone can better match observations, but, to do so, the dwarf's thermonuclear fires must ignite in about 100 different points at once. That's very unlikely. Says Lamb: "We worry one miracle has been replaced by another."



In 2004, a team led by Alan Calder, then at the University of Chicago, including Lamb, stumbled onto a way to blow up a white dwarf. Thanks to the U.S. Department of Energy's computational resources, the team had the hardware to simulate an entire white-dwarf star. After ignition, a narrow front of nuclear flame expanded through the star, leaving behind a 10-billion-degree ash bubble. When this bubble broke through the dwarf's crust, less than 10 percent of the star's mass had been fused — too little to disrupt the dwarf or produce a strong explosion. "It looked like it might be a dud," Lamb recalls.

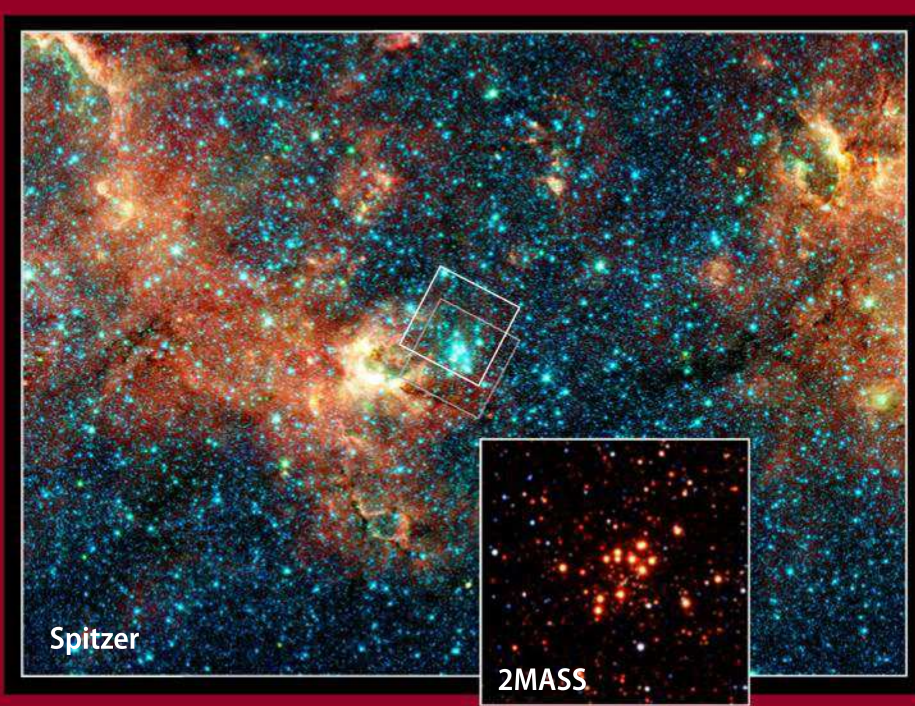
Then, team member Tomasz Plewa performed additional 2-D simulations to see what happens after the bubble breaches the star's surface. The nuclear ash erupts, moving at around 6.7 million mph (10.8 million km/h), just shy of orbital speed. The hot cloud hugs the dwarf's billion-degree surface and rapidly spreads. As it does so, it plows up cooler, unfused surface material. The superheated ash-cloud wraps around the white dwarf and meets itself at the point opposite its breakout. The collision compresses all of the unfused surface material, which explodes and rips the star apart.

The model, called "gravitationally confined detonation," is the most complete description of a type Ia supernova to date — and the only one in which a full-scale detonation naturally occurs. "It's a very promising model for most type Ia supernovae," Lamb says. "It was a serendipitous discovery. And it is a perfect example of how large-scale numerical simulations can lead to discoveries of complex, non-linear phenomena that are very difficult to imagine ahead of time."

More than 85 years after astronomers connected supernovae with stellar deaths, the universe's most powerful explosions still tax astrophysicists. But even the most complete simulations don't yet capture the complex environment of an exploding star. Modelers are beginning to probe how neutrino emission, magnetic fields, and rotation affect the picture. Observers watch and catalog new events, using them both as cosmic yardsticks and to find holes in current understanding. And new facilities designed to capture neutrinos and gravitational waves — signals that directly escape an exploding star's core — one day soon may give us a glimpse of a supernova's chaotic heart.

How the Milky Way got a brand new look

By observing in infrared wavelengths, the GLIMPSE survey revealed the Milky Way's spiral structure. **By Robert Benjamin**



A NEVER-BEFORE-SEEN star cluster resides 18,900 light-years away. Spitzer's Infrared Array Camera took the wide-field view (which shows evolved stars as blue), and the 2MASS survey captured the inset. Both images show 14 supergiant stars — each 20 times the Sun's mass — about to explode as supernovae. NASA/JPL-Caltech/D. Figer (STScI/Rochester Institute of Technology)/E. Churchwell, B. Babler, M. Meade, and B. Whitney (University of Wisconsin)/R. Indebetouw (University of Virginia), 2MASS

At the beginning of the 20th century, astronomers thought the Milky Way encompassed the entire universe. During the past century, as astronomical understanding has raced ahead to decipher the evolution of stars, other galaxies, and the universe itself, the Milky Way has given up its secrets only grudgingly.

Because the galaxy surrounds us, understanding its structure entails observing a large fraction of the sky. In the past, this required decades of data collection and analysis. Now, thanks to advances in detector technology, analysis software, and computing power, it has become feasible to complete such surveys in a few years.

On August 25, 2003, NASA launched the Spitzer Space Telescope on a mission to study the universe in infrared wavelengths. Three years prior to Spitzer's launch, NASA chose six large observing programs — dubbed "Legacy" projects — after a worldwide call for proposals. One of these, the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE), surveys the Milky Way in four infrared spectral ranges.

GLIMPSE-ing the sky

The area covered by GLIMPSE contains most of the galaxy's star-forming regions and about 70 percent

Continued on page 59

The Milky Way inside and out

A century ago, astronomers thought our galaxy spanned the entire universe. Their painstaking work has filled in many missing details. **By Richard Talcott**

Optical telescopes tell us a lot about the Milky Way Galaxy. Despite hundreds of years of telescopic observations, however, astronomers had few clues about the galaxy's structure until the 20th century. In 1900, most people thought our galaxy extended just a few thousand light-years and that the Sun lay at the galaxy's center. Many even believed the Milky Way formed the entire universe.

American astronomer Harlow Shapley (1885–1972) took the first major step in changing this perspective. He determined the distances and directions to nearly 100 globular star clusters. When Shapley mapped the clusters' distribution, he found that they formed a vast sphere centered not on the Sun but on a point more than 20,000 light-years away in Sagittarius. He boldly — and correctly — asserted that the globulars orbited the galaxy's center.

The next leap belongs to American astronomer Edwin Hubble (1889–1953). In the mid-1920s, he discovered Cepheid variable stars in a few bright nebulae scattered across the sky. Hubble used these stars to measure distances to the nebulae, and he found that they were entire galaxies far beyond the Milky Way's confines. We now know the Milky Way is just one of perhaps 1 trillion galaxies in the cosmos.

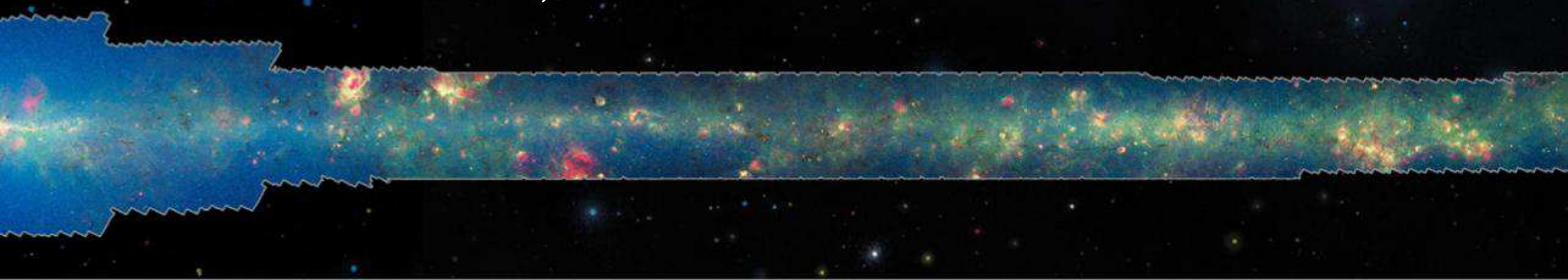
Once observations revealed some galaxies had a spiral shape, astronomers quickly concluded ours is a spiral. The flattened disk that contains the spiral arms appears in our sky as the Milky Way. But tracing the galaxy's spiral arms proved harder. Gas and dust block much of our view, the proverbial trees concealing the forest.

During the 20th century's latter half, radio telescopes led the way. Because radio waves penetrate dust, they made excellent probes of the galaxy's spiral structure. Radio observations revealed four major spiral arms and a few small spurs.

In just the past few years, the view has changed again. The Spitzer Space Telescope, which views in the dust-penetrating infrared, has shown the Milky Way to be a barred spiral galaxy. It has two major arms — one emanating from each end of the bar — and several smaller spurs.

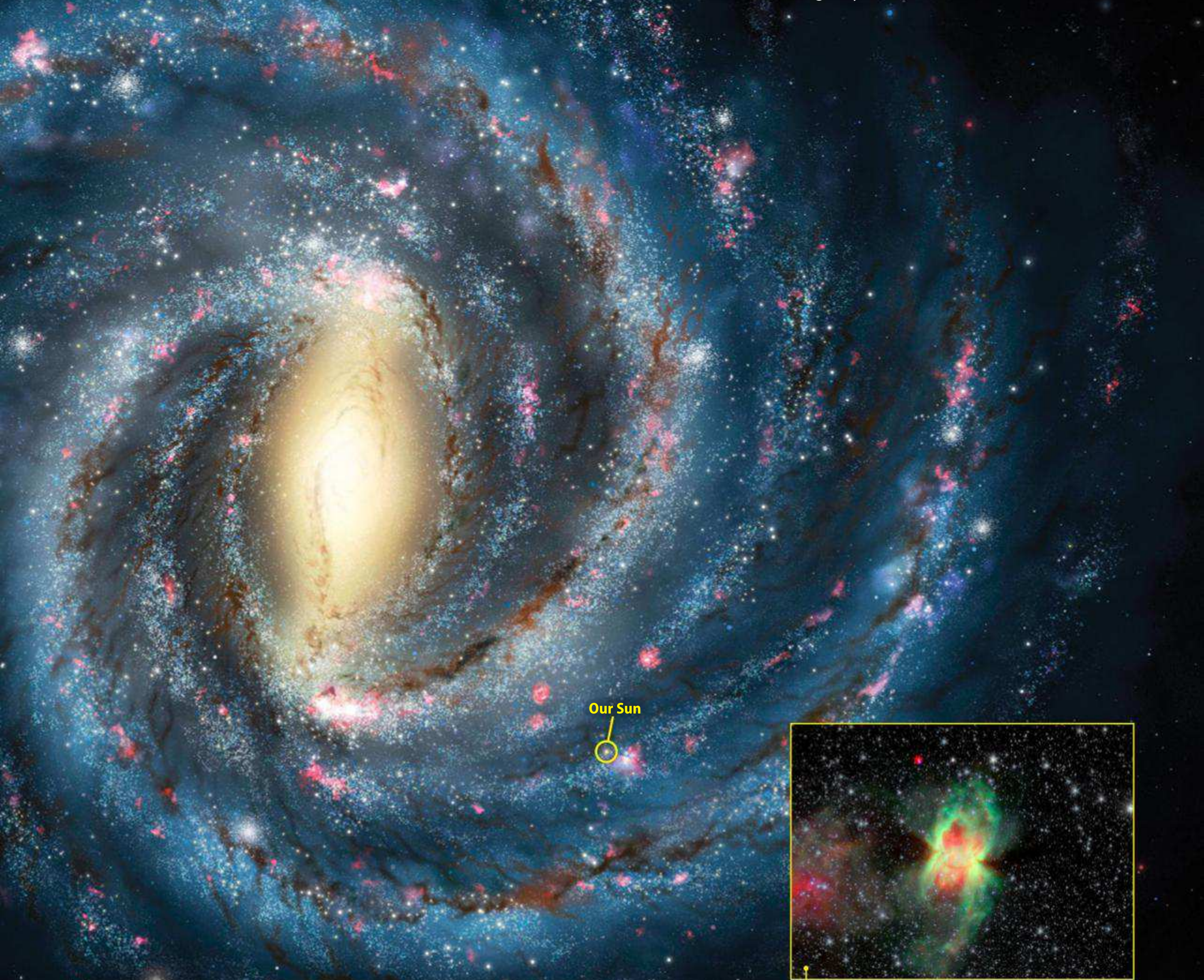
Richard Talcott *is a senior editor of* Astronomy.

Astronomy magazine



A bird's-eye view of the Milky Way

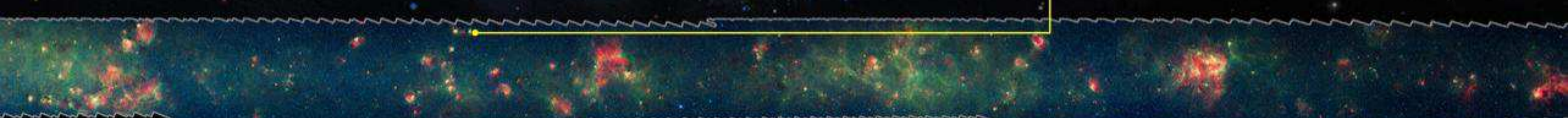
THE MILKY WAY'S CENTRAL BAR stands out in this view from far north of the galaxy's disk. Astronomers spent a good part of the past century understanding the overall structure of our galaxy. Lynette Cook for *Astronomy*



POWERFUL STELLAR WINDS sculpt the Black Widow Nebula in the southern constellation Circinus. The strong outflows from several groups of massive stars forming near the nebula's center create the two opposing bubbles. NASA/JPL-Caltech/University of Wisconsin

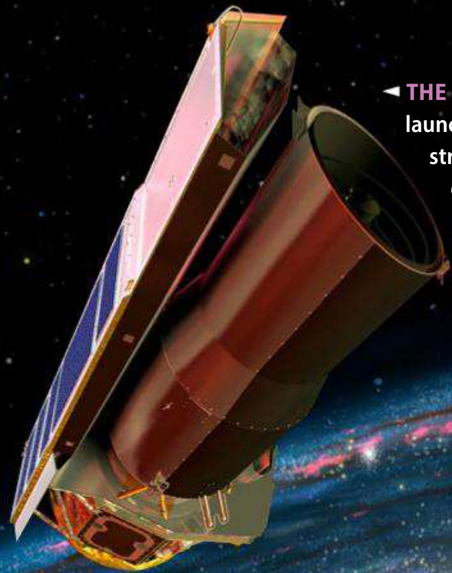
An edge-on view of the Milky Way

THE MILKY WAY'S PLANE glows with heat generated by hot stars embedded within giant clouds of gas and dust. This infrared view from the Spitzer Space Telescope stretches 75° on either side of the galactic center and 1° north and south. (The north-south extent increases to 4° near the galaxy's center.) NASA/JPL-Caltech/University of Wisconsin

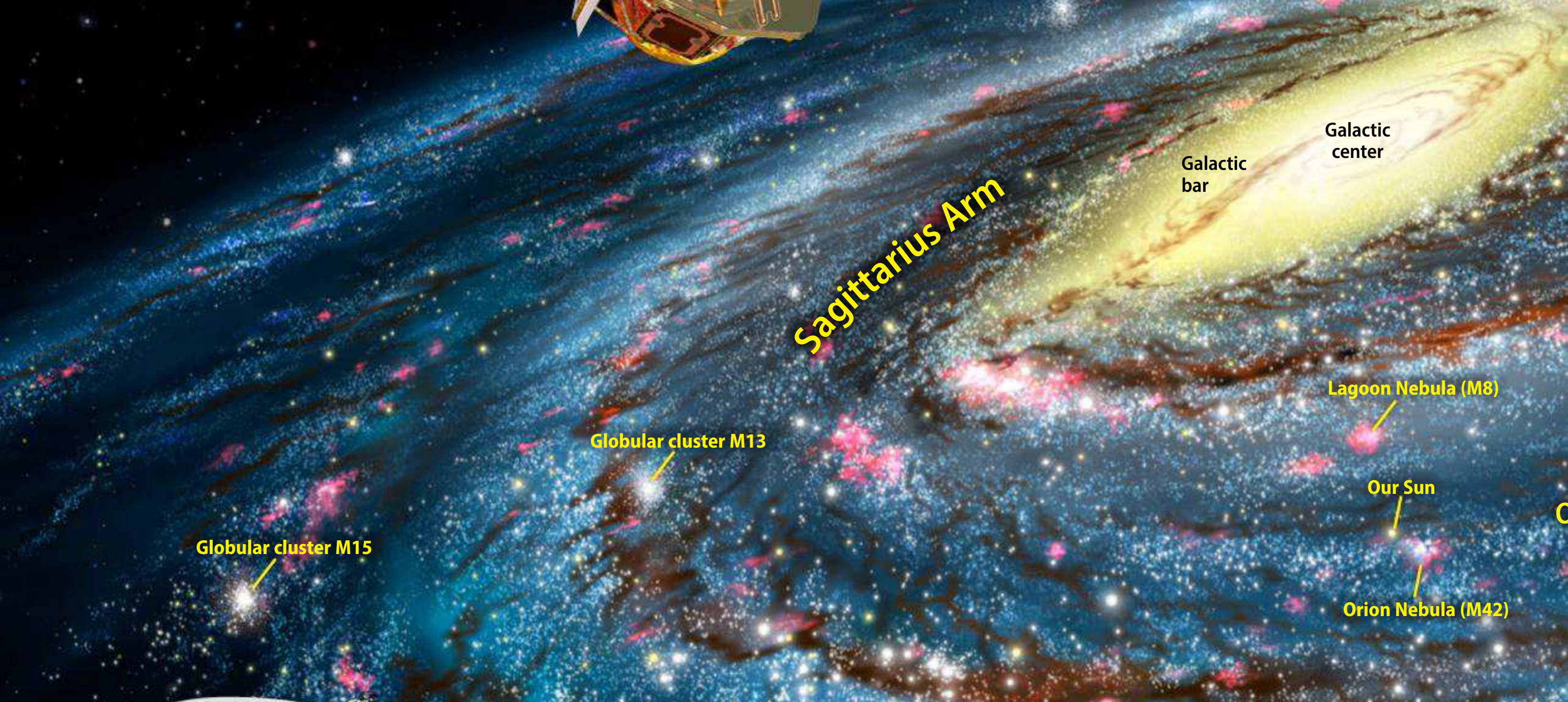


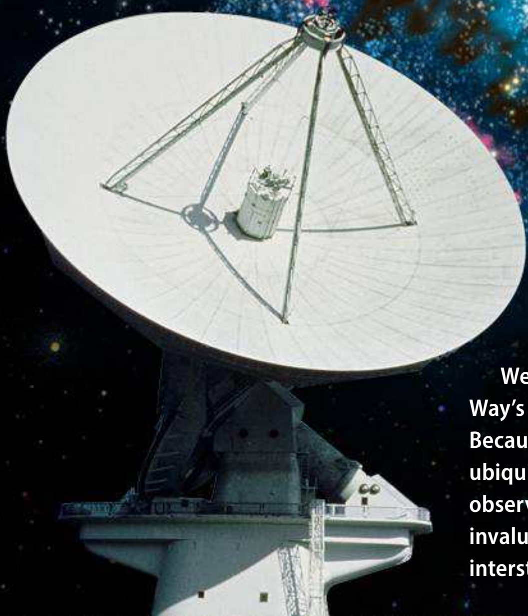
The Milky Way from above

AN OBLIQUE VIEW OF OUR GALAXY puts the Milky Way's spiral structure in perspective. Two major spiral arms wind their way from the bar's end: the Scutum-Centaurus Arm and the Perseus Arm. Two minor arms — the Sagittarius and Norma arms — add to the galaxy's complexity. The Sun lies about 26,000 light-years from the galactic center in a partial arm called the Orion Spur. The sky's brightest nebulae stand out largely because they lie near Earth. Lynette Cook for *Astronomy*

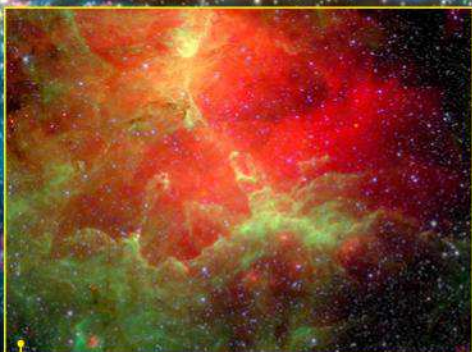


THE INFRARED-SENSITIVE SPITZER SPACE TELESCOPE, launched in 2003, verified the Milky Way's barred spiral structure. Astronomers used Spitzer observations to deduce that the bar extends roughly 28,000 light-years and tilts at a 45° angle to a line between the Sun and the galaxy's center. NASA/JPL-Caltech

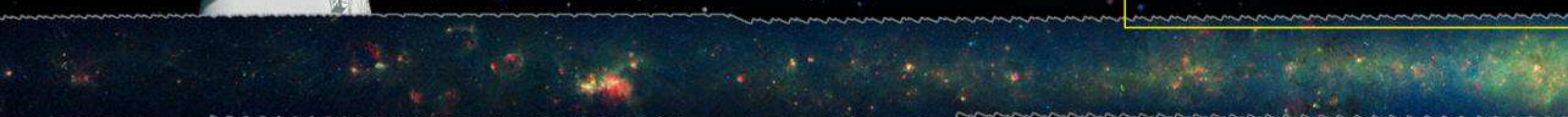


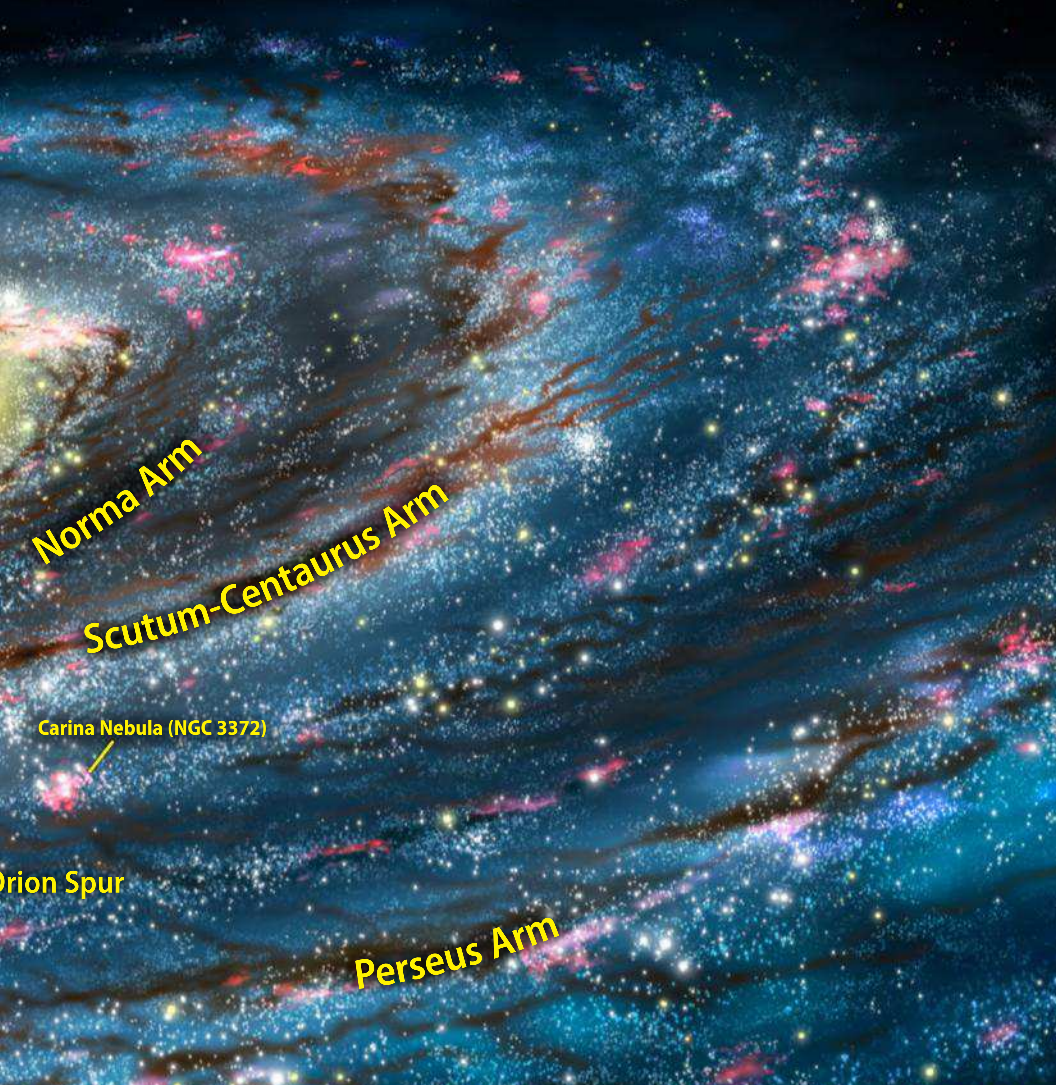


THE 140-FOOT RADIO TELESCOPE at the National Radio Astronomy Observatory in Green Bank, West Virginia, helped map out the Milky Way's spiral structure in the 1960s and later. Because radio waves penetrate the ubiquitous dust in the galaxy's plane, observations at these wavelengths proved invaluable in plotting the locations of interstellar gas clouds. NRAO/AUI



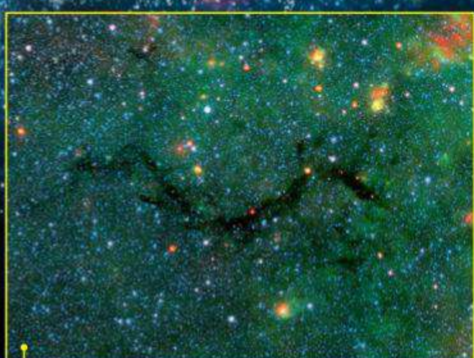
PILLARS OF CREATION highlight the Eagle Nebula (M16) in Serpens. The dark pillars made famous in a Hubble Space Telescope photo glow an eerie light-green color in this infrared image of the star-forming region. NASA/JPL-Caltech/University of Wisconsin





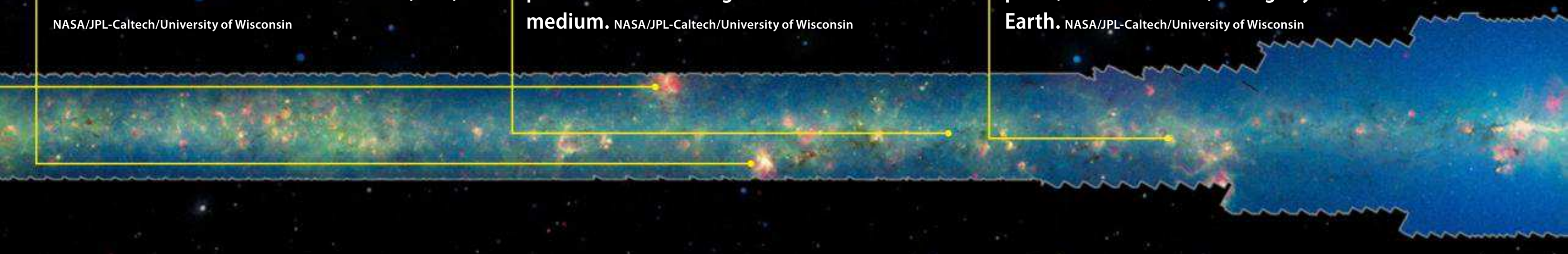
THE COMPTON GAMMA-RAY OBSERVATORY hinted at the presence of the Milky Way's bar during the 1990s. Astronomers used the orbiting observatory to view emission from a radioactive isotope of aluminum, which tracks the locations of massive stars. The results suggested a barred structure in the galaxy's central region. NASA

THE OMEGA NEBULA (M17) in Sagittarius ranks among our galaxy's most prolific star-forming regions. It churns out new stars at an even greater rate than the much closer — and better known — Orion Nebula (M42). NASA/JPL-Caltech/University of Wisconsin



THIS SINUOUS SNAKE slithers along the galactic equator in northern Sagittarius. The snake is a thick, sooty cloud large enough to contain dozens of solar systems in the process of condensing out of the interstellar medium. NASA/JPL-Caltech/University of Wisconsin

THE TRIFID NEBULA (M20) in Sagittarius harbors at least 30 massive embryonic stars and more than 100 smaller protostars. The nebula, which lies just south of the galactic plane, resides about 9,000 light-years from Earth. NASA/JPL-Caltech/University of Wisconsin



The Milky Way at a glance

Our galaxy holds some 200 billion stars — and gas clouds that spawn new ones. **By Richard Talcott**

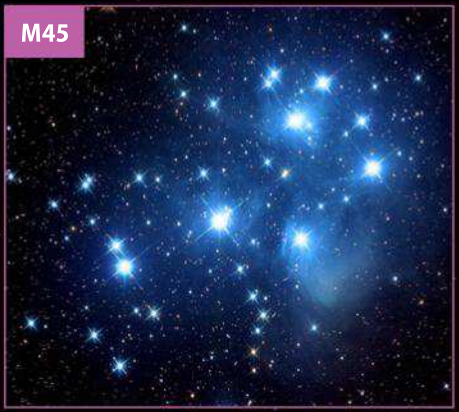
On a clear, dark night, a person with average eyesight can discern roughly 5,000 stars without optical aid. Our distant ancestors knew little else, although they had an advantage in being blessed with dark skies every night. They could see a few star clusters, such as the Pleiades (M45) and Beehive (M44). And they viewed with awe the long, glowing river of whiteness that resembles milk spilled across the heavens — from where we get the name "Milky Way."

The invention of the telescope 400 years ago radically transformed our view of the galaxy. Galileo first saw the Milky Way as a stream of stars too numerous to count. Other observers noted scads of star clusters and amorphous gas clouds throughout the sky, though they were concentrated near the Milky Way.

Today, we know the naked-eye view doesn't adequately represent the Milky Way as a whole. Instead of thousands of stars, the galaxy contains somewhere between 100 billion and 400 billion. And the bright stars we see aren't typical. Most naked-eye stars are more massive and luminous than the Sun, which itself is bigger and brighter than the average star.

The solar neighborhood better represents the overall makeup of the Milky Way's inhabitants. If you take a census of the 100 stars closest to the Sun, only five rank among the sky's 100 brightest stars. And of those, one (Alpha Centauri B) shines intrinsically dimmer than the Sun. Most of the galaxy's stars are dim red dwarfs that produce little light.

Telescopes reveal thousands of star clusters in two main varieties: open and globular. And the glowing gas clouds known as emission nebulae populate some of the space between the stars. Astronomical detective work proved a kinship between open clusters and emission nebulae. The nebulae contract, fragment, and ultimately give birth to star clusters. Over time, these clusters disperse, yielding the solitary suns we see sprinkled across the sky.



THE PLEIADES STAR CLUSTER (M45) in Taurus is the brightest object in Messier's catalog of deep-sky objects. With the naked eye, observers typically spot six or seven stars in the shape of a small dipper. Tad Denton/Adam Block/NOAO/AURA/NSF

OPEN CLUSTER M37 in Auriga lies just 4° from a point located exactly opposite the galaxy's center. The combined light of the cluster's 150 stars glows bright enough to see with the naked eye. NOAO/AURA/NSF

THE LITTLE DUMBBELL NEBULA (M76) lies in western Perseus. This glowing gas cloud formed when a dying Sun-like star puffed off its outer layers. Adam Block/NOAO/AURA/NSF

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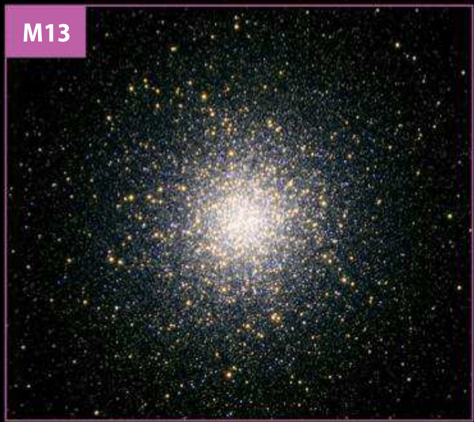
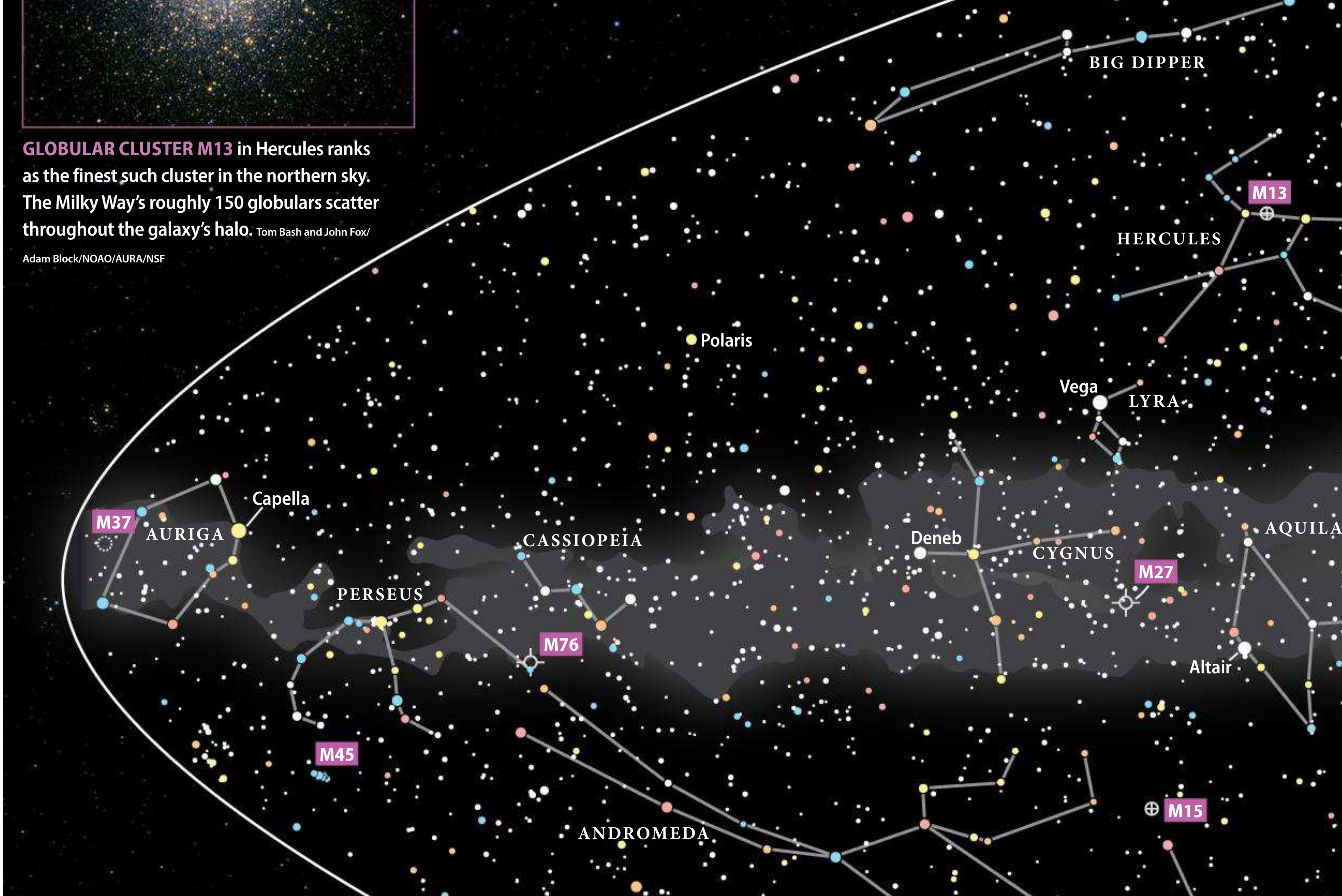


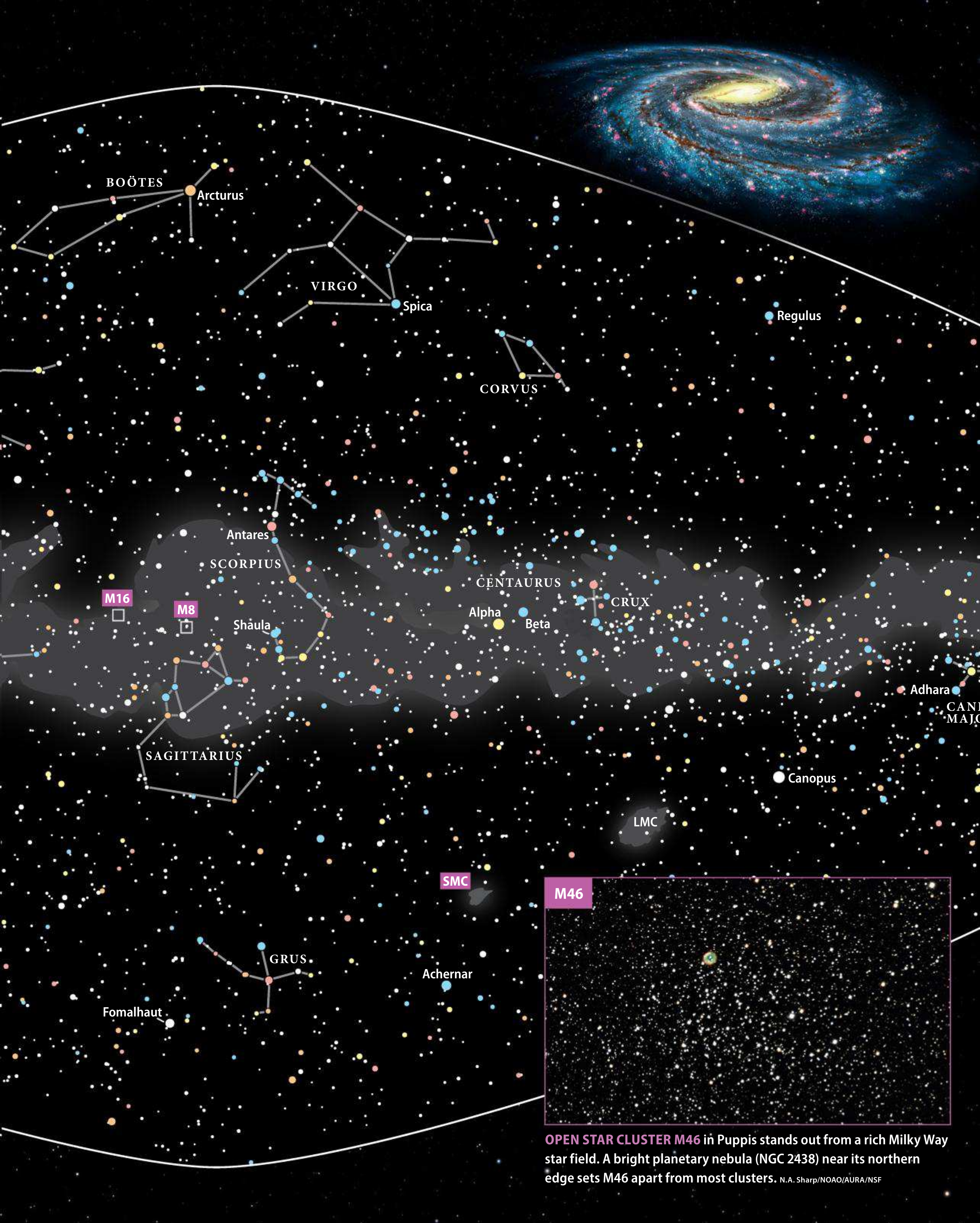
GLOBULAR CLUSTER M13 in Hercules ranks as the finest such cluster in the northern sky. The Milky Way's roughly 150 globulars scatter throughout the galaxy's halo. Tom Bash and John Fox/ Adam Block/NOAO/AURA/NSF

▼ **THE MILKY WAY GALAXY** contains between 100 billion and 400 billion stars. This map, plotted so the galaxy's plane runs horizontally, shows the roughly 5,000 stars visible to the naked eye from a dark site. This map projection distorts constellation shapes, particularly near the edges. (The same thing happens with flat maps of Earth's surface.) In addition to stars, the galaxy contains thousands of clusters and dust-rich gas clouds. *Astronomy*: Roen Kelly



GLOBULAR CLUSTER M15 in Pegasus glows just bright enough to glimpse with the naked eye from a dark site. Like most Milky Way globulars, M15 packs a few hundred thousand stars into a sphere roughly 100 light-years across. Adam Block/NOAO/AURA/NSF

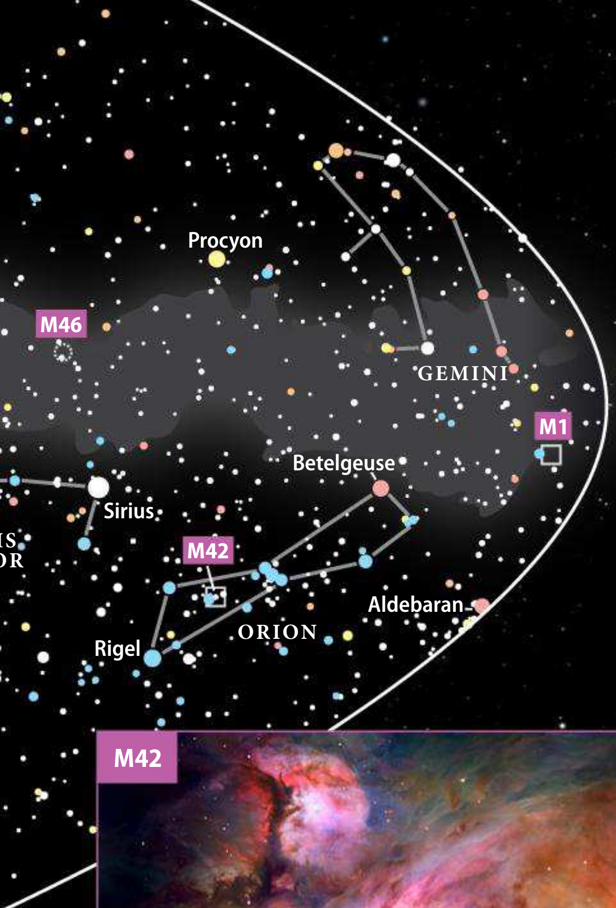
THE DUMBBELL NEBULA (M27) in Vulpecula glows as ultraviolet radiation from the dying stellar ember at its center excites the ejected gas. This planetary nebula lies just 1,200 light-years from Earth, so it appears relatively big and bright. European Southern Observatory

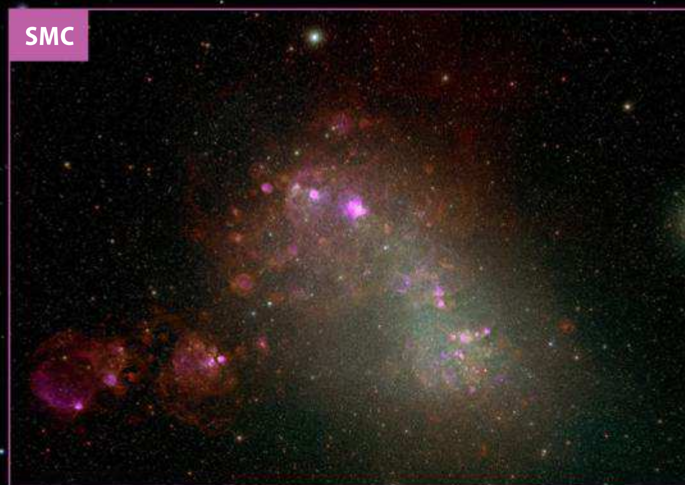


OPEN STAR CLUSTER M46 in Puppis stands out from a rich Milky Way star field. A bright planetary nebula (NGC 2438) near its northern edge sets M46 apart from most clusters. N.A. Sharp/NOAO/AURA/NSF

THE EAGLE NEBULA (M16) in Serpens features dusty pillars of gas from which new stars are forming. The Milky Way's stellar nurseries lie in the galaxy's disk, so they congregate along the central spine of this map. Bill Lofquist/Adam Block/NOAO/AURA/NSF

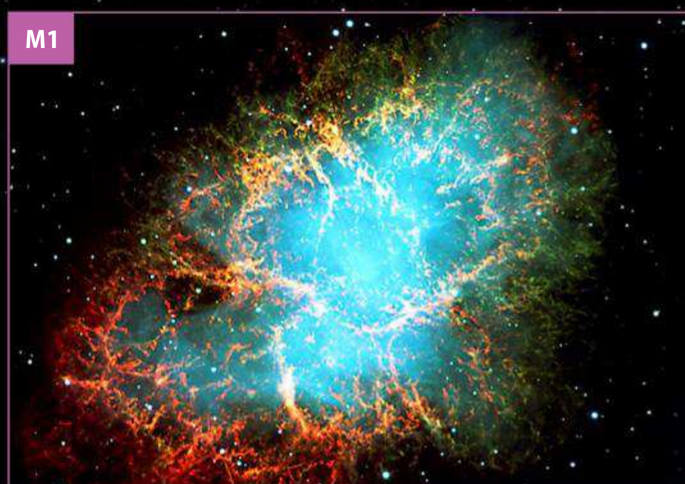
THE LAGOON NEBULA (M8) in Sagittarius lies just a few degrees from the galaxy's center. Several hot young stars have already started to emerge from this stellar nursery. Adam Block/NOAO/AURA/NSF



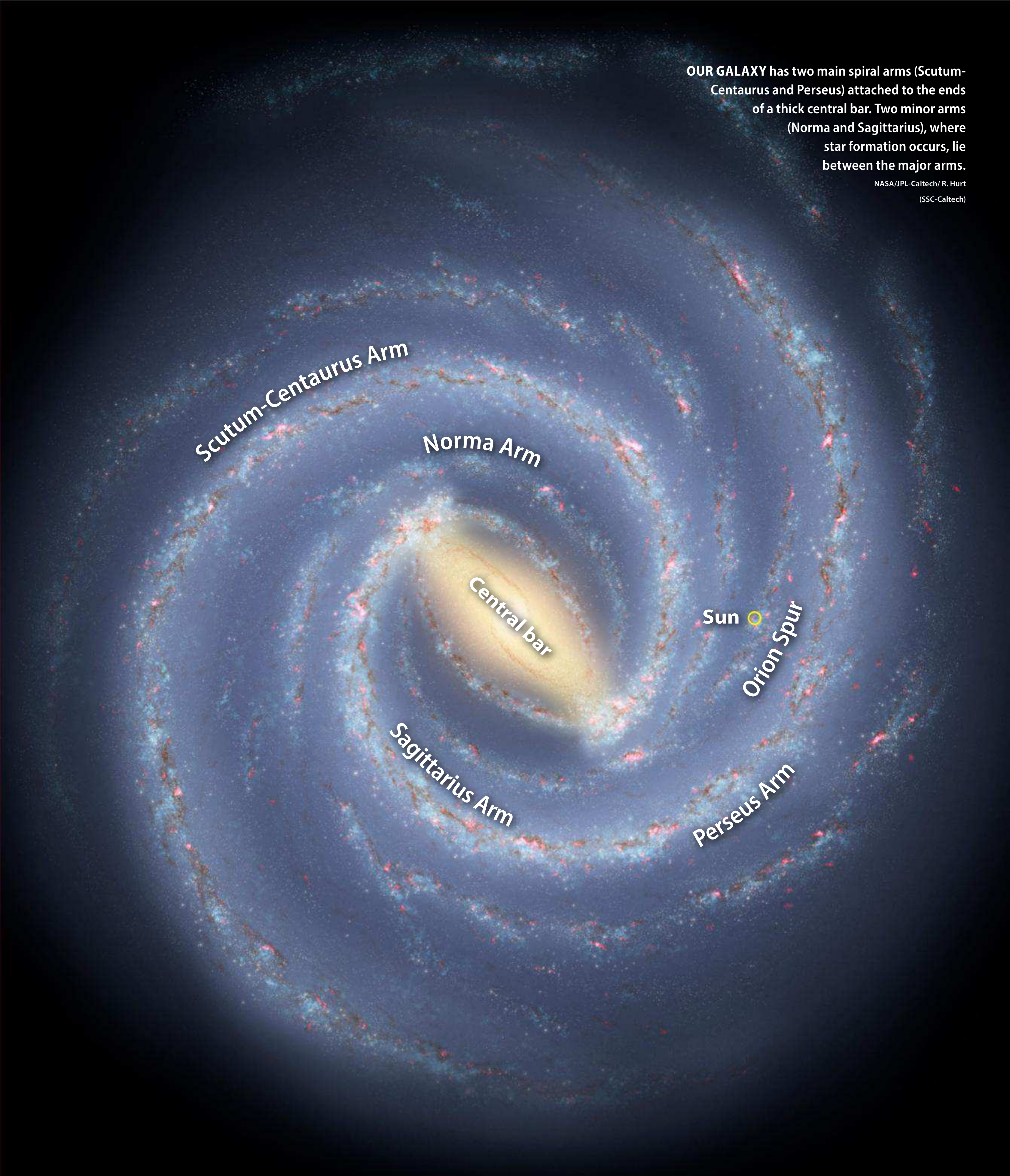


THE SMALL MAGELLANIC CLOUD (SMC) in Tucana is one of the Milky Way's two bright satellite galaxies. It and its bigger cousin, the Large Magellanic Cloud (LMC), lie deep in the southern sky and appear as detached pieces of the Milky Way. F. Winkler/Middlebury College/MCEIS Team/NOAO/AURA/NSF

THE ORION NEBULA (M42) appears big and bright in part because it lies only 1,350 light-years from Earth. This massive stellar nursery has already churned out thousands of new stars, and it contains enough gas to make thousands more. NASA/ESA/M. Robberto (STScI/ESA)/HST Orion Treasury Project Team

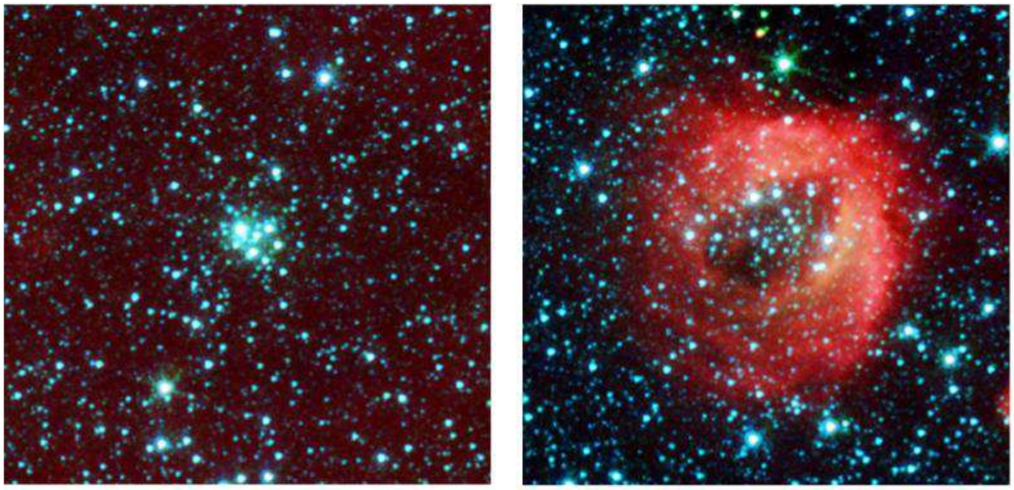


THE CRAB NEBULA (M1) supernova remnant in Taurus started to form in 1054, when our ancestors saw a star explode. Most supernovae occur in the galaxy's spiral arms, home to the massive stars capable of exploding. European Southern Observatory



OUR GALAXY has two main spiral arms (Scutum-Centaurus and Perseus) attached to the ends of a thick central bar. Two minor arms (Norma and Sagittarius), where star formation occurs, lie between the major arms. NASA/JPL-Caltech/ R. Hurt (SSC-Caltech)

Continued from page 50



GLIMPSE uses an automatic cluster-finding computer program developed by astronomers at Boston University. This software searches large areas of sky to find clusters difficult for the eye to pick out. At left is an isolated, tight grouping of stars. The right image shows a looser cluster situated within a wispy red ring, which glows because of the cluster's radiation. NASA/JPL-Caltech/E. Mercer (Boston University)

of its molecular gas. The GLIMPSE team focuses on two questions: What do the distribution of stars and infrared-bright star-formation regions tell us about the inner galaxy's structure, including the disk, molecular ring, number and location of spiral arms, and central bar? What are the physics of star formation as a function of mass, stage of evolution, and location in the Milky Way?

The problem with star counts

When it comes to determining the distribution of stars in the Milky Way, the most straightforward technique is simply to count stars. English astronomer William Herschel (1738–1822) introduced this technique in 1765. Historically, however, star counting has led to some of the most famous wrong answers in astronomy.

Imagine we live in a galaxy comprising a disk of stars (we do), and that we are about halfway from the center to the edge (we are). As we scan its plane, we should see the most stars when we look toward the galaxy's center (we don't). By looking at how quickly the number of stars declines as we scan away from the galaxy's center, astronomers should be able to determine how the stellar density decreases (we can't). When we look in directions for which our line of sight skims tangent to a spiral arm, we should see an excess of stars compared to nearby directions (we don't).

What's wrong? The answer is one of the unpleasant four-letter words of astronomy: dust. Although the density of dust (and gas) in interstellar space is nearly nothing, space is vast, and a whole lot of nearly nothing adds up to something.

What effect does dust have? Imagine watching a terrestrial sunset. The Sun reddens and dims as it approaches the horizon. This impairs your ability to measure the Sun's true color and brightness.

In interstellar space, the Milky Way's dust is not evenly distributed but occurs in clumps and clouds. A few "holes" exist through which astronomers can observe stars to great distances. One such area, called Baade's Window, named for German-born American astronomer Walter Baade (1893–1960), allows a view of the Milky Way's central bulge. But for most of the galaxy's inner disk, dust is a showstopper — a barrier to understanding the distribution of stars there.

Through the dust

The barrier began to crumble with the advent of sensitive infrared detectors. Because infrared light penetrates dust more readily than visible light, an infrared view of the galaxy reveals more stars. The Diffuse Infrared Background Experiment aboard the Cosmic Background Explorer (COBE), launched in 1989, could not resolve individual stars. However, several groups analyzed the light distribution and found evidence for a central stellar bar in our galaxy. Now, using the unprecedented sensitivity of the Spitzer Space Telescope, astronomers can study the galaxy

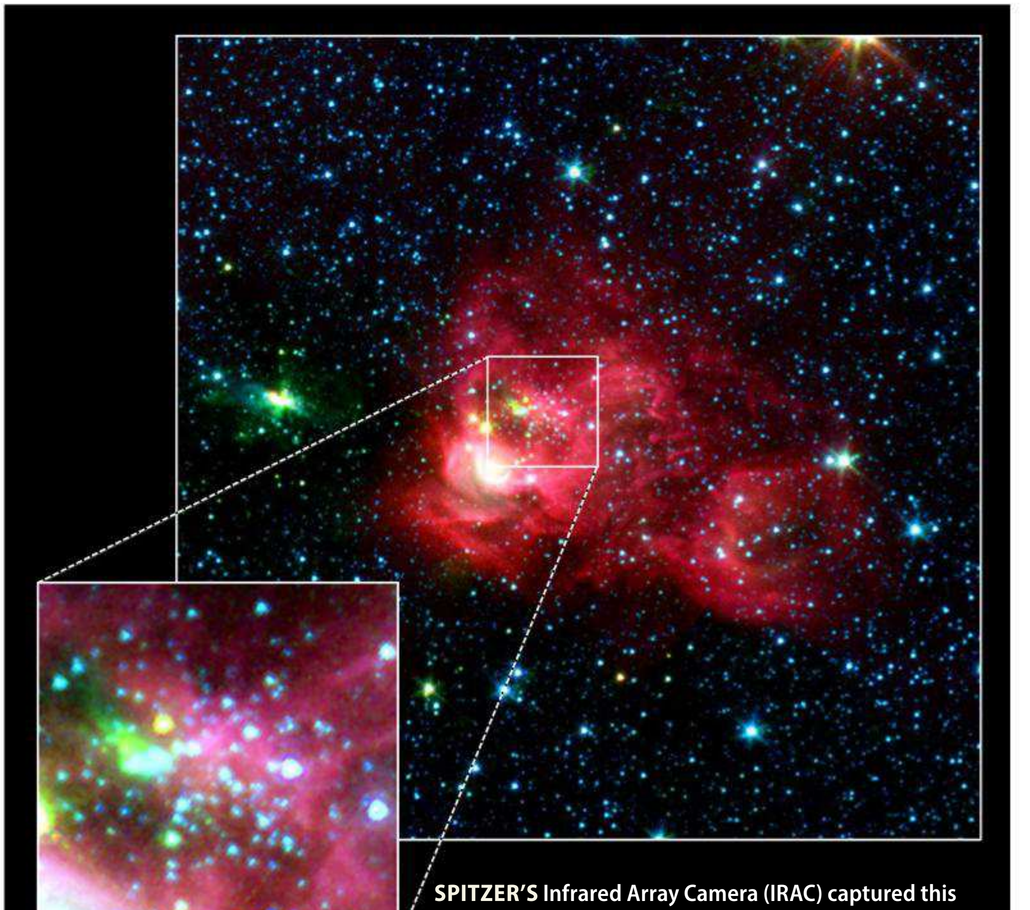
THIS PANORAMIC IMAGE **from GLIMPSE shows a lot of stellar activity in the Milky Way's plane. The image spans 9° of sky (by 2° tall), about as much as the width of your fist held at arm's length. This region represents only 7.5 percent of the GLIMPSE survey, which imaged most of the star-forming regions in our galaxy. The red clouds show the presence of large molecules illuminated by nearby stars.** NASA/JPL-Caltech/E. Churchwell (University of Wisconsin)

at the same wavelengths but with enough angular resolution to observe individual stars.

Using the Infrared Array Camera, the GLIMPSE Legacy team, led by Ed Churchwell of the University of Wisconsin–Madison, surveyed a 130°-long strip stretching 1° above and below the galactic plane. This strip contains most of the galaxy's stars. Unfortunately, it also contains most of the dust. The project's goals were to take a stellar census of the galaxy and study star formation.

The team's stellar census is complete. It produced a catalog of more than 40 million sources in four different wavelengths. Scientists expect more than 90 percent of these sources to be red giant stars. Because red giants are so luminous, they can be seen from large distances across the galaxy. Although dense regions of dust still block our view, even in the mid-infrared, one of the pleasant results of this survey is that the star-counting technique actually works.

By counting stars as a function of direction and brightness, GLIMPSE found the long-expected result that the number of stars increases all the way to the galactic center.



SPITZER'S Infrared Array Camera (IRAC) captured this image of a young star cluster in Aquila. A red nebula surrounds the cluster. Inset: In this false-color composite, reddish wisps are organic molecules illuminated by nearby stars. Green indicates hot hydrogen, and blue reveals older stars. NASA/JPL-Caltech/E. Mercer (Boston University)

Robert Benjamin *is a physics professor at the University of Wisconsin-Whitewater and the principal investigator of GLIMPSE 3D, a follow-up project to study the vertical stellar and interstellar structure of the inner Milky Way.*

THE MILKY WAY'S STELLAR COMPONENTS

Galaxies
Galaxies are stellar "islands" in a largely empty universe. Their stars, gas, and dust are organized into different components, each of which tells us something about how disk galaxies, like the Milky Way, form and evolve.

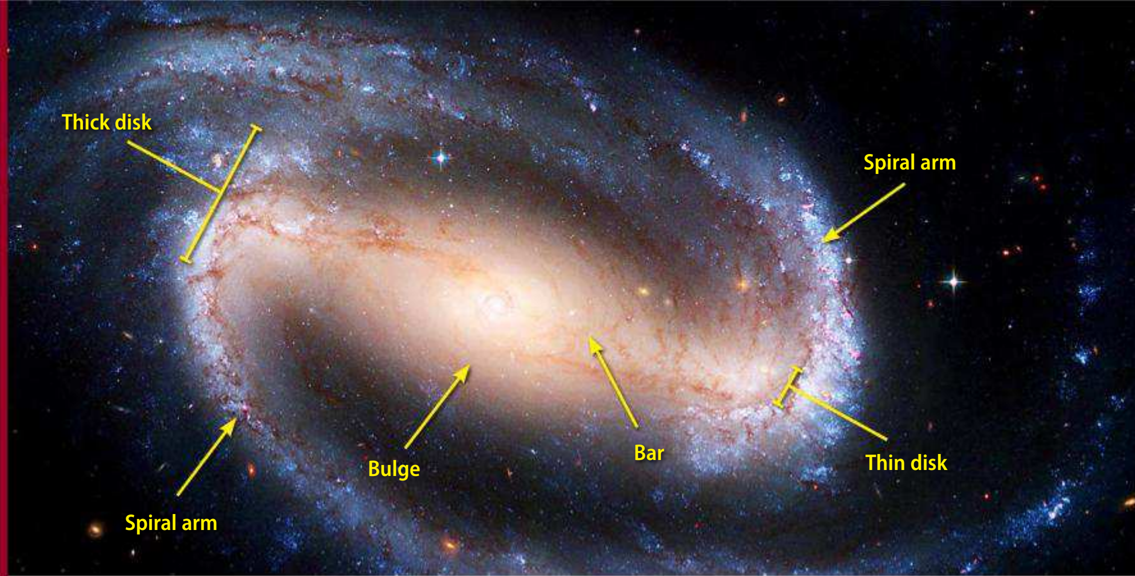
Thin and thick disks
The largest percentage of stars in the Milky Way Galaxy are in a thin disk (1,300 light-years thick) where the star density drops as one gets farther from the galactic center. GLIMPSE measures a radius for the Milky Way's disk of roughly 15,000 light-years. Galaxies like the Milky Way also have a low-density thick disk of stars.

Spiral arms
Nearly all disk galaxies show some evidence of spiral structure with an overdensity of stars in the spiral arms.

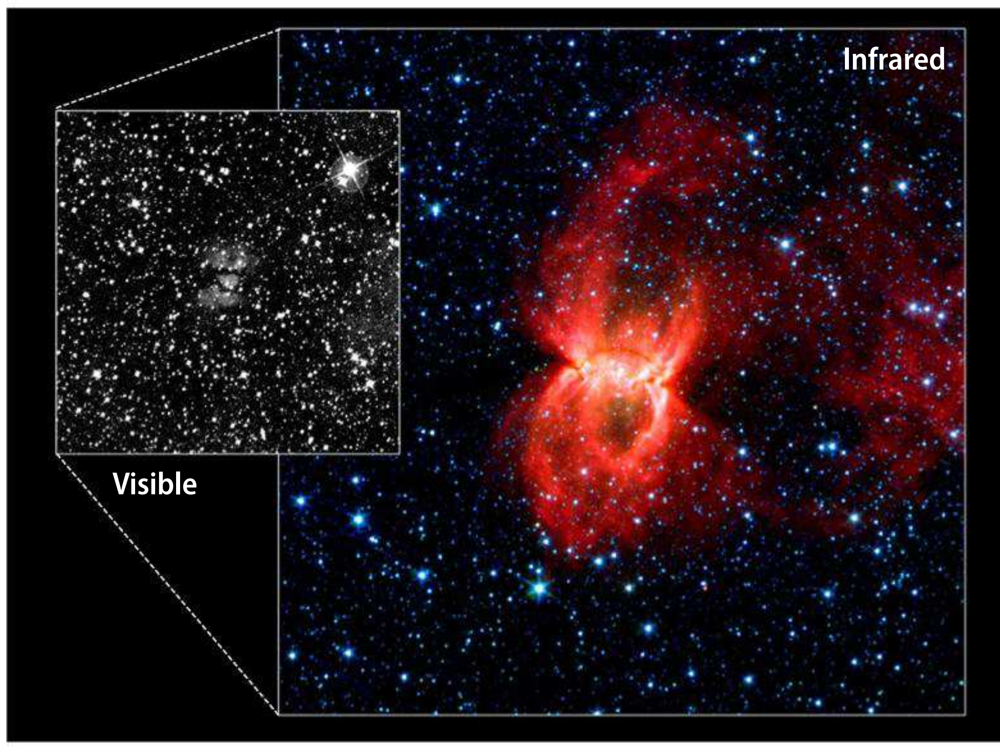
Bar
Using infrared wavelengths, astronomers observe that nearly 80 percent of all galaxies have a central bar of stars. This bar consists of a large group of stars moving in skinny (high-eccentricity) elliptical orbits around the galaxy's center.

Bulge
In addition to the bar, most spiral galaxies have a dense central bulge of stars. This bulge is frequently elongated along one axis, rather than being spherical.

Halo
A low-density gigantic halo of stars (600,000 light-years wide) surrounds the Milky Way. Astronomers think this halo contains important clues on how our galaxy formed.



THE MILKY WAY used to be classified as a spiral galaxy. Recently, the GLIMPSE observing program undertaken by the Spitzer Space Telescope confirmed the existence of a bar. For definitions of the terms above, see the column at left. NGC 1300: Hubble Heritage Team/ESA/NASA

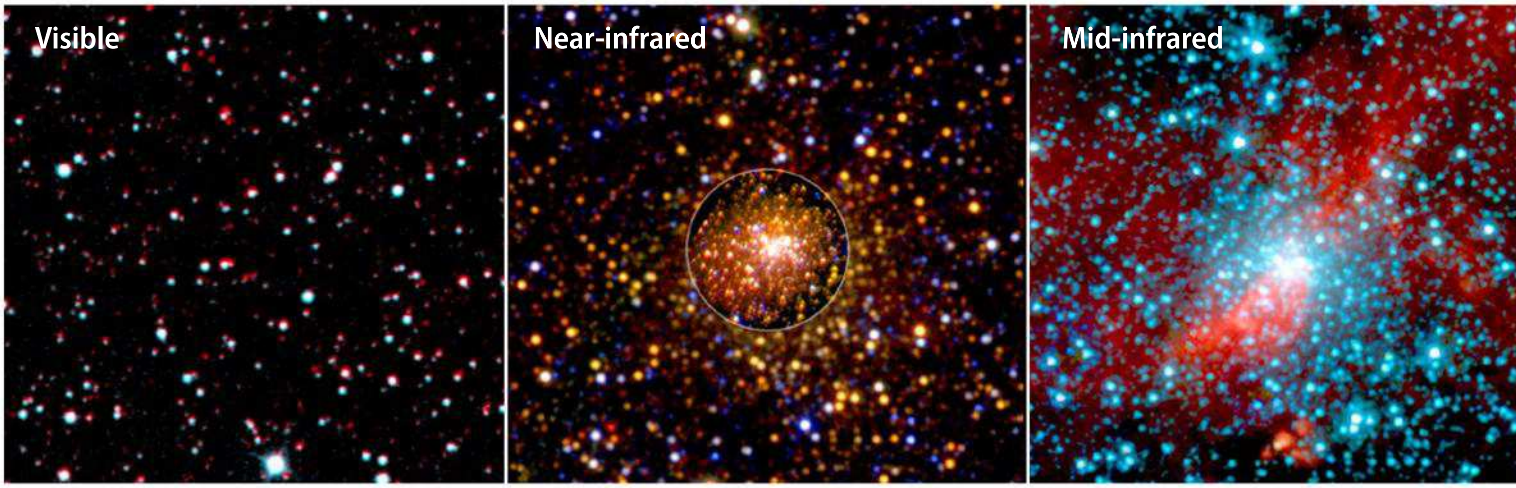


WHAT A DIFFERENCE infrared light makes. Compare these two images of the Black Widow Nebula in the southern constellation Circinus the Compasses. The smaller image is a visible-light exposure taken by the Digital Sky Survey. The larger image, taken with Spitzer's Infrared Array Camera, shows powerful outflows of radiation from massive groups of stars sculpting two opposing gas bubbles. Where the bubbles overlap, new stars appear as yellow specks. NASA/JPL-Caltech/E. Churchwell (University of Wisconsin)/Digital Sky Survey

This enables astronomers to measure the radial "scale length" of the galaxy — the distance one has to go from the center for the stellar density to drop by a factor of nearly two. By determining this number and studying how the galaxy's rotation speed varies at different radii, astronomers can infer how much of the inner galaxy is in the form of dark matter (matter that neither emits nor reflects enough radiation to be detected).

Raising the bar

GLIMPSE also has shed light on two of the major structural features of our Milky Way. First, astronomers counted the number of stars at equal angles to the left and right of the galactic center and examined their brightnesses. These GLIMPSE data confirmed the galaxy has a long stellar bar. This bar is characterized by an excess population of stars called "red giant clump" stars. These stars,



THESE EXPOSURES show the same patch of sky in various wavelengths of light. While the visible-light image (left) shows a dark sky speckled with stars, infrared images (middle and right), reveal a never-before-seen bundle of stars, called a globular cluster. Spitzer's Infrared Array Camera took the right image as part of the GLIMPSE project. NASA/JPL-Caltech/H. Kobulnicky (University of Wyoming)

THE INFRARED ARRAY CAMERA (IRAC) aboard the Spitzer Space Telescope takes images covering a 26-square-arcminute area, or, for comparison, about 3 percent of the area of the Full Moon. IRAC images in four infrared channels simultaneously. The channels' wavelengths center on 3.6, 4.5, 5.8, and 8 micrometers. IRAC's only moving part is its shutter. NASA/JPL-Caltech

Spitzer Space Telescope Legacy programs

The Spitzer Space Telescope launched in 2003. Although the liquid helium needed to cool most of its instruments ran out in 2009, one of its instruments continues to operate in the so-called "warm mission." Early on, NASA initiated a set of large-scale programs collectively called Legacy, and the agency made all observations from these programs available to everyone. The data will remain useful to astronomers for decades. These are the six programs NASA selected:

LEGACY PROJECT	ABBREVIATION	PRINCIPAL INVESTIGATOR	STUDIES
Galactic Legacy Mid-Plane Survey Extraordinaire	GLIMPSE	Ed Churchwell, University of Wisconsin	Stellar content and star formation in the inner Milky Way.
From Molecular Cores to Planet-Forming Disks	C2D	Neal Evans, University of Texas	Details of star formation in nearby molecular clouds.
Formation and Evolution of Planetary Systems	FEPS	Michael Meyer, University of Arizona	Different planetary systems around stars of different ages.
Spitzer Infrared Nearby Galaxies Survey	SINGS	Rob Kennicutt, Cambridge University	Structure and star formation in a sample of nearby galaxies.
Spitzer Wide-Area Infrared Extragalactic Survey	SWIRE	Carol Lonsdale, Caltech	Evolution of galaxies in a 50-square-degree swath of the sky.
Great Observatories Origins Deep Survey	GOODS	Mark Dickinson, University of Arizona	Formation and evolution of galaxies in the early universe.

which shine with a fixed luminosity, were used as "standard candles" to pin down the bar's angle and length. Although other astronomers observed the bar, the sensitivity and full coverage of GLIMPSE provided a dramatic confirmation of the bar's structure.

The second surprise lurking in GLIMPSE star counts concerned our galaxy's spiral structure. The survey's outer regions contained two areas where astronomers expected to see an excess of stars because our line of sight skims along spiral arms at these points. One of these arms, the Scutum-Centaurus Arm, shows a dramatic enhancement of stars in the direction expected from studies of star-forming regions in optical and radio wavelengths. But the second region, the Sagittarius Arm tangency, shows no strong evidence for such an enhancement. This is despite the fact that both tangencies are approximately the same distance from the Sun.

Although the Sagittarius Arm is clearly a major star-forming structure, it lacks any evidence of compression in the older stellar populations. Ron Drimmel and David Spergel of Princeton University first found this using COBE data. Astronomers have noted this characteristic in other spiral galaxies as well because infrared light traces the old stellar populations (and most of a galaxy's stellar mass), while visible light traces recent star formation. It sometimes happens that spiral galaxies show secondary star-forming compressions between the major infrared arms. Is our galaxy such a case? Time and future study will tell.

In search of the galaxy's magnetic monsters

Magnetars unleash mammoth bursts of energy, but how and why? Astronomers are working to understand these bizarre stellar objects. **By Steve Nadis**

In 1987, when Robert Duncan and Christopher Thompson first contemplated the existence of ultramagnetized neutron stars (later dubbed "magnetars"), they had a hard time convincing themselves that the notion made sense. Five years later, when they got their first opportunity to present their ideas at a scientific conference, they were given just three minutes to make their case. Then, in 1998, at a meeting of the American Astronomical Society, Duncan was the last scheduled speaker at the five-day event, seemingly lumped in the fringe category.

Six years later, in 2004, colleagues finally recognized Duncan and Thompson (now at the University of Texas and the University of Toronto, respectively) for their theoretical work on magnetars. Joining them was Chryssa Kouveliotou of the National Space Science and Technology Center (NSSTC) in Huntsville, Alabama, for observations that confirmed the scenario. The three received the Bruno Rossi Prize for outstanding contributions to high-energy astrophysics.

Thus, after almost two decades of doubts, astrophysicists at last acknowledged magnetars are real. These unusual objects constitute a distinct class of pulsars. They are rapidly spinning, intensely magnetic neutron stars — dense remnants of massive stars that expired in fiery supernova blasts.

Armed with this knowledge, researchers then turned their attention to a broad range of questions, such as: Where do these curious objects, with the most powerful magnetic fields known to exist, come from? Or, put in other terms, why do some stars become magnetars rather than black holes or other kinds of neutron stars? Answering these questions can tell astronomers how abundant magnetically powered stars are, thereby providing clues to their astronomical importance.

Contributing Editor **Steve Nadis** *is a science writer based in Cambridge, Massachusetts. He is co-author of* The Shape of Inner Space *(Basic Books, 2010).*

IN A MAGNETAR'S GIANT FLARES, **magnetic field lines break and reconnect, releasing a burst of energy. This process resembles solar-flare formation, except magnetars' flares are much more powerful.** Don Dixon for *Astronomy*

Blasts from beyond

Scientists now believe magnetars exist because of a confluence of theory and observational data from some of nature's most impressive high-energy displays. For astronomers, says Thompson, the turning point came in 1998.

In May of that year, a team led by Kouveliotou showed that the soft gamma repeater (SGR) 1806–20, a pulsing X-ray source about 50,000 light-years from Earth, was likely a magnetar. Kouveliotou's team measured the rate at which the neutron star's spin was slowing down. A magnetic field could supply the drag to slow the star's rotation, but it had to be incredibly powerful. The scientists estimated a magnetic field of about a million billion (10^{15}) gauss. (Earth's magnetic field reaches just 0.6 gauss.)

Then, in August 1998, a powerful blast of gamma rays and X-rays zapped Earth's outer atmosphere. The burst came from SGR 1900+14, some 20,000 light-years away in the direction of Aquila. Kouveliotou and her colleagues showed, based on the object's spin-down rate, that it, too, must be a magnetar.

On December 27, 2004, SGR 1806–20 let loose again. The eruption was the most powerful flare from outside our solar system astronomers had ever recorded. In just 0.2 second, the magnetar released more energy than the Sun gives off in 250,000 years.

An international group of astronomers analyzing the December 27 event supported Duncan and Thompson's hypothesis that magnetar flares arise from twisting magnetic fields. These fields warp and strain the star's crust, creating shearing stress across a region several kilometers long. This shear zone in some ways resembles a geological fault that gives rise to an earthquake. Eventually, the star's crust cracks open.

This work answered some questions about the magnetar flares. But where do these overmagnetized neutron stars come from? "You can't see anything directly related to the progenitor [star] by looking at the flare," Duncan explains. Nevertheless, he adds, you can get hints simply by seeing where astronomers find magnetars.

Digging deeper for answers

That's the approach Bryan Gaensler, then of Harvard-Smithsonian Center for Astrophysics, took when he searched the vicinity of a magnetar called AXP 1E 1048.1–5937, located roughly 9,000 light-years away in Carina. "It occurred to me that the environments around magnetars might tell us something about them," Gaensler recalls.

Gaensler's team studied the region's hydrogen emissions using Australia's Parkes radio telescope and the Australia Telescope Compact Array. The astronomers found a cavity carved out, they think, by stellar outflows from the magnetar's original star. Knowing that the star's mass is proportional to the cavity's size and expansion speed, the team deduced that the progenitor star contained at least 40 times the Sun's mass.

Donald Figer, then of the Space Telescope Science Institute in Baltimore, probed the connections between magnetars, their masses, and star clusters. Prior to SGR 1806–20's massive blast, Figer explored a cluster filled with massive young stars that, coincidentally, contained that same magnetar. The most massive stars die first as supernovae, and less-massive stars expire later. Figer inferred that SGR 1806–20's progenitor had to be bigger than the biggest stars still standing in the star cluster; this implied a mass of at least 50 Suns.

Michael Muno, then of the University of California at Los Angeles, used a similar technique. While surveying the massive star cluster Westerlund 1 with NASA's Chandra X-ray Observatory, he found an X-ray pulsar lurking in the cluster's center. Based on the object's luminosity and spectrum, Muno deemed it a probable magnetar.

His survey showed that Westerlund 1 is teeming with high-mass stars, all roughly the same age. This survey placed a lower limit of about 40 solar masses on the magnetar's predecessor. It's intriguing, says Muno, "that we have a good idea of the mass of the star this magnetar came from even though that star disappeared long before X-ray astronomy began."

Both Muno and Gaensler believe the association of magnetars with massive star clusters looks strong. Moreover, both magnetars and high-mass clusters are rare, which makes chance alignments less likely.

Muno's next step was to confirm that his mystery source is, indeed, a magnetar. He observed AXP CXO J164710.2–455216 intermittently over the course of a year using the European Space Agency's XMM-Newton and NASA's Chandra X-ray observatories to see how its rotation period changes. This enabled him to estimate the object's magnetic-field strength. His team calculated a magnetic field of 10^{14} gauss, which means the object is in fact a magnetar.

Searching star clusters

Figer, now at the Rochester Institute of Technology, undertook an ambitious, five-year project to find all Milky Way star clusters containing at least 1,000 stars, and thus probably 10,000 to 100,000 solar masses of material. To this end, he utilized infrared instruments at the Keck Observatory in Hawaii and aboard NASA's Hubble and Spitzer space telescopes to probe our galaxy's dusty disk.

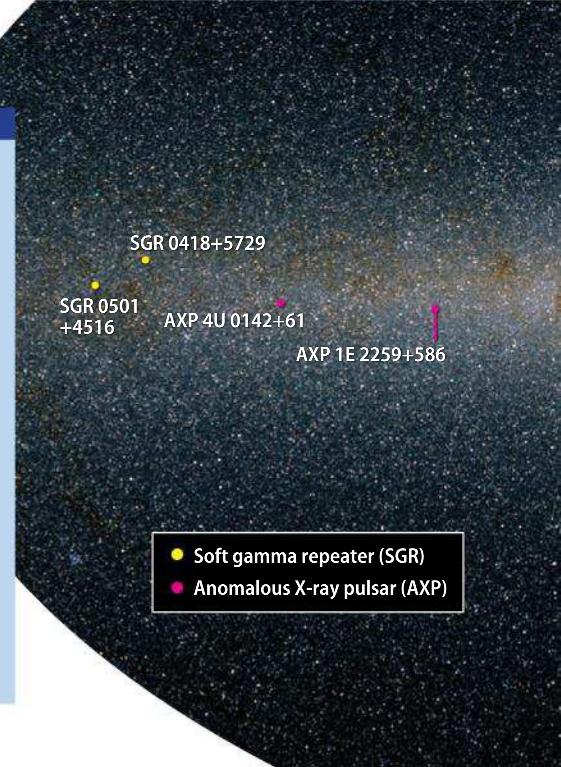
"Our approach," explains Figer, "was to identify the breeding grounds of magnetars — these massive clusters — and then use pointed observations to see how many magnetars are there." Once Figer spotted the clusters — nearly 100 in all — others in the team

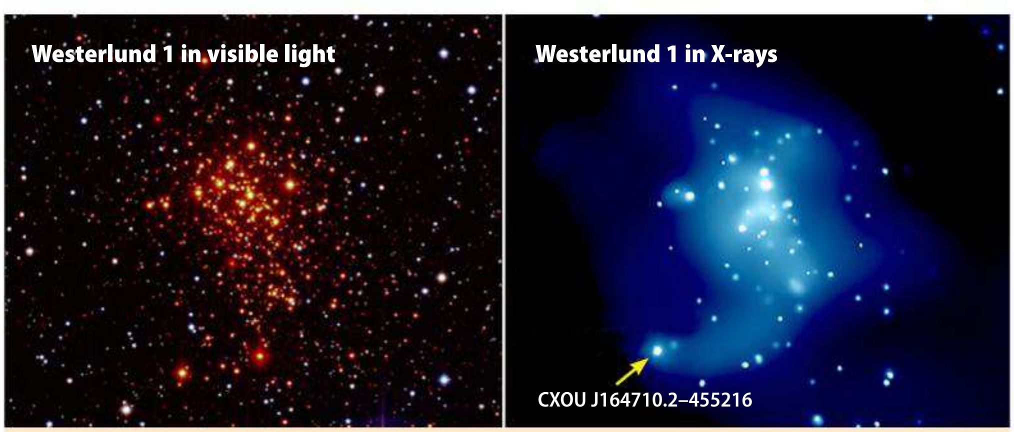
Two types of bursters

Magnetars break into two subclasses: soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Scientists know of 15 probable SGRs (11 of which have been confirmed) and 14 likely AXPs. Twenty-seven of these 29 magnetars are in our galaxy; the Large and Small Magellanic Clouds hold one each.

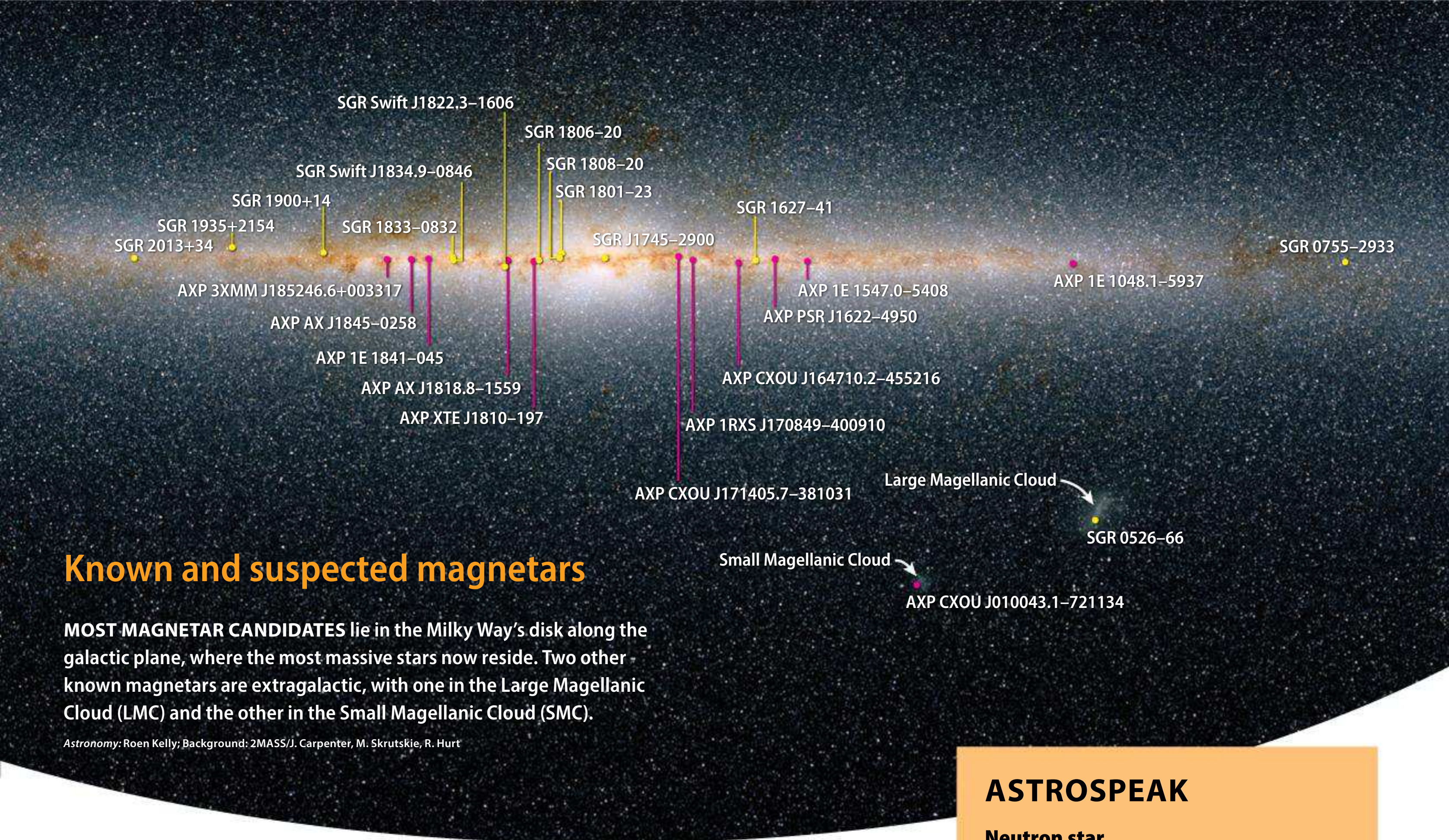
As their name implies, SGRs emit "soft," or low-energy, gamma rays. Soft gamma rays have slightly higher energy than "hard" X rays. The giant flares from AXPs aren't as intense as those from SGRs, although they're still more intense than those from run-of-the-mill pulsars.

— *Liz Kruesi*





MASSIVE STAR CLUSTER Westerlund 1 is home to the magnetar CXOU J164710.2–455216, an anomalous X-ray pulsar (AXP) . Astronomers discovered the object, which spins once every 10.6 seconds, in 2005. They hope to uncover additional magnetars as they explore the Milky Way's most massive star clusters. Visible: ESO; X-ray: NASA/CXC/M. Muno et al. (UCLA)



Known and suspected magnetars

MOST MAGNETAR CANDIDATES lie in the Milky Way's disk along the galactic plane, where the most massive stars now reside. Two other known magnetars are extragalactic, with one in the Large Magellanic Cloud (LMC) and the other in the Small Magellanic Cloud (SMC).

Astronomy: Roen Kelly; Background: 2MASS/J. Carpenter, M. Skrutskie, R. Hurt

started follow-up X-ray observations with Chandra, looking for pulsing X-ray sources and monitoring their spin-down rates.

By looking at many clusters, Figer's team hopes to determine the masses of magnetar progenitor stars to within about five solar masses. Such precision is crucial for estimating the fraction of massive stars that develop into magnetars.

How many magnetars might our galaxy host? Figer believes astronomers have seen only a small fraction of the Milky Way's massive clusters — dust shrouds the rest from view. By extension, this means we've discovered relatively few of the galaxy's magnetars. If Figer is right, the total number in the Milky Way should be between 100 and 200.

90 percent to go

Astronomers also have found a new class of transient magnetars whose X-ray brightnesses can vary wildly. This makes them detectable at some times and invisible at others. A team led by Alaa Ibrahim, then of George Washington University, discovered, with the aid of NASA's Rossi X-ray Timing Explorer, just such a magnetar in 2003, when the object's luminosity suddenly increased by a factor of 100. A different group found another strong candidate at about the same time.

Ibrahim shares Figer's view that the galaxy may host 100 to 200 "live" magnetars. He notes this tally doesn't include magnetars that have spun down and lost their heightened powers. He believes the elusive transient objects might resolve the discrepancy between the observed and expected magnetar populations. Figer's team is surveying for exactly this type of now-you-see-it, now-you-don't object. It's "trying to see whether there is a population of faint magnetars that hasn't turned up yet," says Muno.

Peter Woods, an X-ray astronomer at NSSTC, agrees that pointing telescopes toward massive stars will increase the odds of finding transient magnetars. But identifying magnetars in their "quiescent" state won't be easy, even with extensive telescope time on Chandra or XMM-Newton. "We don't know enough about transient magnetars," he says. "For example, we don't know their duty cycle — how long they're bright versus how long they're dim. X-ray astronomy is only about 40 years old, and we don't know whether these objects stay dim for 40 years or 100 years."

Figer doesn't know either, but he isn't deterred. "More magnetars are still being discovered, so it would seem we're not done discovering them," he says. Rather than relying on estimates of how many magnetars there should be, Figer intends to look and "see what turns up."

ASTROSPEAK

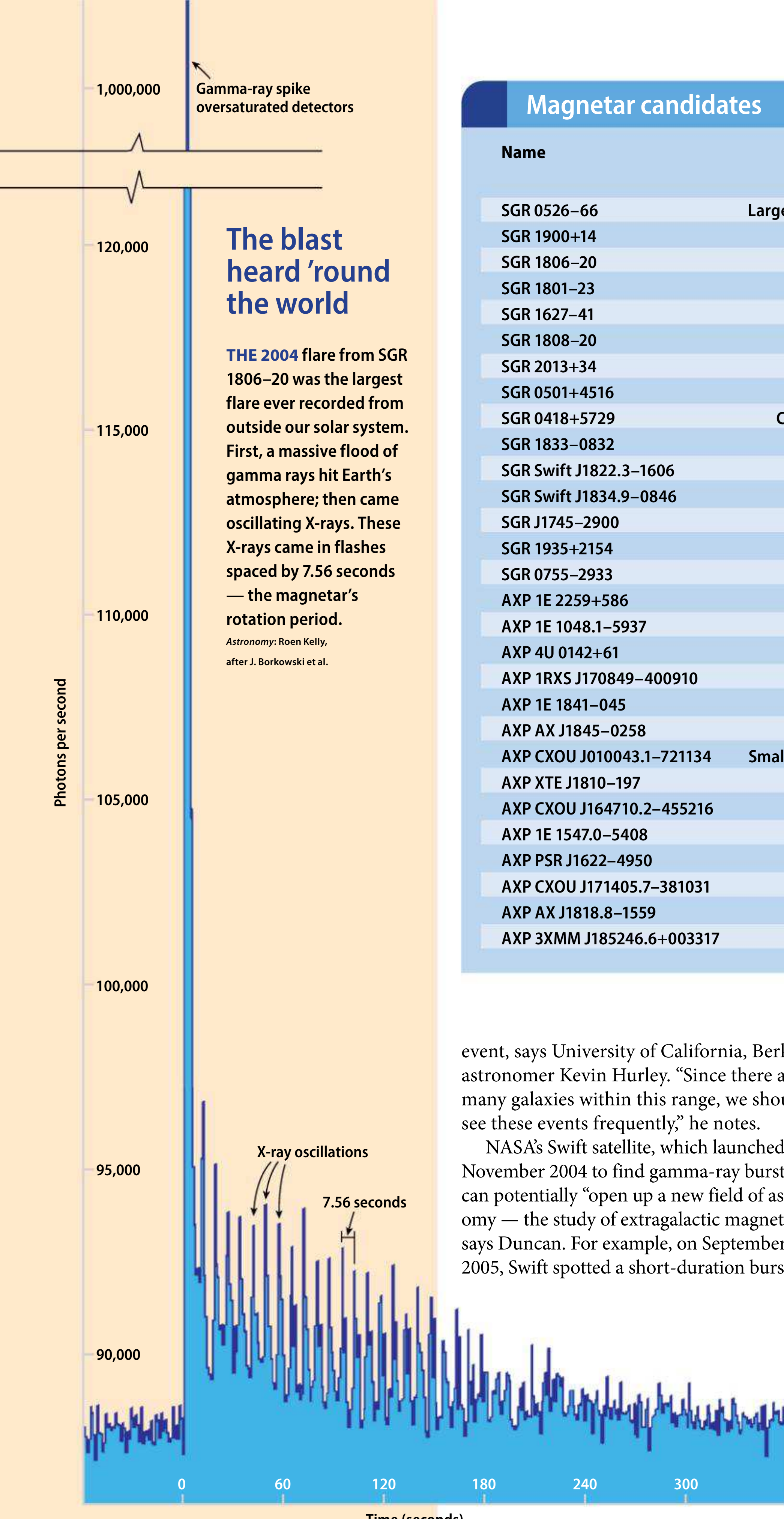
Neutron star
The dense remnant of a once-massive star's core formed in a supernova. Such stars may contain more than twice the Sun's mass crammed into a sphere roughly 12 miles (20 kilometers) across.

Pulsar
A rapidly rotating (many times a second) neutron star whose radiation beam passes Earth on each rotation, creating a pulse.

Magnetar
A neutron star with a magnetic field 1,000 times stronger than normal.

Where are these stars hiding?

The search for magnetars is not confined to our galaxy. In fact, the first known magnetar burst, which was detected in March 1979, came from the Large Magellanic Cloud, a satellite galaxy to the Milky Way. This finding suggests other extragalactic magnetars exist. A flare within 100 million light-years of Earth could be detected with current X-ray and gamma-ray instruments, provided the flare is as bright as SGR 1806–20's 2004



The blast heard 'round the world

THE 2004 flare from SGR 1806–20 was the largest flare ever recorded from outside our solar system. First, a massive flood of gamma rays hit Earth's atmosphere; then came oscillating X-rays. These X-rays came in flashes spaced by 7.56 seconds — the magnetar's rotation period.

Astronomy: Roen Kelly, after J. Borkowski et al.

Magnetar candidates

Name	Location	Rotation (seconds)	Year discovered
SGR 0526–66	Large Magellanic Cloud	8.05	1979
SGR 1900+14	Aquila	5.20	1979
SGR 1806–20	Sagittarius	7.56	1979
SGR 1801–23	Sagittarius	—	1997
SGR 1627–41	Ara	2.59	1998
SGR 1808–20	Sagittarius	—	2003
SGR 2013+34	Cygnus	—	2005
SGR 0501+4516	Auriga	5.76	2008
SGR 0418+5729	Camelopardalis	9.08	2009
SGR 1833–0832	Scutum	7.57	2010
SGR Swift J1822.3–1606	Sagittarius	8.44	2011
SGR Swift J1834.9–0846	Scutum	2.48	2011
SGR J1745–2900	Sagittarius	3.76	2013
SGR 1935+2154	Vulpecula	3.25	2014
SGR 0755–2933	Puppis	—	2016
AXP 1E 2259+586	Cassiopeia	6.98	1981
AXP 1E 1048.1–5937	Carina	6.46	1985
AXP 4U 0142+61	Cassiopeia	8.69	1993
AXP 1RXS J170849–400910	Scorpius	11.01	1997
AXP 1E 1841–045	Scutum	11.79	1997
AXP AX J1845–0258	Aquila	6.97	1998
AXP CXOU J010043.1–721134	Small Magellan Cloud	8.02	2002
AXP XTE J1810–197	Sagittarius	5.54	2003
AXP CXOU J164710.2–455216	Ara	10.61	2005
AXP 1E 1547.0–5408	Norma	2.07	2007
AXP PSR J1622–4950	Norma	4.33	2009
AXP CXOU J171405.7–381031	Scorpius	3.83	2010
AXP AX J1818.8–1559	Sagittarius	—	2012
AXP 3XMM J185246.6+003317	Aquila	11.56	2013

event, says University of California, Berkeley, astronomer Kevin Hurley. "Since there are many galaxies within this range, we should see these events frequently," he notes.

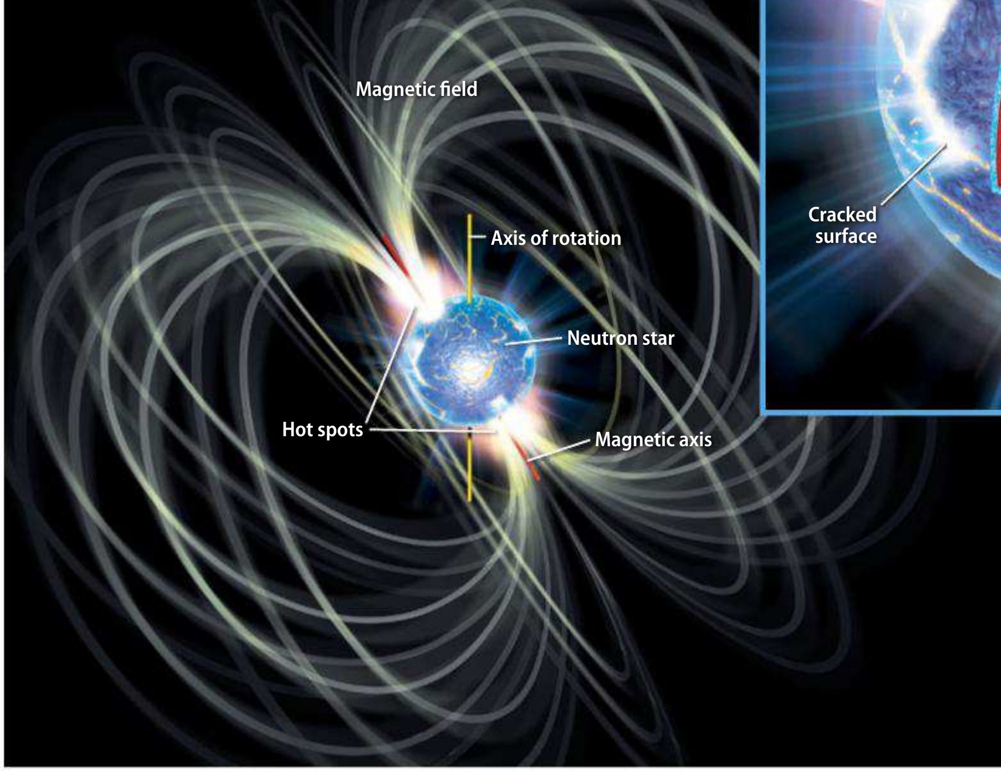
NASA's Swift satellite, which launched in November 2004 to find gamma-ray bursts, can potentially "open up a new field of astronomy — the study of extragalactic magnetars," says Duncan. For example, on September 6, 2005, Swift spotted a short-duration burst that might prove to be a magnetar flare emanating from a distant galaxy, although not all scientists accept this interpretation.

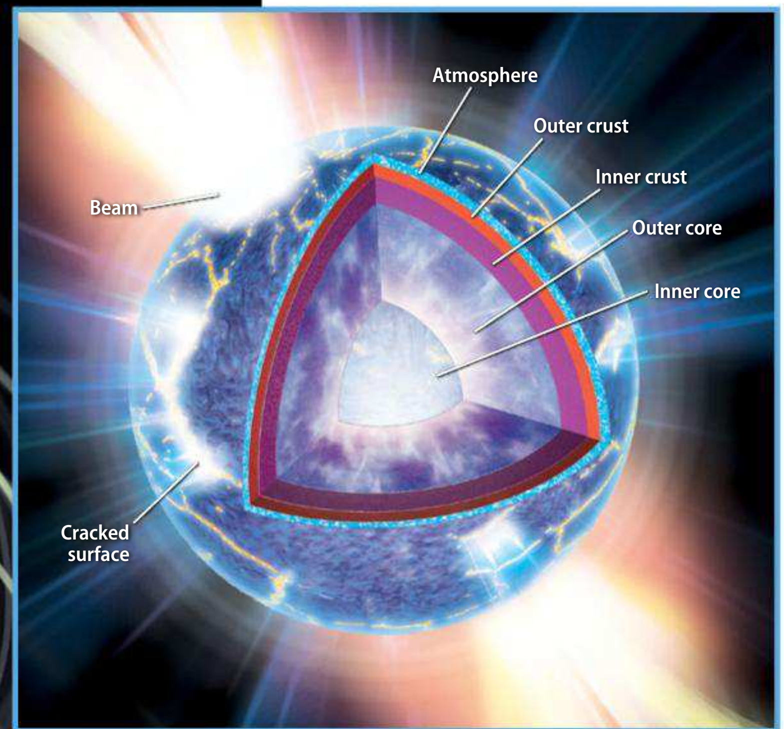
Swift and other instruments detected a November 3, 2005, burst from M81, a galaxy about 13 million light-years away. This, says Duncan, was "the first identified extragalactic magnetar flare outside the Local Group." The flare's energy release appears comparable to SGR 1806–20's big blast in 2004.

For astronomers hunting magnetars outside of our galaxy, NASA's Swift is easily the best instrument around. Still, the satellite isn't optimized for this task. Swift's detectors are tuned to lower-energy (spectrally "softer") events expected from neutron-star mergers. "With the right instruments flying," Duncan explains, "we could detect a magnetar flare each week. Swift can't find that

Inside a magnetar

A MAGNETIC FIELD 1,000 times stronger than normal elevates an ordinary pulsar to a magnetar. Drag from such an ultrastrong field slows a star's spin, which makes a magnetar rotate slower than a pulsar. Right: Astronomers think SGR 1806–20's 2004 flare began when the magnetar's surface cracked. Based on study of the flare, scientists estimate the star's crust is only about a mile (1.6 km) thick. *Astronomy:* Roen Kelly





many but may still spot an appreciable number over its lifetime."

The goal, simply put, is to build up statistics, says Hurley. "We'd like to know the magnetar birth rate, which may be difficult to calculate if we're limited to the magnetars in our own galaxy."

In addition to computing the fraction of stars that turn into magnetars, researchers would like to ascertain these stars' properties. Why does one supernova explosion become a magnetar, while another produces a pulsar? The question extends beyond an interest in magnetars alone. "We're talking about the endpoint of stellar evolution," Gaensler explains. "If you want to learn about the star cycle and understand what happens when stars die, you need to understand magnetars."

Mass, the property that most determines a star's destiny, is definitely an important part of the equation, but it's not the whole story. To make a magnetar, the core of the pre-supernova progenitor star must rotate rapidly (about 1,000 times per second) at the end of its life. In Duncan and Thompson's picture, the core acquires its magnetism through a dynamo effect by converting rotational energy into magnetic energy.

The best current models indicate massive stars rotate more rapidly as they die than when they're young. To wind up as a magnetar, however, the star has to shed much of its mass before it goes supernova, perhaps by expelling it in strong stellar-wind outflows. Stars with high metal content — elements heavier than helium — have stronger winds, Gaensler notes. So, in addition to looking at the masses of cluster stars, scientists should look at metal content, too. "You wouldn't expect to find magnetars in a low-metallicity cluster," he says.

To Thompson, the question of the source of magnetars boils down to this: "What kinds of stars end up with rapidly rotating cores?" That's difficult to say, he notes, "since no one knows how rotation evolves in the center of a massive star." And although astronomers can measure how fast a star's exterior is spinning, they still can't correlate rotation in the outer layer with what's going on inside.

Given the uncertainties at the theoretical end, perhaps our best recourse is to see where the observations are taking us, Woods notes. Duncan agrees: "Many details of how magnetars behave are poorly understood. To a great extent, theorists are now being led by the observations." That's ironic, because when he and Thompson first dreamed up magnetars, there was little evidence the objects existed.

Thompson, for his part, finds it exhilarating to track the magnetar data now coming in. While the findings have supported some of the early views he and Duncan advanced, they also have served to underscore the many puzzles scientists must still resolve.

Fortunately, growing numbers of astronomers are now interested in taking on these challenges. Indeed, many high-energy astrophysicists regard the December 27, 2004, magnetar burst as a watershed event. It's comparable in significance to Supernova 1987A, the first naked-eye supernova in centuries and the only one from which neutrinos were detected. Recognition of this has brought more attention to magnetars.

"It's certainly becoming more of a mainstream field, and we're attracting talented, new people all the time," Woods explains. "That has led to some nice new results, and it's only going to get better." A

Journey to the heart of the Milky Way

▲ **A GALACTIC PANORAMA captured in X-ray wavelengths highlights hot gas and stars in the Milky Way's core. The central jewel is a black hole (not visible) located within the bright white patch. New telescope technology allows astronomers to peer deep into the galaxy's center.** NASA/UMass/D. Wang et al.

A giant black hole anchors our galaxy's core, swarmed by fast-moving young stars. Astronomers aren't sure how they got there.

By John Dvorak

High winds are the norm at the center of the Milky Way. Astronomers have now clocked suns orbiting the galactic core at a staggering 3,000 miles (4,800 kilometers) per second. At this rate, Earth would complete its orbit around the Sun in a mere three days. What lurks at the galaxy's core that can accelerate stars to such speeds?

Astronomers have considered various possibilities. Does the center of the galaxy harbor a tight cluster of superdense stellar remnants (neutron stars)? Or perhaps a huge ball of subatomic neutrino particles?

But these and other more exotic possibilities were eliminated in the spring of 2002 when a star called S2 swept down in its highly eccentric orbit and passed within 17 light-hours of the Milky Way's center — a minuscule distance in galactic terms. In 17 hours, light travels three times the distance between Pluto and the Sun.

Only one object is compact enough and has sufficient mass to accelerate stars to such a high speed: a supermassive black hole. Astronomers had suspected that a black hole must lie at the Milky Way's core, but plotting the orbit of S2 and other stars dramatically strengthened the evidence.

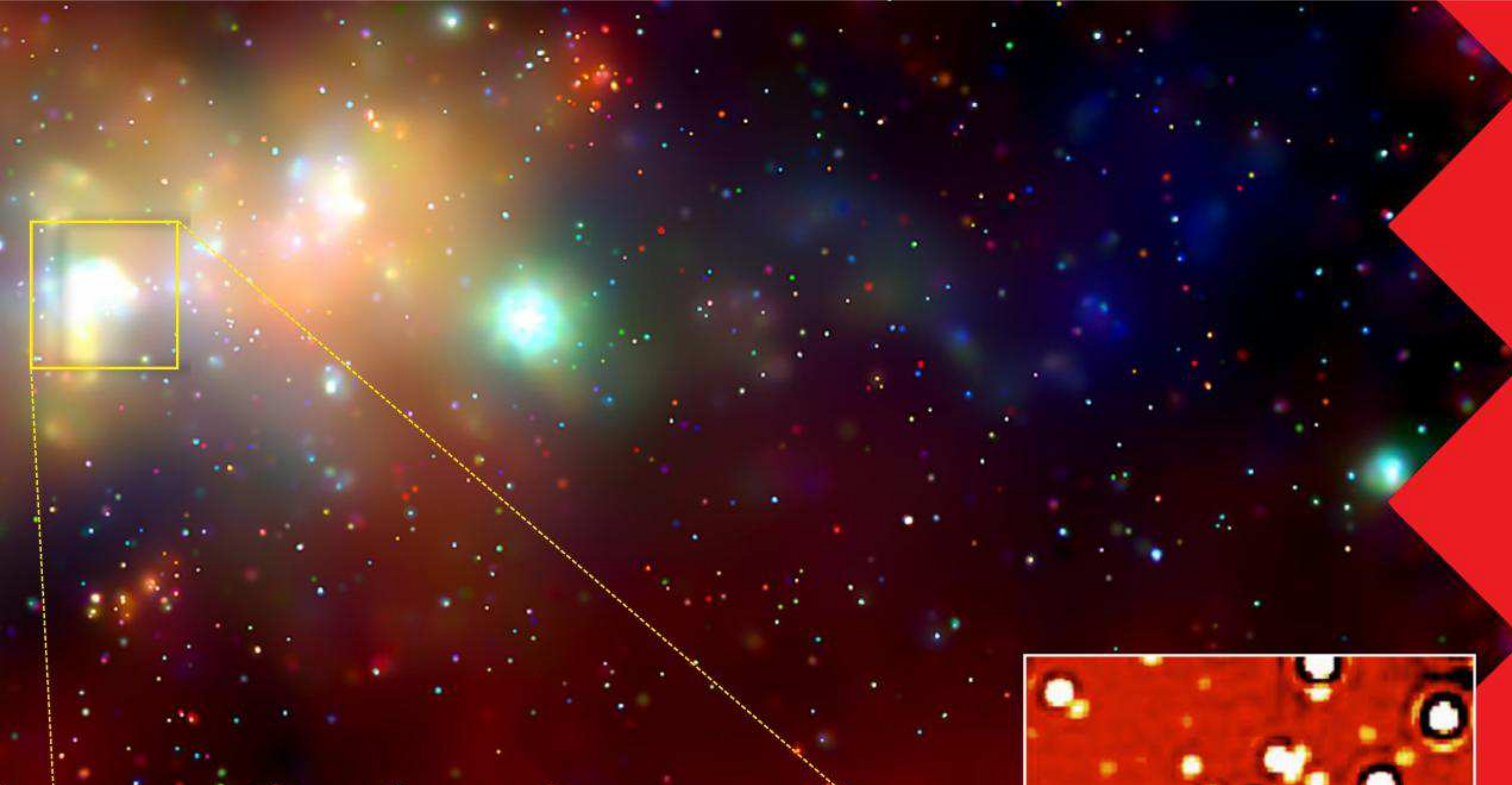
Our central black hole is small by the standard of what lurks in the hearts of other galaxies. Observations of the giant elliptical galaxy M87 suggest the presence of a black hole 6 billion times more massive than the Sun. The interaction of two supermassive black holes probably produces the intense X-rays streaming from the galaxy NGC 6240. The Andromeda Galaxy may harbor a black hole of 140 million solar masses.

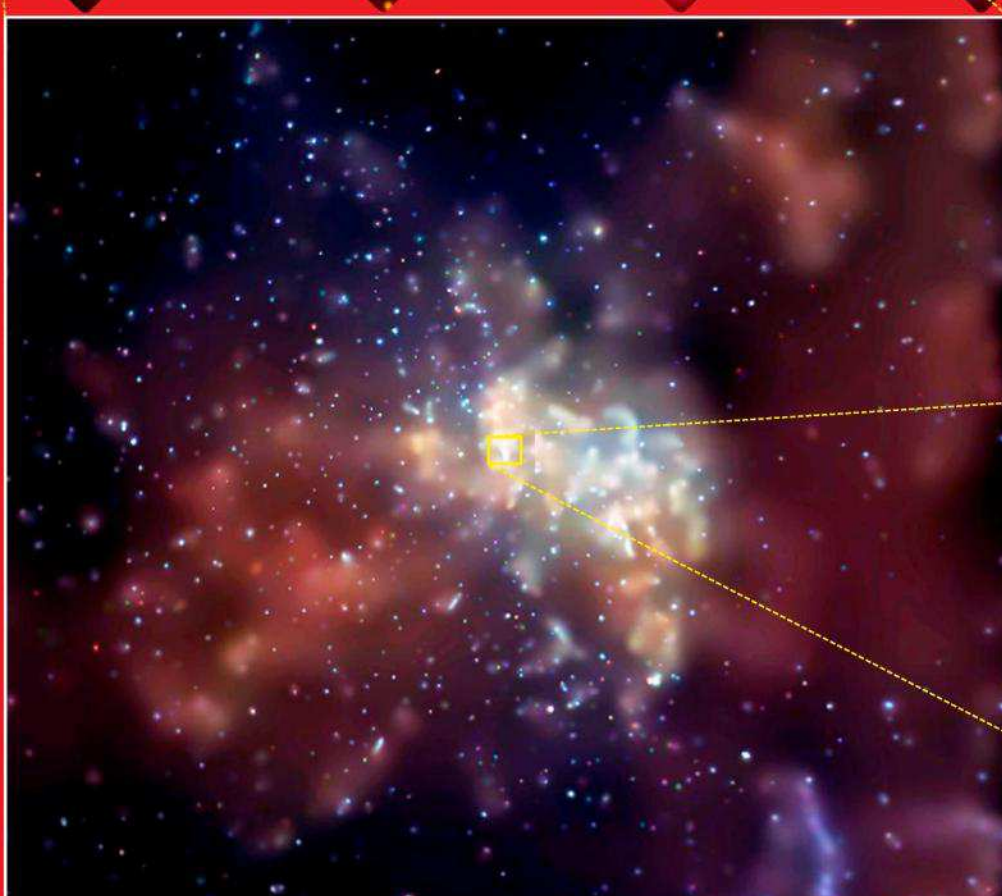
In comparison, our galaxy's black hole is paltry — containing about 4 million solar masses. But its nearness means we can study it in detail, including charting the orbits of dozens of stars buzzing around it like bees. The stellar-mass black holes found in some binary star systems are too small to be observed in detail by telescopes anytime soon. So, the best chance of seeing what happens in the bizarre neighborhood around a black hole is to study the one at the Milky Way's heart. So far, it has not failed to surprise us.

The inner realm

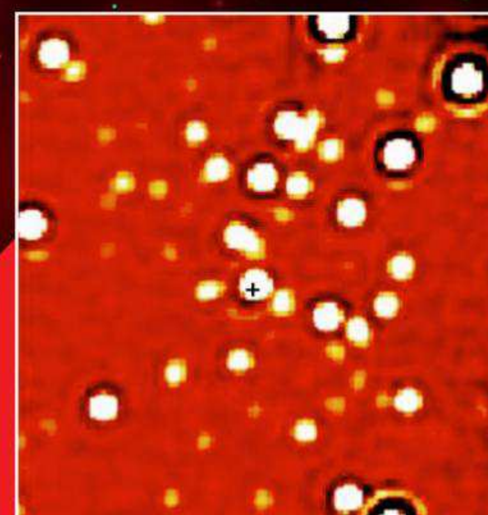
The galactic center lies about 26,000 light-years from Earth toward the constellation Sagittarius. It is a region of the sky where bright stars mingle with dark clouds of gas and dust. The actual center is too obscured to reveal much when astronomers observe it in visible light. What we know of it comes from data collected in infrared and radio wavelengths. These wavelengths can pass through the dust and gas and reach Earth-based telescopes.

Astronomers have long known that the strongest source of radio energy in the sky, after the Sun, lies at the galactic center. This broad core region is called Sagittarius A, often abbreviated as Sgr A.



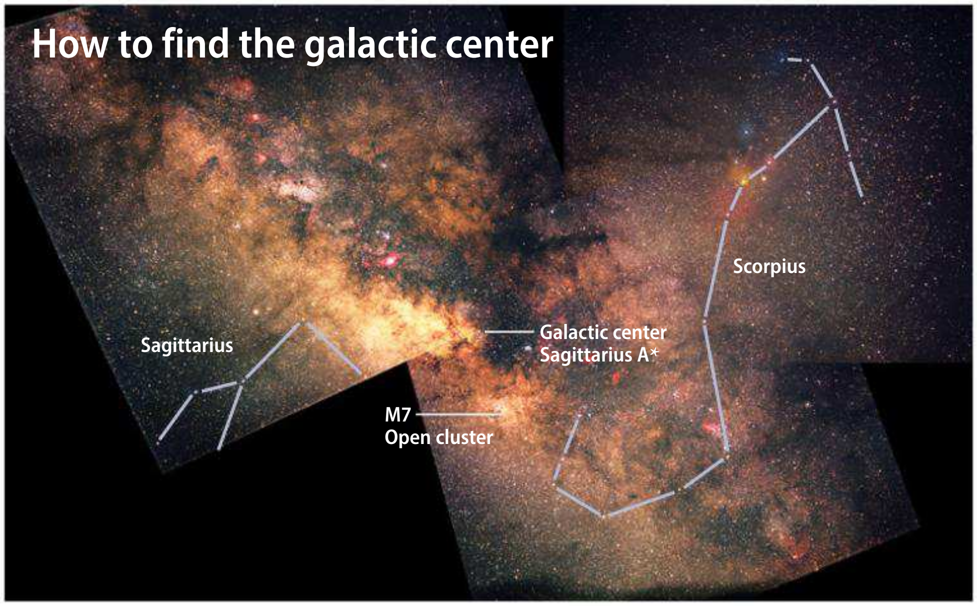


ZOOMING IN AT HIGHER RESOLUTION, the Chandra X-ray Observatory imaged multiple lobes of hot gas extending dozens of light-years from the galaxy's core. The hot gas is the remnant of past supernova explosions — a common event in the galactic center. NASA/CXC/MIT/F.K. Baganoff et al.



ASTRONOMERS imaged individual stars orbiting the galaxy's central black hole, Sagittarius A* (pronounced "A star"). The small cross marks the black hole's location. ESO

ADAPTIVE OPTICS allows telescopes to see individual stars in the Milky Way's crowded core. This image, shot by the European Southern Observatory's 8.2-meter Very Large Telescope, exposes a crowd of hot blue stars and cool red stars near the Milky Way's center. Gas glows in the infrared between the stars. ESO



SAGITTARIUS A*, AT THE MILKY WAY'S CORE, lies in the constellation Sagittarius and to the east (left) of Scorpius. The region is rich with star clusters and nebulae. It's a perfect place to explore with binoculars under dark skies. Sky images: Gerald Rhemann; Constellation outlines: *Astronomy*: Roen Kelly

Sgr A hosts dozens of individual radio sources. One is called Sagittarius A*, pronounced "Sagittarius A star." It lies at the very center of the galaxy and coincides with the position of the supermassive black hole. Everything else rotates clockwise (from Earth's point of view) around this point, making it the dynamic center of the galaxy. And it is a very busy neighborhood.

Surrounding Sgr A* at a distance of several light-years, a shell of dust rotates counterclockwise — opposite to the galaxy's general rotation. Lying inside the shell, and turning in the same direction, is a small spiral structure with three arms.

Each arm is a stream of hot gas set aglow by nearby stars. The gas flows toward the center of the spiral where Sgr A* lies. Radio images taken a few years apart revealed the spiral is rotating. More recently, a close-up look at Sgr A* with new imaging technology has revealed the amazingly powerful gravity of the object the spiral encircles.

Stellar raceway

In 2002, a team of astronomers led by Reinhard Genzel of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, published the first scientific paper announcing S2's 17-light-hour close encounter with Sgr A*. Using the European Southern Observatory's (ESO) Very Large Telescope (VLT) in Chile, Genzel's group caught S2 as it rounded Sgr A* at a fantastic speed. The VLT's adaptive optics reduces atmospheric blurring, allowing astronomers to chart S2's position more accurately.

For the previous decade, the astronomers had been plotting S2's orbit, mostly with ESO's 3.6-meter New Technology Telescope, also in Chile. The orbital positions allowed the researchers to calculate S2's orbital period around Sgr A* as about 16 years. The orbit is quite eccentric. The star swoops in to within 17 light-hours at its closest approach to Sgr A*, but then sweeps outward to a distance of some 10 light-days at its farthest point. To produce such an orbit requires a compact black hole with about 4 million solar masses.

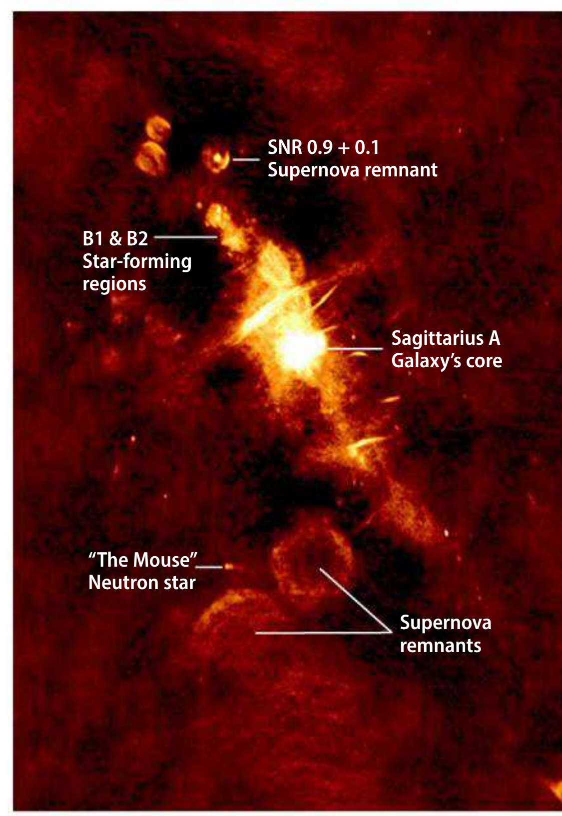
OUR CENTRAL BLACK HOLE IS SMALL by the standard of what lurks in the hearts of other galaxies.

Genzel and his colleagues were not the only ones tracking S2 and the many other stars zipping around Sgr A*. Astronomer Andrea Ghez's Galactic Center Group at UCLA has studied S2 and its motions with the 10-meter Keck Telescope in Hawaii. In 2000, the team reported evidence that S2's path is curved — early evidence S2 is orbiting something at the galactic center. The UCLA team later discovered S2's close orbital distance to Sgr A* at about the same time as Genzel and his colleagues.

Stars of mystery

Extensive observations in recent years by Genzel, Ghez, and others paint a fascinating picture of the flurry of activity around Sgr A*. One of the most challenging observations astronomers have performed on the galactic center stars is spectroscopy, or separating starlight into its component wavelengths. A spectrum reveals much about a star's composition, age, and mass.

Gathering enough light from a distant star to take a good spectrum requires tracking the target through a narrow slit for many hours. Any small shift in the slit's position contaminates the spectrum with light from other sources. Spectroscopy is especially challenging in the crowded star field around Sgr A*, where the density of stars is more than a million times higher than in our stellar neighborhood.



RADIO ASTRONOMY reveals hidden features of the Milky Way's center, including remnants of supernova explosions and stars forming in vast clouds of gas and dust. W.M. Goss/C. Lang/VLA/NRAO

John Dvorak *spent 20 years operating a telescope atop Mauna Kea. His latest book is* Mask of the Sun *(Pegasus Books, 2017).*

In 2003, Ghez took a spectrum of S2 with the Keck Telescope using its adaptive optics system. The slit trained on the star was only 0.04 inch (1 millimeter) wide. Keeping this narrow gap locked on S2 was like aiming a gun sight on an object the size of a basketball 1,000 miles (1,600 km) away.

The spectrum revealed S2 to be a heavyweight star some 15 times the Sun's mass. Such large stars exhaust their hydrogen supply quickly — in this case, in less than 10 million years. That means S2 must be younger than 10 million years. In addition, the star has a very hot atmosphere, as do other stars orbiting close to Sgr A*. This also indicates a relatively young age.

In short, these stars formed 3 to 6 million years ago. This raises a major problem: Why are such young stars orbiting so close to Sgr A*, a region of intense magnetic fields and strong gravitational forces that would normally prevent star formation?

Stellar masquerade

One possible explanation is that S2 and its companions may be old stars masquerading as young ones — "a phenomenon we understand quite well in Los Angeles," Ghez once quipped to a science reporter.

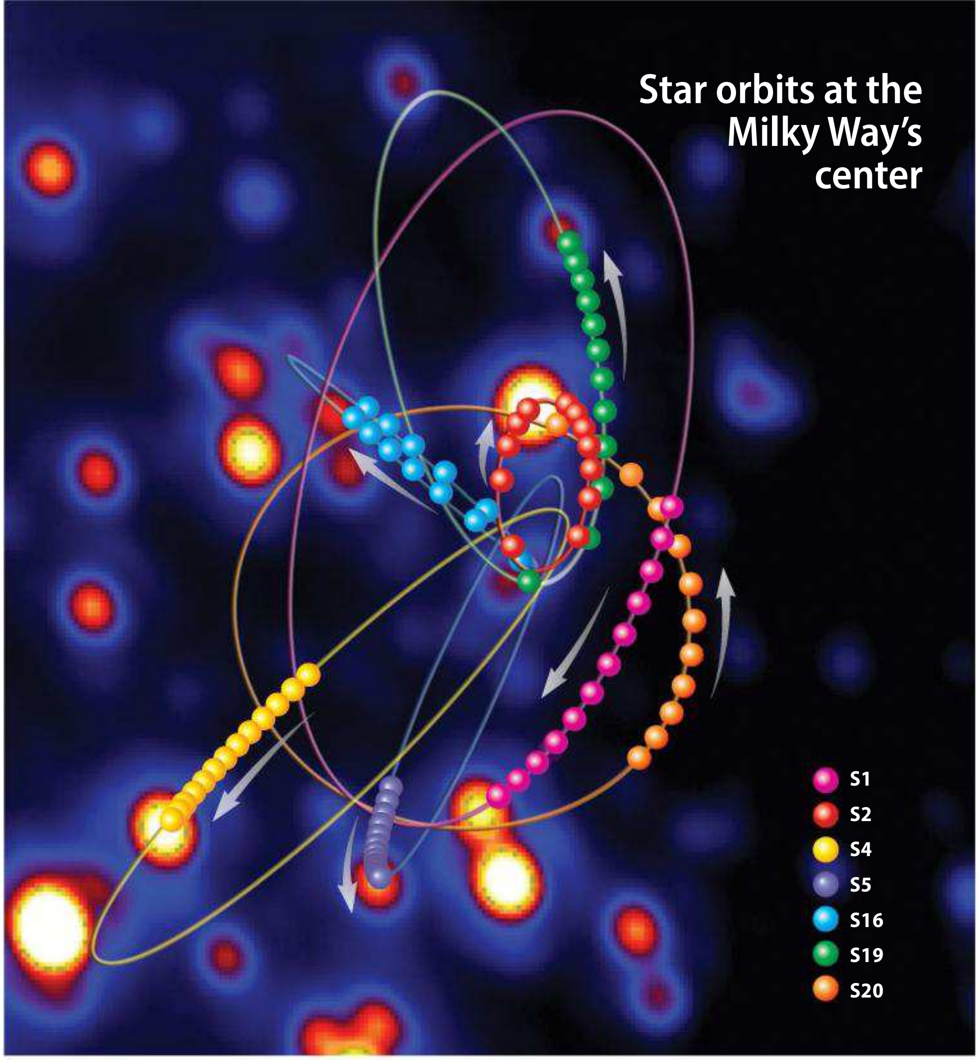
In this case, what seem to be young stars are actually the cores of older suns that collided and merged. The collisions could have stripped away the suns' cool outer layers, exposing their hot interiors. The result would be a cluster of massive stars that appear much younger than they really are.

But there's a problem with this scenario. A collision violent enough to strip away the outer layers should also annihilate both stars and leave only a trail of hot gas. And so astronomers have proposed alternatives. For example, perhaps the stars formed elsewhere and migrated inward under the black hole's gravitational pull.

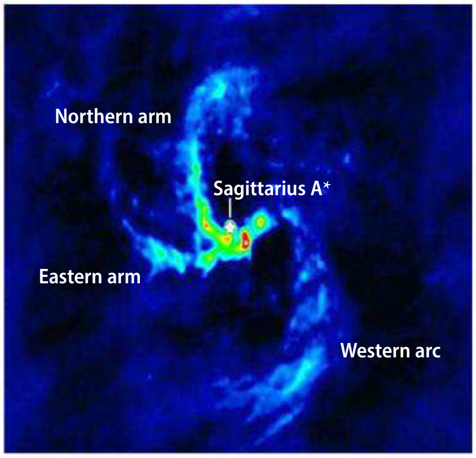
The problem with this explanation is that most active star formation in the Milky Way occurs far from the core, in its spiral arms. It would take the stars too long to migrate as close to the center as S2.

Dense dust clouds do lie closer to Sgr A* than the spiral arms, to within a few dozen light-years. Stars are probably forming inside of them. It's conceivable that a cluster of young stars could spiral down to within a few light-years of the center — and do so in less than 10 million years.

The problem here is that to get closer to the black hole, the stars would have to shed angular momentum — the quantity that keeps planets in nice safe orbits around stars instead of "falling" directly into them.



DOZENS OF YOUNG STARS orbit at high speeds around the galaxy's central black hole. By plotting the stars' positions for years, astronomers calculated their orbits and estimated the mass of the black hole they encircle. *Astronomy*: Jay Smith, after Andrea Ghez (UCLA)



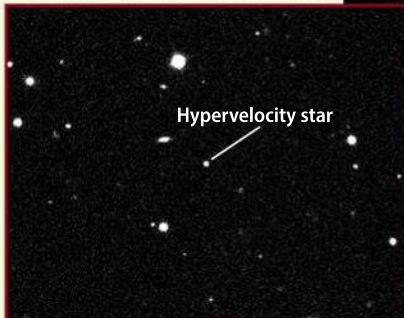
AT THE GALAXY'S NUCLEUS lies a rotating "mini-spiral" of gas, as shown in this image created from radio emissions in the central 10 light-years of the galaxy. NRAO/AUI

One way to lose angular momentum is to bump into other stars. But it's difficult to imagine how stars could endure this process and migrate to within light-hours of Sgr A* without being destroyed. Besides, the process should leave behind a trail of stars toward Sgr A* for a long distance, something astronomers have not yet seen. Instead, the shell of stars orbiting close to Sgr A* has a definite outer edge.

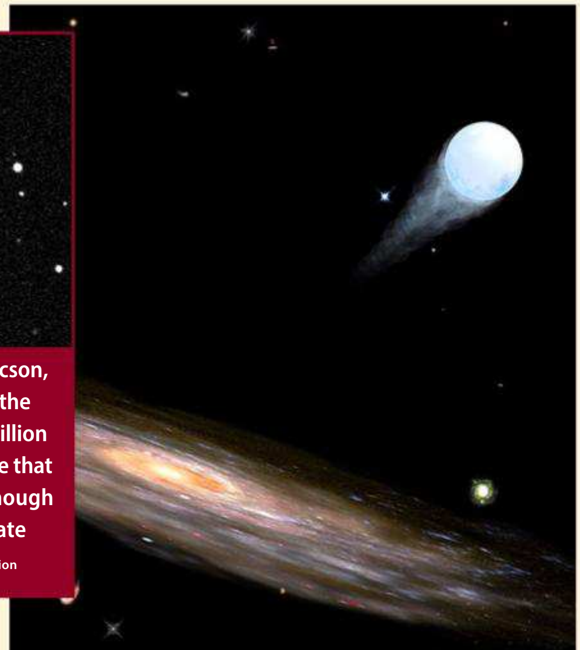
Star birth in a disk

Another possibility is that Sgr A*'s central cluster stars formed within a rotating disk of gas and dust immediately surrounding the black hole. In fact, some observations suggest most stars in the central cluster orbit roughly in the same plane — an arrangement reminiscent of the major planets in our solar system. The planets formed in a disk of gas and dust, so perhaps S2 and its fellow travelers did, too.

However, not all astronomers agree the central cluster has a disklike structure. Another caveat: To spawn stars, the disk would need to be dense enough to withstand the black hole's tidal forces.



THE MMT OBSERVATORY in Tucson, Arizona, captured a star exiting the galaxy at 1.5 million mph (2.4 million km/h). Astronomers hypothesize that only a black hole could exert enough gravitational muscle to accelerate stars to such speeds. SDSS Collaboration



A GRAVITATIONAL TUSSLE with the Milky Way's central black hole flings a star completely out of the galaxy in this artist's depiction. Astronomers have discovered dozens of such "hypervelocity" stars whizzing through space. Ruth Bazinet (CfA)

Cosmic pinballs

The high density of stars orbiting close to Sgr A* means that close encounters are likely, producing something akin to a colossal pinball game.

As stars pass near each other, mutual gravitational attraction perturbs their orbits. As a result, the stars fly off into new directions. In extreme cases, some are tossed out of the galactic center entirely, streaming away so fast that they will leave the galaxy. These "hypervelocity" stars are rare, but astronomers have found some.

Astronomers found the first known hypervelocity star in 2005. It zips through the galactic halo at more than twice the speed necessary to escape the Milky Way's gravitational influence. Today, astronomers know of dozens of hypervelocity stars destined to leave the galaxy and forever wander intergalactic space.

On average, a star escapes the galactic center about once every 100,000 years. Over the Milky Way's history, about 100,000 suns have suffered this fate. But what happens to those that, instead of being flung out of the galaxy, are tossed inward toward the black hole?

Some astronomers have speculated that such a star could meet a spectacular end. The black hole's intense gravity would stretch an approaching star into the shape of a long, thin pancake and heat its interior. The stretching and heating of the star might ultimately trigger a supernova explosion, although the physical details of this process remain to be worked out.

S2 will make its closest approach to the central black hole in mid-2018, though it won't undergo such extreme forces. But its orbit could shift enough in the future so that it does come much closer, and calculations suggest that it then could explode with the power of 100 normal supernovae. Astronomers think that such close encounters and spectacular explosions might occur about once every 10,000 years. The unusually energetic supernova would splatter the star's remains across space. The debris would then expand as a glowing ball of superheated gas, or plasma, many light-years across.

Could the remnant of such a colossal blast still be present in the Milky Way's core? Radio astronomers may have found just such a plasma shell near Sgr A*. In fact, Sgr A* is probably inside it. Also, the eastern part of the galaxy's core region, Sgr A East, shows signs of the kind of heavy elements forged in supernova explosions — further evidence for a blast in the past.

The remains of the star that went supernova may now lie at Sgr A East's northern edge. It's a neutron star, the dense remnant of a star that collapsed and exploded. Known as the cannonball, the star seems to be speeding through space trailing hot gas like an artillery shell. *— J.D.*

It's also conceivable that Sgr A*'s companion stars formed in dust clouds circling at high speed within a few light-years of the galactic center. Collisions between the clouds could have spawned shock waves, triggering star formation. As the result of collisions between the clouds, they and the new stars embedded within them could have shed enough momentum to settle into orbits around the black hole. The galactic core's strong magnetic field would have gradually swept the leftover interstellar dust and gas away from the black hole. What would remain is a disk of young stars in close orbit to Sgr A*.

This scenario explains much of what astronomers see in the galactic core, although not all. UCLA astronomer Brad Hansen thinks he has a viable alternative: Hot young stars now orbit the Milky Way's central black hole because a second smaller black hole dragged them there.

The process begins in a crowded young star cluster, dozens of light-years from the galactic center. Collisions between big stars in the cluster's core form an intermediate-sized black hole in the range of 1,000 to 10,000 solar masses. Gradually, the black hole would migrate toward the galactic center, dragging its cargo of "hostage stars" along with it. Hansen argues this is the only way to quickly transport massive young stars into the galactic center from an outside star-birth location.

All the black-hole ferry scenario lacks is hard evidence to support it. If a second black hole orbits the primary black hole in the galactic core, its presence might be detectable. Its tug on Sgr A* might cause a detectable wiggle. Clearly, astronomers still have a lot of work left to fully understand the processes at work in the galactic core.

Imaging the black hole

Fast-moving stars like S2 remain the best evidence that a black hole lies at the heart of the Milky Way. Other support includes periodic bursts of infrared light from Sgr A*. The bursts suggest the black hole spins, completing a turn every 17 minutes. Astronomers have also detected strong radio pulses coming from Sgr A*. This may indicate that packets of ultra-hot gas and dust are falling into the black hole.

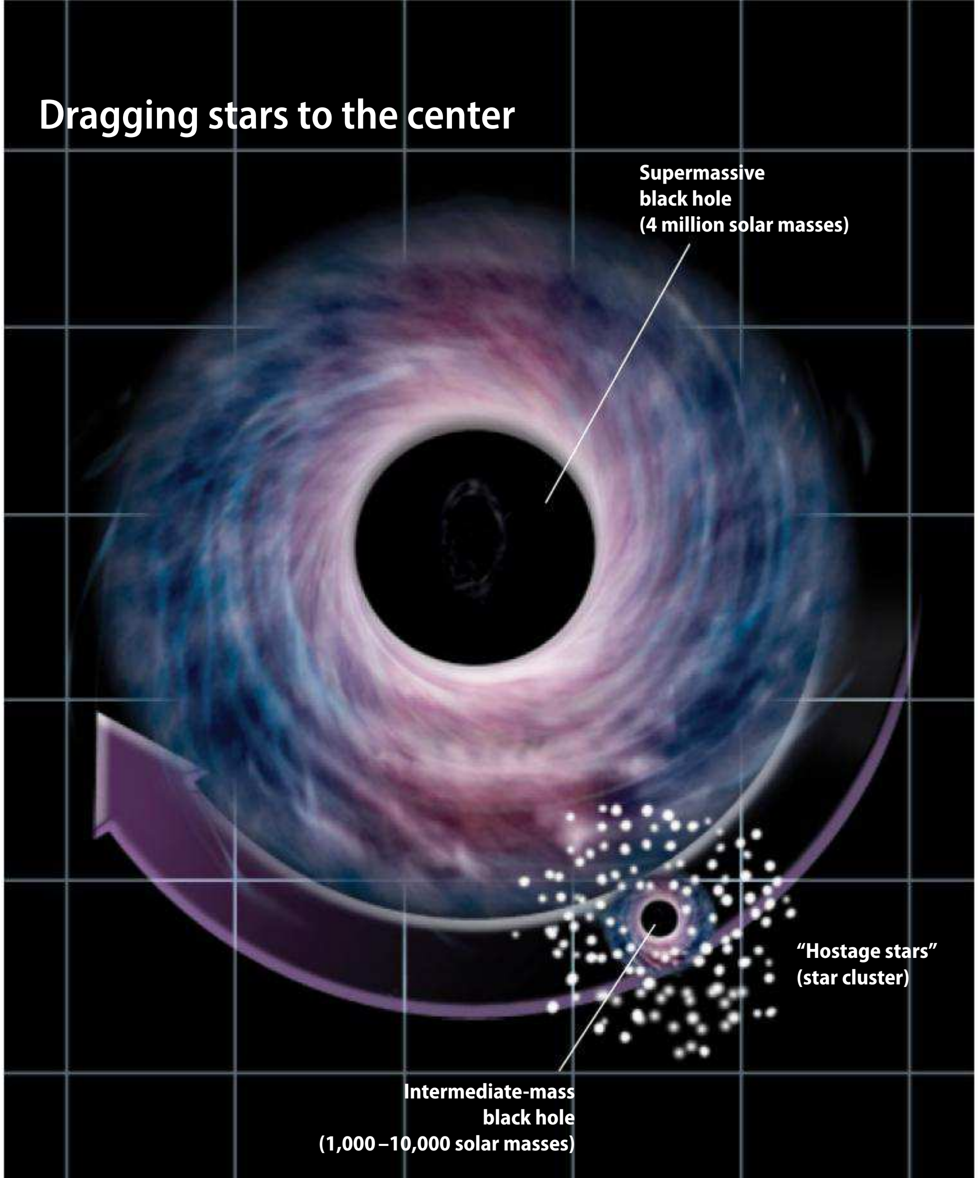
But this is all still circumstantial evidence. The definitive proof might come if astronomers could actually image the black hole's edge or "event horizon," beyond which no light or matter can escape.

Radio energy passes through the veil of obscuring dust and gas around the galactic center, providing a way to directly image a black hole. By itself, a black hole is essentially invisible. But it would be detectable as a silhouette against the accretion disk of gas spiraling into it. The gas emits energy as it accelerates to high speeds around the black hole.

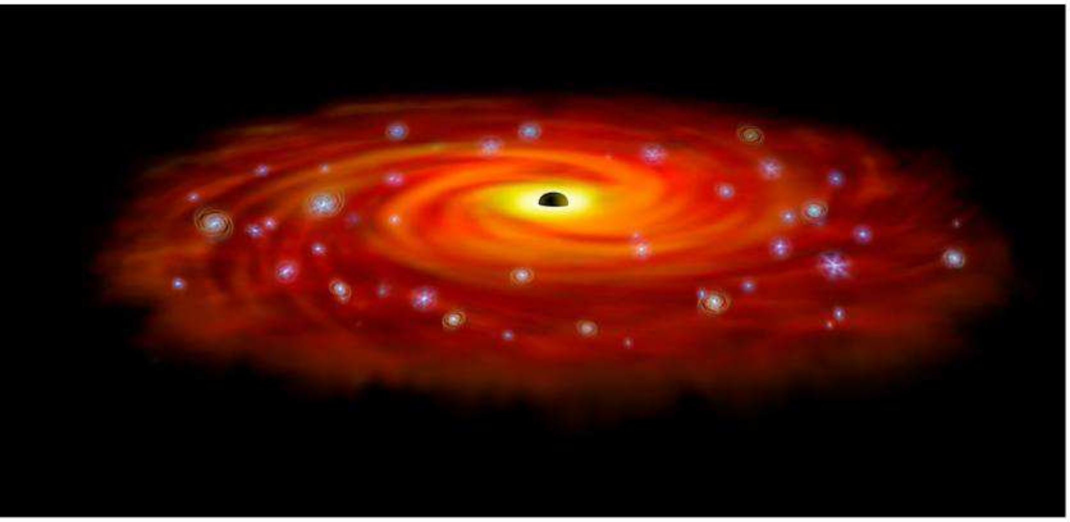
Light follows a highly curved path near a black hole, making its silhouette appear wider than it actually is. Bright rings or arcs, formed as the black hole bends or "lenses" light from background sources, might protrude from the silhouette's edges.

In 2008, radio astronomers announced an important milestone in the study of our galaxy's black hole. By combining the power of three radio telescopes, researchers detected features around Sgr A* as small as 31 million miles (50 million km) across. The study found that radio emission from Sgr A* is offset from the black hole, perhaps because it comes from an accretion disk. Astronomers hope the Event Horizon Telescope — a nearly Earth-sized radio observatory comprising about a dozen separate instruments — will be able to image the black hole's silhouette in the next few years.

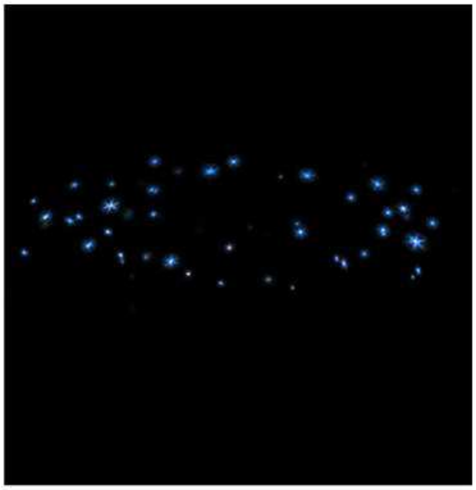
Whatever the result, imaging the Milky Way's central black hole will put the existence of black holes on a firmer footing and perhaps reveal important new insights about the evolution of galactic cores. A failure to see it will bring into question what we understand about the heart of our own galaxy — including the origins of the high-speed roller derby of young stars whizzing around its center.



TO EXPLAIN THE MYSTERY of how young stars reached the Milky Way's core, astronomer Brad Hansen of UCLA proposes that an intermediate-sized black hole dragged them in as a group. The cluster continues to orbit the galaxy's central supermassive black hole. *Astronomy*: Roen Kelly



STARS COULD FORM near a black hole if a sufficiently dense disk of dust and gas surrounded it. Despite the forces exerted by the black hole's tremendous gravity, local regions of the disk could collapse and trigger star birth. NASA/CXC/M. Weiss



AT THE END of the star-birth process, a cluster of hot young stars remains around the black hole, even though the gas from which they formed has dissipated. NASA/CXC/M. Weiss

THE MILKY WAY climbs majestically above the 4-meter telescope at Cerro Tololo Inter-American Observatory in Chile. Despite its peaceful appearance, our galaxy has devoured untold numbers of dwarf galaxies. K. Don/NOAO/AURA/NSF

How the Milky Way devours its neighbors

Our galaxy's current eminence owes much to a past — and present — spent cannibalizing dwarf galaxies.

By Ray Jayawardhana

On a clear moonless night, the arc of the Milky Way overhead seems the very picture of serenity. Yet its gentle glow masks a life of turmoil. Episodes of violence, plunder, and cannibalism pervade astronomers' emerging picture of our galaxy's history.

Unraveling this story, with the help of painstaking observations and sophisticated computer simulations, could shed light on how the Milky Way acquired its present form. It could also help astronomers understand galaxy evolution in general.

The classical view of the galaxy's origin, proposed more than four decades ago, starts with a single large gas cloud that collapsed when the universe was in its infancy. In 1978, however, Leonard Searle and Robert Zinn, then at the Carnegie Observatories in Pasadena, California, introduced a new twist.

The astronomers suggested that some globular clusters — dense knots of hundreds of thousands of stars in the galactic halo — joined the Milky Way after its central regions and disk already had taken shape. Ever since, various astronomers have argued that certain globular clusters are stolen goods, wrested away from other smaller galaxies as they merged with the Milky Way.

Clusters orbiting the galactic center "backward" — opposite to the orbits of the Sun and most other stars — are among the most likely interlopers. Many researchers think Omega Centauri (NGC 5139), the most massive globular known, could be the nucleus of a disrupted dwarf galaxy.

This more chaotic picture agrees better with current theory about how galaxies evolved from an initially near-homogeneous universe. The favored model goes by the name "cold dark matter" (CDM). This theory assumes dark matter — the mysterious substance whose gravity dominates over normal matter — consists of slow-moving (hence "cold") particles.

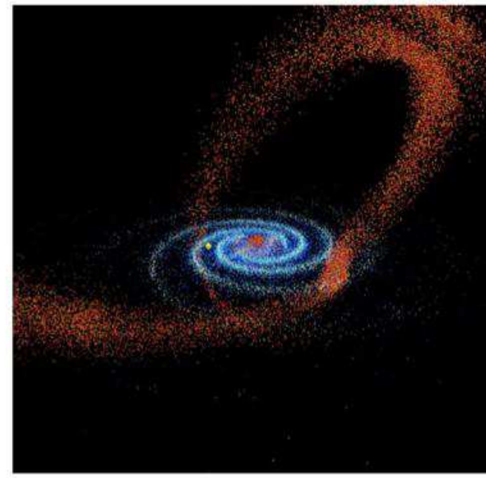
From the bottom up

The CDM scenario, explored in numerous theoretical calculations and simulations, suggests structure formed from the bottom up. Large galaxies grew from the mergers of smaller clumps. Galaxies grouped into clusters and still-larger superclusters. One challenge for the CDM model is that it predicts many more dwarf galaxies in our cosmic neighborhood than astronomers observe.

It could be that the Milky Way and other large galaxies, like the nearby Andromeda Galaxy (M31), already have gobbled up most of their smaller brethren or distorted them so much they are difficult to spot even in our own backyard.

A massive galaxy exerts powerful tidal forces because the gravitational pull acting on

OMEGA CENTAURI (NGC 5139) — the Milky Way's biggest and brightest globular cluster — may be the nucleus of a dwarf galaxy captured long ago by the Milky Way. Daniel Phillips



THE SAGITTARIUS DWARF SPHEROIDAL GALAXY appears as a distorted stream of reddish dots surrounding the bluish spiral arms of the Milky Way. This simulation models data derived from the 2MASS project. David Law/University of Virginia

the near side of a neighbor significantly exceeds that acting on the far side. These forces overwhelm the gravity binding a dwarf galaxy together and rip it apart. The tides draw gas and stars into long trails or streams that eventually disperse. Once the "loot" mixes in with the big galaxy's contents, tracing its origin proves far from easy.

The vast majority of mergers that built our galaxy probably happened early in its history. But the Milky Way continues to destroy and swallow its remaining neighbors.

Big news from small galaxies

The Magellanic Stream has often been held up as the poster child of an ongoing merger. The stream consists of gas stripped from two irregular satellite galaxies well known to Southern Hemisphere observers: the Large and Small Magellanic Clouds. First identified more than 40 years ago, the stream trails the motions of the galaxies for some 600,000 light-years. The so-called Leading Arm stretches between the clouds and our galaxy.

Some models suggest the Milky Way created these filaments. But a decade ago, Nitya Kallivayalil, then at MIT, and her colleagues found that the Magellanic Clouds are moving unexpectedly fast. Unless our galaxy has far more mass than we think, the clouds may be on their first pass — and tides alone likely could not produce the stream.

The Milky Way also seems to be disrupting other Local Group dwarfs. University of Virginia astronomer Steven Majewski leads one of several groups that have discovered tidal debris from several of these dwarfs, including those in the constellations Carina, Leo, Ursa Minor, and Sculptor.

Perhaps the most dramatic case of a cannibalized Milky Way satellite is the Sagittarius Dwarf Spheroidal Galaxy. Rodrigo Ibata, then a graduate student at Cambridge University, found it almost by accident.

In 1994, Ibata was studying the motions and chemical compositions of stars in our galaxy's bulge. While collecting spectra of his sample stars at the Anglo-Australian Telescope in Australia, Ibata noticed a few of the reddest stars had velocities different from all the others. Even stranger, the stars appeared to be moving together. On the next couple of nights, he took spectra of more red stars. They all shared the same unusual motion.

When Ibata returned to Cambridge, he and his colleagues scanned archival photographic plates of that region of sky, then plotted the positions of red stars similar in brightness to those he had found with peculiar velocities. This exercise revealed the contours of a hitherto unknown galaxy. It lies roughly perpendicular to the Milky Way's disk and about 100,000 light-years away, on the far side of the galactic center.

It had been hiding behind the Milky Way's thick veil of stars and dust. What's more, the newly found dwarf spheroidal galaxy, named Sagittarius after the constellation that contains its center, has a rather contorted appearance. This represents clear evidence of bullying by the dwarf's massive neighbor.

During the past 20 years, astronomers have attempted to chart the dwarf galaxy's full extent. Recent maps show its debris scattered in a giant arc that wraps around the Milky Way. Ibata's team and others argue that several

Contributing editor **Ray Jayawardhana** *is the dean of science and a professor of physics and astronomy at York University in Toronto. His research focuses on planetary origins and diversity. His most recent book is* Neutrino Hunters *(Scientific American/Farrar, Straus and Giroux, 2013).*

globular clusters previously thought to belong to our galaxy actually came from the Sagittarius dwarf. Other stolen clusters and individual stars may exist, but they're already so well mixed in with the Milky Way's own that astronomers can't trace their origins.

The surprise discovery of the Sagittarius dwarf raised the possibility others like it may lurk undetected. Astronomers imagined spaghetti-like strands crisscrossing the Milky Way, each filament retaining a faint memory of the path taken by its long-since-destroyed parent galaxy or globular cluster. Scientists tried to identify streams of stars with peculiar motions and odd chemical abundance patterns, which might betray their alien origins.

The tides turn to Sloan

For researchers in pursuit of these elusive fossils, the Sloan Digital Sky Survey has turned out to be a treasure trove. Initiated in 2000 and now in its fourth phase, the multi-wavelength survey covers one-third of the sky.

Michael Odenkirchen and Eva Grebel, then at the Max Planck Institute for Astronomy in Germany, and their colleagues quickly discovered two tidal trails. The trails emerge from a sparse and remote globular cluster cataloged as Palomar 5. One of these trails has now been traced across more than 20° of sky, spanning some 25,000 light-years.

Scientists think Palomar 5 lost much of the observed debris in the past 2 billion years. Simulations suggest this cluster will break apart completely the next time it crosses the Milky Way's disk, just 100 million years from now. Other researchers have since identified an even larger debris arc associated with the globular cluster NGC 5466.

In 2003, Heidi Jo Newberg of Rensselaer Polytechnic Institute in Troy, New York, Brian Yanny of Fermilab outside Chicago, and their colleagues reported the discovery of a "ring" of stars beyond the visible edge of the Milky Way's disk. They named it the Monoceros Stream because its center lies toward that constellation.

The Monoceros Stream's stars stood out in the Sloan data because they have unusual colors. The colors arise from the stars' lack of heavy elements — meaning all those natural elements heavier than helium. Some scientists think the stream

THE LARGE MAGELLANIC CLOUD provides a major portion of the Magellanic Stream, a 600,000-light-year-long concentration of gas perhaps stripped by the Milky Way from this irregular satellite galaxy and its neighbor, the Small Magellanic Cloud. Andreas B'ker & Axel Martin

originates from a dwarf galaxy in the constellation Canis Major that's being torn apart by the Milky Way's gravitational tides.

In 2006, Mario Juric of Princeton University and his colleagues reported discovery of a remarkable increase in stellar density toward the constellation Virgo. The structure turned up in a 3-D map of about 48 million stars the team made from Sloan data.

At an estimated distance of 30,000 light-years, the density structure lies well within the Milky Way's confines. The most likely explanation is that these "extra" stars belong to a slowly dissolving dwarf galaxy.

So many tidal trails surround the north galactic pole that researchers dubbed the region the "field of streams."

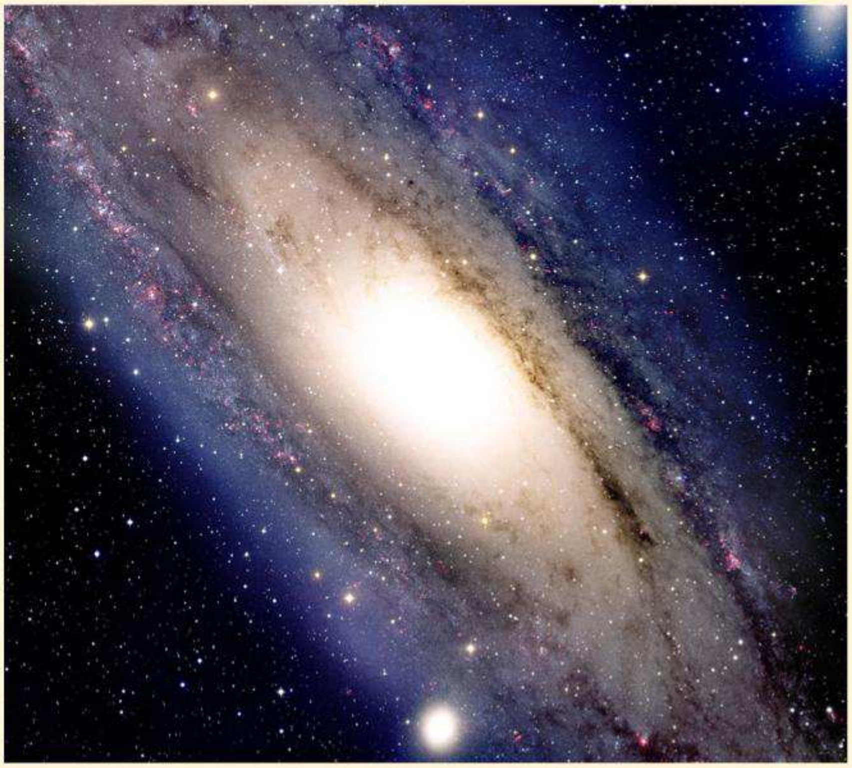
A team led by Kathy Vivas of the Center for Astronomical Investigations in Venezuela had noticed hints of such a beast a few years earlier. The researchers were searching for a type of pulsating variable star known as RR Lyrae stars. "We saw a high density of RR Lyrae stars in the region — more than 20 of them — and speculated that they belonged to a small galaxy being cannibalized by the Milky Way," she says. In light of the Sloan findings, "It appears that the stellar stream we detected is itself part of a larger structure."

Field of streams

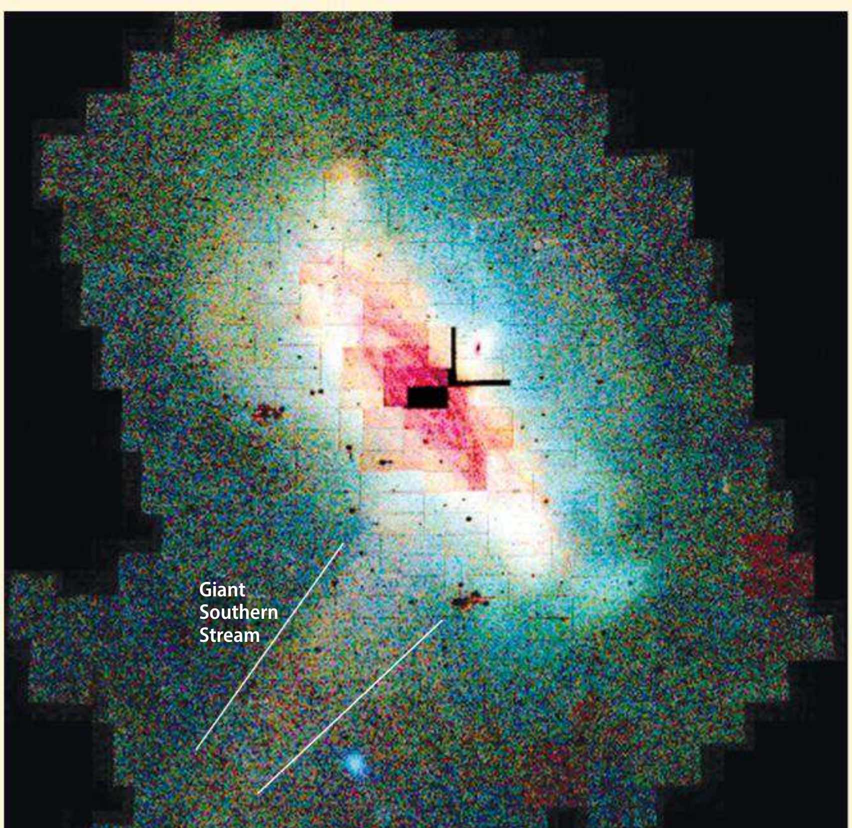
Later in 2006, Cambridge University's Vasily Belokurov and Daniel Zucker and their collaborators identified a number of other trails and lumps in Sloan images taken toward the north galactic pole, not far from the direction of the previously known Sagittarius and Monoceros streams. So many tidal trails populate this region that the researchers dubbed it the "field of streams."

One of these trails covers 30° of sky. It contains two globular clusters deficient in heavy elements and could be the "orphan" of yet another disrupted dwarf galaxy. At least three more faint Milky Way satellites, all showing signs of distortion, turn up in the

The cannibal next door



THE ANDROMEDA GALAXY (M31) looks serene when viewed from Earth, but it disguises a history of rampant cannibalism. T.A. Rector/B.A. Wolpa/NOAO/AURA/NSF



A MASSIVE STREAM OF STARS emerges from behind the Andromeda Galaxy in this computer-processed image from the Isaac Newton Telescope. INT/WFC

With evidence of the Milky Way's cannibalism all around us, it seems logical our galaxy's near twin, the massive Andromeda Galaxy (M31), should show signs, too. The nearest large galaxy to our own, the spiral behemoth M31, lies approximately 2.5 million light-years away. That vast distance makes it difficult for astronomers to discern relic stars left behind by past mergers.

Despite the challenges, astronomers have made progress. In 1993, a team led by Tod Lauer of the National Optical Astronomy Observatories in Tucson discovered what appear to be two dense knots — called a double nucleus — at M31's center. The researchers needed the Hubble Space Telescope's sharp eyes to separate the two structures. Some astronomers speculated that one of the clumps originated in a satellite galaxy that had collided with M31.

One problem with this story: The two clumps should have merged in less than 100 million years — a short time compared with the several-billion-year age of the stars in those knots. Most researchers now prefer an alternate explanation, proposed by Scott Tremaine of Princeton University. He thinks both knots belong to a single elongated disk of stars having a supermassive black hole at one focus.

More convincing evidence of M31's cannibalism came to light in 2001. At that time, astronomers were conducting a deep panoramic imaging survey of the Andromeda Galaxy's halo with the 2.5-meter Isaac Newton Telescope on La Palma in the Canary Islands. Rodrigo Ibata of Strasbourg Observatory in France and his collaborators discovered an extended stream of stars protruding from Andromeda. Astronomers have dubbed this feature the Giant Southern Stream.

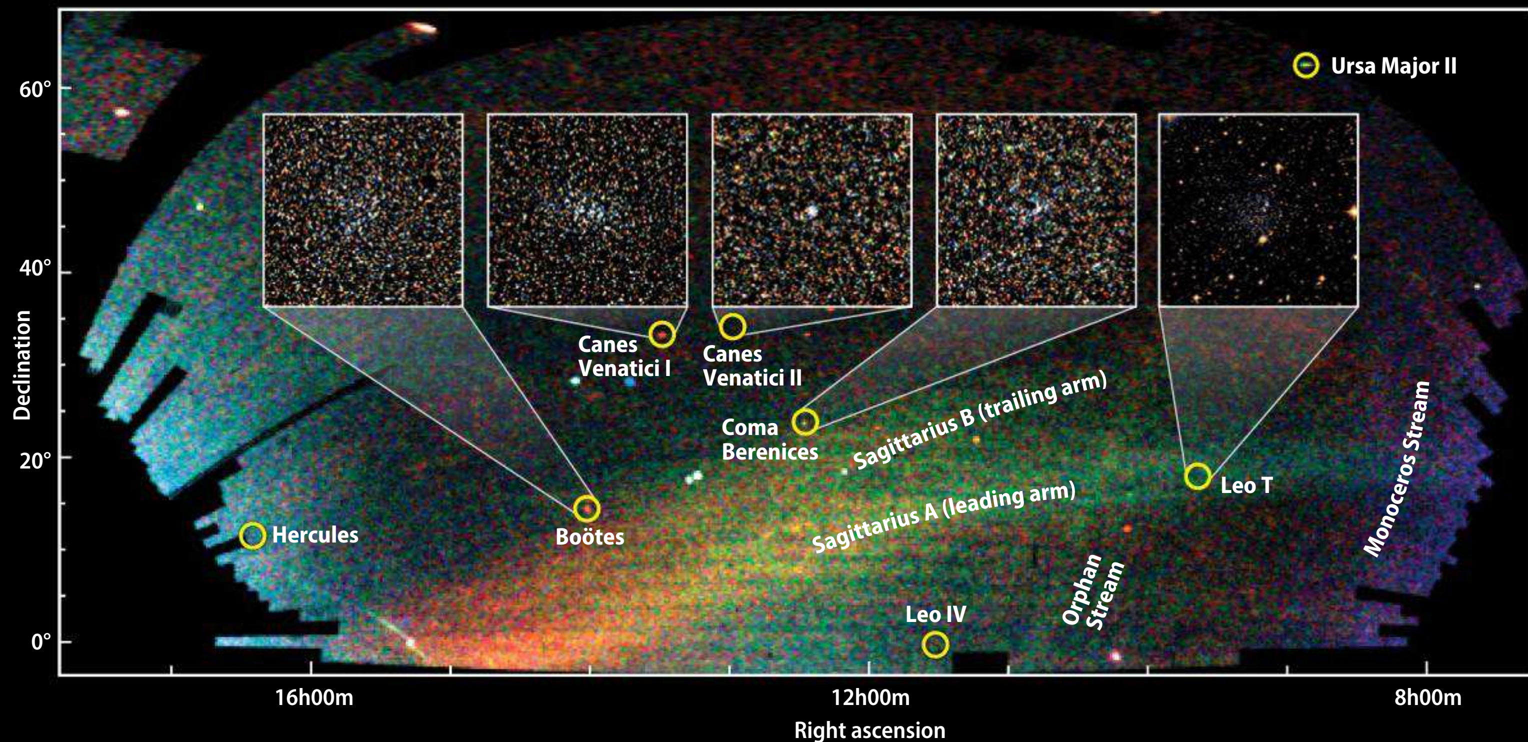
Some researchers have proposed that the Giant Southern Stream consists of stars torn from one of Andromeda's two close companions, the dwarf satellite galaxies M32 and NGC 205. According to Puragra Guhathakurta of the University of California at Santa Cruz, there's no hard evidence for this explanation.

The more likely scenario, Guhathakurta says, is that Andromeda has completely devoured a dwarf galaxy. If this is true, the Giant Southern Stream may be just one segment of an extended debris trail looping around the giant galaxy. The trail marks the dwarf galaxy's extended death spiral into Andromeda.

A team led by Guhathakurta has reported evidence linking the Giant Southern Stream to several other locations in Andromeda where large numbers of stars appear to move as a group. The researchers believe these features are parts of a continuous star stream. "We think we are seeing the debris trail of a small, chemically rich galaxy that fell into Andromeda," Guhathakurta says.

More recently, the Sloan survey revealed a giant, diffuse clump of stars just outside M31's disk that could be the remnants of another satellite galaxy being torn apart by Andromeda's tides. The exact nature of this structure remains a mystery, however. Many astronomers continue to search Andromeda for clues to its voracious and chaotic history. — *R.J.*

Mapping the field of streams



THE NORTHERN SKY is awash with stellar debris cannibalized by the Milky Way from numerous dwarf galaxies (yellow circles). Our galaxy's tidal forces overwhelm the small galaxies' puny self-gravitation. The longest debris stream, which forks into at least two segments, belongs to the Sagittarius dwarf galaxy. In this depiction, blue objects lie closest to Earth and red ones are far away. *Astronomy*: Roen Kelly, after Vasily Belokurov and the SDSS-II Collaboration

Sloan survey. Taken together, these findings are "a striking demonstration of multiple merger events going on in the Milky Way right now," Yanny says.

Astronomers now have little doubt our galaxy has enriched itself at the expense of others. "In fact, the majority of globular clusters might be relics of accretion events," claims Julio Navarro, an astrophysicist at the University of Victoria.

As supporting evidence, Navarro points to the agreement between the distribution of globular clusters around the Milky Way and the density profile of accreted stars in his group's simulations of galaxy formation. He finds a similar match between models and observations of our galaxy's near twin, the Andromeda Galaxy. This suggests galactic cannibalism might be rampant.

Our exotic neighbors

But, the "stolen goods" may not be found just in the galaxy's outer reaches. Some interlopers may lurk in the solar neighborhood, too. Timothy Beers of the University of Notre Dame and his collaborators identified a group of stars in the Milky Way's disk that shares the chemical abundance pattern of stars in Omega Centauri, and may have come from the same disrupted parent galaxy.

Another such grouping includes the relatively nearby red giant star Arcturus. The members of this group move through space in a similar manner to one another, but much slower than most other stars in their vicinity. They also share a distinct chemical imprint.

> There could have been hundreds of small mergers in the Milky Way's infancy, or just a few major collisions.

"You can make a plausible though not conclusive case that these stars came from a disrupted satellite galaxy," says Navarro. His simulations show tidal debris not only can accumulate in the galaxy's halo, but also contribute to the disk. "It may be that most metal-poor stars in the Milky Way's disk originated in various accreted satellites," he argues.

Sloan researchers have also discovered two distinct populations of stars in the galaxy's halo. The groups orbit the galaxy's center in opposite directions, providing more evidence for multiple mergers in the past. Unfortunately, it's probably impossible to pin down just how many neighbors the Milky Way has devoured during its long history. There could have been hundreds of small early mergers, or just a few major collisions that dominated.

A study of 20,000 stars in four dwarf spheroidal galaxies found a puzzling paucity of extremely metal-poor stars. This suggests the Milky Way's current small neighbors may differ fundamentally from those it devoured in the distant past.

Detailed observations of large numbers of stars in the galactic halo could provide more clues to the Milky Way's history. A survey project known as RAVE, for RAdial Velocity Experiment, has measured the velocities and compositions of 483,330 stars. Meanwhile, Sloan's APOGEE-2 survey will collect spectra of another 300,000 stars in both the northern and southern skies by the time it wraps up in the autumn of 2020.

Our galaxy clearly has had a colorful, if not dramatic, history. But the story is far from complete. The challenge for astronomers will be to weave it together from a million pieces scattered in space and time.

BEAUTIFUL BUT BORING was how many astronomers viewed globular clusters such as M13 until advanced telescopes revealed these stellar communities to be full of surprises.

Canada-France-Hawaii Telescope/Coelum/J.-C. Cuillandre

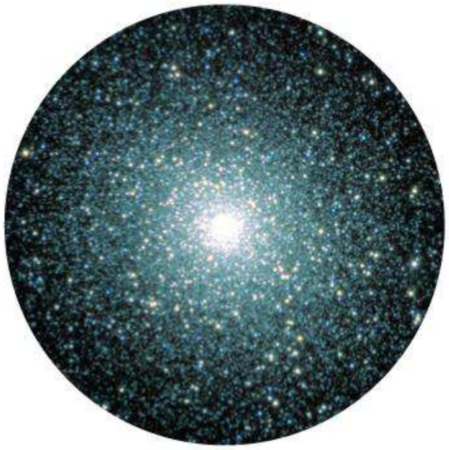
Exploring the galaxy's starry satellites

By studying globular clusters, astronomers are deciphering the Milky Way's oldest secrets. **By Marcia Bartusiak**

The globular clusters surrounding the Milky Way, some 150 in all, gleam like cosmic sparklers frozen in time. In each, brilliant specks of light hover around a dense and blazing core. Within a sphere only 100 light-years wide, anywhere from 1,000 to 10 million stars exist, bound by mutual gravitational attraction.

One of the finest examples lies in the constellation Serpens. The German astronomer Gottfried Kirch and his wife Maria Margarethe first noticed this object on the night of May 5, 1702. In her diary, Margarethe described the compact patch as a *neblichte Sternchen* (nebulous star). The French comet-hunter Charles Messier rediscovered it in 1764 and also was unable to distinguish its clusterlike quality, calling it a "beautiful nebula." It was fifth on the list in Messier's famous catalog of celestial objects that were not comets, so it became M5.

Not until 1791 did William Herschel, the most accomplished observer of his time, at last resolve M5 into a compact ball of stars. With his 48-inch telescope that had a focal length of 40 feet, he counted some 200 stars within it. Herschel already had a theory to explain (and name) this amazing assembly. In a famous 1785 paper in the *Philosophical Transactions of the Royal Society of London* entitled "On the Construction of the Heavens," he wrote about the formation of nebulae. He imagined a particularly large star attracting others to it "by which means they will be, in time, as it were, condensed about a center; or, in other words, form themselves into a cluster of stars of almost a globular figure."



M5 IN SERPENS was mistaken for a star and a nebula before being identified by William Herschel in 1791 as a "cluster of stars of almost a globular figure." It lies about 25,000 light-years away and appears to be a ripe 13 billion years old. Hillary Mathis (REU Program)/NOAO/AURA/NSF

Today, the Hubble Space Telescope can probe into the very heart of a Milky Way globular cluster. Often described as a mound of diamonds on black velvet, a globular cluster seen with Hubble's keen eye takes on a far more colorful appearance, with red giants dotting the cluster like large rubies and blue stragglers resembling glittering aquamarines.

Astronomers have renewed appreciation for more than just the clusters' colors. "At the time I was a graduate student in 1970," says globular cluster expert William Harris of McMaster University, "globular clusters were thought to be a routine area of study. The clusters were considered among the oldest objects in the universe — all the same from one to the other. Some were bigger, some smaller. It was not a terribly active field."

But all that's changed over the last 25 years. Electronic digital detectors on ground-based telescopes, coupled with optical, ultraviolet, and infrared imaging on Hubble, have allowed astronomers to study the magnitudes, colors, and distribution of globular clusters beyond our galaxy, and even beyond the Coma Cluster of galaxies. "We were too caught up with what happened here in the Milky Way," explains Harris.

M87, a massive elliptical galaxy near the heart of the Virgo Cluster, glows diffusely. This giant contains about 13,000 globular clusters. David Malin/Anglo-Australian Observatory

It seems globular clusters patronize all types of galaxies, although the clusters themselves make up just a tiny fraction of most galaxies' stellar mass (usually no more than one percent). A dwarf galaxy may claim just one globular cluster, and giant ellipticals, such as M87 in the Virgo Cluster, may host more than 10,000 clusters that huddle around the galaxy like a swarm of bees. "We're finally seeing other neighborhoods and are forced to conclude that there's a much wider range of globular clusters than we realized," Harris says. "We now have a much larger playground in which to play."

Astronomer James Hesser of the Herzberg Astronomy and Astrophysics Research Centre agrees. "The new technologies were magic," he says. "Instead of using insensitive, nonlinear photographic plates to do photometry and then carrying out laborious photoelectric calibrations via single stars, we suddenly could do hundreds of stars quickly and accurately." The resulting surge of data changed the understanding scientists had of these "globs" (as amateur astronomers like to call them) that had stood for decades.

Early studies

All globular cluster research is inevitably rooted in the observations of astronomer Harlow Shapley, who "cast a long shadow on the field," notes Harris. "He was the first to talk about globular clusters as a system, a population." In the 1910s, while at Mount Wilson Observatory in California, Shapley published a series of articles on the Milky Way's globular clusters.

In the 12th paper, he announced what became his most famous discovery: From the distribution of globulars around our galaxy, he concluded that the Sun is situated not in the galaxy's center but off to one side of the flat disk of stars. Later, Edwin Hubble detected globular clusters in the nearby Andromeda Galaxy, determining that globulars are members of other galaxies as well.

Globular clusters were typically defined as the oldest objects in the universe, all predating their host galaxies and all alike. The first hints that not all globulars are created equal arose in the 1940s and '50s, when a few dedicated cluster observers, particularly N.U. Mayall of California's Lick Observatory, William Wilson Morgan of Wisconsin's Yerkes Observatory, and Tom Kinman of the National Optical Astronomy Observatory in Tucson, Arizona, found evidence that clusters vary both in content and speed. In 1994, when the Sagittarius Dwarf Spheroidal Galaxy was discovered as a companion to the Milky Way, it turned out the dwarf's nucleus was globular cluster M54.

And globular clusters form even today — in the aftermath of recent galaxy interactions, mergers, and starburst events. This finding would have been unbelievable half a century ago, when the first age estimates of globular clusters were made by comparing observations of cluster stars with theories of stellar evolution. "In the early days of globular cluster studies," says Catherine Pilachowski of Indiana University, "astronomers attempted to find one answer to how and when they were made. But now we know there are probably many paths."

For richer or poorer

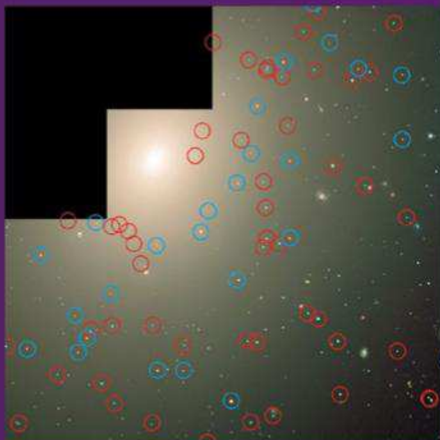
Today astronomers view globular clusters as vital relics of the galaxy formation process itself, offering clues to how a particular galaxy arrived at its size and shape.

Far from being uniform, globular clusters differ by age and content. Some are "metal poor," meaning they do not have great quantities of elements heavier than helium, whose most abundant form contains two protons and two neutrons in its nucleus. Because most of the heavier elements were forged by nuclear fusion in stars and distributed by supernovae, metal-poor clusters indicate an early formation from primordial material.

Other globular clusters have been found to be "metal rich" (containing one-sixth or more of the Sun's abundance of heavier elements). Astronomers believe metal-rich globs formed after one or more rounds of star formation and stellar explosions scattered heavier elements, like ashes, into space. "These [different types] must represent fairly distinct epochs of cluster formation," wrote Harris in a 1999 review of the field.

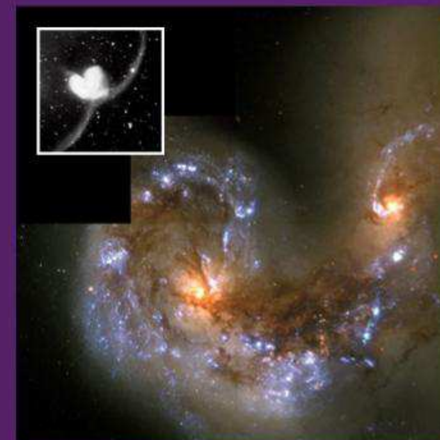
In the Milky Way, the classic, metal-poor clusters reside predominantly in the outer halo of our galaxy and move rather slowly. Metal-rich clusters tend to dwell around the central galactic bulge, to orbit more rapidly, and to be 1 billion to 2 billion years younger than their metal-poor cousins.

Different types of globular clusters inhabiting different zones within our galaxy might be evidence that the Milky Way underwent separate phases of assembly. The exact details



A GENERATION GAP exists among globs in the elliptical galaxy NGC 4365. Blue circles represent clusters only a few billion years old, while red circles signify clusters about 12 billion years old. ESO

THE ATOMS-FOR-PEACE GALAXY, NGC 7252, formed from a galactic merger. Some 40 young bluish globs shine in a gaseous disk in the galaxy's core. B. Whitmore (STScI)/NASA; Inset: François Schweizer



THE ANTENNAE GALAXIES, NGC 4038 and NGC 4039, formed gas trails and globular clusters when they merged. Blue globs surround the galaxies' orange cores. B. Whitmore (STScI)/NASA

are under debate, but "there's a growing sense," says Pilachowski, "that the metal-poor globular clusters were acquired through the merger of smaller systems that had already created their globulars."

This meshes nicely with recent observations showing young galaxies being assembled from smaller fragments. The metal-rich clusters apparently formed later, during the collapse of the larger Milky Way cloud.

That the Milky Way could have developed in phases is still speculative, though, Harris says. "Clusters represent only one percent of the stellar mass of a galactic halo," he points out. "We shouldn't assume that they tell us exactly how galaxy formation took place. They're special objects and may be telling us only part of the story."

In galaxies outside our own, metal-poor globular clusters appear to have similar make-ups, suggesting they formed under identical circumstances before their host galaxies were created. Metal-rich clusters, on the other hand, mirror the metallicities of their hosts, varying from galaxy to galaxy. Moreover, the number of metal-rich clusters in any one galaxy appears to be directly linked to the galaxy's luminosity: The more luminous a spiral bulge or elliptical, the greater number of metal-rich globular clusters surrounding it. What this says about a galaxy's formation and evolution, though, is still being debated. François Schweizer of the Carnegie Observatories believes many of the metal-rich clusters surrounding ellipticals could be fairly new, an idea that provoked gasps among astronomers when he first made the suggestion more than 30 years ago.

Mergers make gobs of globs

In the 1970s, brothers Alar and Juri Toomre, now a professor of applied mathematics at the Massachusetts Institute of Technology and an astrophysicist at the University of Colorado at Boulder, respectively, carried out computer simulations suggesting elliptical galaxies arose from the merger of disk galaxies. Such an idea was a highly radical notion at the time. Schweizer, however, was greatly influenced by the Toomres' work and soon established a career hunting for examples of merged galaxies. His first successful find was spiral galaxy NGC 7252, whose curved filaments jut out of a fuzzy center. Known as the Atoms-for-Peace galaxy for its vague resemblance to the old-fashioned symbol for an atom, NGC 7252 is generally accepted to have formed about a billion years ago from the turbulent union of two galaxies.

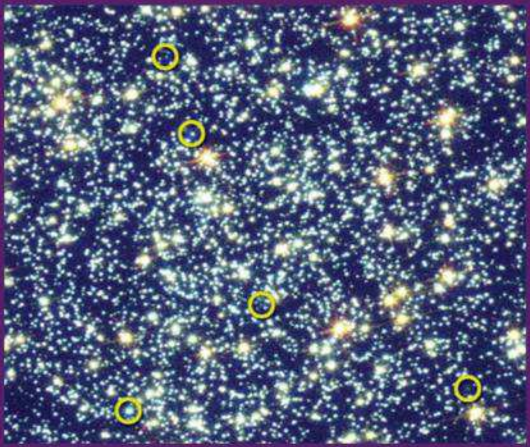
> "In the early days of globular cluster studies, astronomers attempted to find one answer to how and when they were made. But now we know there are probably many paths."

But in 1986, when Schweizer attended an astronomy conference in Santa Cruz, California, generating ellipticals from mergers was still considered heresy. Conferees pointed to the "old" globular clusters surrounding elliptical galaxies as evidence of their great age. Schweizer readily responded that some of those globular clusters likely were new — freshly minted during the merger process. "People at this meeting thought I was nuts," recalls Schweizer. "I had never worked on globular clusters, so I knew the suggestion might ruin my career." At the time, globular clusters were deemed ancient by definition.

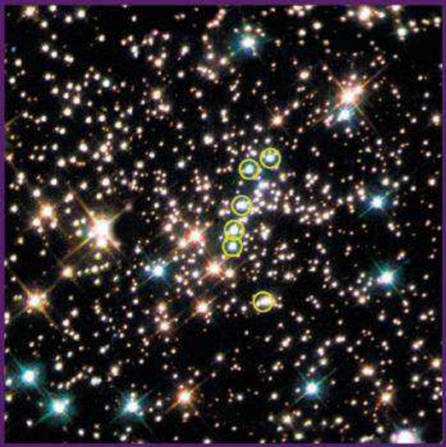
But Schweizer had a hunch: He had seen some weird little dots around NGC 7252 and another merger suspect, NGC 1316 (the noted radio galaxy Fornax A). He thought the dots looked suspiciously like new globular clusters. "Nature knows how to make globular clusters long after the Big Bang — mergers are the process," he explains.

Schweizer was vindicated later by the Hubble Space Telescope as well as larger telescopes on the ground. Looking at the Antennae (NGC 4038 and NGC 4039), a stunning display of two merging galaxies, Schweizer and several colleagues detected thousands of star clusters that had been created within the great clash. When giant clouds of molecular hydrogen embedded in the merging galaxies suddenly experienced rising pressures, they underwent a violent round of star formation.

Within several hundred million years, most of those clusters will be destroyed, their stars dispersed into the field. The most massive stars will die quickly and explode, tearing



IN THE IMAGE AT LEFT, 47 Tucanae (NGC 104), an ancient globular cluster in our galaxy, brims with several million stars. Although the Hubble Space Telescope detected no planets in the cluster during a week of observations, several bright, massive stars called blue stragglers (circled) turned up in the cluster's core (right). Blue stragglers probably result from the merger of two stars. Left: David Malin/Anglo-Australian Observatory; Right: R. Saffer (Villanova Univ.)/D. Zurek (STScI)/NASA



GLOBULAR CLUSTER NGC 6397 lies about 8,200 light-years away in the constellation Ara. Every few million years, two stars merge to form a blue straggler (circled). NASA/Hubble Heritage Team (STScI/AURA)

the cloud apart with supernova blasts. But if the galactic cloud held enough mass in a small volume, some globular clusters probably would survive.

Schweizer and University of Michigan astronomer Patrick Seitzer closely examined older mergers that had time to settle down. In NGC 7252, for example, they found eight young globular clusters that were still very blue, indicating an age of only half a billion years or so (practically newborn in cosmic terms). Many more probably remained hidden by dense clouds of interstellar gas. Schweizer estimates that some 500 globular clusters reside around NGC 7252 — half of them old, half of them new.

This leads to the $64,000 question among globular-cluster observers: Can late mergers explain the thousands of globular clusters found around giant elliptical galaxies? It's still too soon to tell.

"In order to peg the exact ages of globulars in the distant universe, we need larger telescopes to carry out the necessary spectroscopy," notes Hesser. Astronomers no longer doubt that galaxy mergers can create new populations of globular clusters. "But I sense they're a minor component" of the overall pool, he says.

Harris concurs, pointing out that it's difficult to build a tightly bound system like a globular cluster. "Two galaxies merging might make around 300 clusters, but to make thousands would require 10 trillion Suns' worth of mass — the raw material out of which the clusters and all other field stars are made," he says. "The only epoch during which such huge amounts of gas were routinely available within galaxies was the protogalactic era itself." Both Hesser and Harris agree that mergers likely triggered the creation of globular clusters but believe merging protogalactic clouds — as opposed to fully formed galaxies — during the first wave of galaxy formation created the bulk of clusters. From this viewpoint, the Antennae and NGC 7252 are mere shadows of what was happening billions of years ago.

"We were too caught up with what happened here in the Milky Way. There's a much wider range of globular clusters in other neighborhoods."

Ancient globulars date the universe

The small age difference of the Milky Way's globular clusters supports the idea that the majority of clusters were constructed soon after the Big Bang. The most pristine clusters, the ones that have less than one percent of the abundance of metals found in the Sun, are around 12 billion to 13 billion years old. This makes them among the oldest objects in the cosmos and, in essence, yields a good estimate of the universe's age. The more metal-rich clusters in the Milky Way are only a couple of billion years younger. This suggests there was an epoch of massive star cluster formation that began about a billion years after the Big Bang and lasted for a few billion years. It also bolsters views of the early universe, such as in the Hubble Deep Fields, which show galaxies that appear bluer and more agitated in that distant era.

Hesser is pleased that globular cluster ages match estimates of the universe's age calculated from the latest measurements of the cosmic microwave background, the relic radiation from the Big Bang. "Two completely different tests arrive at the same answer!" he says. That wasn't always the case. For many years, calculations based on standard cosmological models indicated the universe was 10 billion years old, younger than the globular clusters. It was a disturbing paradox: How could stars be older than the universe? It was an irreconcilable age difference, and astronomers knew they needed to amend their understanding of the universe.

Help arrived in 1999 with the discovery that the universe is accelerating, its rate of expansion growing faster and faster due to the presence of "dark energy" that appears to pervade space-time. With this added energy

Marcia Bartusiak, *a member of* Astronomy's *Editorial Advisory Board, is a professor in the science writing program at MIT.*

In an ancient glob, planet hunters strike gold

Of the more than 3,700 extrasolar planets found so far, none may be stranger than the one described by astronomers in the July 11, 2003, issue of *Science*. If the discovery team's claims are true, the planet is the oldest and one of the most distant known. It is also the first to be found in a globular cluster, the first to orbit a binary star system, and one of the few planets whose host is a metal-poor star. The world is "different from Earth in just about every way," said NASA astronomer Anne Kinney at the time.

The suspected gas giant orbits a tight pairing of a pulsar and a white dwarf. This system lies within M4, an ancient globular cluster 7,200 light-years from Earth in the constellation Scorpius the Scorpion.

Because M4's stars are all about the same age, astronomers believe the planet formed around the same time as the stars — about 13 billion years ago. Almost all of the nearly 4,000 other planets found to date are estimated to be roughly half that age.

"This implies that planet formation happened very early in the universe," says team member Steinn Sigurdsson of Pennsylvania State University. The globular cluster's stars formed so early that they contain just 1⁄30 the Sun's abundance of heavy elements — a surprise to some scientists who believed planets needed more than hydrogen and helium and a sprinkling of heavier elements to form.

The planet's location suggests it's been through a lot in its long life. "There's no way it could've formed in its current position," Sigurdsson says. He and colleagues imagine the planet formed in the cluster's outer regions around a star slightly less massive than the Sun. In their scenario, the star and its planet migrated toward M4's core and the pulsar they now accompany captured them. Eventually, the original host star puffed into a red giant, which the neutron star stripped of gas. The red giant's remains became a white dwarf, and the pulsar's rotation rate sped up to about a hundred times per second.

Finding the planet (which is too faint for astronomers to image) took a similarly tortuous route. Discovered in 1988, the millisecond pulsar, called PSR B1620–26, emits regular pulses of radio emissions. Variations in these radio waves showed the pulsar was tugged by an object that Hubble revealed as the white dwarf and another, unseen object. Estimated at 2.5 times Jupiter's mass, the third object was inferred to be a planet. It remains about 2 billion miles from the pair (roughly Uranus' distance from the Sun), orbiting the two dead stars once a century.

Carnegie Institution astronomer Alan Boss, whose own theory suggests planets don't need rocky cores but can form quickly from gas alone, called the discovery "a stunning revelation." But Mario Livio, former head of the science division at the Space Telescope Science Institute, isn't 100 percent sold on the "Methuselah" interpretation. "I can definitely think of scenarios in which [the planet is younger than its host star]," he says. "Given that it is associated with a pulsar, there was a supernova involved. Supernovae can produce huge amounts of dust, and dust can [in principle] form planets." — *Vanessa Thomas*

THE OLDEST KNOWN PLANET orbits a binary system made of a pulsar and a white dwarf (circled) in globular cluster M4. NASA and H. Richer (University of British Columbia)

gradually boosting cosmic expansion over the eons, the universe was found to be older, eliminating the paradox.

At the Astronomical Society of the Pacific conference on globular clusters in 1994, Hesser confessed to his colleagues: "I sometimes get the feeling — perhaps some of you do, too? — that I'm not doing real astronomy (for example, the quest for quasars, primeval galaxies, etc.)." He went on to say: "Tonight, however, armed only with binoculars and a chart from any good sky atlas, you can view a majestic object whose chemistry suggests it formed [soon after the Big Bang]: M15 ... and it's only a few kiloparsecs distant!"

Astronomy's own Cirque du Soleil

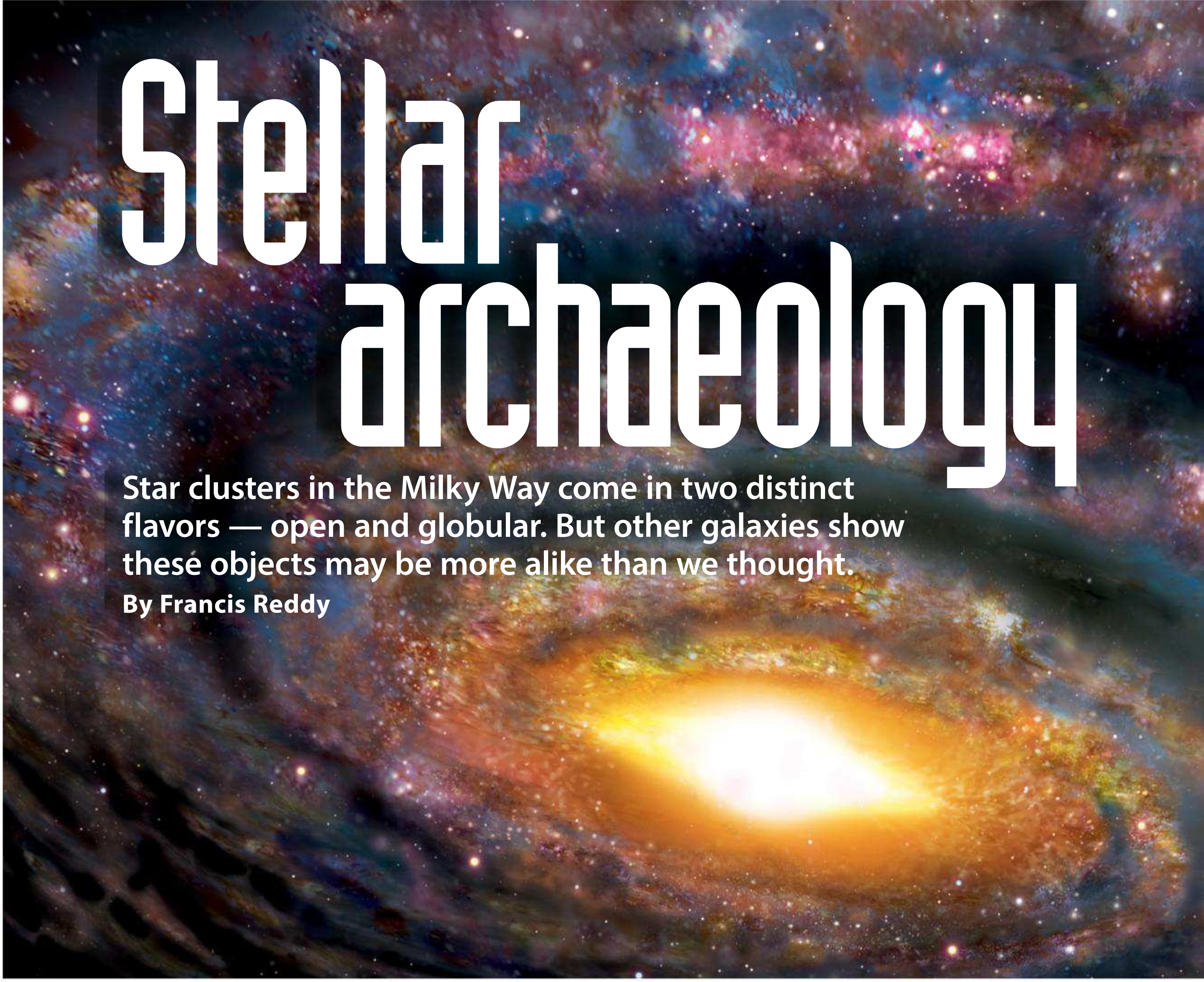
Globular clusters' use as cosmological markers sometimes overshadows their uniqueness as celestial objects. With stars packed in like subway commuters at rush hour, a globular cluster offers a far more exotic environment than the staid suburbs of the Milky Way's disk. Here in the disk, the Sun's closest stellar neighbor, Alpha Centauri, is some 4 light-years away. But if the Sun were located in the center of a globular cluster, it would have a bustling community of 1,000 or more stars closer than Alpha Centauri, lighting up Earth's sky during both day and night. Near-misses between stars would be commonplace.

What holds these stars together so compactly? Powerful computer simulations have begun to answer this long-held mystery. A cluster in its youth does not just sit; it evolves as kinetic energy is exchanged continually between the stars. Lower-mass stars rev up their velocity and eventually "evaporate" out of the system, while higher-mass stars lose energy and sink toward the center. Over time, the outskirts of a cluster spread out, and the core gets denser, creating the hallmark spherical shape of a globular.

Why doesn't the entire globular cluster completely collapse into a black hole as it shrinks? Simulations show that before this happens, some stars begin to interact and form binary systems, which puts a stop to the crunch. Like partners in a fast-paced square dance, these stars swiftly swing around one another, sometimes pairing up for good or, on rare occasions, merging.

That explains the mystery of "blue stragglers." Long seen in clusters, these massive stars are bluer and brighter than the average main sequence star; astronomers now realize they result from mergers of two smaller stars. "They stand out very easily," notes Harris. "They're rare but easy to spot."

And blue stragglers aren't even the most exotic characters in these jam-packed systems. X-ray telescopes reveal the truly bizarre: cataclysmic variable stars, millisecond pulsars, and neutron-star binaries. The oldest known planet recently turned up around a binary consisting of a pulsar and a white dwarf star in the relatively nearby globular cluster M4 — the first time a planet has been found in a glob (see above). Says Harris, "The field has opened up in ways that no one had imagined."



Stellar archaeology

Star clusters in the Milky Way come in two distinct flavors — open and globular. But other galaxies show these objects may be more alike than we thought.

By Francis Reddy

One of astronomy's fundamental concepts is that Earth orbits an average star, which coasts through a nondescript portion of our Milky Way, a typical spiral galaxy.

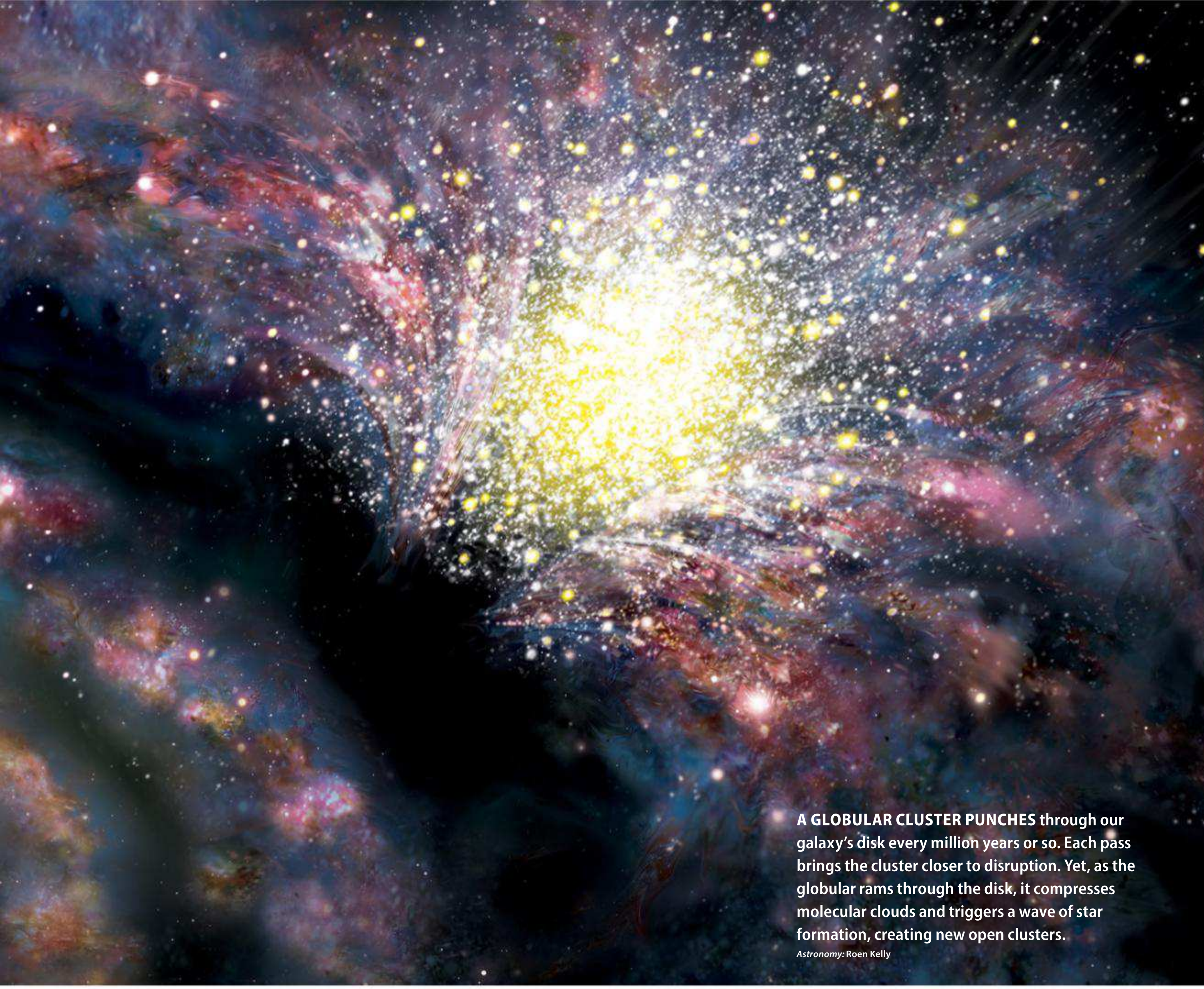
It's a notion that harks back to Copernicus — he did, after all, nudge Earth from the center of the universe — but it also dovetails with the natural human tendency to regard those things most familiar to us as normal.

Our location in the Milky Way Galaxy gives astronomers a great opportunity to see how stars live and die. One of the best ways to see this comes from star clusters, groups of newborn and aged stars that hang together and provide important clues about the past.

What has become clear in the past 25 years is that the way astronomers have traditionally characterized star clusters — classing them as either open or globular, the two forms seen in our home galaxy — no longer holds up. Colliding galaxies, or those undergoing intense bursts of star formation, seem filled with objects that don't easily fit into either category. In the past few years, astronomers have found hard-to-classify clusters even in normal spirals, galaxies otherwise like our own.

Star clusters have been objects of intense study for more than a century. They are the glittering gems of the night sky, aggregations of a few hundred to about a million stars, usually forming a single gravitationally bound entity.

Most stars probably form within clusters, so the problem of understanding star formation is inextricably linked to understanding how clusters form. Clusters are important because they provide a sample of stars at the same age, with about the same chemical content, and at the same distance from Earth — which makes them useful for testing theories of stellar evolution. Because observers can identify and study star clusters in other galaxies at distances where individual stars can no



A GLOBULAR CLUSTER PUNCHES through our galaxy's disk every million years or so. Each pass brings the cluster closer to disruption. Yet, as the globular rams through the disk, it compresses molecular clouds and triggers a wave of star formation, creating new open clusters. *Astronomy:* Roen Kelly

longer be distinguished, astronomers gain insight into star-formation processes across a broad expanse of space and time.

"We live in the Milky Way, and as a result, we have a certain perspective about what we might call a star cluster," says Rupali Chandar, an astronomer at the University of Toledo, Ohio. In our parochial view, star clusters come in two flavors — open and globular — that at first glance could not be more different.

The view from within

Open clusters reside in our galaxy's disk, typically contain stars no older than a billion years, and hold a few hundred to perhaps a few thousand solar masses. Their stars exhibit metallicity — the complement of elements heavier than helium — similar to or greater than our Sun's. Open clusters range in size from several to more than 50 light-years across and appear diffuse and irregularly shaped. About 1,000 have been cataloged, with the most famous examples being the familiar Pleiades and Hyades in Taurus. Thousands more likely exist beyond our ability to detect them.

Globular clusters ride orbits highly inclined to the Milky Way's disk and are associated with its more spherical halo and bulge components. Globulars typically contain 100,000 solar masses, all of it packed into a spherical or elliptical volume 100 or so light-years across. With ages around 12 billion years, globular clusters are truly ancient objects, a fact reflected in the low metallicity of their stars. About 150 globulars — including several visible to the unaided eye — orbit the Milky Way.

Star clusters in the Andromeda Galaxy, the nearest large spiral, appear to break down in much the same way. "If we lived in Andromeda, I think probably it would reinforce our view of this dichotomy in cluster properties," Chandar says. But astronomers in a more extreme galactic environment — such as a

MANY MASSIVE YOUNG STARS make the famous Double Cluster in Perseus one of the brightest stellar collections in the Milky Way Galaxy. The two open clusters, known individually as Chi (χ) Persei (NGC 884, at left) and h Persei (NGC 869, right), formed 11 million and 12 million years ago, respectively. Only about 100 light-years separate the pair. Both clusters are visible to the unaided eye despite lying 7,000 light-years away from us. N.A. Sharp/NOAO/AURA/NSF

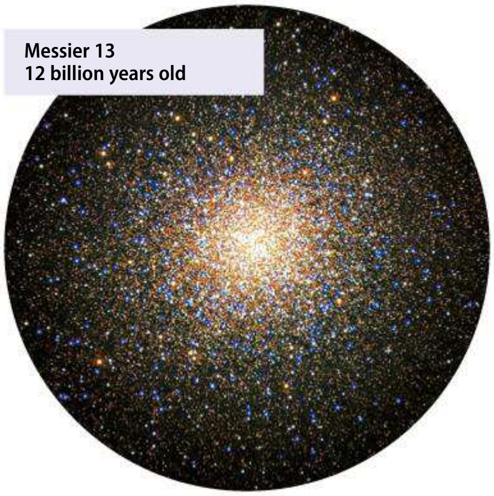
galaxy undergoing a burst of intense star formation, like M82, or galaxies in the process of merging, like the Antennae — would reach starkly different conclusions.

"The main result [of work over the past 25 years] is that anytime you look at starburst and merging galaxies, you see very rich systems of young, compact clusters," Chandar explains. "The most massive end of these, the brightest end, has all the properties — masses, sizes, current luminosities — we would expect of young globular clusters." If we could look at these massive young clusters far in the future, when the universe is twice its current age, they'd resemble the globular clusters we see orbiting the Milky Way today. Moreover, these objects aren't unique to disturbed galactic environments. They occur in normal spirals like M83 and NGC 6946, too.

When astronomers re-examine the Milky Way's cluster system with this realization in mind, the once-clear distinction between open and globular clusters becomes blurred. At 10 billion years old, Berkeley 17 is considered the oldest open cluster, but it overlaps the range of globular-cluster ages (8 to 12 billion years). The two cluster types show a slight overlap in metal content as well. And then there are clusters where classification simply has been ambiguous. Astrophysicist Søren Larsen of Radboud University in Nijmegen, Netherlands, says: "Consider the Milky Way clusters NGC 2158, NGC 6791, NGC 5053, and Terzan 3, all of which look

Francis Reddy *is the senior science writer for the Astrophysics Science Division at NASA's Goddard Space Flight Center in Greenbelt, Maryland.*

OPEN OR GLOBULAR? Discovered in 1964 in the constellation Norma, Lyngå 7 was originally classified as an open cluster. Decades later, astronomers recognized its stellar content is closer to that of a globular cluster. Atlas image mosaic by S. Van Dyk, courtesy 2MASS/UMASS/IPAC



MESSIER 13, located in the constellation Hercules, is a globular cluster some 23,000 light-years from Earth. M13 holds approximately half a million stars bound together by their mutual gravitational attraction. Caltech/NASA/NSF/Canada-France-Hawaii Telescope/J.-C. Cuillandre/Coelum

Brightest young clusters

When compared to young star clusters in other galaxies, the Milky Way's brightest turn out to be about average. Absolute magnitudes for the brightest young clusters in a range of galaxies are listed below.

IC 1613: –6

NGC 1023 and NGC 3384: –6.5; these are Larsen's faint fuzzies.

Milky Way: –7 for NGC 3603, Arches, and Quintuplet; –9 for the Perseus Double Cluster

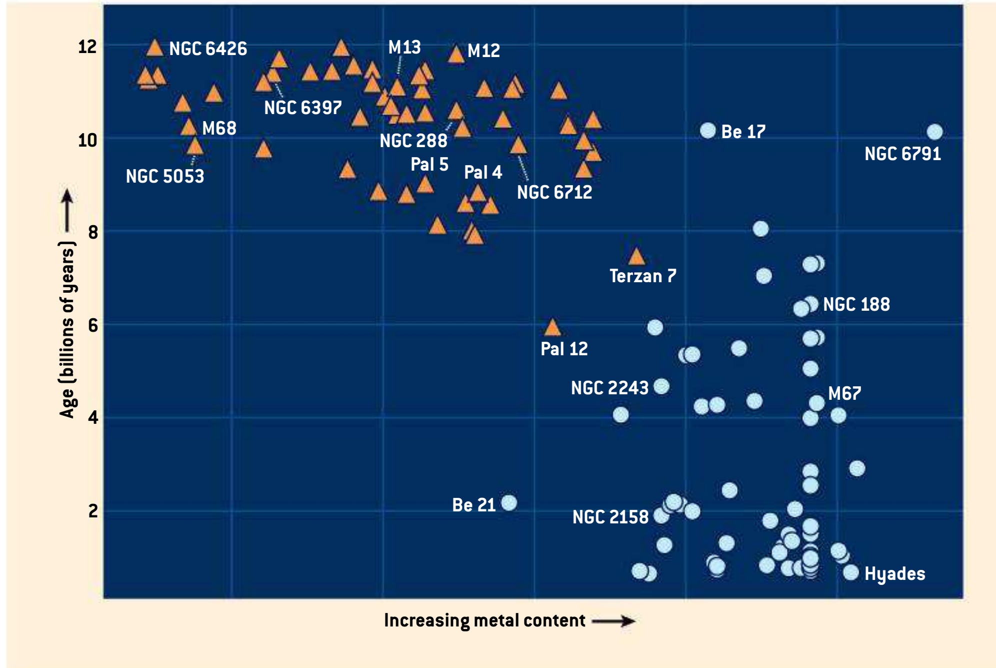
NGC 3184: –10.5

Large Magellanic Cloud (LMC): –11 for R136

M83: –12

M51 and NGC 6946: –13

NGC 4038/NGC 4039 ("Antennae"): –14



EVEN WITHIN THE MILKY WAY, the dividing line between globular clusters (triangles) and open clusters (circles) is blurred. Most globulars formed between 10 and 12 billion years ago, but there are a few objects only half that age. The proportion of metals — elements heavier than helium — also overlaps for both cluster types. *Astronomy*: Roen Kelly, from data provided by Maurizio Salaris, Liverpool JMU, UK

very similar. But the first two are classified as open and the other two as globular."

Beyond the Milky Way

The Large Magellanic Cloud (LMC), a satellite of the Milky Way, confuses the issue further. In 1930, Harlow Shapley referred to the LMC's "blue globular clusters," recognizing that these objects couldn't be shoehorned into either cluster category. Both the LMC and spiral galaxy M33 have formed these objects, also known as "blue populous clusters," more or less continuously.

Additional cluster types described in the astronomical literature include super star clusters (in M82) and massive young clusters (in the Antennae). The most recent entry — faint fuzzies — comes from a 2002 study by Larsen and Jean Brodie of the University of California's Lick Observatory. They discovered these objects on Hubble Space Telescope images of galaxies NGC 1023 and NGC 3384. A follow-up investigation with the Keck I Telescope in Hawaii revealed faint fuzzies to be 8-billion-year-old, metal-rich star clusters up to five times larger than typical open or globular clusters. No such objects occur anywhere in the Local Group, the assemblage of galaxies that includes our Milky Way.

"The general idea has always been that these clusters formed from different mechanisms, that there must be something different in how the star formation was actually triggered," explains Chandar. In other words, certain types of clusters may form only in certain types of galaxies — a notion Bradley Whitmore of the Space Telescope Science Institute playfully has called "special creation."

Instead, Whitmore, Chandar, Larsen, and others see tantalizing evidence for an underlying property that connects different classes of star clusters. Most studies of young clusters show their stars' luminosities follow a mathematical relationship called a power law. Plotted on a logarithmic scale, the number of ultraluminous stars, and the number of modestly bright stars, trace out a straight line. Open clusters in the Milky Way also seem to display the same demographic feature.

This distribution of luminosities within individual clusters — called the cluster's luminosity function — shows little variation among clusters within the same galaxy. But what's even more surprising is that when astronomers compare luminosity functions for clusters in different galaxies, the results seem to converge on a single "universal" luminosity function.

"This suggests that merging galaxies have the brightest clusters only because they have the most clusters," explains Whitmore. "It appears to be a matter of simple statistics rather than a difference in physical formation mechanisms."

At first glance, the demographics of old globular clusters seem to be at odds with this conclusion. Globular clusters, which once were thought to form in a way uniquely related to the physics of the early universe, appear to be forming today as massive young clusters. However, globulars follow a bell-curve-shaped distribution. Says Chandar: "This bell-curve shape was interpreted for many years as meaning that globular clusters formed with a preferred mass — the mass at the [curve's] peak — rather than as the result of evolution."

One way out of the difficulty is to imagine that smaller globulars evaporate with time, a process demonstrated in computer simulations for many years. Over time, as the stars in a cluster interact gravitationally, stars of different masses take up residence in different parts of the cluster. Like water settling in oil, massive stars — and those linked gravitationally as binaries — work their way into the cluster's center at the expense of low-mass stars, which move outward into the cluster's fringes. The galaxy's gravitational field strips away those stars that stray too far.

Sooner or later, globulars must pass close to their parent galaxy's bulge or plunge through its disk. During these encounters, globulars experience rapidly changing galactic tides. Each such "tidal shock" speeds cluster stars in their orbits and sends them

Cluster's last stand

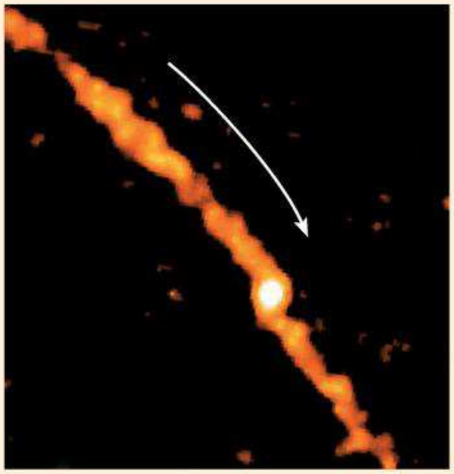
A globular cluster may look resilient, but it is not forever. Its steeply inclined orbit repeatedly takes it through the disk or central bulge of its parent galaxy. Galactic tides can strip off a cluster's most loosely bound stars. And each time a globular makes its closest approach to a galaxy, it experiences rapid changes in the galactic gravitational field's strength. This creates a "tidal shock" that stirs up the globular like a quick shake to a snow globe, sending stars to the cluster's fringes.

Astronomers lacked direct evidence that these processes occurred until 2000, when images taken during the commissioning phase of the Sloan Digital Sky Survey (SDSS) revealed that a globular named Palomar (Pal) 5 lies embedded in a starry trail of its own making.

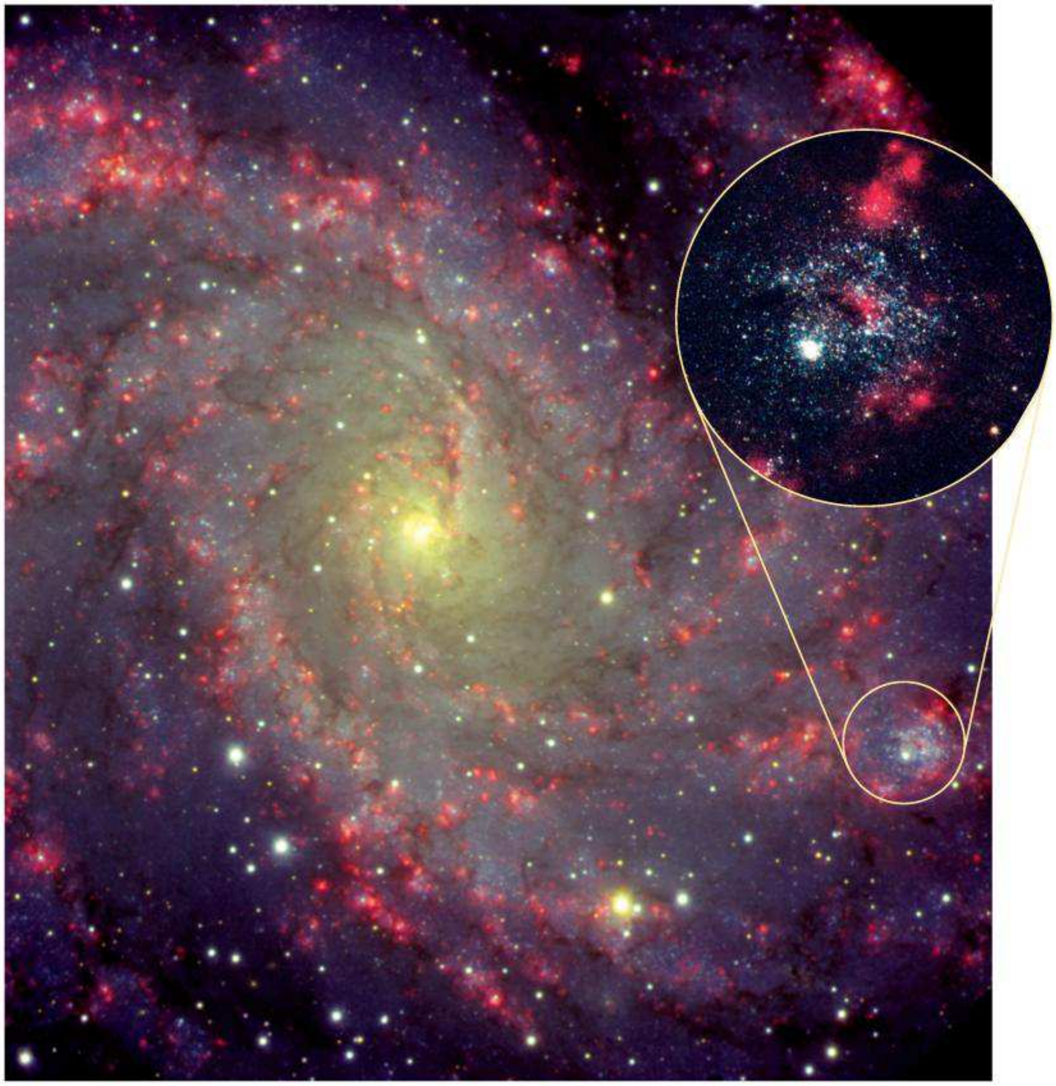
Pal 5 is one of many sparse, faint, low-mass globular clusters orbiting the Milky Way. It lies about 75,000 light-years away, which is about as far from the Sun and our galaxy's disk as Pal 5's orbit will take it.

Follow-up studies showed the cluster's faint debris trail spans at least 10° (20 times the diameter of the Full Moon, equivalent to about 13,000 light-years) and that this globular has been drizzling stars into the Milky Way's halo for at least 2 billion years. In fact, astronomers estimate Pal 5's tidal tails now hold 20 percent more stars than the cluster itself.

Palomar 5's next encounter with the Milky Way's disk, roughly 100 million years in the future, likely will destroy the cluster completely. — *F.R.*



ESCAPED STARS TRACE the orbit of Pal 5 (white knot). One trail of castaway stars leads the cluster, another follows. The arrow indicates Pal 5's orbital motion. Michael Odenkirchen et al./SDSS



SUPERNOVAE POP OFF frequently in NGC 6946, a spiral galaxy in Cepheus. Eight stellar explosions have been recorded since 1917, a clear sign of intense star formation. Inset: A bright knot in one spiral arm resolves into a brilliant cluster about 420 light-years across with a mass of roughly a million Suns. Many astronomers refer to it as a young globular cluster. Adam Block/NOAO/AURA/NSF; Inset: Søren Larsen/NASA/STScI

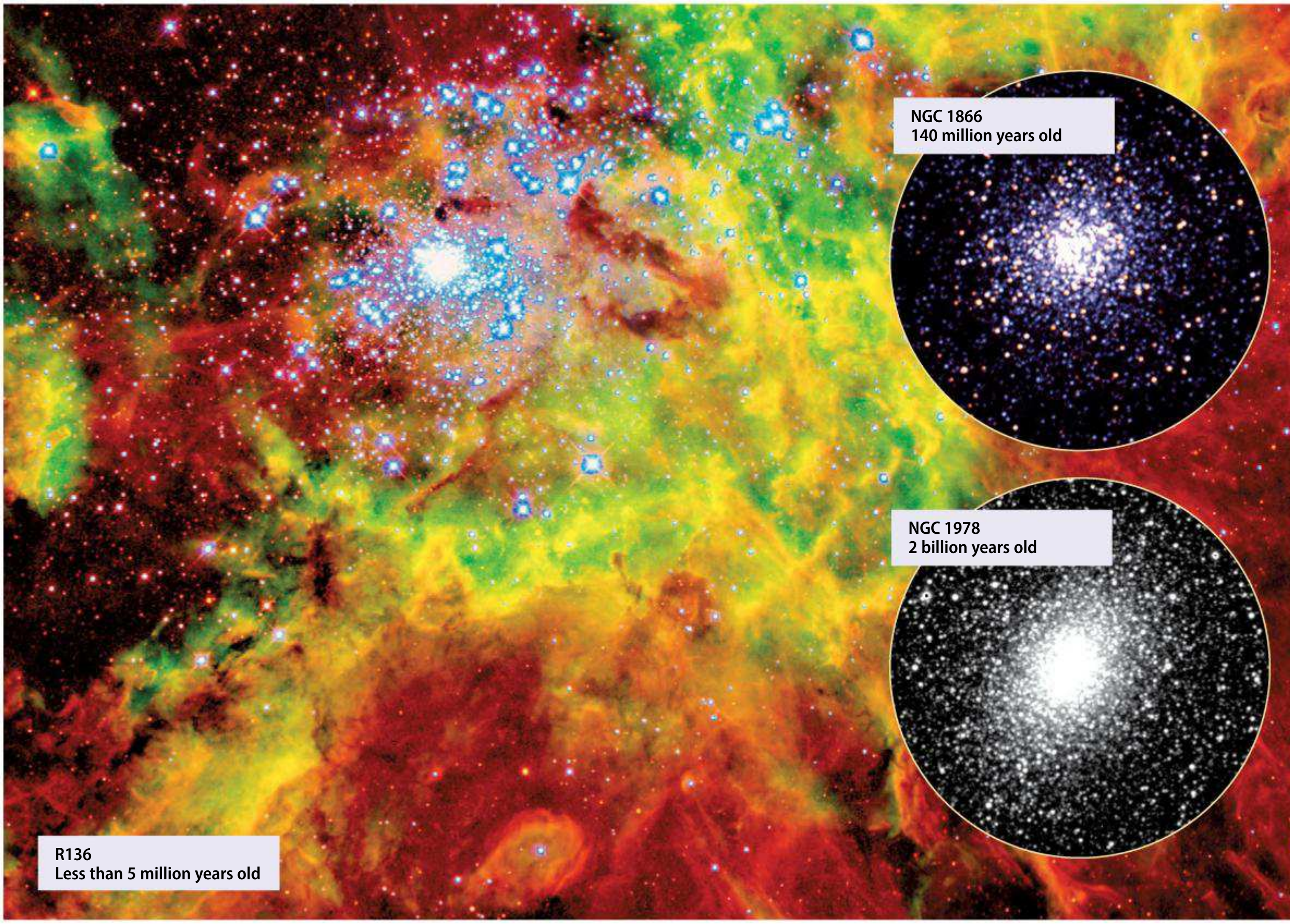
careening into the globular's fringes. Once there, these loosely bound stars ultimately may be stripped from the cluster.

Evaporating clusters

Twenty years ago, there was no observational evidence that globulars actually dissolve. In 2000, a team led by Michael Odenkirchen of the Max Planck Institute for Astronomy in Heidelberg, Germany, found twin tails of stellar debris arcing away from the faint globular cluster Palomar (Pal) 5 (see "Cluster's last stand" at left). Subsequent studies found tidal tails issuing from 20 other globulars, including NGC 288 and Pal 12 and 13. Globular clusters do evaporate, and astronomers today observe only the most massive remnants of the Milky Way's original globular population.

Further evidence supporting a unified view of clusters arrived in 2003. A team led by Richard de Grijs, then at the University of Cambridge in England, examined a billion-year-old "fossil starburst" at the center of M82, the nearest and best-studied starburst galaxy. Tidal interactions with neighbors M81 or NGC 3077 probably triggered M82's fierce pulses of star formation.

The astronomers looked at a region where they had previously identified more than 100 gravitationally bound clusters. If the unified view is correct, then many low-mass clusters that formed in this episode of star formation have already evaporated. If de Grijs and his colleagues could see sufficiently faint clusters, they could determine if those in M82 follow a bell-curve distribution like globular clusters.



A STAR FACTORY CLOSE TO HOME, the Large Magellanic Cloud (LMC) is a satellite of our own galaxy that lies some 160,000 light-years away. It has been making massive young star clusters more or less continuously. R136, the brilliant young cluster in the Tarantula Nebula, has a mass of 30,000 Suns. NGC 1866 and NGC 1978, two of the LMC's "blue populous clusters," have roughly similar masses — about 100,000 Suns — but vastly different ages. R136: Jesús Maíz-Apellániz and Nolan Walborn (STScI) and Rodolfo Barbá (Astronomical Observatory of La Plata); NGC 1866 and NGC 1978: Søren Larsen (ESO)

In fact, de Grijs and his team did just that. They produced conclusive evidence that young clusters show characteristic luminosities and distributions nearly identical to globulars orbiting M31, M87, old elliptical galaxies, and our own Milky Way. Young globular clusters are, indeed, forming today, and the distinctions we make regarding the Milky Way's clusters are artificial at best. Some astronomers, like Whitmore, suggest it's time to create an objective classification system for star clusters, one that provides more meaningful terminology for clusters near and far, young and old.

Still, there remain many caveats with the "continuum view" of star clusters. "Clearly, things become more complicated once you start looking at the details," says Larsen. As early as the 1950s, astronomers realized the Milky Way's globular clusters contain different populations distinguished by metal content, location, and orbital motion.

"The origin of the different subpopulations is currently a matter of much debate, and we are still very far from having a clear picture," explains Larsen. "Generally, globular clusters residing in the halo appear to fall into two groups, based on their ages and other properties, and the younger ones may have been accreted."

The Sagittarius Dwarf Spheroidal Galaxy, which is now passing through the Milky Way's disk, may have contributed a handful of globulars. They include Terzan 7 and 8, Arp 2, Pal 12, and M54 — the last an object some astronomers point to as the disrupted galaxy's nucleus. Omega Centauri, the Milky Way's brightest and most massive globular, likewise may be the stripped nucleus of another dwarf galaxy.

In a 2004 study of globular subpopulations, Dougal Mackey and Gerry Gilmore, then of Cambridge University's Institute of Astronomy, estimated that our galaxy has experienced at least seven merger events. They argue that as much as half of the stellar mass in the Milky Way's halo originated in cluster-bearing dwarf galaxies swallowed by our own. If so, young globulars are the remnants of our most recent acquisitions.

For every cluster that survives to an age of 10 billion years, a thousand were created and have been destroyed, their stars dispersed throughout the galaxy. To put an astronomical twist on Mark Twain's famous quip about thunder and lightning, galaxies are impressive, but it's star clusters that do the work.

How the Milky Way's neighborhood came to be

Our galactic surroundings — filled with an array of galaxy types — provide astronomers with a mini version of the universe. **By Ray Villard**

Our Local Group of galaxies lies on a side street 50 million light-years from the great intersection of two dark matter filaments that created the magnificent Virgo Cluster of about 2,000 galaxies. To alien astronomers living in the Virgo Cluster, our little galactic neighborhood would appear as two smudges of light: the Milky Way Galaxy and the Andromeda Galaxy (M31). Together, they might be dismissed as a "binary galaxy" on some extraterrestrial's star chart. Only with extraordinarily powerful telescopes would Virgo astronomers pluck out the roughly four dozen small dwarf galaxies.

The innocuous name Local Group belies the fact that our neighborhood is more like a rough and tumble town in the Wild West. Murder, mayhem, missing bodies — even cannibalism — stalk the streets. In reality, we are seeing order emerge out of the chaos of energy and matter that followed our universe's birth; the Local Group is a microcosm of the rowdy cosmos at large.

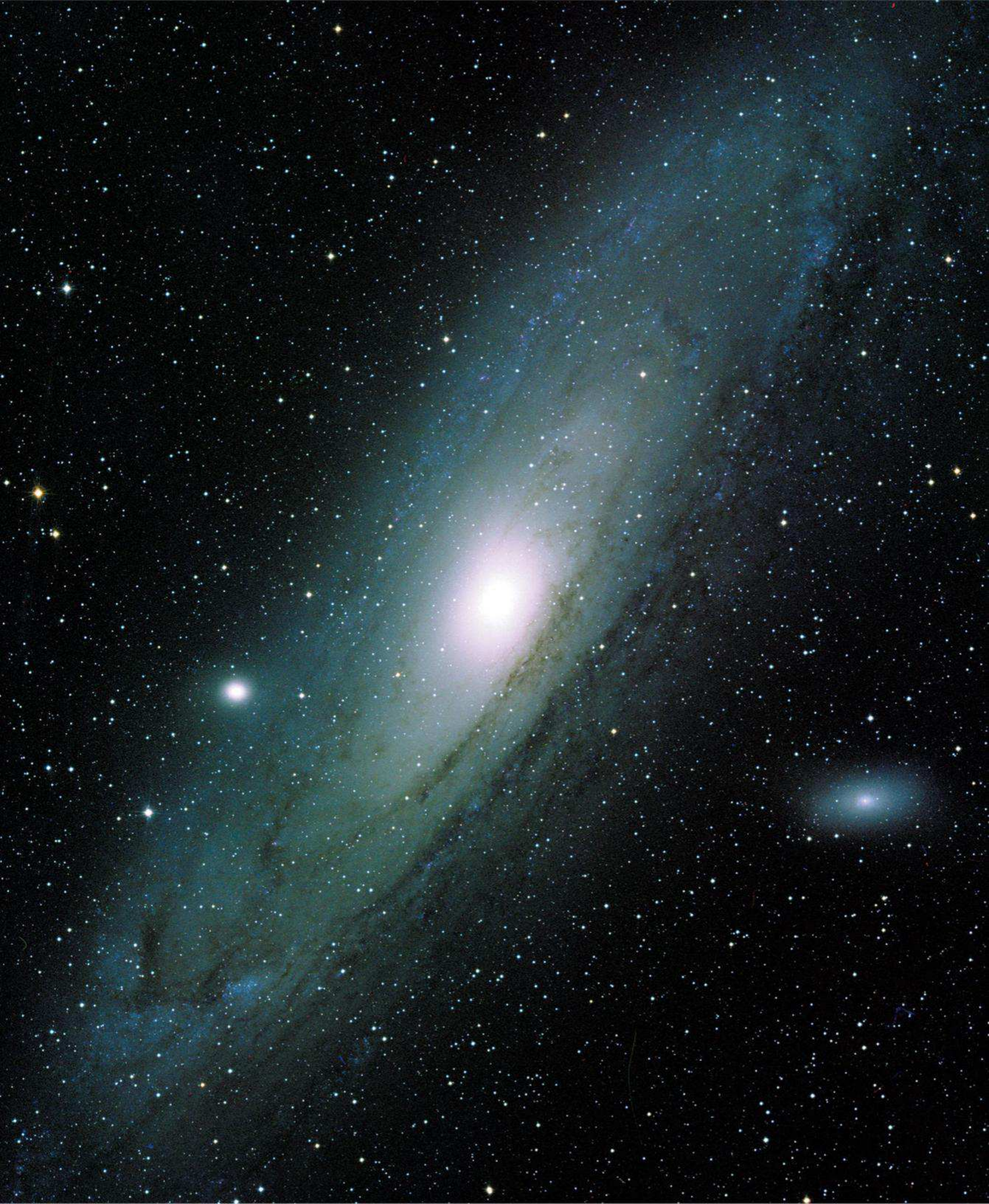
Nearly 10 million light-years across, the Local Group "is the universe in a nutshell," says Mario Livio, former head of the Space Telescope Science Institute's science division. But, more importantly, in an expanding and accelerating universe, the Local Group provides our only opportunity to decode the origin, structure, and evolution of galaxies.

New eyes on the Local Group

The road to discovering the Local Group started more than 90 years ago. In 1923, American astronomer Edwin Hubble used the 100-inch Hooker Telescope atop Mount Wilson in Southern California to find Cepheid variable stars in the Andromeda "Nebula." Scientists had long debated whether this cigar-shaped cloud was an oblique disk around a young star or a vastly more distant "island universe" unto itself. By using the intrinsic brightnesses of Cepheid variables to calculate their distances, Hubble finally had observational evidence to prove the latter. The Andromeda

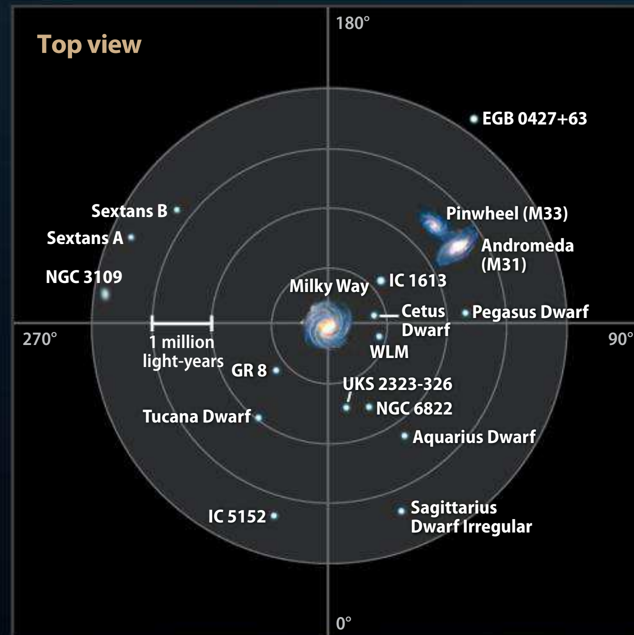
THE ANDROMEDA GALAXY stands as one of the two largest members of the Local Group. This view shows its galactic bulge and the spiral arms that make up its disk. Two of its satellite galaxies, M32 (just left of center) and NGC 205 (at lower right), also can be seen. B. Schoening, V. Harvey/REU program/NOAO/AURA/NSF

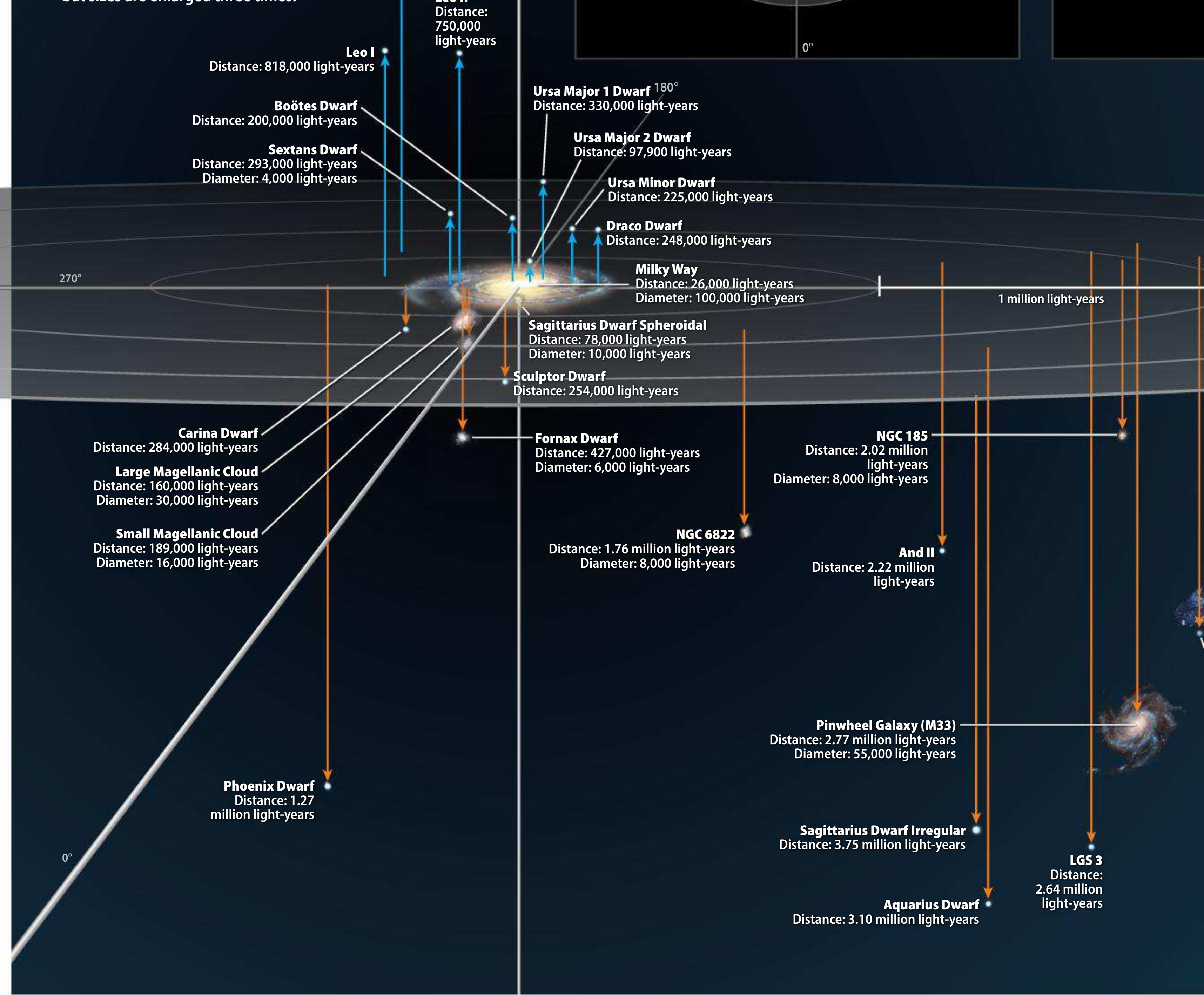
THE MILKY WAY — our home galaxy — has roughly the same amount of mass as the Andromeda Galaxy. This infrared image nicely shows its thin disk and galactic bulge, along with two satellite galaxies — the Large and Small Magellanic Clouds (lower right). 2MASS /J. Carpenter, M. Skrutskie, R. Hurt

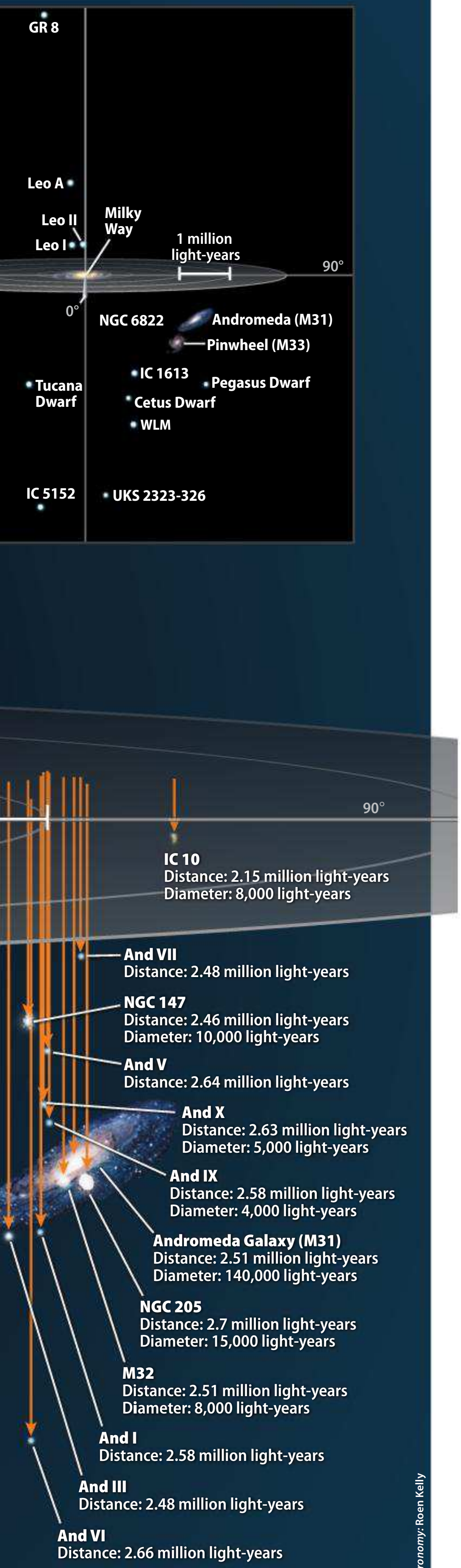


The Local Group

MOST OF THE nearby galaxies that make up the Local Group are dwarfs that cluster around the three large spirals — M31, M33, and the Milky Way. This illustration gives distances in light-years to the brightest members, as well as sizes for those at least 4,000 light-years across. Galaxy distances are shown to scale, but sizes are enlarged three times.







Astronomy: Roen Kelly

Nebula was extraordinarily far away, at least 20 times the Milky Way's diameter.

After another decade of meticulous observations, the idea of galaxies being organized into a local grouping "sprang from the mind of Hubble as completely as the goddess Athena, in full battle garb, sprang out of the head of Zeus in Greek mythology," says retired Canadian astronomer Sidney van den Bergh. Hubble described it as a fortunate accident that the Local Group contains nearly all the types of galaxies he saw in the universe at large.

Hubble likely never envisioned that 90 years later a telescope comparable in size to the Hooker Telescope, lofted far above the blurry atmosphere — and bearing his name — would routinely resolve stars in the Local Group barely 1⁄10,000 the brightness of M31's Cepheids. "The Hubble Space Telescope has opened up the Local Group to completely new, detailed studies," says William Harris of McMaster University in Hamilton, Ontario. "What we knew about these systems was in a completely different state [a quarter-century] ago."

"With Hubble and large ground-based telescopes, we can get an incredible amount of data on a huge number of individual stars," says Rosemary Wyse of the Johns Hopkins University in Baltimore. "At last we can try to fit it all together."

Stars are like clocks in space. The earliest stars — now 13 billion years old — contain few elements heavier than hydrogen and helium. That's because elements like oxygen, nitrogen, and silicon had not been cooked up yet through nuclear fusion. Younger stars are successively richer in heavier elements forged in earlier generations of stars. So, tracing the abundance of different elements in stars is the astronomer's equivalent of digging through geologic strata, a way to learn what parts of the Local Group came first.

From chaos to order

Hubble proposed an evolutionary sequence for elliptical, spiral, and irregular galaxies with his classic Hubble Tuning Fork diagram. But the Hooker Telescope did not have the power to look far enough into the universe to reveal how galaxies might have changed over time.

Today's Great Observatories Origins Deep Survey, or GOODS program, (using observations by Hubble, the Chandra X-ray Observatory, and the Spitzer Space Telescope)

Ray Villard *is the news director at the Space Telescope Science Institute in Baltimore.*

THE LARGE MAGELLANIC CLOUD, the largest satellite of the Milky Way, contains the brilliant Tarantula Nebula. NOAO/AURA/NSF

shows increasing galaxy size in the universe is consistent with "bottom-up" models of galaxy formation. In these schemes, galaxies grow through mergers and by accreting smaller galaxies.

Such models support the "cold dark matter" theory, which states dark matter (an invisible form of matter that makes up 85 percent of the universe's mass) pooled into gravitational "puddles" in the early universe, long before normal matter could. It then collected hydrogen gas that quickly contracted to build star clusters and small galaxies.

These dwarf galaxies merged piece by piece over billions of years to build the immense spiral and elliptical galaxies we see today. The forensic evidence in our Local Group allows astronomers to scrutinize the past 13 billion years in a new level of detail. The results agree beautifully with those from the GOODS program, but some mysteries linger.

Most astronomers think the Local Group "turned on" roughly 13 billion years ago, when seedling star clusters that formed from hydrogen gas flowed into dark matter "potholes." This occurred at the end of the "Dark Ages," the brief interval of time when the universe cooled below a temperature of 3,000 degrees Fahrenheit. "We now know a lot of action happened in the first few million years," says Harris. "Somehow we have to connect all of this into a single formation scenario."

When the earliest clusters emerged from the Dark Ages, the Local Group was only 600,000 light-years across, just a quarter of the current distance to the Andromeda Galaxy. Higher density means star clusters must have collided and merged quite frequently. Picture these cluster mergers as many little brooks coming together to form streams, which then converge into a mighty river.

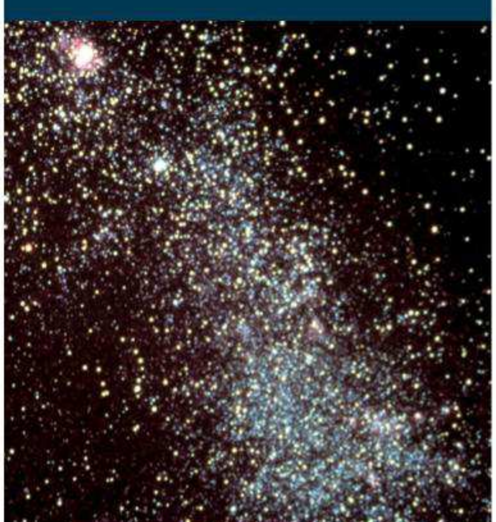
It's raining stars

The Milky Way Galaxy today is usually depicted as a sedate-looking disk, bulge, and halo. A DVD makes a useful model. The silvery disk is the approximate diameter-to-thickness ratio of the Milky Way's stellar disk. The central bulge of stars would be a ping-pong ball glued in the DVD's center. The galactic halo of orphaned stars and surviving globular clusters is a beach-ball-sized swarm enveloping the DVD. Ticker tape streamers arranged in a pretzel pattern through this volume would resemble shreds of dwarf galaxies being devoured by the Milky Way. Now imagine another DVD inside a beach ball located about 10 feet (3 meters) away: That's the Andromeda Galaxy. Dwarf galaxies would be scattered between these two beach balls out to a distance of about 15 feet (4.6 m).

The emerging view is that early globular star clusters crashed together to build up the Milky Way's central bulge. The Milky Way pulled in surrounding gas, which settled into a vast, thin disk. Cluster collisions scattered stars into a halo, and the disk puffed up, becoming thicker.

Only a fraction of the original globular clusters survive today. Harris compares them to old castles in different states of disrepair. Their ability to survive depends on their mass and trajectory through their host galaxy — either M31 or the Milky Way. Some of the globular clusters are relatively unscathed; some have been torn into star streams.

THE SMALL MAGELLANIC CLOUD, a dwarf irregular galaxy, orbits the Milky Way at a distance of 200,000 light-years. NOAO/AURA/NSF



ANDROMEDA'S SATELLITE NGC 205 is one of many dwarf spheroidal galaxies that call the Local Group home. NOAO/AURA/NSF

Observations of the Milky Way suggest a complex galaxy shaped by dynamical evolution. "Our galaxy is pretty hungry and is accreting all kinds of satellites in different ways," says Mary Putman of Columbia University. Put even more succinctly, Wyse says, "Our Milky Way has merged, is merging, and will continue to merge."

Like a toddler with a face full of jam, the Milky Way is a sloppy eater. The halo contains shreds of smaller galaxies being devoured. The disk is warped by passing dwarf galaxies. High-velocity hydrogen clouds far above the galactic plane trace the destruction of these dwarfs, whose debris literally rains down onto the galactic disk.

One of the earliest clues to cannibalism came in 1992 when astronomers discovered a dwarf galaxy merging with the Milky Way. The great star clouds of Sagittarius largely hide this dwarf. "This could be the archetype of larger satellite galaxy mergers that happened in the past," says Steven Majewski of the University of Virginia. Computer simulations show this galaxy is being stretched like taffy as it falls into the gravitational sinkhole of our galaxy.

The most obvious relic of our violent past is the Magellanic Stream, a trail of cold hydrogen that extends across 100° of sky without any obvious stars. The prominent satellite galaxies, the Large Magellanic Cloud and Small Magellanic Cloud, are at the head of the stream, which makes an arc around the south galactic pole.

Odd couple

Formation models don't predict two giant galaxies growing next to each other in such an isolated part of the universe. In fact, M31 may have been even closer to the Milky Way at one time.

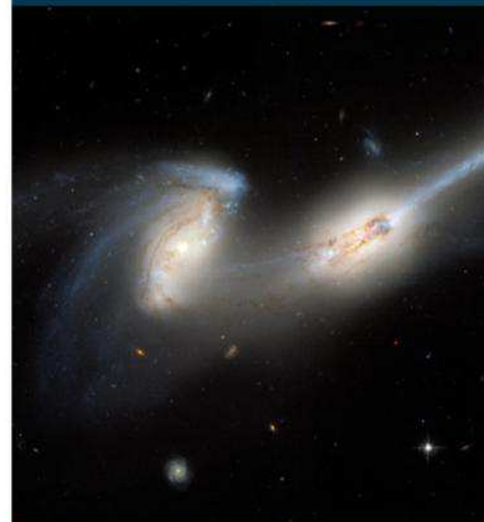
Hubble would agree that nature was generous in giving us such a close companion to study. Nature also generously tilted M31 nearly edge-on to our line of sight. This allows its halo, bulge, and disk populations to be segregated rather easily for study. "The Andromeda Galaxy gives us a more democratic view of stellar populations," says Puragra Guhathakurta of the University of California at Santa Cruz. By comparison, foreground dust and star clouds almost totally obscure the Milky Way's bulge.

We need to look at M31 because our Milky Way "is not typical," asserts Wyse. "It has not done much major merging for quite a while." The Andromeda Galaxy gives astronomers a better view of the complex forensics of cannibalism and large galaxy growth.

Like the Milky Way, M31 contains many globular clusters. One in particular, called G1, may be only *masquerading* as a globular. It might really be the stripped down core of a dwarf spheroidal galaxy shredded by the Andromeda Galaxy. One piece of evidence: G1 may contain a 20,000-solar-mass black hole — something astronomers once expected to find only in galaxies. Equally mysterious is M33, a disk galaxy that has avoided being torn up by M31. "It should not have survived," says Ken Freeman of the Mount Stromlo Observatory in Australia.

IRREGULAR GALAXY NGC 6822 lies about 1.8 million light-years from Earth in Sagittarius. Local Group Galaxies Survey Team/NOAO/AURA/NSF

NGC 55, another dwarf irregular, lies just outside our Local Group, at roughly 7 million light-years from Earth. NOAO/AURA/NSF



THE MICE, a pair of colliding galaxies, show how the Milky Way and Andromeda may appear in 2 billion years. NASA/ESA/ACS Science Team

A striking difference is that both young and old stars abound in M31's halo, whereas the Milky Way's halo contains predominantly old stars. This suggests the Milky Way formed in isolation while M31 underwent a major merger that threw a bunch of stars and gas into the halo only 7 billion years ago.

Backyard laboratory

The Local Group serves as an astrophysics laboratory for taking a close-up look at fundamental cosmological mysteries. Our neighborhood offers a sample of the range of massive black holes that emerged in the early universe. Our own homegrown black hole in the galactic core, its cousin in M31, and possible smaller relatives in globular clusters M15 and G1 allow astronomers to study black holes in detail.

A landmark census of galactic black holes by astronomers using the Hubble Space Telescope revealed that a black hole's mass is roughly no more than 0.2 percent of the mass of a galaxy's bulge. Amazingly, the suspected black holes found in M15 and G1, which are 10,000 times less massive than a galaxy, also obey this trend. It appears that some yet-to-be-discovered underlying process ties a black hole to its host galaxy.

Astronomers even use the Local Group to reduce the list of dark matter candidates. Scientists have searched the halo of our galaxy looking for invisible objects that would bend the light of background stars; this effect is called gravitational lensing. So far, these searches have ruled out Massive Compact Halo Objects — hypothetical small, dark objects — as the last potential hiding place of baryonic dark matter (made of electrons, protons, and neutrons). The dark matter skeleton has been exorcised from the astrophysical closet. This mysterious material cannot be made of the same atoms that stars, planets, and people are forged from. Instead, it is now a phantom for particle physicists to hunt down.

Living in the Local Group

No doubt, countless extraterrestrial civilizations in the Local Group peruse it with a similar archaeological curiosity and fervor. It is a collective search for our cosmic roots. What's sobering is that planets may have started being made in the Local Group billions of years before our Sun and Earth formed.

Imagine if the Local Group contains even one extraterrestrial civilization billions of years older than ours. However improbable this scenario, such a civilization could have an archive of the evolution of our galactic neighborhood.

We'll need such an *Encyclopaedia Galactica* because the Local Group's history will get ever blurrier to future astronomers. The big makeover should begin in some 2 billion years when the Milky Way and Andromeda galaxies begin merging. A few billion years after that, the merger will be complete.

Computer simulations and telescopic images of other mergers give exquisite details of what's in store: Stars will scatter into a huge sphere, long tidal tails will form, and the cores will merge. When the central black holes coalesce, the newly forming galaxy will shudder momentarily in the wake of gravitational waves rippling time and space.

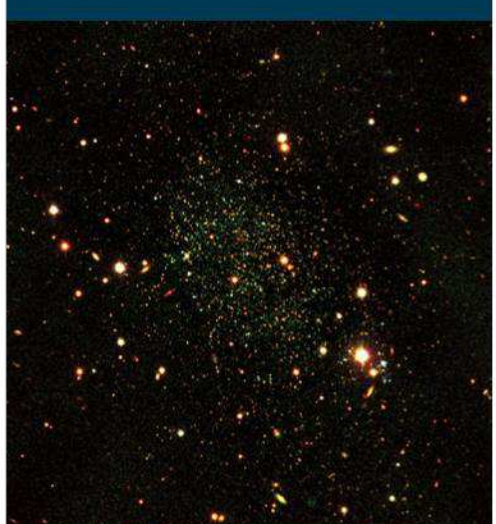
In the far future, astronomers will gaze at the sky and see all the way into the core of a new elliptical galaxy. They will have no evidence that there were once two majestic spiral galaxies called the Milky Way and Andromeda by a long-forgotten civilization.

A look at the nearby giant galaxy NGC 5128, better known as Centaurus A, presages the future of the Local Group after the Milky Way and M31 merge. This monster elliptical, no doubt, has grown through major mergers. Its appetite hasn't abated. It's currently cannibalizing a wayward disk galaxy, and shreds of others are in its halo. A refueled supermassive black hole at the core spews out a fountain of energy in the form of extragalactic jets.

The Local Group is being pulled toward the Virgo Cluster at the rate of 3 million light-years every billion years. In an accelerating universe, however, we may never get there because the space between the Virgo Cluster and our Local Group will stretch apart at an even-faster rate.

After untold billions of years, we will be the singular island universe, much like what some of Hubble's contemporaries believed. An inky sea of absolute nothingness will surround a single elliptical galaxy of purely ancient red stars and a burned-out supermassive black hole. It will no longer be the universe in a nutshell. To far-future inhabitants, it will be the entire observable universe. They will never know the effervescent glory of raw creation and renewal we witness now in our Local Group.

THE ANTLIA DWARF gives a good idea of what a healthy majority of the 55 or so Local Group galaxies look like. ESO



Our galaxy's date with destruction

The Milky Way is on a collision course with its neighbor, the Andromeda Galaxy. What will the night sky look like after the crash? **By Abraham Loeb and Thomas Cox**

Our galaxy, the Milky Way, and its nearest large neighbor, the Andromeda Galaxy (M31), are on a collision course. Billions of years from now, the merger will transform the structure of both galaxies and create a new arrangement of stars we have dubbed Milkomeda ("milk-AHM-mee-da"). The merger will radically transform the night sky. But into what?

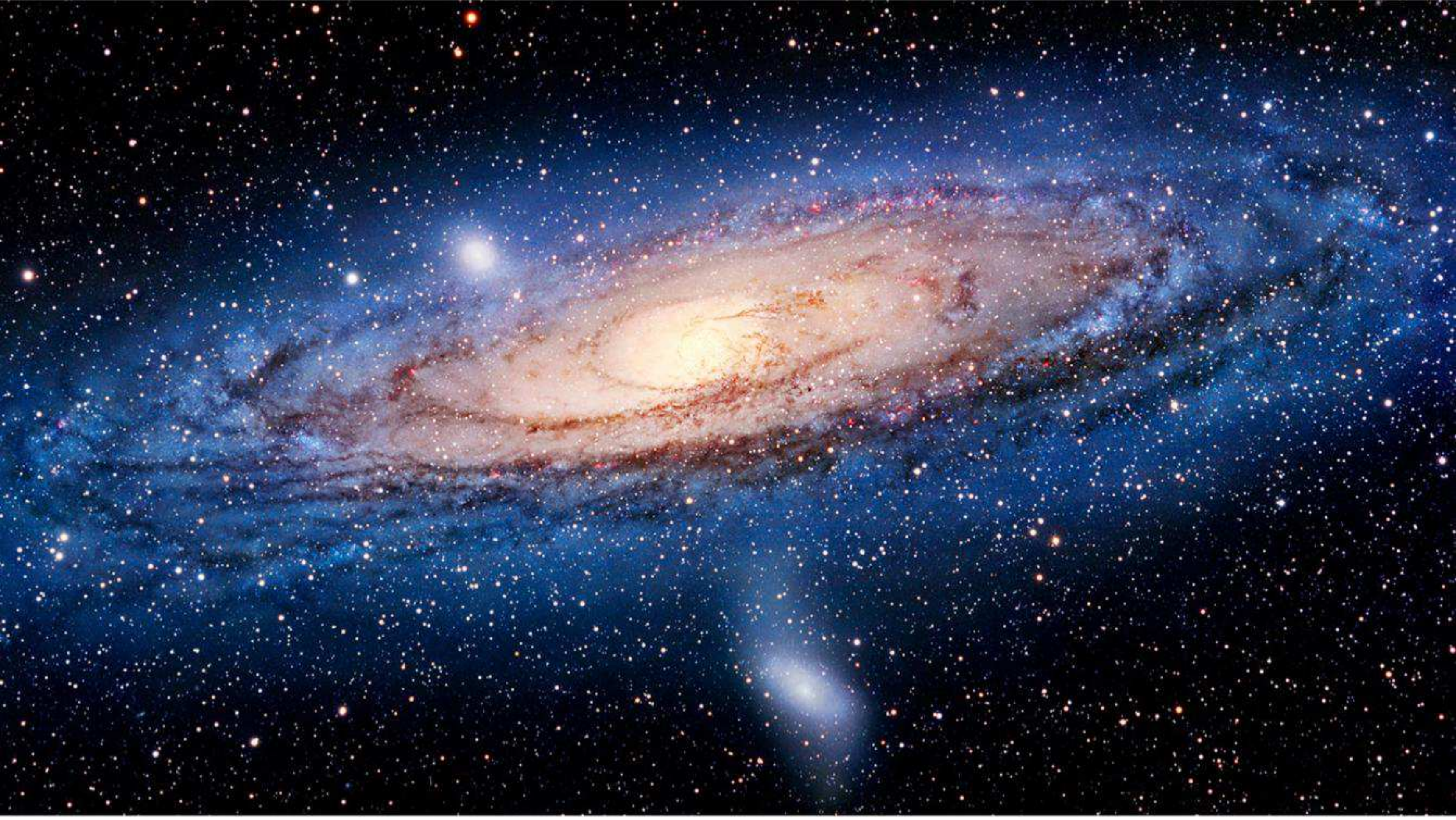
Currently, the Milky Way's thin disk of stars and gas appears as a nebulous strip arching across the summer sky. As Andromeda grazes the Milky Way, a second lane of stars will join the one that presently graces the night sky. After the final merger, the stars will no longer be confined to two narrow lanes, but instead scatter across the entire sky.

In our research, we have explored the Milky Way's fate by simulating Milkomeda's birth in a supercomputer. The simulations are at a sufficient level of detail to learn a lot about the coming merger and how it will change our perspective on the universe. Although we won't be here to witness the event — nor to take responsibility for whether our forecast proves accurate — this is the first research in our careers that has a chance of being cited 5 billion years from now.

The Local Group

The night sky's vastness might suggest the Milky Way resides in a relatively remote part of the universe. But astronomers know the Milky Way to be one of the two largest members of the Local Group of galaxies. The other is the Andromeda Galaxy, nearly 2.5 million light-years distant yet visible to the naked eye in the northern sky in dark conditions. The Local

BILLIONS OF YEARS FROM NOW, the night sky will glow with stars, dust, and gas from two galaxies: the Milky Way, in which we live, and the encroaching Andromeda Galaxy (M31). Lynette Cook for *Astronomy*



THE ANDROMEDA GALAXY **(M31) is a typical spiral of stars, dust, and gas. Spiral galaxies dominate the night sky in the local universe. At least 14 satellite galaxies accompany Andromeda, including the two visible in this image: M32 (above Andromeda) and NGC 205 (below). Andromeda and the Milky Way are the largest members of the Local Group of galaxies.** Tony and Daphne Hallas

Group's remaining members include a bevy of much smaller satellite galaxies.

A galaxy group contains two or more relatively close, massive members. The compactness of galaxies that form groups suggests that they are gravitationally bound and dynamically coupled to each other. This simply means the galaxies attract each other gravitationally, so a change in one affects the characteristics of the other.

Evidence of the dynamic connection between the Milky Way and Andromeda galaxies comes from their relative motions. The galaxies are barreling toward each other at nearly 268,400 mph (432,000 kilometers per hour). We know this because Andromeda's light is blueshifted — displaced toward the blue end of the spectrum — by the Doppler effect. In contrast, most galaxies in the universe are flying away from the Milky Way.

Timing is everything

Nearly 60 years ago, astrophysicist Franz Kahn and astronomer Lodewijk Woltjer pioneered the "timing argument." This hypothesis held that the Milky Way and Andromeda formed close to each other, during the dense, early stages of the universe.

Subsequently, the general expansion of the universe pulled the two galactic neighbors apart. Later, the Milky Way and Andromeda reversed their outward trajectories owing to mutual gravitational attraction. Since then, they have completed nearly a full orbit around each other.

The timing argument, combined with estimates of the galaxies' relative velocities and other factors, indicates the Local Group contains about 3 trillion times the Sun's mass. It also suggests the Milky Way and Andromeda will make a close pass in about 4 billion years.

Kahn and Woltjer inspired a generation of studies that further constrained the mass of the Local Group and revealed important characteristics of Andromeda's orbit, such as its total energy of motion.

But the timing argument does not have the ability to follow the complex dynamics that accompany the merger of extended galaxies. Therefore, it cannot predict the future arrangement of the Local Group. For processes as complex as galaxy mergers, astronomers need more powerful tools.

Simulating the Local Group

Numerical simulations are indispensable for understanding processes too complex to solve with pen and paper. In galactic mergers, for example, simple gravity shapes the merged galaxy. But the sheer number of atoms interacting over time makes it difficult or impossible to simulate the merger without the assistance of massive computer power.

To simulate the evolution of the Local Group, first we create a mathematical model describing its present state. This is straightforward for the Milky Way and Andromeda. Several decades of observations allow us to estimate the quantity of gas, stars, and other matter that the galaxies contain. We can determine a plausible mass estimate for the

Abraham Loeb *is chair of Harvard University's Department of Astronomy, a visiting professor at Tel Aviv University, and the director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics.* **Thomas Cox** *was a postdoctoral fellow at the Institute for Theory and Computation when he and Loeb developed these simulations.*

Milky Way and Andromeda to well beyond the visible inner portion of each galaxy.

However, the combined mass of the Milky Way and Andromeda is still less than nearly every number the equations of the timing argument yield. This implies there is additional mass in the Local Group.

The missing mass turns out to be the diffuse "intergalactic medium" of atoms, gas, and dust between the galaxies. Galaxies are simply the visible peaks of massive icebergs of matter. Much of the mass is not readily apparent, just as most of an iceberg's bulk lies underneath the water's surface.

When galaxies collide

Full-scale simulations typically require two weeks of number crunching. This calculation demands power equivalent to that of 16 high-performance desktop computers.

Since the early days of astronomy, merging galaxies have remained curiosities owing to their complex and irregular shapes. But astronomers now appreciate that mergers significantly drive galaxy evolution. Mergers touch off bursts of star formation, give birth to bright galactic cores (quasars), and transform pinwheel-shaped spiral galaxies into spheroidal or elliptical galaxies.

FROM EARTH, WE SEE THE MILKY WAY from an insider's perspective. Depending on the time of year, an earthbound observer can see three or four of our galaxy's spiral arms. John Chumack

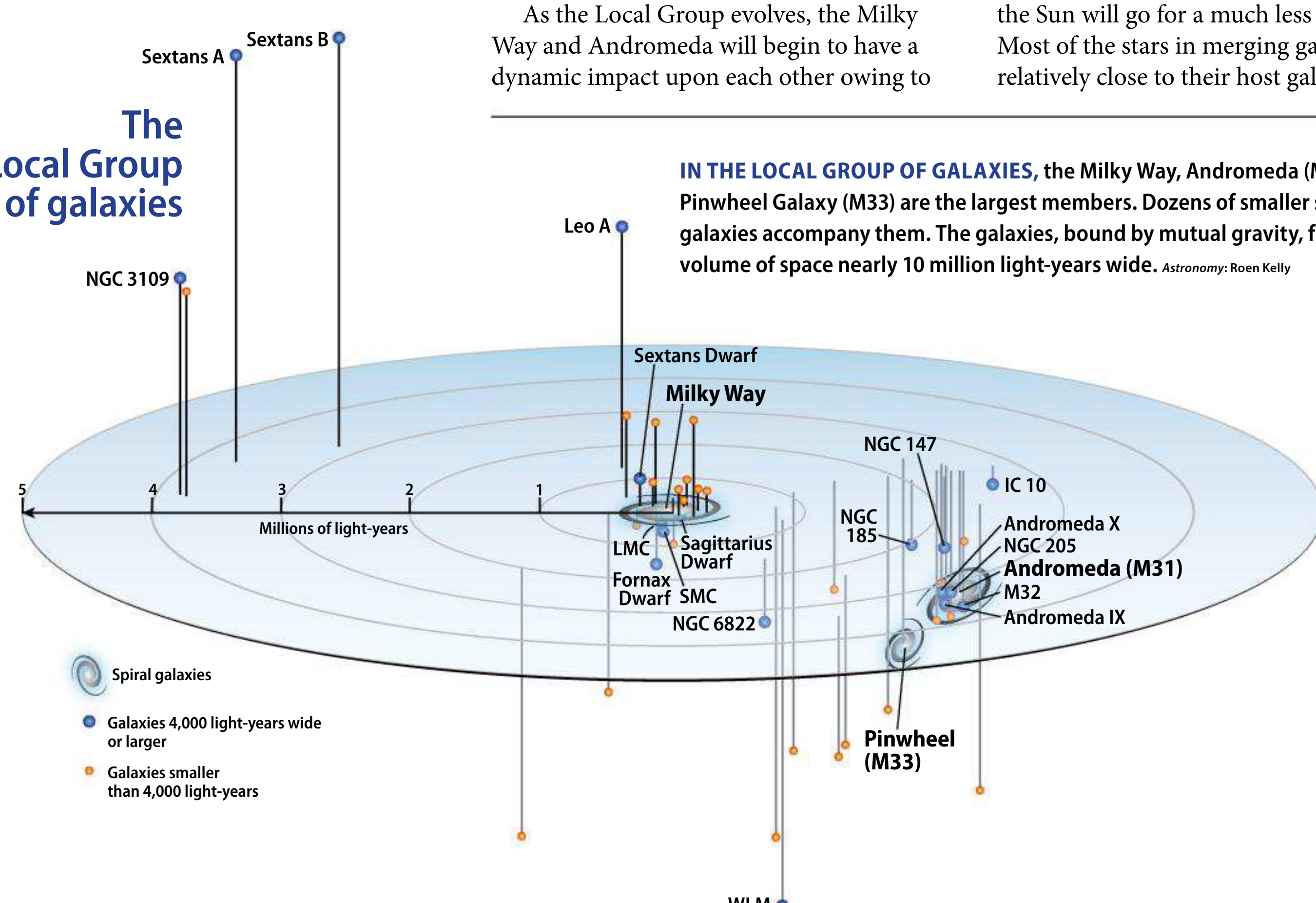
One of the distinguishing characteristics of galaxy interactions is the appearance of long streams of stars and gas that stretch from one or both of the participant galaxies. We commonly call these features tidal tails.

Tidal tails develop as a result of the powerful gravitational forces at work between merging galaxies. As the tails form, they rip stars and gas from their home galaxies and hurl them into intergalactic space.

As the Local Group evolves, the Milky Way and Andromeda will begin to have a dynamic impact upon each other owing to their mutual gravitation. As a result, it's possible the Sun and planets will be dragged into a tidal tail. During this period, an observer would have one of the most spectacular vantage points imaginable. Torn shreds of the Milky Way will fill a large fraction of the night sky as our galaxy experiences its gravitational dance with Andromeda.

Because only a small fraction of a galaxy's mass ends up in tidal tails, it is more likely the Sun will go for a much less dramatic ride. Most of the stars in merging galaxies remain relatively close to their host galaxies. The

The Local Group of galaxies

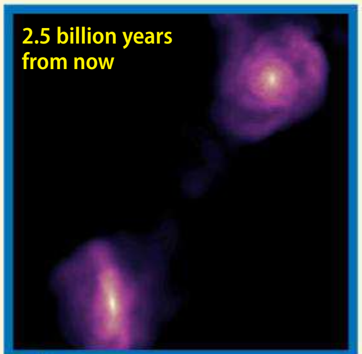


IN THE LOCAL GROUP OF GALAXIES, the Milky Way, Andromeda (M31), and the Pinwheel Galaxy (M33) are the largest members. Dozens of smaller satellite galaxies accompany them. The galaxies, bound by mutual gravity, fill a total volume of space nearly 10 million light-years wide. *Astronomy*: Roen Kelly

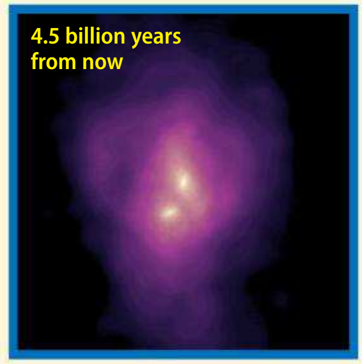
GALAXY MERGERS IN CYBERSPACE

Astronomers don't simulate galaxy mergers just to create pretty pictures. The simulations are serious and time-consuming scientific experiments. Simulations enable astronomers to test new ideas about the merger process and the role of mergers in the evolution of galaxies and the universe. The images below, sampled from a merger simulation by Harvard astronomers Thomas Cox and Abraham Loeb, depict the merger of the Milky Way and Andromeda galaxies. These frames highlight important milestones in a merger process lasting billions of years. Unless otherwise noted, merger images by Thomas Cox (CfA)

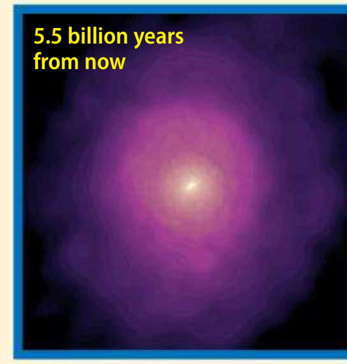
TWO BILLION YEARS from now, the galaxies swing around each other in a close pass. Mutual gravitational attraction draws out tenuous tidal tails of stars and gas. Tidal tails are hallmarks of galaxy mergers.



IN 2.5 BILLION YEARS, the galaxies are still moving apart. A ghostly bridge of gas and stars still connects them. Stars in the bridge, some perhaps sporting planets, could end up literally lost in space as the galaxy bridge dissipates.

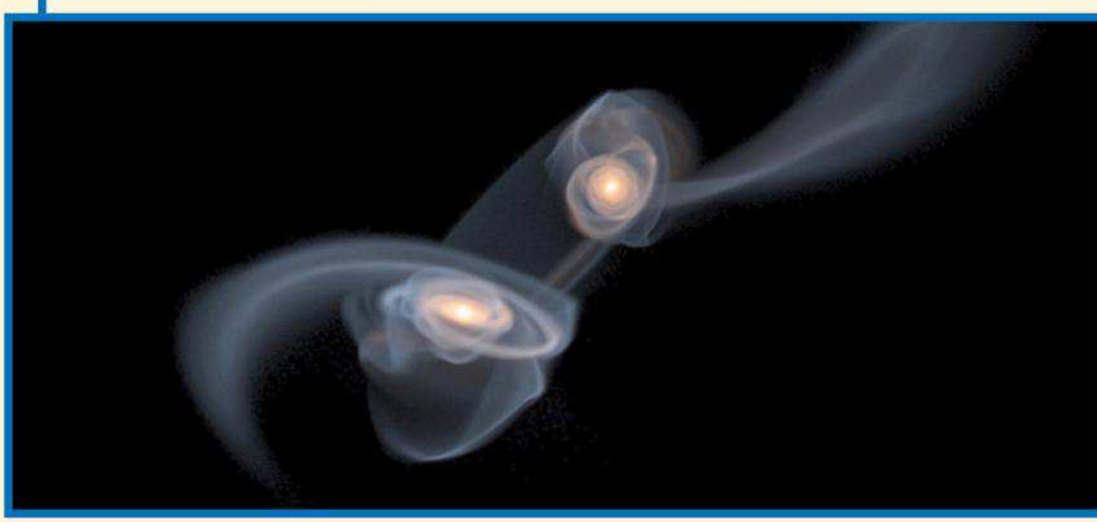


IN 4.5 BILLION YEARS, the galaxies loop around again and finally coalesce into a single mass. Their dense cores, each harboring a supermassive black hole, combine to form a single nucleus. The merging galaxies experience a brief pulse of star formation as the black holes merge.



IN 5.5 BILLION YEARS, the new Milkomeda Galaxy is born. Tidal swirls, tails, and eddies left over from the violent merger slowly relax and dissipate. Individual stars spread out, forming a more homogeneous elliptical galaxy.

NGC 2207 (lower galaxy) as it merges with smaller IC 2163. NASA/ESA/The Hubble Heritage Team (STScI)



THE BEAUTY OF MERGING GALAXIES stands out in this simulation of a possible model of the Milky Way-Andromeda collision by astronomer John Dubinski. The simulation reveals more detailed structure than Cox and Loeb's images because it includes more than 300 million particles of interacting matter. John Dubinski

chance of the Sun being banished to the tidal-tail boondocks is relatively small, based on our computer simulations.

Change of fortune

The Sun has circled the Milky Way more than 20 times since its birth. During the merger, our home star's peaceful orbit will forever change. Its new path will be far more chaotic due to the rapid fluctuations in gravity induced by the merger. What would this mean for Earth and its inhabitants?

Our research suggests the Milky Way and Andromeda will begin to interact strongly about 2 billion years from now. The merger will conclude in about 5 billion years. The latter date is especially notable because it coincides with the Sun's remaining life span. Currently, our Sun is about halfway through its projected lifetime and eventually will begin to expand. As it does, our home star

THE MERGER OF SPIRALS often produces a single, new spherical type of galaxy called an elliptical. The elliptical galaxy above, M32, is one of the 14 known satellite galaxies of Andromeda. Most galaxies in the Local Group are small satellites. Wolfgang Promper

will consume all of its available hydrogen and become a red giant within 5 billion years from now. In short, the Sun will be in its death throes on Milkomeda's birthday.

The Sun's red giant stage will make life on Earth rather uncomfortable. Indeed, it will spell the end of life as we know it. However, it does not preclude the possibility for colonization of habitable planets around nearby stars. Thus, it is possible future astronomers will be able to witness some, if not all, of the Local Group evolution we have simulated.

Although the Milky Way and Andromeda will merge, stars within the two galaxies, such as our Sun, will not physically collide. The reason is the extremely large distances between individual stars in galaxies. For example, if the Sun were the size of a ping-pong ball, the nearest star (Proxima Centauri) would be about the size of a pea and nearly 715 miles (1,150 km) away.

Our final resting place

The Sun's orbit will follow a chaotic path until the merger concludes. Then the system will relax and expand. The Sun will reside inside a new galaxy: Milkomeda. It will look very different from both its forebears.

The Milky Way and Andromeda are spiral galaxies. That means most of their billions of stars concentrate into a disk and move in nearly circular orbits around the galactic center. In contrast, Milkomeda will be nearly spherical in shape and much smoother in appearance than any spiral galaxy.

In addition, Milkomeda's stars will follow more complex orbits. They will spend brief periods near the dense galactic center, but orbit much farther away most of the time.

Milkomeda's spheroidal shape is not unusual. In fact, it characterizes a major class of objects called elliptical galaxies. Such galaxies typically contain relatively old stars. Presumably, many of these galaxies in the present-day universe formed by mergers between galactic disks, in which the stars had formed at earlier cosmic times.

The Sun's likely fate will be to spend much of its time closer to the outskirts of the galaxy. The merger will redistribute the orbital momentum (energy) of the former Milky Way and Andromeda galaxies among Milkomeda's billions of individual suns. Because the stars will gain momentum in the course of the merger, they will orbit Milkomeda's center at a larger average distance.

The Local Group's fate

Astronomers have discovered that our universe is expanding at an ever faster pace, increasing the distance between galaxies so fast that, eventually, light itself won't be able to keep pace. A hundred billion years after the merger, Milkomeda will represent our entire visible universe.

In the next tens of billions of years, the accelerating expansion of space itself will pull all distant galaxies farther and farther away from us. Once the recession rate of any distant galaxy exceeds the speed of light relative to us, its light will be unable to traverse the ever-widening gap.

At that point, we will no longer be able to see those galaxies. They will gradually wink out of reach of the most powerful telescopes. No longer will astronomers be able to gaze into the sky and study distant galaxies in order to learn about our own.

However, the prelude to this final gloomy fate would be full of fun. Over the next 5 billion years, astronomers will witness the stellar fireworks in one of the greatest shows of all time: the transformation of the Milky Way and the Andromeda Galaxy into Milkomeda. So sit back and wait for the show to begin.