Stellar science

New light on our Sun’s fate

The Sun will lose 46 percent of its mass before becoming a carbon and oxygen cinder in 6.5 billion years. Here’s how astronomers know its destiny. **by Jason Kalirai**

In the late stages of stellar evolution, a Sun-like star’s envelope is blown away into the surrounding interstellar medium, leaving the hot exposed core. In this image of a planetary nebula, the ultraviolet radiation from the core illuminates the expelled gas and dust, creating the shape that gives it the name “Butterfly Nebula.” In the future, only the core of the initial hydrogen-burning star — a white dwarf — will remain. NASA/ESA/THE HUBBLE SM4 ERO TEAM

IN the future, Earth will be inside the Sun. That new location will be a result of the Sun’s evolutionary path because our star will change dramatically in mass and, especially, size.

If we think of today’s Sun as a soccer ball, in the future it will grow enormously in size — similar to a soccer field — and then shrink down to an ant walking on that field. But the Sun is presently in a stable, long-lasting portion of its life, so how can we possibly know what it will do in the future? Well, we’ve observed such evolutionary life cycles for Sun-like stars in the Milky Way. These studies give us clues predicting our own star’s life.

The life cycles of stars

A century ago, Danish scientist Ejnar Hertzsprung and American astronomer Henry Norris Russell independently made a remarkable observation while analyzing several of the stars nearest to the Sun. Some stars of the same color that lie at the same distance from us surprisingly have very different luminosities. Hertzsprung referred to those nearby stars with high luminosities as “giants” and those with low luminosities as “dwarfs.” Then, in a December 1913 talk, Russell presented an early version of what we now call the “Hertzsprung-Russell diagram.” This plot compares a star’s brightness (on the vertical axis) to the star’s color, or spectrum (on the horizontal axis).

With these 20th-century observations, the first ideas on stellar physics emerged — that a

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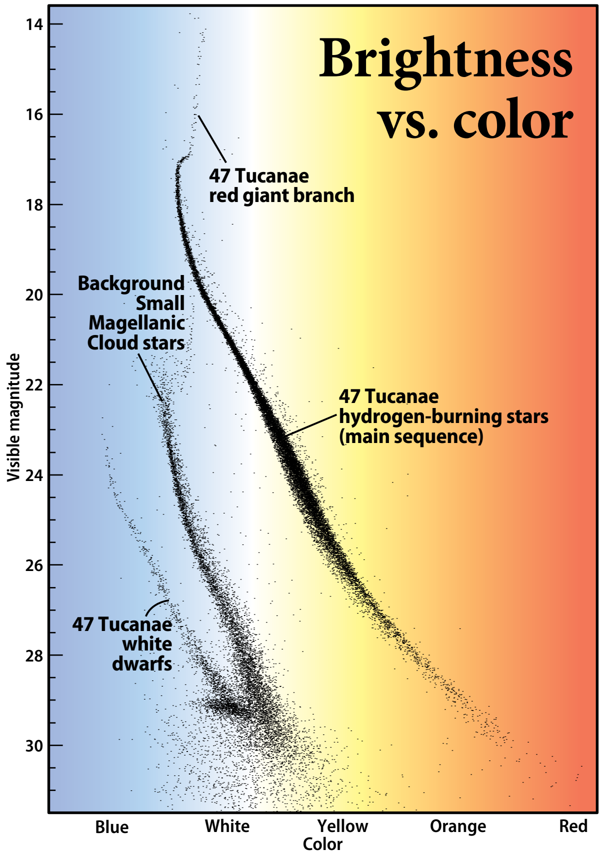
The globular star cluster 47 Tucanae lies some 15,000 light-years from Earth and contains thousands of white dwarfs, which the author and colleagues studied with the Hubble Space Telescope and ground-based observatories. THOMAS V. DAVIS



This Herztsprung-Russell diagram shows the luminosity of the stars in cluster 47 Tucanae along the Y-axis and their colors (which correspond to their temperatures) along the X-axis. The data show three populations within the globular cluster in addition to hydrogen-burning stars that belong to the background Small Magellanic Cloud (SMC) dwarf galaxy. This galaxy is 200,000 light-years behind 47 Tuc, but the Hubble Space Telescope's sensitivity and resolution detect the SMC's individual stars. *ASTRONOMY*: ROEN KELLY, AFTER J. KALIRAI, ET AL.

star's mass and luminosity are correlated. Astronomers also began to wonder how stars evolve and thought that perhaps they “move” across the H-R diagram. Over decades, we've learned that a star's mass controls its life; along the way, that property also determines its brightness and temperature. We now summarize all stages of stellar evolution on this important diagram.

Today, astronomers use powerful telescopes, on the ground and in space, to measure stars' brightnesses, colors, and positions. For example, the Hubble Space Telescope can observe individual Sun-like stars some 2.5 million light-years distant in the Andromeda Galaxy — suns that appear 10 billion times fainter than the faintest star your unaided eye can see. For engineering marvels like Hubble, stars in our solar neighborhood are a piece of cake. By measuring their properties to exquisite precision, astronomers are able to study the process of stellar evolution in great detail.

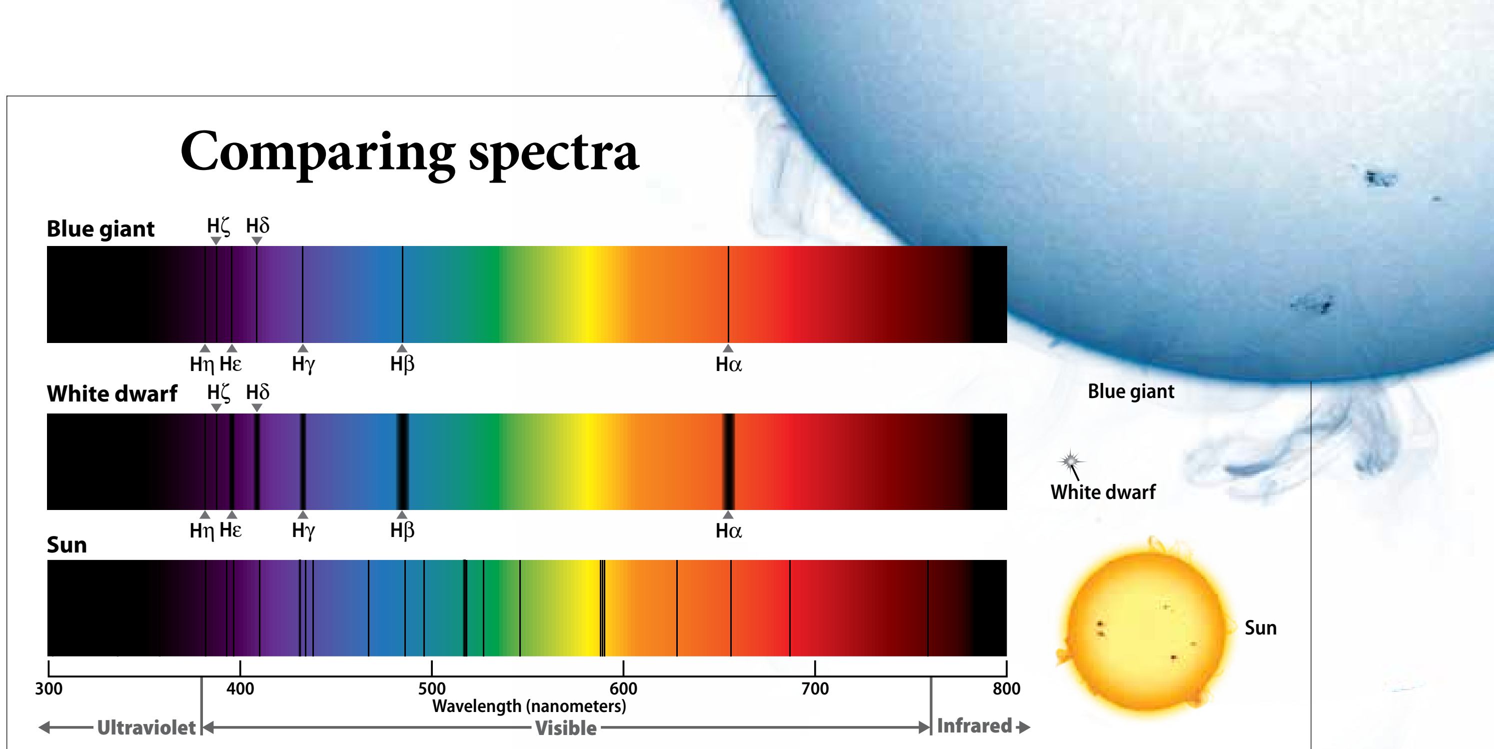
We know that long quiescent phases dominate the life cycles of most stars. Shortly after a star forms, its central core reaches a temperature of tens of millions of degrees, hot enough to fuse hydrogen into helium and energy. During this phase of nuclear “burning,” a star's appearance remains quite stable, with little change in its luminosity, size, and temperature. At the end of their lives, most stars (those less than 10 times the Sun's mass) will use up their nuclear fuel, swell, and shed their outer layers. Their cores will simply cool over time as “white dwarfs.” This end product is a carbon-oxygen remnant — because those elements are what the nuclear fusion of hydrogen and helium create in stellar cores — with a thin surface layer of hydrogen. The stars have no nuclear energy sources, so they simply cool over time and radiate away stored heat.

The missing pieces

We have a solid understanding of both the hydrogen-burning phase and white dwarf stage of stellar evolution, but tracking what happens in the middle remains one of the biggest mysteries in stellar astrophysics. It is during these years that stars undergo dramatic changes and can rapidly transform over size scales of tens of thousands. This evolution begins when a star, depleted of hydrogen in its core, begins to burn hydrogen in a shell surrounding that interior. The sun's outer layers become diffuse and expand; we classify it as a red giant. In this stage, the star is much brighter than a dwarf of the same temperature because it emits energy from a much greater surface area.

The amount of mass that a star sheds as a red giant directly shapes its future.

As the star continues to evolve on this “red giant branch,” as it's called on the H-R diagram, getting brighter as time passes, stellar winds can propel the outer layers away from the sun and dump material into the surrounding environment. The amount of mass that a star sheds as a red giant directly shapes its future. And knowing the details of what happens with other red giant stars can help us figure out what our Sun will experience later in life.



While the Sun shows many dark absorption lines, hotter stars have simple spectra exhibiting just the “Balmer sequence” of hydrogen. Newly formed white dwarfs have temperatures similar to hot blue giants, and therefore also show Balmer lines. But given the intense pressure on the surface of white dwarfs, these lines are “pressure-broadened” and have much larger widths than hydrogen-burning stars. By observing these Balmer lines, scientists can accurately measure the remnant's temperature and surface gravity. *ASTRONOMY*: ROEN KELLY, AFTER NASA/ESA/A. FIELD AND J. KALIRAI (STScI)

After a star's red giant phase, it burns helium in its core. It again changes in temperature and size as it ascends the “asymptotic giant branch” and burns helium in a surrounding shell. A sun's lifetime on this branch depends on how long it takes to fully blow off its gaseous envelope and the luminosity it will reach. If the star loses the envelope quickly, then the evolutionary stage ends and it forms a white dwarf; if the star instead loses the material slowly, it will live on the asymptotic giant branch longer and continue to become brighter and more bloated. Knowing how much material such a sun loses helps us understand this later phase of stellar evolution. This branch of evolution is extremely difficult to model theoretically, but by measuring the mass loss directly, we can refine computer models that predict stellar timescales and luminosities.

We can take the color and brightness observations of stars and use models that predict how physical changes will affect the emergent spectrum (and therefore the color) to learn about the properties of the galaxies those suns live in, such as age, chemistry, and star formation rate. Ultimately, understanding a star's mass loss is an anchor for much of what astronomers do: interpreting unresolved red and infrared light from distant galaxies because, after all, galaxies are made of stars.

Connecting the dots

My colleagues and I have studied suns in different phases of evolution to piece together the process. To measure how much material stars lose through stellar evolution, we need to figure out both the initial and final masses *for the same stars*. Yet the timescales — millions to billions of years — are too long to watch a given sun evolve. We have no way to infer the final white dwarf properties of a hydrogen-burning star shining in the night sky. Similarly, for a nearby white dwarf, we have no way to infer the initial sun's mass. (Astronomers refer to this initial star as the progenitor.)

But we do have “laboratories” to tackle the problem: star clusters, environments where thousands of suns are cut from the same cloth. All of the suns within a given cluster formed at the same time and with the same composition, yet over a range of individual masses. Each cluster gives us a snapshot of stars at a given age. We can directly see the impact that stellar evolution has played on stars with different masses.

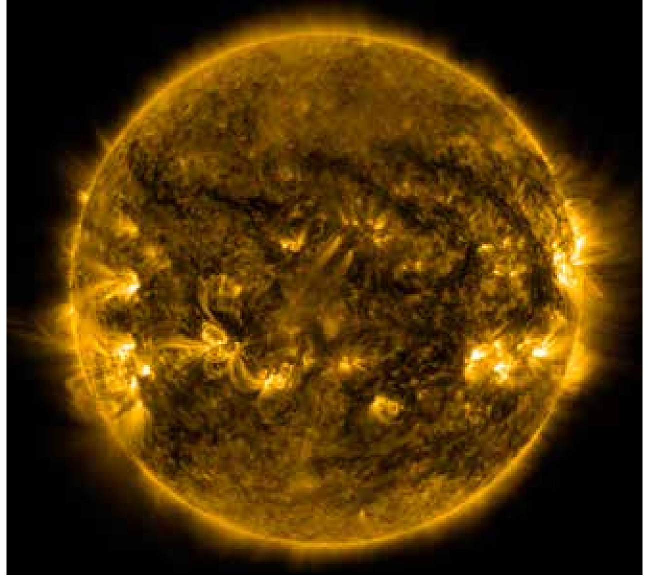
Each cluster gives us a snapshot of stars at a given age.

Star clusters are extremely dense environments. Over a distance similar to that between the Sun and its nearest neighbors — a few light-years away — a given cluster can contain hundreds of stars. All of these suns share incredible similarities and therefore represent a controlled environment for studying stellar evolution. To explore both the initial and final phases simultaneously, and therefore measure how much mass stars lose through their evolution, we can use a three-step process.

Step 1: Find needles in a haystack

In the past decade, research teams have measured the brightnesses and colors of all the stars in a cluster. In this step, we make sure not only to study the brighter hydrogen-burning and giant phases of stellar evolution, but also to hunt the fainter remnant white dwarfs. Not long ago, these stars burned hydrogen in their cores, but they have evolved faster than their counterparts because they were initially more massive.

The author and colleagues used the Keck telescopes atop Mauna Kea, Hawaii, to gather the light signatures, called spectra, of white dwarfs in globular cluster 47 Tucanae. ETHAN TWEEDIE PHOTOGRAPHY



Following a study of nearby white dwarf stars, the author and colleagues concluded that the Sun will lose 46 percent of its mass through its evolution to become a white dwarf. NASA/SDO

My colleagues and I recently used Hubble to observe one of the nearest globular clusters, 47 Tucanae (NGC 104). Hubble's razor-sharp vision allowed us to see the faintest white dwarfs at nearly 30th magnitude. We plotted all the stars on the H-R diagram (see illustration on p. 46); with such figures, we can place tight constraints on the fundamental properties of each cluster, such as its age. This is because stars' evolution corresponds to how massive they are at birth. To determine a cluster's age, we can see what mass of stars in a cluster are still burning hydrogen and which have evolved past that point. With this diagram, we also can measure the census of brighter white dwarfs, which we will then observe in greater detail with other telescopes. Other teams of astronomers work with our group to make similar diagrams using ground- and space-based telescopes for clusters ranging in age from 50 million to 13 billion years; 47 Tuc is about 10.5 billion years old.

Step 2: Exploit natural labs

One of the most remarkable properties of white dwarf stars is their density. The mass of a typical white dwarf is about half that of the Sun, but its size is similar to Earth's. So, the density of white-dwarf matter can be a million times higher than the Sun's average.

Because white dwarf densities are so high, we call these stellar remnants natural condensed-matter laboratories. The pressure at a white dwarf's surface is extreme because of that density, and that makes its characteristic light signature, or spectrum, unlike any other star's. These spectra hold important clues to stars' properties. For a "normal" white dwarf with a temperature of 20,000 to 30,000 kelvins (36,000° to 54,000° Fahrenheit), the spectrum shows common lines of hydrogen. But these lines look nothing like what you would observe in a lab or even from a more typical hot, hydrogen-burning sun like Sirius A. The pressure on the surface of a white dwarf blurs the absorption lines to widths five to 10 times greater than those in normal stars (See "Comparing spectra" on p. 47).

To observe these broadened lines, we use special instruments called spectrographs to split apart stellar light. Specifically, we employ multi-object spectrographs on large 10-meter class telescopes, such as the Keck telescopes in Hawaii, to measure spectra for dozens of white dwarfs in a given cluster at one time. We then compare computer models of those hydrogen lines with a white dwarf's spectrum to measure its surface pressure, temperature, and surface gravity. From that information, we can accurately calculate the star's present-day mass and how long it has been since the original star spewed all of its outer gaseous layers and left its remnant core.

Step 3: Put it together

The age of each cluster (determined in step 1) is the same as the ages of all of its member stars. For the white dwarfs, that value is the sum of the already determined cooling time of each remnant and the hydrogen-burning lifetime of the progenitor. That means we can calculate the initial star's lifetime using the following equation: star cluster's age – white dwarf cooling time = progenitor lifetime.

We can derive the initial star's mass simply from using well-tested theoretical models at that age. This novel method lets us explore both the initial and final masses of the *same* stars.

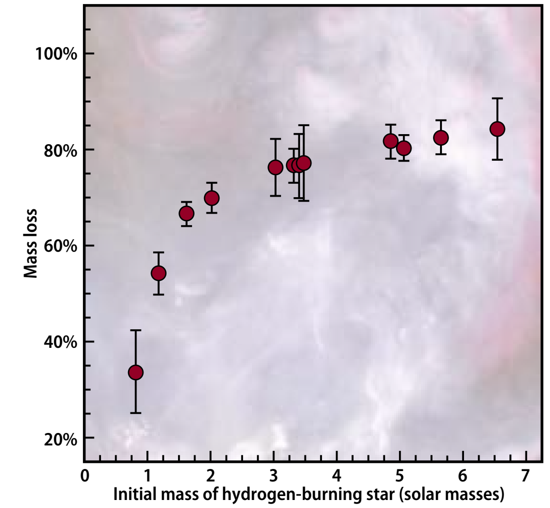
> The mass of a typical white dwarf is about half that of the Sun, but its size is similar to Earth's.

How much mass is lost?

After applying this calculation to decades of observations of white dwarfs in nearby star clusters — including our study of 47 Tuc — my colleagues and I find that hydrogen-burning stars will lose a significant amount of their mass through stellar evolution. The higher-mass suns will proportionally lose more material. For example, stars born with five times the Sun's mass will lose 80 percent through evolution and end their lives as massive white dwarfs with approximately the Sun's mass. (The nearest white dwarf to the Sun, Sirius B, matches that prediction, as it has a mass approximately the same as our star.) These larger suns are rarer because nature produces many more low-mass stars than high-mass ones.

Whereas the evolution of Sun-like stars leads to more typical carbon-oxygen white dwarfs, the progenitors of such massive white dwarfs may reach much higher temperatures and densities. In these extreme environments, even the carbon and oxygen in the stars' cores can fuse into heavier elements such as neon and magnesium. Therefore, astronomers believe the cores of these massive white dwarfs have different compositions from more "typical" ones. At intermediate sizes of two to three times the mass of the Sun, a star will lose two-thirds to three-quarters of its mass.

Stellar weight loss



The more massive a Sun-like star is initially, the larger fraction of material it will lose through stellar evolution. The author and colleagues compared the properties of white dwarfs in star clusters and correlated their masses to those of their original hydrogen-burning selves. While some of the plotted points come from research from other scientists, the data points for stars with masses less than twice the Sun's mass are from the author's team.

ASTRONOMY: ROEN KELLY, AFTER J. KALIRAI, ET AL.

At the center of the Helix Nebula lies a white dwarf. That stellar remnant's radiation causes the surrounding gas to glow in ultraviolet (shown in blue) and infrared (green and red). NASA/JPL-CALTECH

The fate of our Sun (and Earth)

Our measurements of the initial and final masses of stars also extend to nearby Sun-like stars and therefore predict the fate of the Sun. We know that our star will exhaust the hydrogen within its core in about 6.5 billion years. (This information comes from a long-used scientific method — comparing observations with theoretical models. Astronomers measure and characterize stars at different life cycles and then match those observations to theoretical models to predict the evolutionary future of stars.)

With no hydrogen left in its core, our Sun will begin to burn the element within a surrounding layer, like normal red giants. This tenuous layer will expand due to the heat generated and grow to 200 times its present radius. The Sun's surface temperature will drop to about half its present value — about 3000 K (4900° F). However, given its much larger size, the Sun will be 1,000 times more luminous than it is now.

As it expands, the Sun will completely engulf both Mercury and Venus. Earth, on the other hand, will attempt to play a "catch me if you can" game with our star. As the Sun loses mass, and hence gravitational influence, Earth's orbit will expand to some 50 percent farther out than it currently is. Unfortunately for our planet, the Sun will lose mass rapidly as a red giant, and its outer layers will overtake Earth's migration; our planet will "cook." By that time, however, the heat will have already dried up the oceans and burned away our atmosphere. After encountering the gas particles in the Sun's tenuous outer surface, Earth will feel a "drag" and begin to slow its rate around the Sun. Its orbit will then spiral toward the center of our star.

> As a white dwarf, our star will slowly release its stored heat into space and dim as time passes.

According to stellar evolution models, after its giant phases, the Sun will have lost its envelope and only its core will remain. This core — a white dwarf — initially will be extremely hot, but without nuclear fuel, it will quickly cool. This is the fate of our Sun: After losing 46 percent of its mass, a value my colleagues and I calculated, it will be a normal white dwarf with 54 percent of its present weight (see "Stellar weight loss" above). Like the white-dwarf-progenitor stars within globular cluster 47 Tuc, our Sun will end up with a fraction of the mass it was born with.

Just as it lived a relatively boring life while burning hydrogen in its core for billions of years, the Sun will enter another long state of stellar evolution. As a white dwarf, our star will slowly release its stored heat into space and dim as time passes. It will join the stellar graveyard of the Milky Way, a place where 98 percent of the galaxy's stars end up.

A+ VIEW A GALLERY OF PLANETARY NEBULAE, THE BEAUTIFUL REMNANTS OF SUN-LIKE STARS, AT **www.Astronomy.com/toc.**