White Dwarf Stars

The remnants of Sun-like stars, white dwarfs offer clues to the identity of dark matter and the age of our Galaxy

Steven D. Kawaler and Michael Dahlstrom

Six billion years from now, someone looking up at the sky on a summer's day would not see the same bright Sun we now see. In its place would be a tiny orb—a "white dwarf"—shining feebly in a black sky. Whether anyone will be around to see such an alien sky is another question: All life on Earth would have been obliterated when the Sun entered its red-giant stage a billion years earlier. The white dwarf will endure for many billions of years afterward as a small monument to our solar system.

Our Sun may be billions of years away from such a fate, but there are countless numbers of white dwarfs now in our Galaxy. "Countless" is an apt term in this case, since their total number is not known—they are too small and too dim to be easily seen. Indeed, white dwarfs were only identified as a distinct class of stars less than 100 years ago, a testimony to their relative obscurity. Almost all of the catalogued white dwarfs lie within the immediate solar neighborhood, and nearly half of these can be found within 75 light-years of our Sun.

Although they are difficult to locate, there are many reasons to care about these fascinating stars. Since they represent the final stage in the evolution of 98 percent of all stars, the study of white dwarfs is very nearly the study of all stars. As the remains of once-brilliant suns, white dwarfs can provide information about their earlier lives in much the same way that human remains provide information to forensic anthropologists. White dwarfs are also convenient astrophysical laboratories in which we can study matter at pressures and temperatures that cannot be achieved in terrestrial laboratories.

Much of this information is revealed through complex vibrations created in the interiors of white dwarfs that can be measured using a unique tool known as the Whole Earth Telescope. What astronomers have learned about white dwarfs has implications beyond our understanding of stellar evolution. Recent work shows that these stars can be used to find the age of our Galaxy and may even make up a large fraction of the mysterious dark matter in the universe.

Strange Little Stars

In the year 1783, two years after discovering the planet Uranus, British astronomer William Herschel became the first person to see a white dwarf star. On the evening of January 31, Herschel observed a star in his telescope named 40 Eri B, which actually proved to be a pair of stars, one of which was a "faint, dusky star." At the time he didn't recognize it as being anything unusual.

The strangeness of Herschel's star did not become apparent for another 127 years. In 1910 spectroscopy revealed that 40 Eri B (and two other stars like it) had surfaces that were hotter than our Sun. But they were so close to the Earth that, were they normal stars, they would be easily visible with the naked eye. Obviously, something was different about these new objects. By 1914 the mystery was clear. For these stars to be so faint, they had to be extremely small—about the same size as the Earth, or just 1/100 the diameter of the Sun. Their white-hot surfaces and small diameters provided a name for this new class of stars: white dwarfs.

White dwarfs were truly a puzzle. A star with the mass of the Sun confined to the volume of the Earth must have an enormous density. How could such an object support itself against its own gravity? What processes could make such a star? Today we can answer these questions.

During a star's lifetime there are two forces fighting for control. The first is the inward force of gravity, trying to compress the star to as small a point as possible. Opposing gravity is the outward force of gas pressure provided by high temperatures inside the star. Although energy is lost by radiation, the star maintains its high temperature through nuclear fusion as it burns hydrogen into helium. These two forces balance each other precisely, creating a stable stellar structure—at least for a while.

Eventually, the star's central reserves of hydrogen are exhausted. Fusion ceases at the center, but continues in a thin shell surrounding the now pure helium core. Within the core, the inward force of gravity starts to win out over the outward gas pressure, and the core collapses. The gravitational energy released by the core, combined with the energy output of the burning shell, puffs the outer layers of the star to a huge radius with a low surface temperature (forming a red giant star) and briefly increases its energy output by a thousand times.

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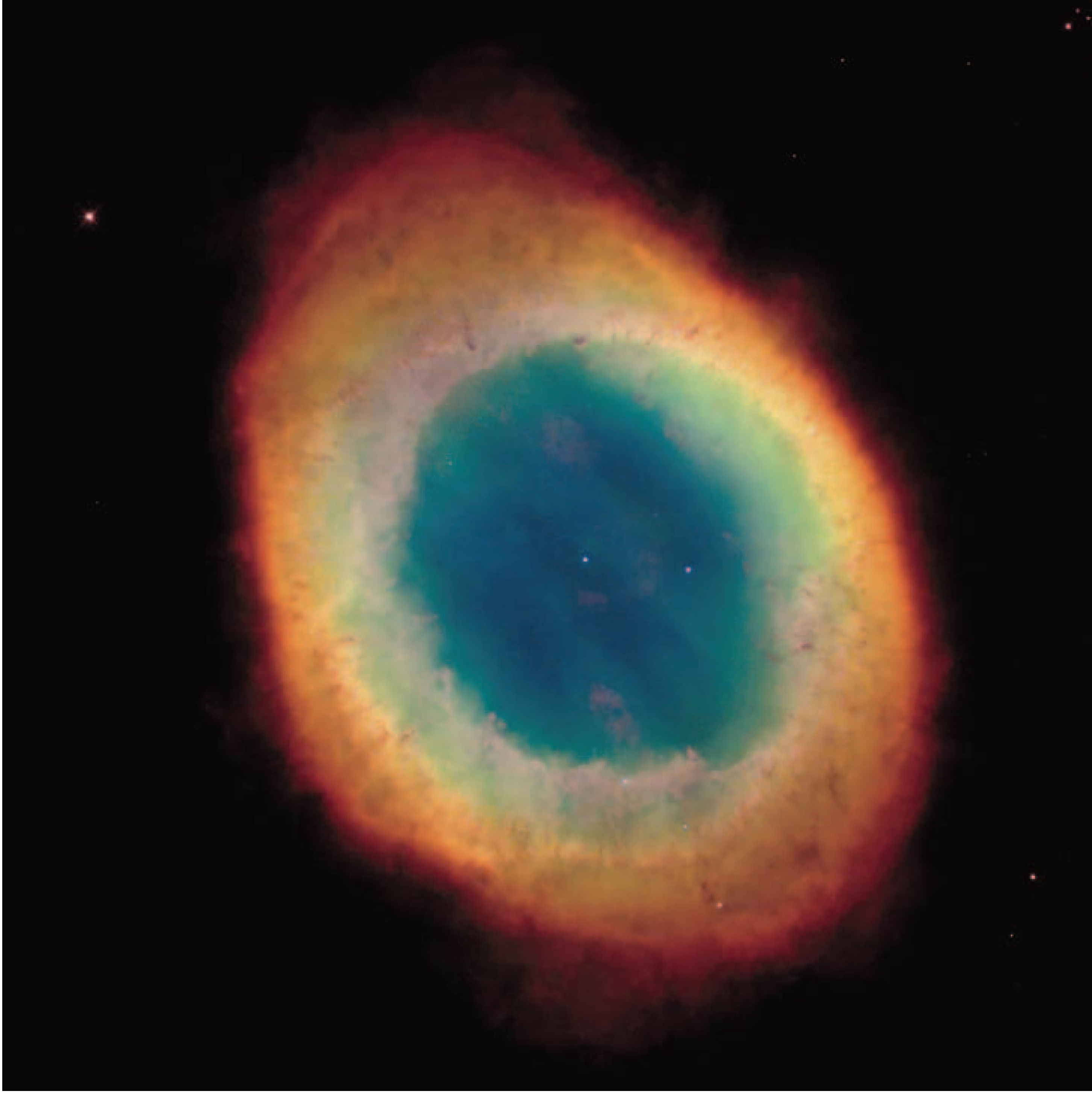


Hubble Heritage Team (AURA/STScI/NASA)

Figure 1. Spectacular ejection of material from a dying star forms a planetary nebula and leaves behind a feeble remnant, which will become a white dwarf ***(visible here in the center of the ring)*****. Although some consider a white dwarf to be a dead star (since nuclear fusion has ceased to provide energy within), it is hardly a quiet corpse. Changes in temperature and pressure within the white dwarf result in vibrational instabilities that resonate throughout the object, resulting in "starquakes." Stellar seismologists have learned much about the structure and composition of white dwarfs by continuously following their activity with a global network of telescopes, collectively known as the "Whole Earth Telescope." Here a high-resolution image of the Ring Nebula (M57) reveals details in the radial patterns sculpted in the gas and dust exhaled by the dying star. Our Sun will undergo a similar transformation in the course of its death throes about 5 billion years from now.**

Soon, the compression of the core generates enough heat to ignite the fusion of helium into carbon, and the star returns to nearly normal dimensions. Eventually, the central helium supply also becomes exhausted and the dying star succumbs to gravity again: The core collapses, shell burning resumes and the star becomes a red giant for a second time (as an *asymptotic giant-branch star)*. As the core shrinks, some of its outer envelope breaks free and cools to become a colorful planetary nebula (so called because early astronomers confused these structures with distant planets like Uranus; see "The Shapes of Planetary Nebulae," *American Scientist* July–August 1996). Finally, glowing proudly at the center of the nebula is the collapsed core—a newly formed white dwarf.

To understand the magnitude of a white dwarf's collapse, imagine going to the local bowling alley and finding the heaviest bowling ball they have. Take it in your hands and squeeze it until it is the size of this letter "o." Compressing that much mass into

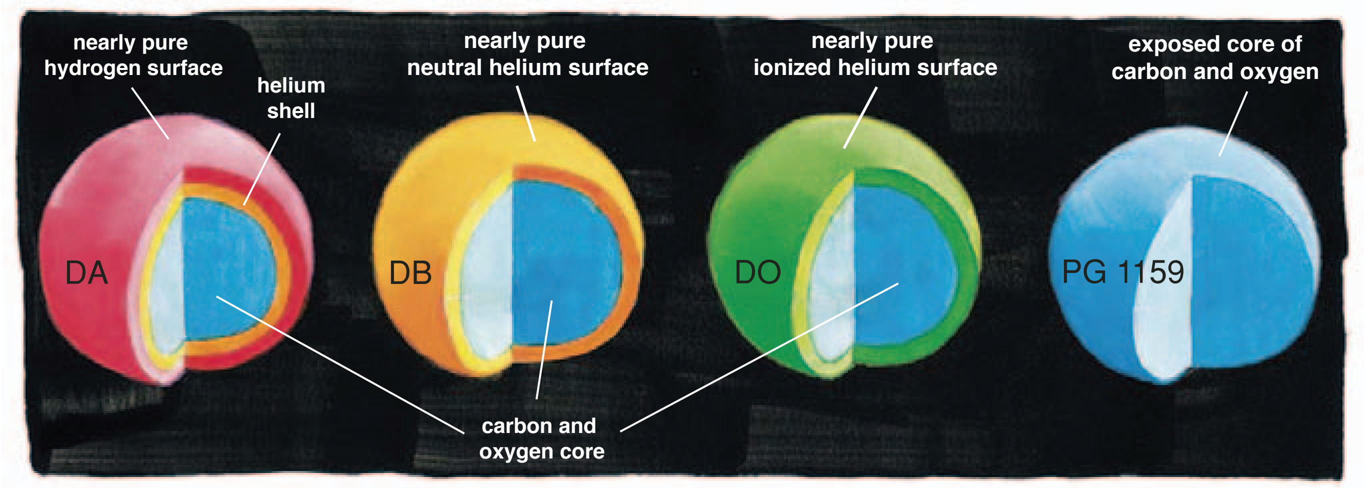


Figure 2. White dwarf varieties are defined by the elements that dominate their surfaces as revealed by their spectra (the continuum of light they emit). Nearly all white dwarfs are believed to contain a core of carbon and oxygen *(blue)*. Three varieties—DA, DB and DO white dwarfs—have nearly pure surfaces of hydrogen or helium lying atop their cores, whereas PG 1159 stars appear to be partially exposed cores. White dwarfs may also have a mixture of elements on their surfaces, and are named accordingly. For example, DAB stars contain hydrogen and neutral helium, whereas DAO stars have hydrogen and ionized helium.

such a small volume creates a very dense vowel! This is the same degree of compression a white dwarf faces during its final gravitational collapse.

At these high densities, the self-gravity of the star is too strong for ordinary gas pressure to resist. The only force keeping the star from total destruction is the behavior of electrons. According to the Pauli exclusion principle, no two electrons can share the same quantum numbers and therefore cannot share the same state. The gravity of a white dwarf compresses the electrons to the point where they cannot be any closer. (This explanation was first given in 1926 by the astrophysicist Ralph H. Fowler of the University of Cambridge. It was later clarified with numerical models by one of his students, Subrahmanyan Chandrasekhar, who won a share of the 1983 Nobel Prize in physics for his efforts.) This *electron degeneracy pressure* stabilizes the star at an incredibly high density: one million times that of water. No substance on Earth has a density anywhere close. The densest terrestrial material is pure iridium, with a density of 22.65 times that of water. Gold weighs in at merely 19.3, and iron is a lightweight at 7.9.

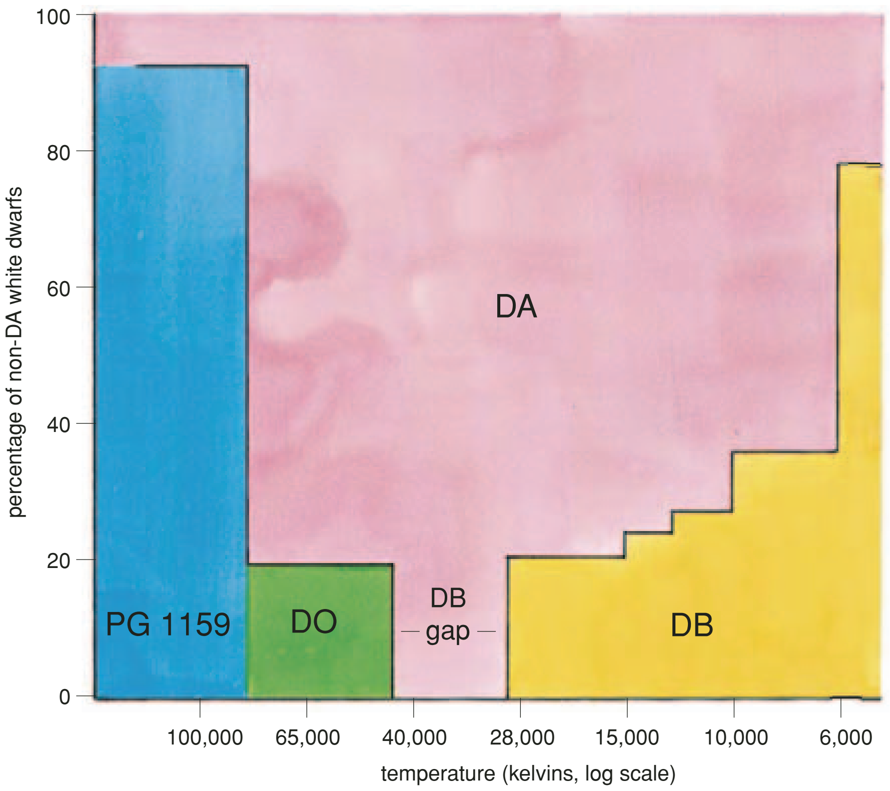


Figure 3. Distribution of white dwarf varieties according to their temperatures reveals a mysterious absence of non-DA stars around 40,000 kelvins, known as the "DB gap." As their temperatures drop, DO white dwarfs are believed to become DB stars when the ionized helium recombines with free electrons to form neutral helium. The absence of DO and DB stars at the DB gap suggests an intermediate stage in which a DB star is masked as a DA star. The reason for the DB gap is not fully understood.

From this we can understand the makeup of a typical white dwarf. Like the three layers of a melon, a white dwarf consists of an electron-degenerate core of carbon and oxygen, which is surrounded by a thin rind of helium and an outer skin of hydrogen. Not all white dwarfs have the same structure, however. Subtle differences among white dwarfs show that a star may take one of several possible evolutionary paths as it runs out of nuclear fuel.

White Dwarf Flavors

Spectroscopy reveals that most white dwarfs have almost pure surfaces of either hydrogen or helium. This provides a handy classification system that reflects the unusual surface composition of these stars. White dwarfs with surfaces of hydrogen are called DA stars. White dwarfs that have pure helium atmospheres with strong neutral helium (He I) lines are named DB stars. If the helium white dwarf shows relatively strong lines of singly ionized helium (He II) it is called a DO star. As a DO star cools, the He II will recombine with free electrons to form He I, eventually changing the DO into a DB white dwarf.

Although most white dwarfs show only hydrogen or helium on their surfaces, there are a few with mixed spectra. They are named accordingly. Hydrogen-covered white dwarfs with lines of He I are named DAB stars, whereas hydrogen stars with lines of He II are logically named DAO stars. Some rare white dwarfs show evidence of carbon in their spectra (DQ stars) or other heavier elements (DZ stars).

One of the most bizarre classes of white dwarf is the very hot, hydrogen-deficient PG 1159 stars. These are the hottest white dwarfs, with temperatures as high as 170,000 kelvins. They have no hydrogen or He I lines, but do show weak He II lines and stronger lines of ionized carbon and oxygen. PG 1159 stars appear to be the exposed inner core of a white dwarf. As a delightful tongue twister, PG 1159 stars can also be classified as DOZQ stars!

The flavor of a white dwarf is determined, in part, by the type of shell burning (hydrogen or helium) that dominated as it became a planetary nebula. If the star was burning hydrogen, the white dwarf that resulted would probably be a hydrogen-rich DA. If the parent star was burning helium, the most likely outcome would be a DO (and later, a DB) star. In rare instances, a final burst of helium-generated nuclear energy occurs after the planetary nebula has formed. This blast ejects the hydrogen and almost all of the helium from the white dwarf, exposing a PG 1159 star.

A very interesting phenomenon appears when we tally the actual numbers of DA, DB, DO and PG 1159 stars according to the range of white dwarf temperatures. PG 1159 stars appear at the hot end, followed by the helium-rich DO stars. As the temperature decreases from 80,000 kelvins to 45,000 kelvins, the hydrogen-rich DA stars increase in number. Then suddenly, from 45,000 kelvins to 27,000 kelvins, all helium white dwarfs disappear, leaving only hydrogen DA stars. At tempera-

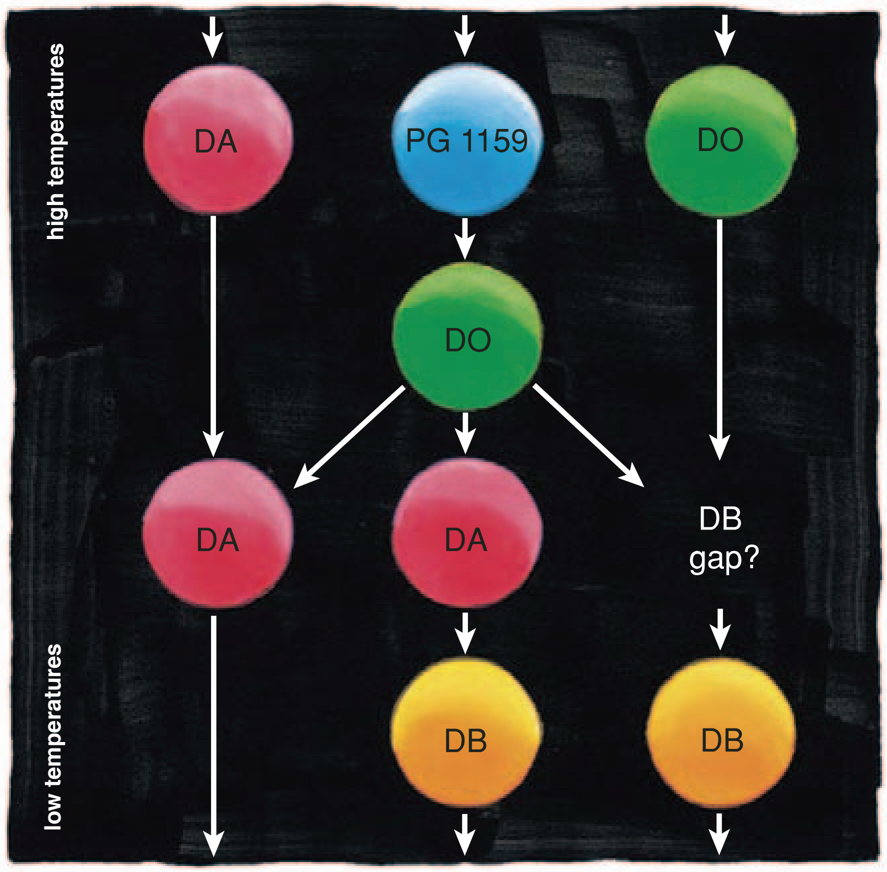


Figure 4. **Hot white dwarfs** ***(top row)*** **pass through one of several evolutionary paths** ***(white arrows)*** **as they cool with age. Some white dwarfs remain as DA stars throughout their existence** ***(left column),*** **whereas PG 1159 stars** ***(middle column)*** **may evolve through two or more other white dwarf varieties. DO stars may evolve through the DB gap to become identifiable DB stars** ***(right column)*****, but none has been observed within the gap.**

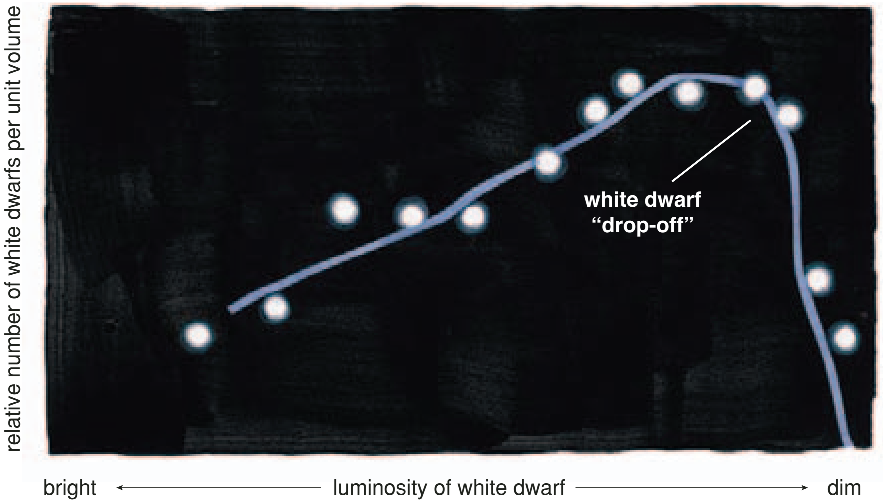


Figure 5. White dwarfs become cooler and dimmer over time, allowing astronomers to estimate their age. Because the oldest white dwarfs must be the remnants of the Galaxy's first stars, estimating their age provides astronomers with a tool to measure the age of the Milky Way. Here a rapid decrease in the numbers of very dim white dwarfs (a so-called "drop-off") suggests that the Galaxy is not sufficiently old to contain cooler (hence older) stellar remnants. Current estimates based on the cooling rate of white dwarfs suggests that our Galaxy is about 9 billion years old, an age consistent with independent estimates of the age of the universe (about 13 billion years old).

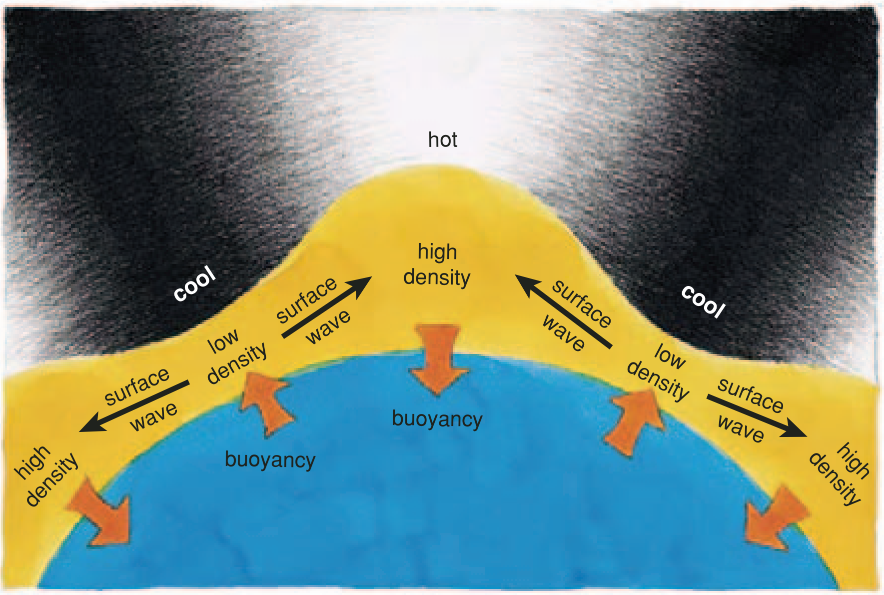


Figure 6. "Starquakes" on a white dwarf can be observed as periodic changes in the relative brightness of the star. Temperature changes within the white dwarf result in the vertical movement of dense material above its equilibrium point in the star. High-density material is relatively hotter (and thus brighter) than low-density material, which results in variations in the amount of light emitted across the surface of the star. Since the changes in density are restored by buoyancy *(orange arrows)*, or gravity, these pulsations are known as "g-mode" oscillations. The small vertical motions also generate larger, horizontal motions *(surface waves)* that propagate across the star.

tures cooler than 27,000 kelvins, the helium DB stars begin to appear and dominate in numbers below 10,000 kelvins. The decreasing surface temperatures are indicative of a progressive cooling, which suggests a general evolutionary sequence from PG 1159 stars to DO, then DA and then DB stars.

Such a linear scheme is a little too simple, however. Consider the "disappearance" of helium white dwarfs between 45,000 and 27,000 kelvins. This mysterious observation is called the DB gap. Something strange is happening in the outer layers of helium white dwarfs as they cool below 45,000 kelvins causing the helium to disappear.

A possible explanation lies in the chemical evolution of white dwarfs. Four processes can change the structure of a white dwarf: gravitational settling, interstellar medium accretion, mass loss and subsurface convective mixing.

Like the separation of oil and vinegar, gravitational settling separates the white dwarf's constituents by atomic weight. Under the intense gravity at the surface of a white dwarf (as much as 100,000 times stronger than at the Earth's surface), heavier elements sink to the core, whereas lighter elements float to the surface. This diffusion is the dominant physical process in a white dwarf, and it is responsible for the ultra-pure surfaces we see with spectroscopy.

Two of the processes oppose one another: accretion from the interstellar medium and the loss of mass. The interstellar medium is made mostly of hydrogen and helium, with trace amounts of heavier elements. These materials can fall onto the white dwarf, polluting an otherwise pure surface. The opposite is true of mass loss. The material near the surface of a white dwarf can drift off into space, exposing deeper material of different composition.

Subsurface convection is the rapid and active mixing of the material inside a star. As a white dwarf cools, convection can mix material from below into the surface layers.

These evolutionary processes act at different times in the cooling history of a white dwarf, and the interplay be-

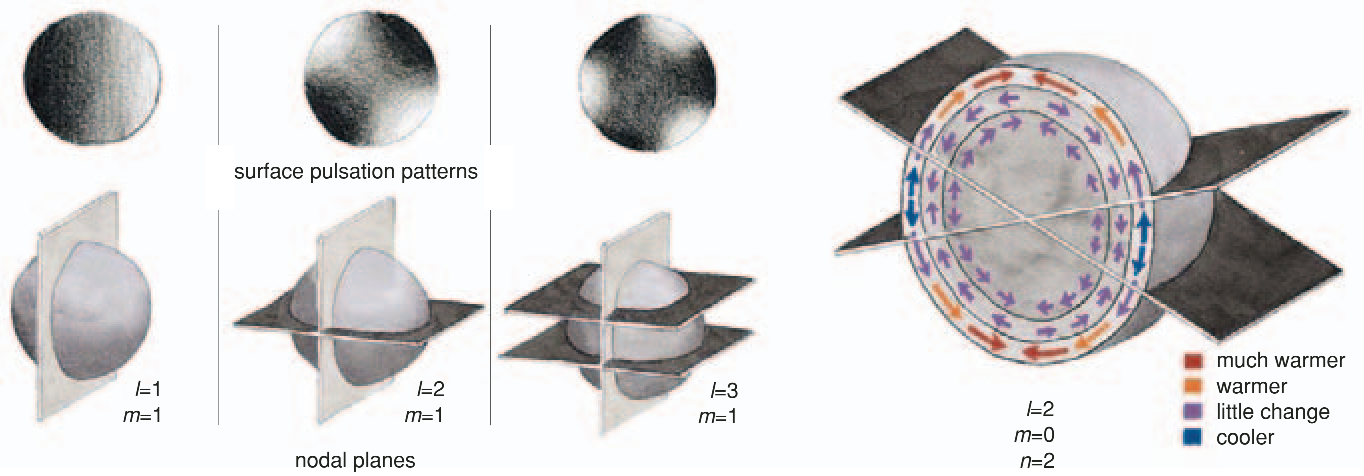


Figure 7. Stellar pulsations *(shading in the top three spheres at left)* can be characterized by three harmonic components—*l, m* and *n*—that define nodal surfaces or planes, which mark a change in the phase of the vibrations. Thus a nodal surface corresponds to a region of the star where there is very little temperature change. The *l* component gives the number of nodal planes that slice through the star's surface. The *m* component defines the number of these nodal planes that include the star's axis. The *n* component identifies the number of nodes that lie in the radial dimension, concentrically layered inside the star *(right)*. (Arrows signify the direction and size of the motion across the star).

tween them offers one possible explanation for the DB gap. The picture begins with a white dwarf that has a helium surface with some trace amounts of hydrogen: a helium-rich DO white dwarf. As it cools towards the hot end of the DB gap, hydrogen (being lighter than helium) floats to the surface via gravitational settling. By 45,000 kelvins the atmosphere has become almost pure hydrogen, masking the star as a DA white dwarf. Further cooling drives subsurface convection, mixing the components of the star and bringing helium back to the surface. The star would now be classified as a DB white dwarf.

Though this logical scheme explains the DB gap nicely, it only serves as an outline that must be filled in with computational models of white dwarf evolution. Efforts to model the evolution of white dwarfs by Ben Dehner, then of Iowa State University, and one of us (SK) have successfully reproduced some features of the observed stars. However, no single, self-consistent computational model has been able to satisfy all of the observed constraints. A complete explanation of the DB gap remains elusive.

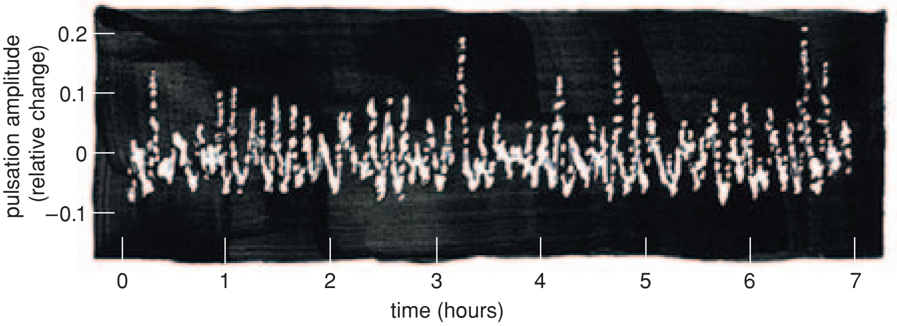


Figure 8. Light curve from a pulsating DA white dwarf shows the relative change in the amplitude of the star's pulsations over the course of about seven hours. The pulsation amplitude temporarily drops to nearly zero (at about 3.75 hours) as simultaneous pulsation modes of slightly different periods cancel each other by destructive interference. This star pulsates in more than 10 independent modes. Some pulsating white dwarfs show hundreds of separate periodicities. Distinguishing these modes is one of the challenges faced by stellar seismologists *(see Figure 9)*.

Cooling With Age

Everything we know about white dwarfs comes from the energy they radiate into space. But where does this energy come from if white dwarfs ceased burning their nuclear fuel long ago? In 1952, British astrophysicist Leon Mestel showed that this energy is the leftover heat from the star's days of fusion that leaks slowly into space.

Mestel's model likens a white dwarf to a heated piece of iron that is placed in a cool environment. Such a chunk of iron would cool rapidly when exposed to the outside air unless it was surrounded by some sort of insulating blanket. In degenerate matter, such as is found in the core of all white dwarfs, the electrons are so close together that some are "free to roam," resulting in a material that is similar in thermal properties to a terrestrial metal. This means that just like the exposed iron, the cores of white dwarfs would cool very rapidly. However, the nondegenerate outer layers of the star do not act like metals. They trap the heat and act as an insulating blanket. It therefore takes a long time for a white dwarf to lose all of its stored heat, allowing it to glow for billions of years.

Mestel's theory is a good approximation of how a white dwarf cools, but two processes complicate the behavior of real white dwarfs.

The first is neutrino emission. Neutrinos are tiny, almost massless particles that are formed inside the white dwarf. As the neutrinos are released into space, they take a little bit of energy with them. Early in the white dwarf's life, there are so many neutrinos escaping into space that the white dwarf radiates more energy through these particles than through normal photon luminosity. Thus neutrinos increase the cooling rate over that outlined by Mestel.

The other effect is crystallization. In a fully ionized medium, such as a white dwarf, a cloud of electrons completely cancels the charge of the positive ions, creating a neutral star. But at the cooler end of a white dwarf's life, the density increases and the charge cancellation become imperfect. As the

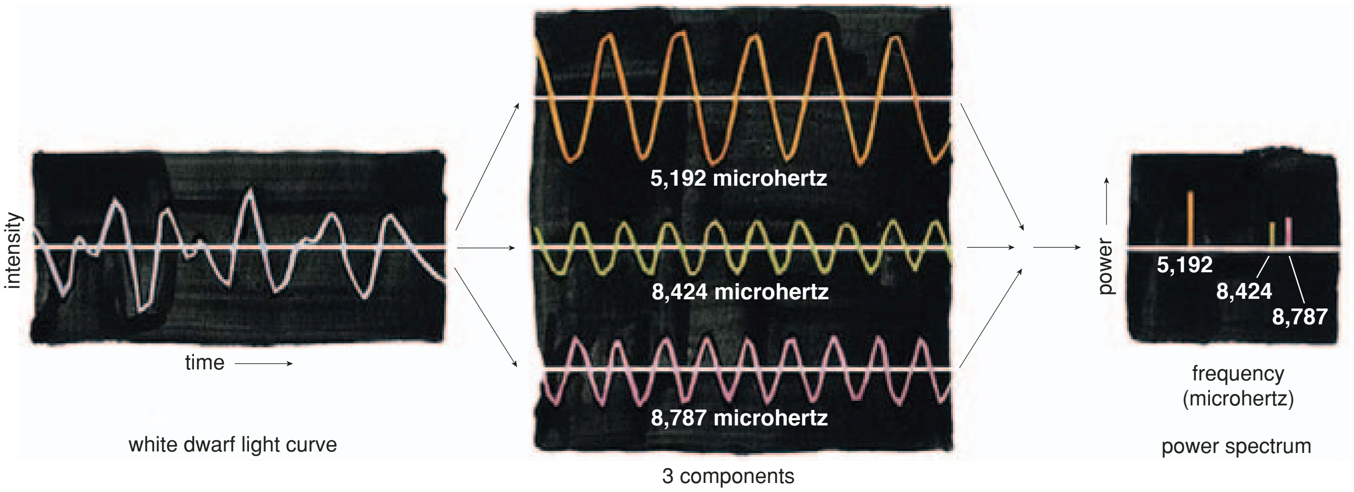


Figure 9. Complex light curve *(left)* from a white dwarf can be decomposed into its single-period components *(middle)*, allowing scientists to characterize the frequency and the strength of the individual pulsation modes *(right)*. The individual frequencies are very sensitive to various properties of the white dwarf—including its mass and temperature, its rate of rotation and the depth of the transitions between its layers (for example, from hydrogen to helium to carbon and oxygen).

Figure 10. The Whole Earth Telescope, consisting of many observers across the globe, allows astronomers to obtain a continuous light curve from a white dwarf 24 hours a day. Since the whole cycle of a white dwarf's oscillation may take several weeks or months to complete, this approach is crucial to understanding a white dwarf's properties. (A typical observing-run configuration is shown here.) The data from the individual telescopes are usually collected and analyzed at the Telescope's control center at Iowa State University, where the astronomers are fueled by high-density jelly beans and hot pizza.

interactions between ions strengthen, the mutual Coulomb repulsion becomes strong enough to lock the star into a giant crystal. As the star crystallizes it releases latent heat, providing an additional energy source that slows the cooling process compared to Mestel's model. Once the bulk of the star is crystalline, heat can travel through the star more easily and the white dwarf cools faster.

The cooling rate of a white dwarf is proportional to its temperature (hotter white dwarfs cool faster). Therefore, one would expect to see more white dwarfs at the cooler end of the spectrum because their cooling rate has slowed down. This is indeed the case. However, there is an abrupt and steep drop-off in the numbers of white dwarfs at very cool temperatures that cannot easily be explained as a cooling effect.

This drop-off is a result of the finite time that white dwarfs have had to cool. The time it takes for a white dwarf to cool below this temperature must be almost as long as the age of the original ancient star, and therefore a measure of how long ago stars first formed in the Galaxy. Thus the temperature of this drop-off is a direct measure of the age of the Galaxy. From current studies, the best estimate of the age of the disk of the Milky Way Galaxy is 9.3 ± 1.5 billion years. This is consistent with the Hubble age estimate of 12 billion to 14 billion years for the universe.

The precise age of the Galaxy based on the cooling of white dwarfs depends on computational models that include Mestel's effects, neutrinos, crystallization and other details. One of these important factors is the composition of the white dwarf's interior. The cooling rate depends on the mean atomic weight of the core, as well as the thickness of the "insulating blankets" of hydrogen and helium. These regions lie well below the observable surface of white dwarfs and were once impossible to probe until the techniques of stellar seismology were applied to white dwarfs.

Leukonanoseismology

Nearly everything we have learned about white dwarfs, and all stars in fact, is based on the light that comes from their surfaces. This light not only contains information about the white dwarf's chemistry, but in certain instances it also encodes information about the star's interior. This "inside information" is contained in complex, but well-ordered, pulsations that are caused by disturbances or quakes

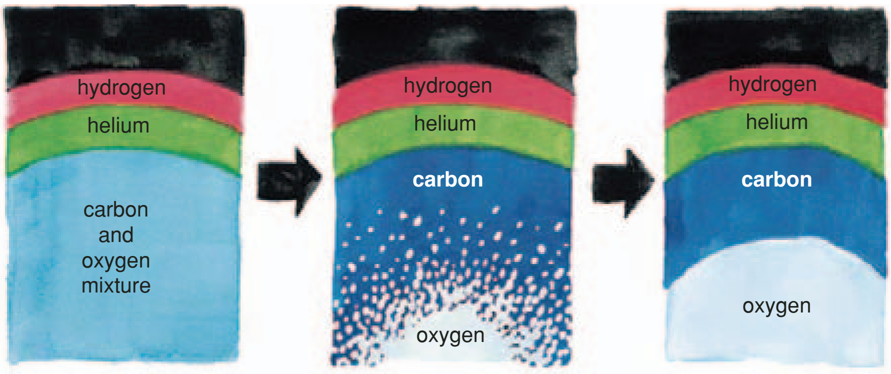


Figure 11. Separation of the oxygen and carbon in a white dwarf's core may include a process in which oxygen "snow" falls through the carbon toward the center of the star. The question is now being addressed by scientists using the Whole Earth Telescope.

within the star. Much as earthquakes can be used to probe the interior of the Earth, "starquakes" reflect the internal conditions of a star.

Asteroseismologists have been able to discern distinct classes of stellar pulsations. Stars like our Sun appear to be dominated by pulsations that travel through its interior by means of pressure waves, or "p-mode" oscillations. The p-mode oscillations are caused by changes in the temperature of the Sun's outer layers, which cause the material to absorb heat, expand, and then cool and contract again. These expansions and contractions generate sound (pressure) waves of assorted frequencies that travel to various extents throughout the Sun, depending on their wavelength and the Sun's internal structure. By "listening" to these solar oscillations, helioseismologists have learned much about the Sun's interior (see "Sounds of the Sun," *American Scientist,* January–February 1994).

By contrast, white dwarf pulsations are dominated by buoyancy (gravitational) waves, or "g-mode" oscillations. (These buoyancy waves should not be confused with the "gravitational waves" predicted by general relativity.) As the temperature or pressure changes within a white dwarf, stellar material of a particular density moves temporarily above its equilibrium point in the star but is then restored back down again by its relative buoyancy. These small vertical movements generate larger, horizontal motions within the white dwarf. Their propagation through the star is determined by their wavelength and the star's interior structure. When these oscillations reach the white dwarf's surface, they produce areas of higher density and temperature. Where the temperature is locally higher, the surface of the star is brighter. This change in the white dwarf's luminosity can be observed with sensitive photometers on the Earth. Such measurements allow accurate determinations of the star's mass, rotation rate, cooling and contraction rate, compositional stratification and magnetic-field strength.

Aside from their oscillations, pulsating white dwarfs look like "normal" white dwarfs. From this we conclude that all white dwarfs either have been or will be pulsators for some fraction of their lives. By studying the pulsators we get a snapshot that should apply to all white dwarfs.

Examples of pulsating white dwarfs can be found among the DA, DB and PG 1159 categories. Each flavor of white dwarf pulsates only when its surface temperature lies in a relatively narrow range: DA stars pulsate between 13,000 and 11,000 kelvins, DB stars pulsate between 27,000 and 25,000 kelvins and the PG 1159 stars pulsate between 140,000 and 80,000 kelvins.

All three classes of pulsating white dwarfs oscillate with periods ranging between 100 and 1,000 seconds, which means they undergo several oscillations per hour. This makes them fun to observe—they actually do something while we watch. It's been said that asteroseismology makes stellar evolution a spectator sport!

The changes in the white dwarf's luminosity over time are recorded to produce a "light curve." The job of the asteroseismologist is to break up the light curve into its many single-period components. In other words, we must separate the individual g-modes from a mixture of hundreds of g-modes all pulsating at the same time. An equivalent effort would be to identify the sound of an individual violinist during a symphony performance, when most are playing similar parts.

Fortunately stars have a limited number of available "normal modes" of oscillation. Each component of the oscillation is made up of two angular components known as "spherical harmonics" and one radial component. They are characterized by three integers: *l, m* and *n*. The *l* value signifies the number of nodal lines on the surface of the star that separate variations of opposite phase. The *m* value denotes the number of these nodal lines that pass through the poles. The *n* value gives the number of nodal surfaces between the surface of the star and its center. Each oscillation mode (a given value of *l, m* and *n)* has a specific frequency.

Once the individual frequencies are known, we can compare these to theoretical models to determine the star's properties. The frequencies are very sensitive to the mass and temperature of the star, the rate of rotation and the depth below the surface of the transitions from hydrogen to helium to carbon and oxygen. By varying these parameters in a model to reproduce the observed pulsation frequencies, we can probe the depths of the star.

This is the power of stellar seismology. One can learn a great deal about many qualities of a white dwarf using simple pulsation theory. However, good results can come only from good data.

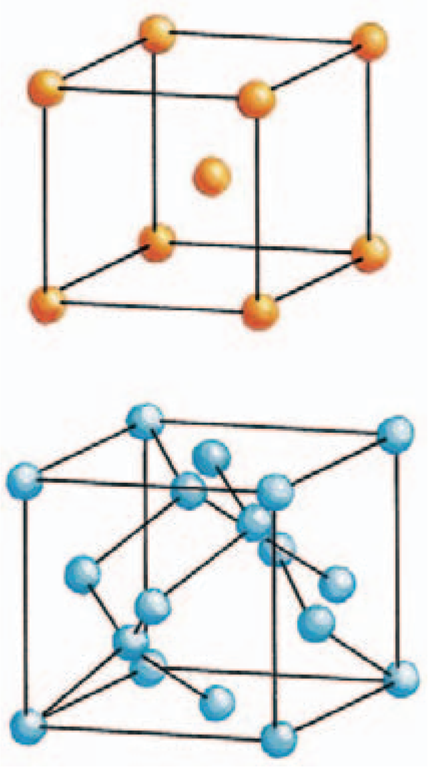
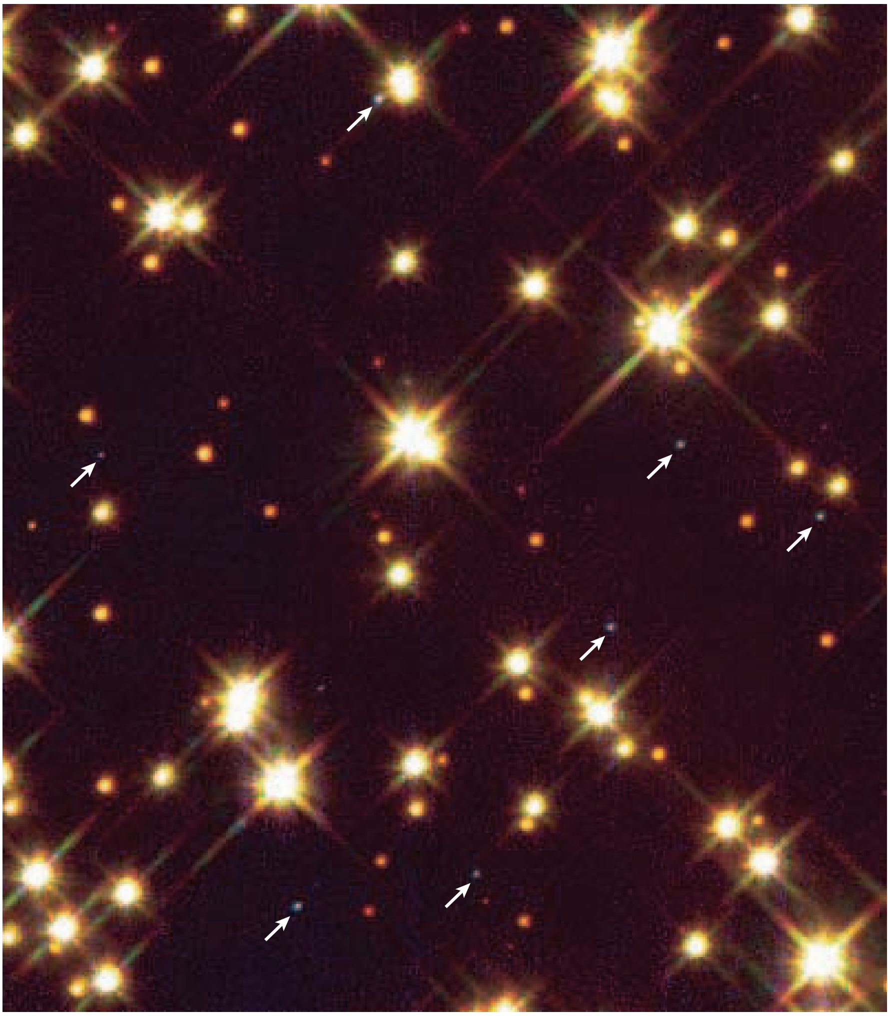


Figure 12. Crystal structure of carbon in a white dwarf *(top)* is unlike any carbon structure found on the Earth, including diamond *(bottom)*. It is a "nuclear crystal" consisting of bare carbon nuclei *(orange balls)* which are held in position by their mutual repulsion. In contrast, diamond is an "electronic crystal" in which the carbon atoms *(blue balls)* are held together by electron shells that form attracting bonds. The unit cell (the simplest repeating pattern) of the white-dwarf carbon crystal is about 100 times smaller than the diamond's unit cell.

The Whole Earth Telescope

The most challenging aspect of white dwarf seismology is not the faintness of the stars or the low amplitude of the variations in the signal, it is observing the pulsating star continuously for as long as needed to see the whole pattern of the oscillation. The period of each individual oscillation is usually only a few minutes long, but because the signal from a pulsating white dwarf is made up of many different modes, the overall pattern of the pulsation can take much longer before it repeats. Because modes "beat" against one another, they create a cycle from constructive to destructive interference on a frequency that is the difference between the individual oscillation fre-



NASA, H. Richer (University of British Columbia) and AURA/STScI

Figure 13. White dwarf stars must be relatively close to the Earth for astronomers to observe them with optical telescopes because of their faintness. These white dwarfs *(arrows)* lie within the globular cluster M4, which is situated about 7,000 light-years away within the halo of the Milky Way. Many other "invisible" white dwarfs are believed to reside in the galactic halo and may constitute a large fraction of the so-called missing "dark matter" in the Galaxy.

quencies. Since there are many possible modes, these beats are quite complex, and it may take weeks or months for the overall cycle to repeat.

A single telescope cannot observe such a pulsating star for an entire beat cycle because the Earth gets in the way at starset, and the Sun gets in the way at sunrise. Data from a single site have periodic interruptions corresponding to the daylight hours, and these breaks can hide important features of the star's spectrum.

To solve this problem, observations must be conducted 24 hours a day. This requires coordinated observations at telescopes all over the world. Such observations are obtained for pulsating white dwarfs by using the Whole Earth Telescope, or WET. WET scientists track the pulsations of stars from several points across the globe. As the subject star is setting for one observer, the next site to the West can continue the observation, and so on around the globe. Data from each site in the network are sent by Internet to the control center (usually at Iowa State University) where they are reduced and examined by the local scientists. The WET is a powerful instrument, which has obtained data of extremely high quality on several pulsating white dwarfs.

An early success of the WET came with observations of PG 1159-035 back in 1989. Results from these observations gave us a precise mass and rotation rate for the star, and revealed that it was layered as theory predicted. Later observations of a pulsating DB white dwarf, GD 358, showed that it too was stratified. Computational models were able to link PG 1159-035 and GD 358, showing that the stratified outer layer evolved precisely as described by the theory of gravitational settling in white dwarf stars.

One of the most exciting observations made by the WET team is of an extremely massive DA white dwarf, BPM 37093. BPM 37093 is so large that the carbon and oxygen in its core is expected to be completely crystallized. BPM 37093 provides a test bed for theories of how crystallization occurs. Does the oxygen crystallize first and "snow" down to the core, or does it remain suspended in the carbon? If the former is true, this process would increase the cooling time, thereby adding roughly one billion years to the estimated age of the galaxy. Theory also predicts that the crystal structure of carbon under white dwarf conditions is very different from anything seen in Earthly carbon. These issues and more are now being addressed.

White Dwarfs and Dark Matter

When astronomers measure the rotation of our Galaxy they find that there is 10 times more matter than can be accounted for in the stars, nebulae and other visible matter. This unknown and mysterious mass is called dark matter, and it appears to make up between 90 and 99 percent of the entire universe. The distribution of galactic dark matter is presumed to be in a spherical region called the dark halo extending far beyond the visible disk of the Milky Way.

Just what dark matter is composed of is unknown. Much of it should be ordinary matter, and it must be dark, meaning too faint to detect, yet widespread. One effort to identify the dark matter, assuming it is in the form of stellar-mass objects, is known as the MACHO (Massive Compact Halo Object) survey, led by Charles Alcock, formerly of the Lawrence Livermore National Laboratory, and others. As these massive dark objects (or MACHOs) drift through space, they should come between Earth and a more distant star. When this happens, the gravity of the MACHO will cause the light from the distant star to brighten in a predictable way (using the theory of gravitational lensing, a consequence of Einstein's theory of general relativity). By observing this change in the brightness of the star, the MACHO project can determine the mass of the intervening object.

A startling conclusion of the MACHO survey was that the dark objects typically had masses near 0.5 solar masses. Had these objects been ordinary stars, they would have been detected long ago by their own light. Their relative mass and dimness leaves open only one possibility: They could only be white dwarf stars. The MACHO scientists estimate that up to 50 percent of the mass of the dark halo is in the form of old white dwarfs! If this interpretation is correct, not only are white dwarfs common, but they also outnumber ordinary stars five to one.

Another interpretation, by American astronomers Geza Gyuk and Evalyn Gates, suggests that these white dwarfs may lie not in a spherical halo, but in a thick disk surrounding the galaxy. If so, then only four percent of the dark halo's mass needs to be made of white dwarfs. This scenario requires the existence of an entirely new population of stars in our galaxy to make up the remainder of the dark matter.

Further evidence supporting the theory that ancient white dwarfs make up a significant fraction of the dark halo comes from the Hubble Deep Field, a long-exposure survey by the Hubble Space Telescope. The northern part of the Hubble Deep Field reveals several very faint stellar sources, whose color and extreme faintness are consistent with distant white dwarf stars. If these results hold up, white dwarf stars may provide a solution to the riddle of the dark matter in our galaxy. In addition to illuminating our understanding of the Sun's ultimate evolutionary fate, white dwarfs may be very important on a galactic or even cosmological scale.

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