White dwarfs crystallize as they cool

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White dwarfs crystallize as they cool

A new star survey and statistical analysis vindicate a 50-year-old theory.

A white dwarf is the final stage in the evolution of all but the most massive stars in the sky. Before then, as the last of a star's hydrogen and helium fuel is exhausted, nuclear burning can no longer support it from its considerable gravity, and it contracts to a diameter comparable to Earth's. A white dwarf packs the mass of the Sun into a millionth of its volume. Densities inside reach 10^9 g/cm^3—a billion times that of water—and the only thing preventing further implosion is the pressure of degenerate electrons, which, obeying Pauli's exclusion principle, cannot get any closer to each other. (See the article by Hugh Van Horn, PHYSICS TODAY, January 1979, page 23.)

Fifty years ago Hugh Van Horn predicted that as a white dwarf radiates and cools, electrostatic interactions between the ionized nuclei in the star's interior cause the nuclei to freeze into a lattice—even at temperatures as high as a few million kelvin—through a first-order phase transition.[1] One consequence of that transition is the release of latent heat, an effect Van Horn realized ought to be observable, if not in individual stars then in a statistical ensemble. Because they radiate through a surface area 1/10 000 the size of the Sun's, white dwarfs are faint, and prior to two years ago star surveys had found fewer than 200 at accurately measured distances.

The paucity ended in September 2016 with the first publication of data from the European Space Agency's (ESA's) *Gaia* observatory, a satellite that provided astrometric information for 1.1 billion stars. In April 2018 ESA released the celestial positions of an additional 1.7 billion stars (see figure 1 and PHYSICS TODAY, January 2019, page 19).[2] The number of white dwarfs at well-known distances shot up beyond 200 000, more than enough to hunt for the predicted release of latent heat. From that bounty, Pier-Emmanuel Tremblay of the University of Warwick, Gilles Fontaine (Van Horn's first doctoral student) of the University of Montreal, and their colleagues have presented the first empirical evidence that white dwarfs crystallize.[3]

They took a subset of *Gaia*'s data—about 15 000 white dwarfs that reside within 100 parsecs (roughly 330 light-years) from Earth—and populated a Hertzsprung–Russell (HR) diagram with the stars (black dots in figure 2). The white dwarfs were so varied—spanning a wide range of masses, luminosities, temperatures, and ages—that Tremblay and company were able to search the HR diagram for a telltale pattern in the number density predicted by theory. A histogram of the number of white dwarfs per unit volume per unit luminosity confirmed that a few thousand of those stars had likely been caught in the act of going through the phase transition.

From apparent to absolute

The first satellite-based astrometric survey was conducted by ESA's *Hipparcos*, which was launched in 1989 (see the article by Michael Perryman, PHYSICS TODAY, June 1998, page 38). Its more capable successor, *Gaia*, collects more than 30 times the light and measures stellar positions and motions 200 times as accurately. More importantly, thanks to its advanced CCD cameras, *Gaia*'s parallax measurements resolve far smaller angles, and thus more accurate distances, than *Hipparcos* could. With those better distance measurements, astronomers convert each star's apparent brightness into an absolute magnitude—a proxy for luminosity, the total energy radiated per unit time.

Figure 2 plots the absolute magnitude

FIGURE 1. THE OUTER REACHES OF THE MILKY WAY, in color. This map is a reconstruction of the total integrated light flux measured by the *Gaia* space observatory. To date, the European Space Agency, which built, launched, and manages the satellite, has released astrometric measurements of nearly 3 billion stars. (Adapted from ref. 2.)

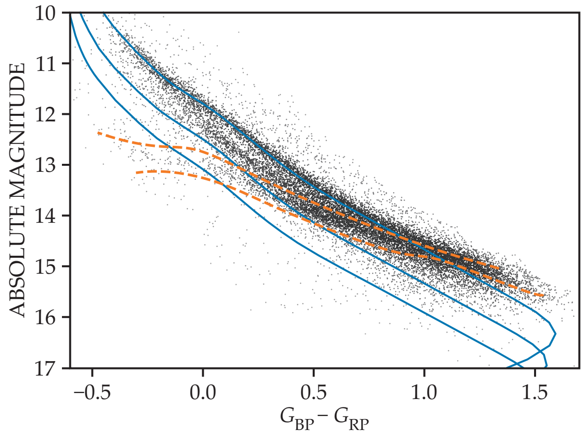

FIGURE 2. THIS HERTZSPRUNG–RUSSELL DIAGRAM plots the absolute magnitude of some 15 000 white dwarf stars (black dots). Its horizontal axis, as explained in the text, is a proxy for temperature. The more massive a white dwarf, the smaller and less luminous it is. The blue curves illustrate the cooling sequences for three masses of stars (0.6 $M_\odot$, 0.9 $M_\odot$, and 1.1 $M_\odot$, from top to bottom, where $M_\odot$ is the mass of the Sun). The two orange dashed lines delimit the regions where models predict that 20% (top) and 80% (bottom) of the white dwarf masses would crystallize. The liquid-to-solid phase change is accompanied by a release of latent heat that slows the stars' cooling and causes a pileup in their number density. (Adapted from ref. 3.)

for each of the 15 000 white dwarfs and the difference in their magnitude in two wavelength passbands, G_{BP} (blue) and G_{RP} (red). That difference is a proxy for color or temperature. The HR diagram captures stars of different ages as they progress along their cooling tracks.

As white dwarfs become cool enough to crystallize, the concomitant release of latent heat from the phase transition slows their cooling rate. The slowing, in turn, causes a statistical pileup—an above-average density in the number of stars at the luminosity where the heat is released. The two orange dashed lines in figure 2 delimit the regions where most stars undergoing crystallization are theoretically expected to occur.

The higher number density isn't evident to the naked eye in the HR diagram, so to confirm it, the researchers plotted the raw data as an integrated histogram: Figure 3 shows the number of white dwarfs per unit volume per unit luminosity as a function of luminosity.

White dwarfs start hot and cool quickly at first. Not surprisingly, their plotted number density (red dots) steadily rises as total luminosity drops. After a few billion years, when the luminosity is below one thousandth that of the Sun, the number density locally peaks (the shaded region)—a direct signature of the pileup—only to briefly fall again as the dwarfs resume cooling at a faster pace after most of their mass has solidified and the latent heat is spent.

After rising again to a second peak at the far right, the number density plummets, a result of the finite age of the universe; few dwarfs have cooled to such a low luminosity. The local peak in the

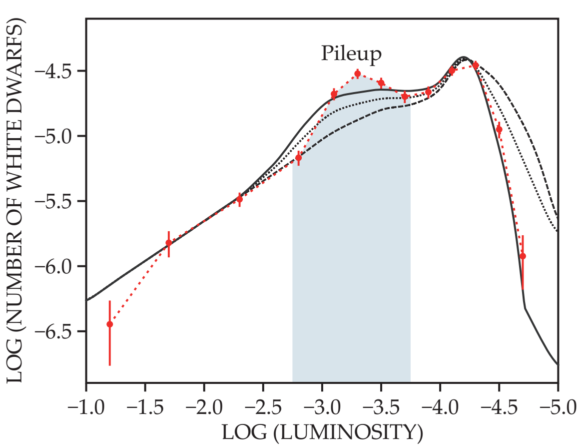

FIGURE 3. THE NUMBER OF WHITE DWARFS (RED DOTS) per unit luminosity per unit volume versus luminosity $L/L_\odot$ for stellar masses 0.9–1.1 $M_\odot$, where $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun. The number steadily rises as the luminosity falls until the stars cool to less than 1/1000 of the Sun's luminosity. The plot's peak in the shaded region is a direct observational signature of crystallization. Three model simulations (black lines) approximate the experimentally observed number of white dwarfs. The best fit (solid line) includes both latent heat released by crystallization and the gravitational energy released by oxygen sedimentation. The dotted curve neglects phase separation but includes latent heat, whereas the dashed curve neglects both. (Adapted from ref. 3.)

shaded region caught the researchers' attention for its relevance to crystallization. White dwarfs on the left, more luminous side of that peak are primarily liquid, and those to the right, less luminous side are primarily solid.

A metal that unmixes

Devoid of nuclear burning, a white dwarf is thought to exist as a homogeneous mixture of carbon and oxygen whose nuclei are liquid. (In the star's ionized-plasma state, the electrons remain a Fermi gas and the nuclei are either liquid or solid.) When the nuclei freeze, the elements start segregating. Oxygen nuclei carry a higher charge than carbon, so they are the first to solidify—into a body-centered-cubic metal, according to calculations. Oxygen also has a higher density than carbon, and after nucleating, it "snows out" of the liquid and sinks to the core.

Tremblay and colleagues hope the new work will help them disentangle the energetics of sedimentation—the segregation of the two phases—from the energetics of crystallization. The carbon in the liquid phase is forced outward by the growing, solid oxygen-enriched core. The release of gravitational potential energy from the sedimentation further delays cooling.

The absence of latent-heat release is ruled out in white-dwarf evolution: Simulations that neglect latent heat and sedimentation produce the poorly fitting dashed black line in figure 3. Progressively better simulations—accounting for the effects of latent heat, either alone (dotted black line) or with sedimentation (solid black line)—approach, but do not match, the experimental results (red).

"I would have been astonished had our theoretical predictions perfectly reproduced the white dwarfs' number density," says Fontaine. "The mismatch may, in fact, open the door to a keener understanding of stellar processes." For example, theorists can test whether modifications to the initial mixture of carbon and oxygen improve the fit. Judging by the narrowness of the crystallization peak, the phase transition also occurs more quickly than simulations predict.

Improvements to the theory will likely yield payoffs. White dwarfs are near-perfect thermal conductors, and since 1987, their uniform temperatures have made them reliable clocks to gauge the ages of various classes of star systems—globular clusters, galactic disks, and others—that contain them.[4] Although the ubiquity of white dwarfs has made the technique common, its accuracy is limited to 15–20% of the white dwarfs' actual age because of their intrinsic faintness.

The new work shows that many of the white dwarfs we see today cool more slowly and are thus older than previously thought—by as much as 2 billion years. Why should the better age estimates matter? Matt Caplan, a postdoc at McGill Space Institute and unaffiliated with the work, puts it succinctly: "Stars' ages largely tell us when and in what amounts they make certain elements. Only then can we trace the chemical evolution of the universe we live in today."

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