Quantum Crystal in the Sky

Dwarf stars chilled to a quantum crisp

By IVARS PETERSON

The galactic graveyard is littered with smoldering hulks. Known as white dwarfs, these slowly cooling, spent stars glow with a steadily fading light.

A similar fate awaits our own sun in another 5 billion or so years. Its hydrogen fuel exhausted, the sun will swell into a red giant. Bloated and unstable, it will likely shed its outer layers of hydrogen and helium to form a gaseous cloud, or nebula, while helium fuses into carbon and oxygen at its core.

Finally, the aging sun's carbon-oxygen core will collapse to an Earth-size remnant, cramming its mass into a volume so small that its density will end up more than a million times that of terrestrial materials. With no possibility of generating additional energy by the fusion of its remaining elements, the dying star will simply begin to cool, slowly radiating away the heat stored in its hot core.

This final act contains an intriguing tale of its own.

The cooling core starts off as a peculiar fluid consisting of a jumble of atomic nuclei immersed in a sea of electrons. But as the white dwarf cools, this fluid begins to crystallize, with nuclei freezing into a lattice, starting at the star's center.

At first glance, a white dwarf star seems an unlikely setting for the counterintuitive quantum effects associated with phase changes – like those responsible for superconductivity. After all, such effects usually become evident only on microscopic scales and at very low temperatures – not on stellar scales and not at temperatures that can approach 100,000 kelvins at a white dwarf's surface and millions of kelvins at its center.

Nonetheless, researchers have now calculated that quantum effects play a major role in white dwarf interiors. "Although the conditions are pretty extreme in temperature, the density more than compensates," says physicist Neil W. Ashcroft of Cornell University. "Viewed the right way [from a quantum mechanical perspective], these things are darn cold."

In other words, white dwarfs eventually become quantum crystals, with characteristics quite different from ordinary crystals. "And they freeze from something that is actually a quantum liquid," Ashcroft remarks. "This alters the whole picture [of white dwarf evolution] in a rather dramatic way."

Ashcroft, Gilles Chabrier of the École Normale Supérieure de Lyon in France, and Hugh E. DeWitt of the Lawrence Livermore (Calif.) National Laboratory describe their findings in the Nov. 5, 1992 NATURE.

"These new considerations may have an important effect on the cooling rate of white dwarfs and thereby on their inferred evolution and ages," the researchers note. And that would affect estimates of the age of our galaxy.

For more than 30 years, astronomers studying the interiors of white dwarfs had generally assumed that quantum effects are negligible during cooling. They had usually treated the interior's atomic nuclei as charged points free to take on any energy, rather than as quantum objects having only certain energies. Basing their calculations on the "classical" approximation, astronomers obtained estimates of a white dwarf's freezing temperature and cooling rate.

In 1989, Ashcroft attended a workshop on dense plasmas, held at the Institute for Theoretical Physics of the University of California, Santa Barbara. While listening to a lecture on the internal condition of white dwarf stars, he was struck by the temperatures and densities involved. By the end of the lecture, he had figured out on a scrap of paper that quantum effects ought to play an important role. By neglecting such effects, astronomers were perhaps getting an incorrect estimate of a white dwarf's freezing point.

As primarily a solid-state physicist, Ashcroft didn't have the necessary expertise in astrophysics to check his reasoning. He brought his conclusion to DeWitt, who had organized the workshop.

"I wrote up a set of notes and gave them to him, then left and promptly forgot about it," Ashcroft recalls.

But there were others at the workshop who had a strong interest in the issue that Ashcroft had raised. In particular, DeWitt, Chabrier, and astrophysicist Hugh M. Van Horn of the University of Rochester, a leading expert on the evolution of white dwarfs, continued thinking about the problem.

"We all had some interest in this," DeWitt says. "The crystallization of white dwarfs is fairly important because it affects the lifetime of these stars."

Researchers already knew that quantum phenomena slightly affect the freezing of interiors made up of elements lighter than carbon and oxygen. And computational physicists had simulated the purely quantum mechanical crystallization of a gas made up of free electrons. But no one had yet performed a detailed simulation, including quantum effects, that matched conditions inside a white dwarf.

Over the next two years, Chabrier and DeWitt developed a simplified model of conditions within a white dwarf and succeeded in demonstrating that quantum effects significantly modify the distribution of energy among the nuclei present. "Eventually we decided we were sure enough of our grounds that we ought to put together a paper and publish it . . . to encourage more exact, numerical simulations of the problem," DeWitt says.

In their NATURE paper, the researchers conclude that freezing in a white dwarf involves the transformation of a quantum liquid to a quantum solid. They suggest that the freezing temperature may be somewhat lower than the value obtained using classical methods.

However, the size of that decrease depends on a white dwarf's mass. In the majority of white dwarfs, which have masses smaller than that of the sun, quantum effects change the freezing temperature only slightly. Although quantum effects are appreciable in both the solid and fluid phases, they tend to cancel each other out – leaving the freezing temperature virtually unchanged.

"That was somewhat surprising," DeWitt says.

The analysis also indicates that quantum effects lower by about 10 percent the freezing temperature of the most massive white dwarfs – those having masses approximately 1.4 times that of the sun. "Consequently, these stars must cool considerably more than had been realized before crystallization effects start to set in," notes physicist Paul C. Joss of the Massachusetts Institute of Technology.

Moreover, the quantum characteristics of the solids and fluids in a massive white dwarf that strips material from a companion star may have a substantial influence on the white dwarf's eventual explosion as a supernova. "Since some models for supernovae begin with a white dwarf accreting matter from a close binary companion, it is likely that as accretion [increases the white dwarf's mass], the quantum effects . . . become increasingly significant," Van Horn says.

In addition, the rate at which a star cools depends on how quickly it can transfer heat from its interior to its surface, and that involves its heat capacity – how well it stores heat. "Quantum effects change the heat capacity, and that influences the cooling rate," Ashcroft notes. "This has all sorts of interesting ramifications."

But the details remain hazy.

"Our published work in NATURE gives a fairly good result for the solid state, but we can't say much about the fluid phase yet," DeWitt says. "That will require numerical simulations that will take dozens of hours on a very large Cray [computer]."

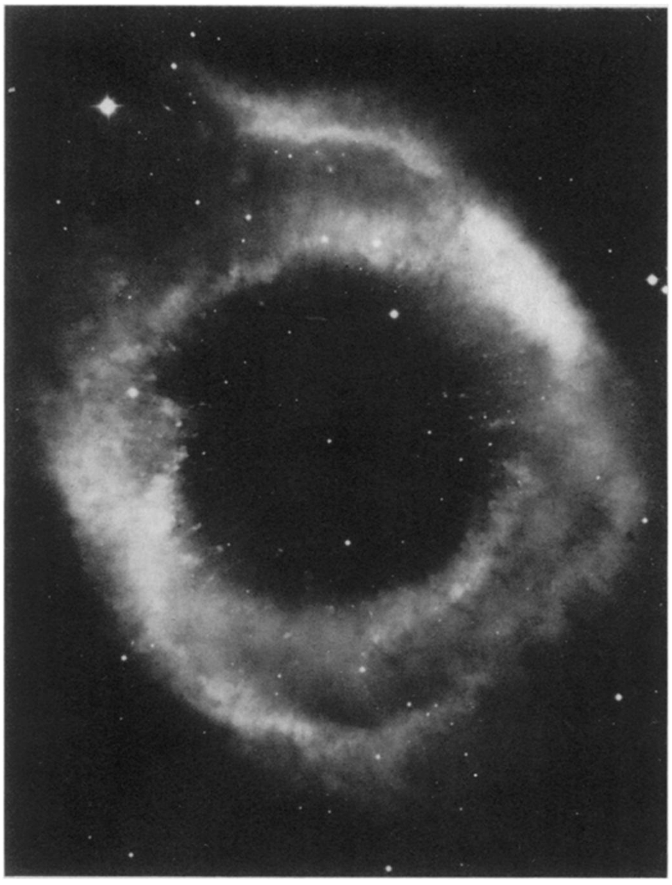
Computational physicist David Ceperley and his group at the University of Illinois at Urbana-Champaign have just started putting together the computer program required for determining the energy of both the fluid and solid states. "We've done quantum calculations for related systems," Ceperley says. "We want to see if we can do more accurate calculations than [Chabrier and his co-workers] did."

Such calculations, however, provide a glimpse of what happens only in an idealized situation. In reality, a white dwarf contains a mixture of elements. "It's not pure carbon or pure oxygen; it's a mixture of carbon and oxygen in unknown proportions, with probably a scattering of heavier elements," DeWitt says.

That makes it impossible for a white dwarf to freeze into a single, pure, perfect crystal. "There's a possibility that the very heaviest elements will freeze out first," DeWitt notes. For example, "the little bit of iron that might be present will likely go to the center and freeze into a tiny iron core."

A white dwarf's carbon-oxygen mixture presents a trickier problem. Astronomers have generally assumed that carbon and oxygen nuclei, which carry nearly the same electrical charge, can mix freely and don't separate into distinct phases during freezing. If that assumption proves incorrect and oxygen nuclei tend to sink to a star's center, thereby releasing gravitational potential energy and making the star brighter, some white dwarfs may actually be older than they look. This would suggest that the Milky Way may be older than current estimates.

"We're interested in establishing criteria for when elements will separate," says DeWitt.



Carnegie Observatories

The helix nebula, NGC 7293

Because white dwarfs rotate, the crystal phase also suffers rotational strains and stresses, which induce cracks and dislocations. "There won't be any perfect crystals," Ashcroft says. "They're more likely to be quantum sludge."

"The whole question of the influence of quantum effects on the freezing of dense matter is an interesting one," Van Horn comments. He would like to see additional calculations aimed at determining the properties of the fluid state in massive white dwarfs.

Van Horn finds another possibility even more intriguing. "The interiors of the giant planets and – if they're ever discovered – brown dwarf stars [which lie in size between large planets and small stars] are almost certainly going to include hydrogen-helium mixtures, which are at sufficiently high densities so that quantum effects should be very important," Van Horn says. "To my knowledge, nobody has reasonable estimates of what those effects are likely to be."

Solid-state physicists dealing with terrestrial materials may also learn something from the stars. "This exercise exposes a rather deep problem in condensed matter physics – namely, how we understand the melting of a system that is neither wholly quantum nor wholly classical, but intermediate," Ashcroft notes. "I think that is a very interesting point for discussion."

Physicists have gotten used to dealing with quantum effects not just at a microscopic level, but also on a macroscopic scale – in flasks of helium chilled to millikelvin temperatures, in superconductors, and in a number of other systems. But the possibility of quantum stars and quantum planets raises to an enormous scale the kind of quantum phenomena involved in the thermodynamics of phase changes and cooling.

"Ordinary solids at low temperatures have been known for maybe 60 or 70 years to exhibit fundamentally quantum properties," Van Horn says. "The effects that Chabrier, DeWitt, and Ashcroft are talking about in white dwarfs are precisely the same."

He adds, "The peculiar thing is that one is unaccustomed to thinking of low temperatures being millions or tens of millions of degrees kelvin." □