relative to the passage of the electrical signal, and the sequence of events in the unwounded leaf will now need to be addressed in earnest. Many of the regulatory factors involved have already been mentioned but their ordering is deeply problematic[18,19], as is the question of whether a similar or different set of signal transduction steps goes on in the wounded, and the unwounded, leaf (see figure).

Two further complexities also need to be taken into account. The first is the plant growth factor auxin, which has been proposed[20] as an endogenous natural repressor of *pin* expression[11]. The second is that *pin* 2 protein is developmentally regulated as well as being wound-inducible; it is abundant, for example, in floral buds[8]. However things fall into place eventually, the results of Wildon *et al.* will stimulate a flurry of research and it will be some time before the curtain falls on this particular show. □

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ASTRONOMY

Stars at the quantum limit

Paul C. Joss

QUANTUM effects are familiar in the realm of the microscopic, and they are fundamental to the behaviour of semiconductors, but on page 48 of this issue[1] Chabrier, Ashcroft and DeWitt show that they can affect the properties of matters even on the giant scale of stars.

As stars with masses less than about three times the mass of the Sun exhaust the last of their nuclear fuel, they shed their outer layers and shrink down to become white dwarfs. These final cinders of stellar evolution still have masses close to that of the Sun, but only a millionth the volume; their sizes are comparable to that of the Earth, and their central densities can reach 10^9 g cm^{-3} (a billion times that of water). White dwarfs are responsible for all sorts of astronomical phenomena, including cataclysmic variables, novae and type I supernovae, and their luminosity can be used to calibrate the ages of the stellar systems in which they reside.

Because nuclear burning in their interiors has been extinguished, the internal structure of white dwarfs is simpler than that of stars in earlier evolutionary phases. Since the pioneering work of Chandrasekhar[2], it has been understood that it is primarily the pressure of 'degenerate' electrons (electrons in the lowest-energy configuration available) that supports a white dwarf against collapse from its considerable self-gravity — Heisenberg's uncertainty principle prevents the electrons getting any closer together. For more than 30 years, it has also been recognized[3] that as a white dwarf radiates and cools, the electrostatic interactions among the fully ionized nuclei in its interior eventually cause the nuclei to freeze into a lattice. The crystallization wave that propagates outwards from the stellar centre has important consequences for the thermodynamics and heat-transport properties of the white-dwarf interior. It is in this freezing phenomenon that Chabrier *et al.* now find significant quantum effects which were previously neglected.

Previous studies of the crystallization of white-dwarf interiors have treated the nuclei in a purely classical manner, in both the fluid and solid phases. This seemed to be a reasonable approximation, because under white-dwarf interior conditions the de Broglie wavelength, Λ, of the nuclei is smaller than the mean internuclear separation, r, suggesting that the nuclei can be treated as an ensemble of classical point charges. However, Chabrier *et al.* note that the criterion $\Lambda/r < 1$ is not a sufficient condition for quantum effects to be negligible. They show that the irremovable quantum-mechanical zero-point energy per nucleus in the solid phase actually exceeds the thermal energy, so that the nuclei must be treated as a quantum solid. The authors further argue that quantum corrections will be comparably important in the fluid phase as the freezing point is approached; hence the fluid, too, is a partially quantum liquid rather than a classical one. In both states, the quantum effects raise the free energy by 10–25 per cent (depending on the density and chemical composition) over the value obtained in the classical limit.

Applying a semi-empirical analysis, Chabrier *et al.* estimate that quantum effects lower the melting temperature by about 10 per cent in the most massive white dwarfs, which have masses about 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. Such massive examples are known only as members of close binary stellar systems. The more common isolated white dwarfs typically have much lower masses, clustered near 0.6 solar masses. For these, the estimates by Chabrier *et al.* suggest that the melting temperature is almost unaffected by quantum effects — the quantum corrections are still appreciable but are nearly equal in the solid and fluid phases, and so tend to cancel out.

Despite this cancellation, the quantum corrections may have an important bearing on the cooling history of all white dwarfs regardless of their masses. Because quantum effects are already significant in the fluid phase, Debye cooling (a quantum mechanical phenomenon that lowers the heat capacity of the nuclei) should commence even before crystallization sets in. As a result, a white dwarf will cool more rapidly than had previously been expected. This accelerated cooling will, in turn, decrease estimates[4,5] of the age of the galactic disk derived from the distribution of luminosities among white dwarfs in the solar neighbourhood, perhaps by $1–2 \times 10^8$ years.

Although Chabrier *et al.* have convincingly demonstrated the importance of quantum effects on the thermodynamics of the matter in white dwarfs, their estimates are too crude to permit a definitive evaluation of the astrophysical consequences. As they point out, there is now a pressing need for more accurate theoretical determinations of the impact of these quantum phenomena on crystallization and cooling under the conditions prevalent in white-dwarf interiors. □

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