108. White dwarf physics

Gaia is making a significant contribution to the understanding of white dwarfs. I have already written about the *number* of objects within Gaia's grasp (essay #29); first insights into their Hertzsprung–Russell diagram (#42); the pollution of their atmospheres by planetary debris (#73); and about the mass–radius relationship as determined by the physics of a degenerate electron gas (#107). Here I look further into some of the physics conveyed in their Hertzsprung–Russell diagram.

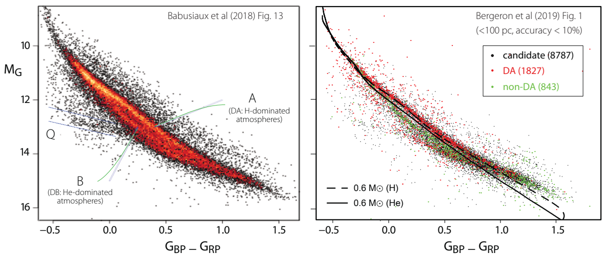
To summarise some of their most relevant properties, white dwarfs consist of a degenerate core (providing most of the mass and the energy source; most expected to be a mixture of C and O), and a partially degenerate envelope (controlling the energy outflow) comprised of a thin He layer ($M \sim 10^{-2} M_\odot$), itself usually surrounded by an even thinner H layer ($M \sim 10^{-15} - 10^{-4} M_\odot$).

Masses of single DA white dwarfs (i.e. those with H in their spectra) are strongly peaked around $0.59 M_\odot$. The 20% with undetectable H envelopes are further classified as DB (showing He lines), DC, etc. (see essay #29).

White dwarfs evolve by radiating their residual thermal energy, over time scales of order 10 Gyr. Their cooling can be divided into four luminosity-controlled stages: neutrino cooling, fluid cooling, crystallisation, and Debye cooling. Numerous complexities relate to the initial conditions and the chemical structure of their interiors, and effects such as convection, overshooting, and sedimentation (e.g. Isern et al., 2022).

In a paper accompanying Data Release 2, Babusiaux et al. (2018) constructed a Hertzsprung–Russell diagram for 26 000 white dwarfs with $\sigma_\pi/\pi < 0.05$.

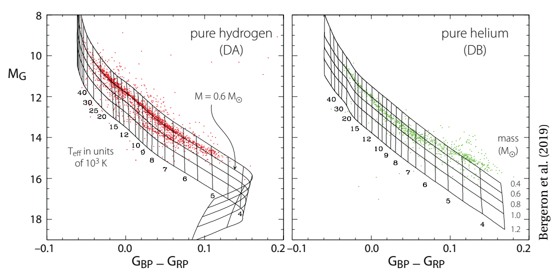
They commented on various features which I have already described briefly in essay #42: the clear segregation between types DA (with H-dominated atmospheres) and DB (He-dominated), especially in the range $0.0 < G_{BP} - G_{RP} < 0.8$; the narrowness of the sequence confirming the sharp peak of their mass distribution around $0.6 M_\odot$; points above the main DA sequence attributed to white dwarfs in binary systems; and a 'sloping band' (Q in the left figure) attributed to core crystallisation as the white dwarfs cool.



Bergeron et al. (2019) revisited this diagram (right figure), using $\sigma_\pi/\pi < 0.1$, excluding *known* binaries, and colour-coded according to whether the object is confirmed (spectroscopically) as DA or DB, or simply a Gaia *candidate*. Again, the clear bifurcation between DA and non-DA stars is striking. But although the pure H model (dashed line) clearly follows the sequence of objects classified as DA, the He *model* (solid line) actually passes through the gap between the two observed sequences.

Babusiaux et al. (2018) had noted two possible explanations: shortcomings in the He model atmospheres, or unexpectedly higher masses of the non-DA dwarfs.

To investigate further, Bergeron et al. (2019) discarded the *candidates*, split the DA and non-DA stars into two plots (below), then superposed theoretical colour grids for pure H or pure He atmospheres respectively, and for various values of $T_{\rm eff}$ and mass.



The DA stars (left) follow the $0.6 M_\odot$ model almost perfectly. There is also a population of (apparently) low-mass DA white dwarfs ($M < 0.4 M_\odot$), which they consider to be unresolved *double* degenerate binaries. For the others (right), their analysis indicates that, at lower temperatures, the non-DA stars (modelled as pure He) also include DZ, DQ, and DC white dwarfs.

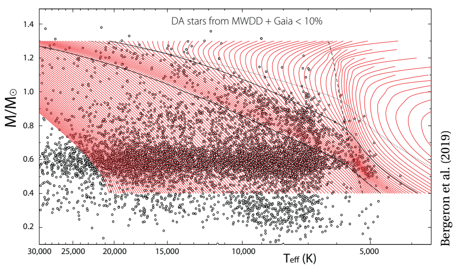
By (incorrectly) assuming a pure He composition, the observed shift in absolute magnitude corresponds to a shift in mass in the M–$T_{\rm eff}$ diagram. But the high masses could be reduced to more normal masses, $\sim 0.6 M_\odot$, by invoking a small amount of H in their atmospheres.

How this modifies the need for a population of massive white dwarfs arising from stellar mergers, also inferred from Gaia by Kilic et al. (2018), remains to be seen.

Moving on, the faint concentration of white dwarfs forming the almost horizontal feature, labelled 'Q' in the first diagram on the previous page, was noted by Babusiaux et al. (2018), and attributed to core crystallisation as they cool (Tremblay et al., 2019).

Gaia reveals the crystallisation as a pile-up in the Hertzsprung–Russell diagram as they spend time at this location while they release their latent heat.

The topic was picked up by Bergeron et al. (2019). Using only the most reliable M and $T_{\rm eff}$ for spectroscopically identified DA white dwarfs, and with Gaia parallaxes $\sigma_\pi/\pi < 0.1$, they superposed their cooling isochrones (below). The varying isochrone densities identify periods of slower or more rapid cooling.



The lower solid curve corresponds to the onset of crystallisation at the white dwarf's centre. Latent heat is released as the solidification front moves outwards, and the upper solid curve corresponds to 80% of the star's mass having solidified. The slowdown in evolution as the cooling rate decreases is seen as the crowding of the isochrones between the two solid curves.

At around these luminosities, the cooling of white dwarfs is further modified by two other physical effects, included in the stellar models but not yet explicitly characterised observationally (Bergeron et al., 2019).

The first is Debye cooling: the subsequent transition, in the solid phase, from the classical regime (where the specific heat is independent of temperature) to the quantum regime (where it decreases with decreasing temperature), increasing the cooling rate still further.

The second effect is the onset of convective coupling (dashed curve), when surface convection first reaches into the degenerate core where most of the thermal energy resides, further accelerating cooling (Tremblay et al., 2015). For DA white dwarfs of $0.6 M_\odot$, crystallisation and convective coupling occur at nearly the same time, making it, as yet, impossible to disentangle the two.

Both effects lead to a rapid shift to the (hypothetical) black dwarf phase, in which no further significant heat or light is emitted. Because the time to reach this state is longer than the current age of the Universe, no black dwarfs are expected to exist at the present time.

There is indirect evidence for crystallisation for a few individual objects and, again, Gaia is contributing to their understanding. Let me stress again that the effects of crystallisation are a large source of uncertainty in calculating ages of the coolest white dwarfs, an important chronometer for the Galactic disk, where the effects of crystallisation can affect age estimates by of order 1 Gyr (Winget & van Horn, 1987).

Winget et al. (1997) argued that BPM 37093 was a (massive) pulsating white dwarf with a possibly crystalline interior, with a crystallised mass fraction probably exceeding 90%. Their arguments were based on its location in the M–$T_{\rm eff}$ plane, compared with theoretical models for C and O interiors by Wood (1992), which gave the locus of points of constant crystallised mass fraction.

Two observational tests, both based on asteroseismology, were suggested. The first was based on the spacing of non-radial g-mode frequencies, predicted to depend on the crystallised mass fraction. The second, based on models indicating that the crystallisation front moves outwards at a few cm per year, was to measure the rate of period change of some stable pulsation mode. They estimated that current observational techniques would require 10–20 yr to confirm such a period change.

Two decades later, Córsico et al. (2019) reported an asteroseismic analysis of three ultra-massive ($M \gtrsim 1 M_\odot$) H-rich (DA) white dwarfs in the ZZ Ceti instability strip at $T_{\rm eff} \sim 12\,500$ K, expected to have a significant mass fraction in such a crystalline state: BPM 37093, GD 518, and SDSS J0840+5222. They found that the first two were best characterised by a thick H envelope, with the latter best modelled by a thinner H envelope. They estimated the percentage of crystallised mass as 92%, 97%, and 81% respectively.

Asteroseismology also provides a distance estimate independent of astrometry (essay #51). And while their abstract suggests asteroseismic distances in agreement with Gaia, the numbers are more discrepant. For example, for BPM 37093 they derived $d = 11.38 \pm 0.086$ pc, $\pi = 87.87 \pm 0.40$ mas, compared with $d = 14.81 \pm 0.01$ pc, $\pi = 67.52 \pm 0.04$ mas (from Gaia DR2).

Perhaps it is the underlying assumption that ultra-massive white dwarfs result from single-star evolution, with O–Ne cores. If they instead result from binary white dwarf mergers, they would presumably have CO cores.

The study of white dwarf composition, and their cooling, is evidently complex, and Gaia is playing a key part in clarifying their observable consequences.