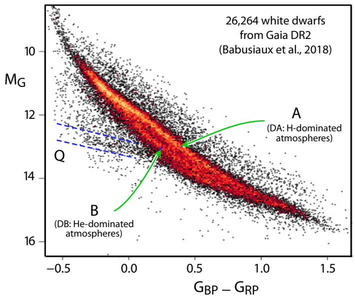
178. Bifurcation in the white dwarf HRD

The possibility to position hundreds of millions of stars accurately in the observational Hertzsprung–Russell diagram was one of the central goals of Gaia, and is proving to be one of its many successes.

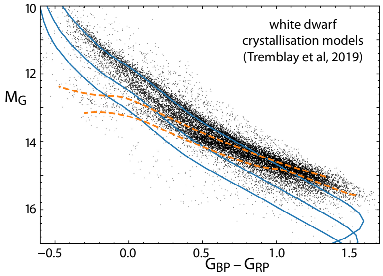
In this context, an early discovery was a bifurcation in the white dwarf colour–magnitude diagram, the 'Gaia gap', which I first described in essay 42 (October 2021). Revised analyses of this feature, which I discuss here, further illuminate the insights that Gaia is providing into the complex physical processes at play in these objects.

In their original paper, Babusiaux et al. (2018) used Gaia DR2 to select 26 264 nearby white dwarfs with relative parallax uncertainties better than 5%. The accurate parallaxes, combined with simultaneous accurate Gaia photometry, then yield accurate absolute magnitudes, which allow them to be precisely located in the HR diagram. Occupying the lower-left part of the diagram, the resulting white dwarf sequence showed several prominent features which they commented on.



First is the concentration of stars running continuously from upper-left to lower-right (A), coinciding with the evolutionary tracks for $0.6M_\odot$ DA white dwarfs (whose envelopes are dominated by hydrogen). Below the main band is a second, distinct concentration (B), which they favoured attributing to DB white dwarfs (whose atmospheres are dominated by helium). The feature corresponds to those seen in Sloan Digital Sky Survey colour–colour diagrams (Harris et al., 2003).

The second prominent feature is the objects lying *above* the main DA sequence, considered to be white dwarfs in binary systems. A third, weaker structure is the rising transverse feature 'Q', a faint band of stars visible between the two dashed lines which, as Tremblay et al. (2019) and others have shown, results from core crystallisation as the white dwarfs cool (see essay 108).



I will say no more about these last two features, other than to show this figure from Tremblay et al. (2019). It illustrates (orange lines) the region over which crystallisation is relevant, which should therefore not affect the bifurcation, A–B, and is not considered further here.

To go further into the explanation for the bifurcation or gap, some background on white dwarfs is useful (see also the broad review by Saumon et al., 2022).

White dwarfs are the endpoint of stellar evolution for ∼97% of stars, specifically those below $8-10M_\odot$, depending on metallicity (Ibeling & Heger, 2013; Woosley & Heger, 2015). They result from the star fusing H into He (on the main sequence, and later on the red giant branch), then fusing He into C and O (first on the horizontal branch, and later on the asymptotic giant branch), thereafter losing its outer layers to leave only a dense C–O core, representing ∼99% of its total mass.

The remaining 1% is made of any H/He not fused during earlier evolutionary phases, arranged in a He envelope surrounding the core, and an outer H envelope, with their thicknesses depending on details of the nuclear burning. The upper layers of the H/He envelope constitute the atmosphere, the only region observable.

Some 20–25% of white dwarfs consume virtually all their H during previous evolutionary phases, resulting in H-deficient (and hence He-rich) atmospheres (Althaus et al., 2005). Furthermore, if the progenitor is close to the $10M_\odot$ upper mass limit, it may reach temperatures high enough to fuse C, leading to an O–Ne white dwarf.

White dwarfs are classified accordingly: an initial D, and a letter describing the dominant (atmospheric) spectral feature: DA dwarfs have *atmospheres* dominated by H I, DB by He I, DC have a continuous spectrum, DO are dominated by He II, DQ by carbon, and DZ by metal lines. DA and DB are the most common.

GAIA DATA are used to define samples to 100 pc or so (essay 29), of which those to 20 pc (Hollands et al., 2018), 40 pc (Gentile Fusillo et al., 2021), and 100 pc (Vincent et al., 2020) are widely used. Gaia astrometry and photometry are then used to construct the HR diagram, to derive mass estimates, and so on. Let me also recall these points to frame the subsequent studies:

- masses of field white dwarfs are obtained only indirectly by combining surface fluxes (using distance and radius), spectroscopic $T_{\rm eff}$ and $\log g$, evolutionary models, and by appeal to the appropriate mass–radius relationship (e.g. Saumon et al., 2022, Eq. 1; essay 107);
- derived masses follow a narrow distribution peaking at $0.55-0.58M_\odot$, similar for DA and DB dwarfs (Bergeron et al., 2019, Fig. 13; Ourique et al., 2019, Fig. 2; McCleery et al., 2020, Fig. 7). 60% are in the range $0.5-0.7M_\odot$, but a few extend to $0.2-1.35M_\odot$ (Pelisoli & Vos, 2019);
- very low-mass white dwarfs, $M \lesssim 0.3M_\odot$ are believed to have formed by mass loss in binary systems (Iben & Livio, 1993). The 'ultra-massive' objects ($\gtrsim 1.1M_\odot$) are (generally) thought to have O–Ne cores (Siess, 2007);
- cooling is dominated by core neutrino emission for the first 20 Myr. Thereafter, over many Gyr, it is controlled by the thermal conductivity of the core and envelope, the radiative opacity of its atmosphere, element transport in its interior, and the passage through phase transitions;
- the relation between progenitor mass and final white dwarf mass (the 'initial-to-final mass relation', IFMR), must account for the various mass-loss processes, and hence provides a probe of the local star-formation and stellar evolutionary history. It can be inferred, by population synthesis methods, from an initial stellar population matched to the observed white dwarf mass distribution (e.g. El-Badry et al., 2018; Cunningham et al., 2024).

SUBSEQUENT studies agree that the gap cannot simply arise from different evolutionary tracks for DA and DB objects. The subsequent debate illustrates the complexity of the physics, and how Gaia is contributing.

El-Badry et al. (2018) noted that the distribution remains bimodal even if only spectroscopically-confirmed DA white dwarfs are considered. They found that an initial-to-final mass relation that flattens at around $3.5M_\odot$ (and which they attributed to a mixed-age stellar population) results in a bimodal white dwarf mass distribution with the normal peak at $0.58M_\odot$ and a secondary peak at $0.8M_\odot$. In this explanation, it is the large number of massive white dwarfs which leads to a secondary DA sequence offset below the primary DA sequence.

Kilic et al. (2018) also used a population synthesis approach to infer a significant contribution from more massive white dwarfs, but argued that while the El-Badry et al. (2018) hypothesis of a modified IFMR could explain the gap, it could not explain the different binary fractions found on the main-sequence and for white dwarfs. They argued instead that their significant contribution from relatively massive white dwarfs likely arose through mergers. Studies with somewhat similar conclusions were also reported by Jiménez-Esteban et al. (2018) and Gentile Fusillo et al. (2019).

A DIFFERENT explanation was given by Bergeron et al. (2019). They found that the pure He atmospheric models previously used do not properly describe the white dwarfs collectively assigned to the 'non DA' class.

Specifically, their theoretical models for the DB stars agreed with the observed sequence for $T_{\rm eff} > 11\,000$ K, but not at lower temperatures where non-DA stars exist both as He-dominated (DB) stars, but also as DZ, DQ, or DC objects. Assuming a pure He compositions for *all* non-DA stars gave a shift in absolute magnitude corresponding to a shift in mass in the $M_{\rm WD}-T_{\rm eff}$ diagram.

However, these high inferred masses would instead be interpreted (via evolutionary models) as more normal masses, of $\sim 0.6M_\odot$, with the inclusion of a small amount of hydrogen, and/or metals, in their atmosphere.

Similar arguments were presented by Serenelli et al. (2019) and Ourique et al. (2020), where the term 'spectral evolution' describes the evolution from H to He envelopes (Chen & Hansen, 2011; Chen & Hansen, 2012; Rolland et al., 2018; Ourique et al., 2019).

IF THIS INDEED represents a consensus interpretation, it can now be simply stated: to reproduce the observed split in the cooling sequence, and specifically to replicate the B branch, trace amounts of hydrogen and/or metals must be present in the He-dominated atmospheres of hydrogen-deficient (DB) white dwarfs.

Blouin et al. (2023) found that neither the convective mixing of residual hydrogen, nor the accretion of hydrogen (or metals) can be the dominant cause of the bifurcation. Rather, convective dredge-up, from the deep interior, of small quantities of carbon, below the threshold of optical detection, can account for the observations.

New evolutionary models including this effect in cold He-rich white dwarfs have recently been given by Camisassa et al. (2023). The presence of carbon in their atmospheres produces a continuum absorption favouring the emission at bluer wavelengths, so creating the B branch. The resulting mass distribution peaks around $0.6M_\odot$, consistent with standard evolutionary channels.

AND SO we can now conclude: Gaia's accurate placing of solar neighbourhood white dwarfs in the HR diagram has revealed structure not predicted by previous evolutionary models. But trace amounts of carbon, added by convective dredge-up, can explain the gap. And it makes a specific prediction: that traces of carbon should be seen, perhaps in ultraviolet spectra.