42. Surprises in the HR diagram

All professional astronomers, and many amateurs, will have heard of the Hertzsprung–Russell (or 'HR') diagram. Like the works of Shakespeare, perhaps, few will be familiar with all of its details, but different experts have studied every aspect of it, such that any new or unexpected features will be greeted with surprise and excitement: they tell us something about the workings of Nature that we didn't know before.

The Hertzsprung–Russell diagram shows the relationship between a star's luminosity (or absolute magnitude) versus its temperature (or colour). It was created independently around 1910 by the Dane Ejnar Hertzsprung and American Henry Norris Russell (physicists will know his name in the context of quantum mechanical 'LS coupling' or Russell–Saunders coupling).

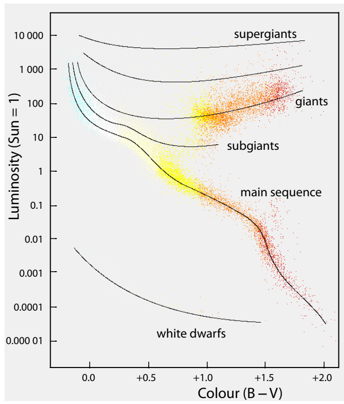
This graphical presentation of stellar properties, in which stars of higher luminosity are towards the top of the diagram, and stars with higher surface temperature (or bluer colour) are towards its left side, facilitated a major step in understanding stellar evolution.

It remains a powerful tool for interpreting, through stellar evolutionary models, the properties of individual stars, star clusters, and entire stellar populations.

As an example of its main features, and the state-of-the-art pre-Gaia, the HR diagram shown here was constructed from 22 000 stars from the Hipparcos Catalogue, supplemented by 1000 low-luminosity stars (red and white dwarfs) from the Catalogue of Nearby Stars.

The ordinary hydrogen-burning 'dwarf' stars, like the Sun, are found in the main band running from top-left to bottom-right, which is referred to as the 'main sequence'. Giant stars form their own clump on the upper-right side of the diagram. Above them lie the less common, and particularly bright, supergiants.

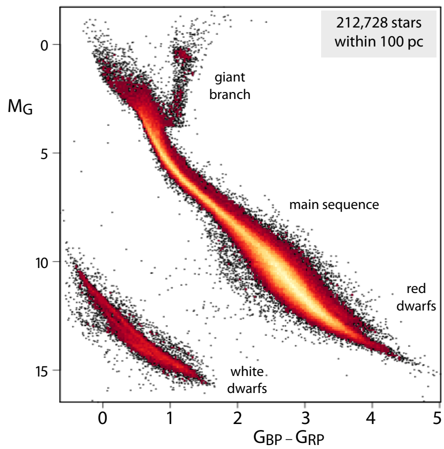
Tracing a band at the lower-left are the white dwarfs. These are the dead cores of old stars which have finally exhausted their H or He 'fuel supply' and, with no energy source remaining, simply cool, slowly over billions of years, down towards the bottom-right of the diagram.



Richard Powell (2011, Wikimedia, CC BY-SA 2.5)

With the Gaia second data release, Gaia DR2, with high-precision distance measurements to more than 1.7 billion stars, many new examples and applications of the HR diagram are appearing. The unprecedented numbers of stars now available for study paints a remarkable panoramic picture of stellar evolution.

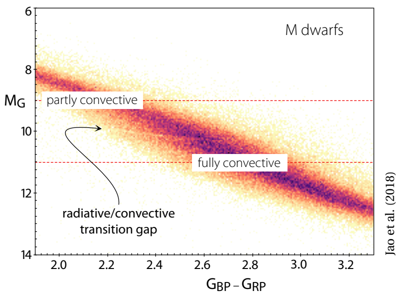
A detailed discussion, and many examples, of these HR diagrams constructed from DR2 are given by Babusiaux et al. (2018). In the following I will focus on some new features in these diagrams at the lowest luminosities: the regions of the red dwarfs and white dwarfs.



Babusiaux et al. (2018)

THE FIRST OF THESE is a distinct gap which has been discovered in the main sequence for M dwarfs, in the region towards the lower-right of the HR diagram.

While the main sequence is generally smoothly populated as a function of stellar temperature, a tiny but pronounced discontinuity in number density occurs within the sequence of the coolest, faintest red dwarfs. This gap was first reported in the Gaia data by Jao et al. (2018), confirming a similar feature already hinted at in infrared data from 2MASS.



Qualitatively, the gap arises because of the very different internal structure of stars on either side of it: low-mass M dwarfs have a fully convective interior, while more massive stars (including the Sun) have a convective envelope surrounding a radiative zone, a denser area where these convective motions are suppressed. The transition occurs at about $0.35M_\odot$ (solar masses).

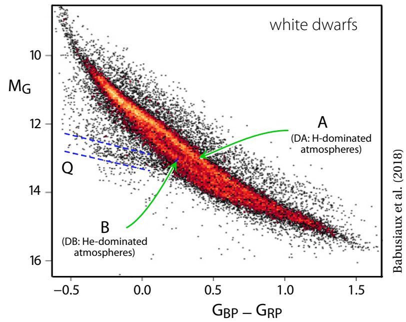
A detailed theoretical explanation was soon forthcoming (McDonald & Gizis, 2018). The gap arises because the convective motions in the cores of low-mass stars help mix the intermediate nuclear fusion products, allowing the star to fuse hydrogen more efficiently.

Their detailed models show that the mixing of ^{3}He during the merger of the envelope and core convection zones occurs over a narrow range of masses. This successfully replicates an associated dip in the luminosity function which is responsible for the gap.

IN THE LOWER-LEFT part of the HR diagram, the white dwarf sequence shows several remarkable features, identified by Babusiaux et al. (2018).

They constructed a sample with relative parallax uncertainties better than 5%, yielding a set of 26 264 white dwarfs. The accurate parallaxes, combined with simultaneous accurate Gaia photometry, then yield accurate absolute magnitudes, which allow them to be precisely located in the Hertzsprung–Russell diagram.

Several new structures are evident. First is a clear concentration of stars distributed continuously from the upper-left to the lower-right (A), coinciding with the evolutionary tracks for the DA white dwarfs (whose envelopes are dominated by hydrogen). Just below the main band is a second, distinct concentration (B). Babusiaux et al. (2018) attribute this to the DB white dwarfs (whose atmospheres are dominated by helium).



This prominent split in the white dwarf cooling sequence between H and He white dwarfs was actually first detected in the colour–colour diagrams from the Sloan Digital Sky Survey. But the Gaia data reveal it for the first time in the HR diagram. The very narrow sequences also confirm the sharp peak of their mass distribution around $0.6M_\odot$. Further details are given by, e.g., El Badry et al. (2018) and Gentile Fusillo et al. (2019).

There are also a number of white dwarfs which lie above the main DA sequence, and these are attributed to white dwarfs in binary systems.

A THIRD, WEAKER concentration is evident in the figure. A rising transverse feature labelled 'Q', it is a faint but significant 'band' of stars visible between the two dashed lines. Tremblay et al. (2019) showed that this is due to core crystallisation as the white dwarfs cool.

In the early 1960s, Abrikosov, Kirzhnitz, and Salpeter independently predicted that their cores should slowly crystallise as they cool, resulting in a lattice rather than a gas. In the process, the hot plasma fluid (of nuclei and electrons) releases an associated latent heat, providing a new source of energy that delays the object's cooling.

There has only been indirect evidence for this theory to date, although the details are crucial in estimating cluster ages. Gaia reveals the crystallisation as a mass-dependent pile-up in the HR diagram as they spend time at this location while they release their latent heat.

Tremblay et al. (2019) showed that the observed position of this transverse sequence (Q) agrees with the range of absolute magnitudes and colours at which the bulk of the latent heat from crystallisation is released over the full range of white dwarf masses.

THE GAIA DATA on white dwarfs thus provides direct evidence that a first-order phase transition occurs in high-density Coulomb plasmas. Importantly, it is a theory that cannot be tested in terrestrial laboratories because of the extreme densities involved.

Meanwhile, it will be some 5 billion years until the Sun evolves into a white dwarf, and another 5 billion years before it cools enough to form a crystalline sphere.

I imagine that Hertzsprung and Russell would have been astonished at these results: the spectacular emergence of subtle physics from exquisite data.