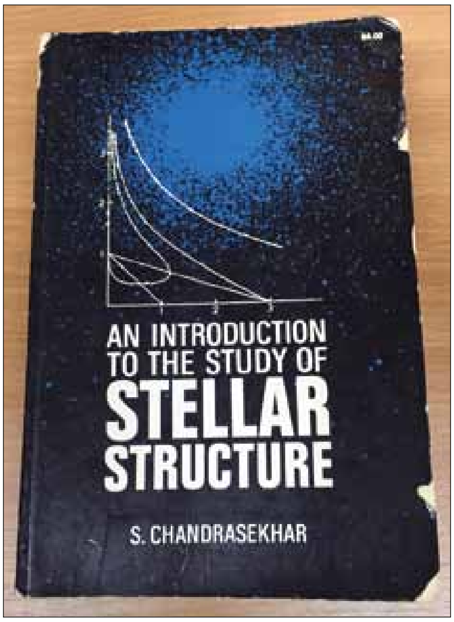
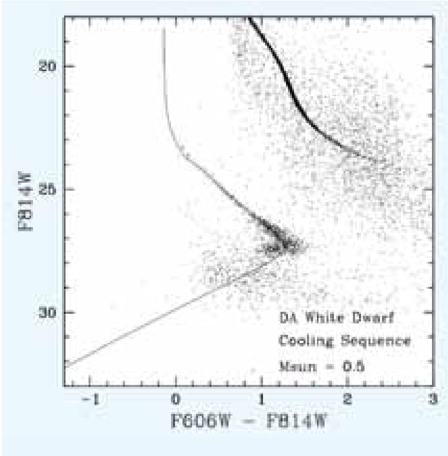
Diamonds in the sky

In his Presidential Address for 2016, **Martin Barstow** discusses the importance of white dwarfs in modern astrophysics.

1 Artist's impression of the binary star system of Sirius A and the smaller white dwarf Sirius B. With a diameter of 7500 miles, Sirius B is slightly smaller than Earth. (NASA, ESA and G Bacon [STScI])





2 (Left) The author's own copy of Chandrasekhar's 1939 book, containing an influential explanation of white dwarfs.

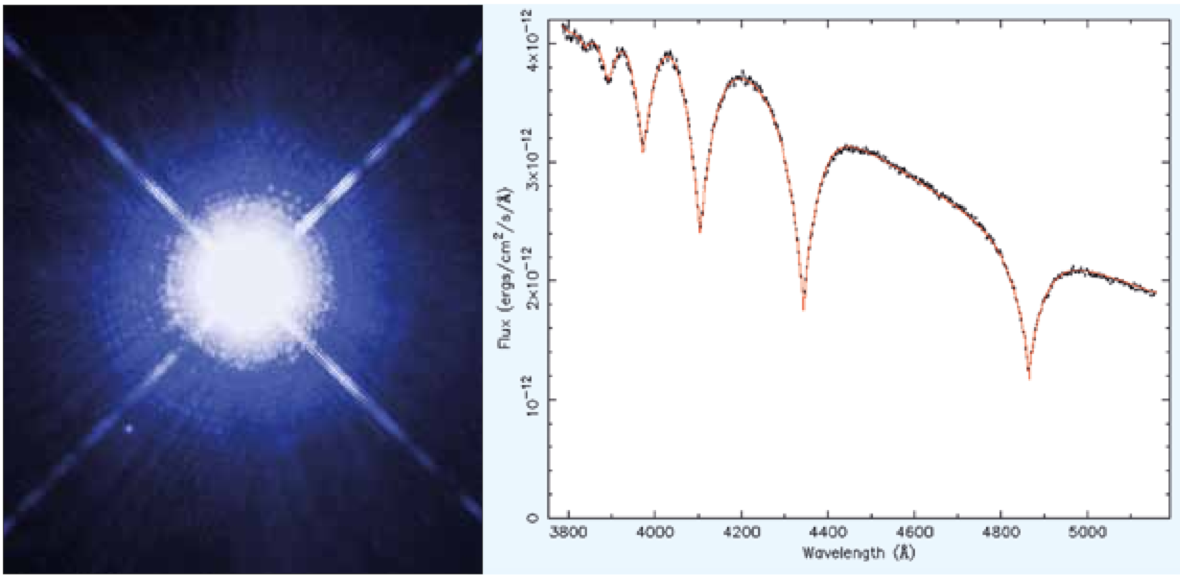
3 (Above) HR diagram showing white dwarf cooling sequence.

First discovered around 170 years ago, white dwarf stars have been a challenge to astronomers. Initially, their small size (about that of the Earth) and stellar mass (typically 0.6 solar masses, $M_\odot$) defied explanation. However, as understanding of these objects deepened it became apparent that they are of great importance, providing probes of galactic structure and evolution and, more recently, indirect measurements of the composition of rocky exoplanets. This Presidential Address reviews the history of our understanding of white dwarf stars and discusses some of the latest astrophysical discoveries with which they are associated.

The story begins with Friedrich Bessel's 1844 discovery that Sirius and Procyon had hidden companions, based on their influence on the proper motions of the primary stars, appearing as an apparent oscillation of their position on the sky. These objects were christened Sirius B and Procyon B. However, it was some time before Alvan Clarke finally resolved Sirius A and Sirius B in 1862 (see Holberg 2007). The faintness of the companions when set against their stellar-size mass was an early indication that these objects had a peculiar nature. At the time, obtaining spectra of the companions was almost impossible because of the overwhelming brightness of the nearby primary stars. However, an isolated example, 40 Eri B, was discovered and Henry Norris Russell issued instructions for it to be included in spectral typing programmes at the Harvard College Observatory (Russell 1914, Cannon & Pickering 1918). It is apt that, in the year when the Society celebrates the 100th anniversary of the admission of women to Fellowship, the work was carried out by Williamina Fleming in 1910, giving it spectral type A.

Subsequently, other examples were discovered; one of the best known is Van Maanen 2, first identified in 1913, which is an isolated white dwarf. In 1915, W S Adams published a first spectrum of Sirius B (Adams 1915), which emphasized the peculiar nature of these objects. As all this information came together, astronomers realized quite how peculiar these objects were, with rather small radii yet containing stellar masses of material – breaking all the then-known laws of physics. These were stars with massive surface gravity, 10^4 times that of a normal star, and unfeasibly high densities.

The 20th century brought new physics, including quantum theory, and the development of a theory of stellar structure. Many now-famous names in astronomy contributed to those advances. Karl Schwarzschild, Arthur Eddington (a Gold Medalist of this Society), Ralph Fowler, Paul Dirac and Wolfgang Pauli all



4 (Left) Sirius B clearly resolved in the HST image; note how close it lies to the diffraction spike from its much brighter companion. (NASA, H E Bond and E Nelan [STSI]; M Barstow and M Burleigh [Univ. Leicester]; J B Holberg [Univ. Arizona]) (Right) Balmer line spectrum of Sirius B from the Balmer limit to H β, obtained from the STIS instrument on HST, using the G430L grating.

developed elements of the theory that Subrahmanyan Chandrasekhar built into his *An Introduction to the Study of Stellar Structure* (1939). I still have the rather battered copy of this book that I bought when I was an undergraduate (figure 2). In it, Chandrasekhar provides a seminal analysis of what a white dwarf actually is, in a short chapter at the very end. He predicted the maximum mass that a white dwarf could have, i.e. which degenerate matter could support without collapsing, 1.44 $M_\odot$.

Leon Mestel

By the mid 20th century, white dwarfs were a well-known phenomenon. Leon Mestel, another RAS Gold Medalist, who encouraged me as a young Fellow of this Society beginning my studies of white dwarfs, was interested in the physics of their interiors. A white dwarf is an object in which nuclear burning in the interior has ceased. Mestel examined how these apparently dead objects would cool, radiating energy into interstellar space. He developed a theory of white dwarf cooling, demonstrating that the temperature declines exponentially over billions of years – in other words, over much of the lifetime of the universe (Mestel 1952) – a theory refined by Hamada and Salpeter (1961) a few years later. Since then, physicists and astronomers have added more sophisticated physics around that model, including details of the differentiation of the structure of the core and the composition of the envelope, but the basic theory remains.

Observations also progressed. To develop real understanding of a group of stars requires decent samples – and that means searching for these very faint objects. During the 1950s and 1960s, astronomers such as Willem Luyten, Henry Giclas and Jesse Greenstein carried out proper motion surveys looking for them (e.g. Luyten 1971). In the 1970s, 1980s and 1990s there were several important surveys, including Palomar Green survey (Green *et al.* 1986) and the Sloan Digital Sky Survey (Abazajian *et al.* 2003). These were looking for blue objects such as distant galaxies, but as a by-product found large numbers of white dwarf stars. At the same time, theories for understanding their envelopes were developed by Jesse Greenstein, Harry Shipman and Detlev Koester, among others, providing the tools to begin to understand the physical structure of these objects – the tools that I have used throughout my own career to try to understand what white dwarfs are and what they are doing.

Two fundamental things we can measure about any white dwarf are its mass and radius; Chandrasekhar predicted a relationship between the two that is quite simple and independent of temperature. Figure 3 shows a colour–magnitude diagram (the Herzsprung–Russell diagram). The main sequence is in the top right-hand corner and, at the bottom left, Mestel's white dwarf cooling sequence, with later refinements. The white dwarf cooling sequence is important because our galaxy hasn't been around long enough for white dwarfs to cool below a few thousand degrees; the temperature of the coldest white dwarfs provides a direct measure of the age of the galactic disc. This is a very important tool for measuring the ages of clusters, particularly for globular clusters where there have been anomalies in understanding the main sequence. All this work underpins our understanding of the late stages of stellar evolution, which are very important for recirculating gas and dust into interstellar space.

"Sirius B is one of the best-known white dwarfs – probably my favourite sky object"

White dwarfs are laboratories for matter under extreme conditions. In addition they are clearly implicated in Type Ia supernovae explosions, but the details of the mechanisms that produce these supernovae are not at all clear. There are a number of possibilities, all of which include at least one white dwarf. Yet we still do not have the smoking gun that tells us what the progenitors for Type Ia supernovae really are. Is it a binary white dwarf? Is it a white dwarf with a main sequence companion? There are still no obvious counterparts identified so it is important to understand the process of evolution of white dwarfs.

Sirius B is one of the best-known white dwarfs – and probably my favourite sky object. It is the nearest white dwarf to Earth and the companion to Sirius A in a close orbit with a period of 50 years. This makes it a challenging object to observe: Sirius A is overwhelmingly bright. However, because it is the nearest white dwarf to Earth it is also one of our best opportunities for understanding these stars, if we can get good observations. We know the distance to Sirius A very accurately so, by implication, we also know the distance to Sirius B. Attempts have been made to measure spectra from the ground, starting with Oke (1963). Kodaira (1967) achieved a very nice spectrum but, in common with any such spectrum, it was contaminated by the large amount of light scattered from Sirius A. Attempts were made to measure the temperature, the surface gravity and an important parameter, the gravitational redshift (which can lead to another determination of the mass), but these data had poor accuracy, giving inconsistent results.

Space-based data

It was only in the space age that things improved. We had access to the Hubble Space Telescope and, in the late 1990s and early 2000s, Sirius B started to become more distant from its companion. These results were published including exquisite imaging from the HST that clearly resolved the B component of the binary (Barstow *et al.* 2005); the data gathered a lot of interest. Figure 4a shows Sirius B close to the diffraction spike of Sirius A, highlighting how much scattered light there is. Figure 4b shows the visible light spectrum of Sirius B from the Space Telescope Imaging Spectrometer (STIS), including diffraction spikes from Sirius A, which cannot be completely eliminated. However, we have very good contrast between Sirius B and the scattered light background, producing absolutely exquisite spectra, among the best ever obtained for any white dwarf. Using calculations from stellar model atmosphere theory, it is possible to fit a predicted normalized spectrum to the observations and use that to determine physical parameters of the white dwarf itself, including the temperature and surface gravity, from which mass and radius can be determined.

Mass and radius

There are a number of ways to do this. The measurements are not all independent, but use different combinations of parameters – all in standard astrophysical relations – that approach the problem from different angles. For example, the flux equation, which relates the Eddington flux to the observed flux using R^2/D^2, i.e. the parallax, is important:

$$F_\lambda = 4\pi(R^2/D^2)H_\lambda \quad (1)$$

Surface gravity also matters:

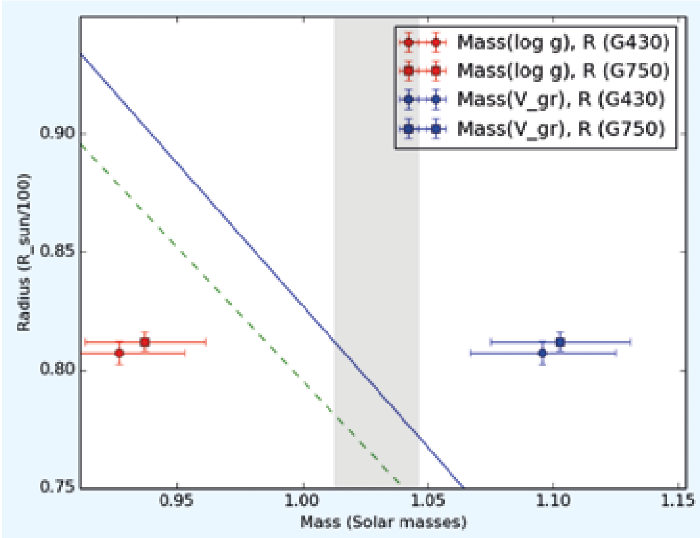
$$g = GM/R^2 \quad (2)$$

As does the gravitational redshift, from general relativity:

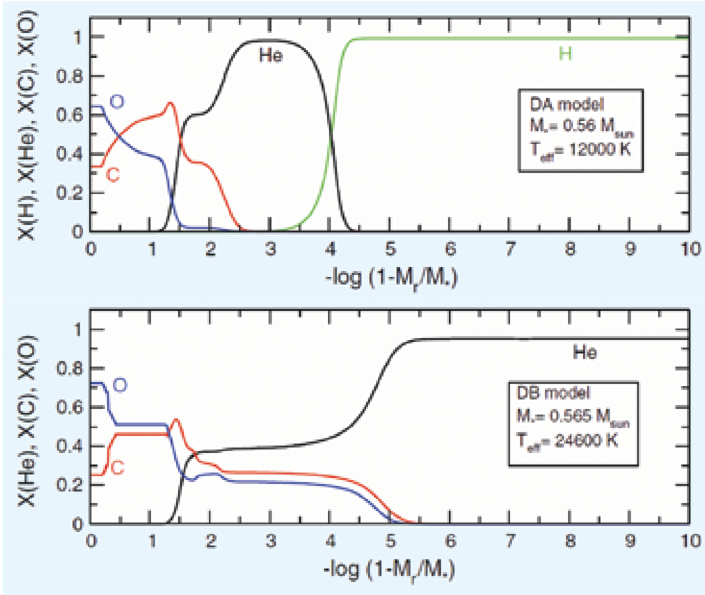
$$Z = 0.636M/Rc \quad (3)$$

Knowing some of these parameters allows you to examine interesting measurements from various angles and abstract, by combining these measurements, the mass and the radius. Working on this in 2005, we got four measurements of mass and radius, each taken from different spectra. We used the long wavelength spectra from the Balmer lines and some of the Hα line; we extracted these using g from the spectral fitting to get a mass and radius, but we could also do that from the gravitational redshift (equation 3) and the normalization of the parallax (equation 1).

There is a distinct difference between measurements taken from log g, which gives a mass around 0.9 $M_\odot$, and those taken from the gravitational redshift, which give measurements between 1 and 1.1 $M_\odot$. We couldn't reconcile those at the time, but felt there may be systematic effects in how the star is located in the aperture of the spectrograph. We planned to use a combination of narrow slits to reduce some of those systematics but, unfortunately, the STIS then broke; it wasn't repaired until 2009. In 2013, we were able to go back and get those observations, but things didn't work out quite how we had hoped.



5 Red points show Sirius B masses derived from log *g* for the G430L and G750M spectra; blue points, masses derived from the gravitational redshift. The blue line is the theoretical relation from Fontaine *et al.* (2001) for a CO core thick H layer; the green line for a thin H layer, both at 25 000 K. Shading shows the allowed range of the astrometric mass determination.



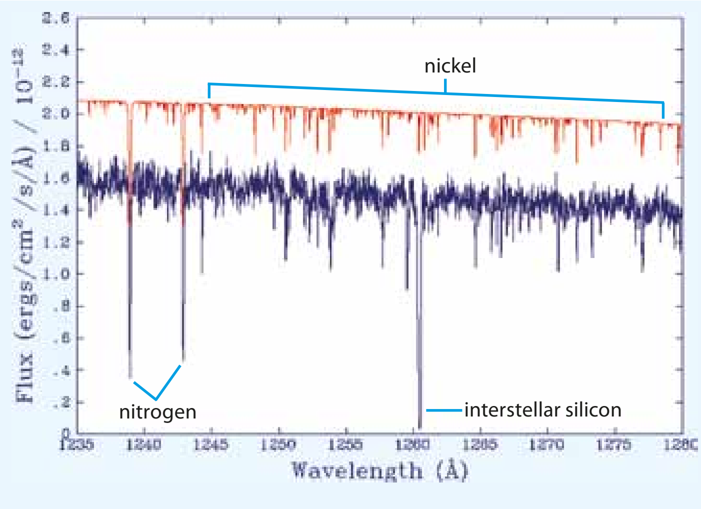
6 Profiles of white dwarf compositions from the surface down to the interior for both DA (top) and DB (bottom) white dwarfs. Typically their cores are mixtures of carbon and oxygen, then all white dwarfs have a helium envelope. (Fig. 17 in Althaus *et al.* 2010)

We had thought that the measurements would come together and we would get mutual agreement between the two different techniques that we were using to measure the mass and radius. Figure 5 shows the two data points from gravity and the two from gravitational redshift. The shaded area represents what was the current best estimate of the astrometric mass – and you couldn't get three sets of measurements that disagree more. This was enormously frustrating, but it indicated that there is something we do not understand about this star. This was – and is – worrying and, especially because of the importance of the white dwarfs in a lot of other measurements, we need to solve this problem.

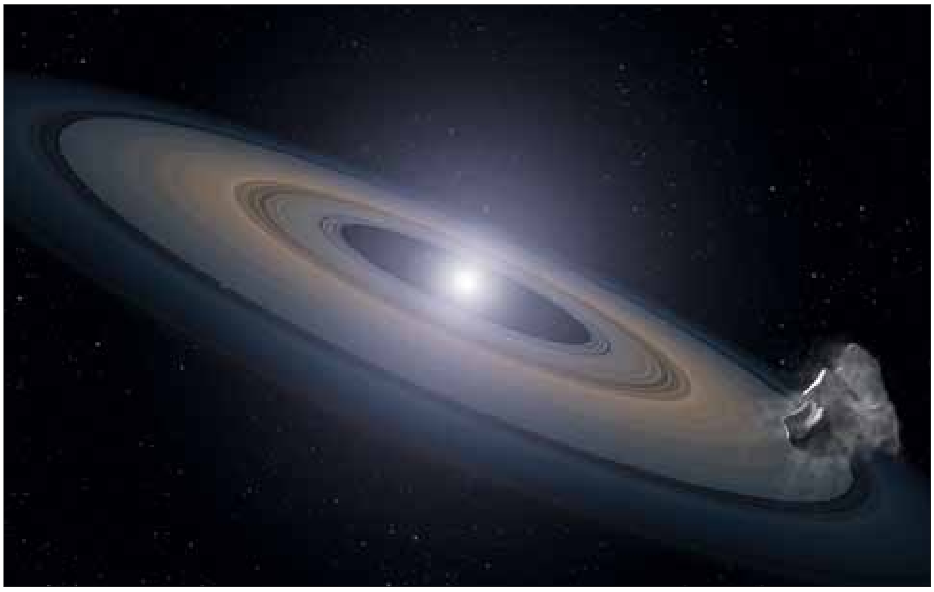
I don't have an answer yet; at the moment we are working on the astrometric mass. This work is not complete, but what is really challenging us is understanding what is going on: we have two robust methods of determining the values of these parameters, which give results that are about as far apart as you can get, well outside the error bars. There is either something going wrong with general relativity, for which we have no other evidence, or – rather more likely – there is something we don't understand about stellar atmosphere physics. The astrometric mass and where it sits in these results will be an important test.

White dwarf composition

One of the intriguing features of these stars is the fact that something as dense as a white dwarf with such a strong gravitational potential would be expected to have a very pure hydrogen or helium atmosphere. White dwarfs come in two flavours: the majority of white dwarfs (classified as DA) are hydrogen-rich with a hydrogen envelope. If the evolution of the progenitor star goes a bit further, that hydrogen envelope can be stripped leaving a helium envelope white dwarf: a DB or DO white dwarf. Figure 6 shows profiles of white dwarf compositions from the surface down to the interior. Typically their cores are



7 White dwarf spectrum (purple) and synthetic spectrum (red) demonstrating the typical composition of a white dwarf envelope. The synthetic spectrum is offset from the observation for clarity.



8 Artist's impression of a white dwarf accreting rocky debris left behind by the star's surviving planetary system. (NASA, ESA and G Bacon [STScI])

mixtures of carbon and oxygen, then all white dwarfs have a helium envelope.

Because of the strong gravitational field of these dense stars, species more massive than hydrogen or helium should sink rapidly, leaving simple atmospheric compositions. However, we have known for a long time that this is not necessarily the case. In the early 20th century, when nobody quite appreciated the nature of these stars, observers found calcium, magnesium and iron lines in the spectrum of Van Maanen's star (Van Maanen 1917) in plates archived at Carnegie Observatories. This finding was parked for about 70 years before people began to think more carefully about what to expect in the composition of white dwarf atmospheres (Farihi 2016). Studies of hot hydrogen-rich white dwarfs with IUE (the International Ultraviolet Explorer), ROSAT (the German Röntgen Satellite) and HST demonstrated that this simplified picture of a pure hydrogen envelope was not at all true for many white dwarfs. Figure 7 shows the spectrum of a typical white dwarf, including features from iron, oxygen and silicon in the atmosphere. As we probed more of these stars, we found that heavy elements are common, although not ubiquitous, in the atmospheres of DA white dwarfs. We started to wonder why.

"The implication is that many white dwarfs have circumstellar discs of gas and dust"

The theories that were developed to explain the presence of these heavy elements centred on radiation pressure holding material in the atmosphere, preventing it sinking down under gravity. This is described as radiative levitation and it works, at least qualitatively, in the calculations. Nickel and iron have many thousands of lines in the ultraviolet part of their spectra that can block radiation, giving rise to the radiation pressure that supports these elements. This seemed to be a very nice explanation and came to be accepted.

The white dwarfs that we had been examining were selected through surveys in the extreme ultraviolet part of the spectrum, so we knew that we were preferentially examining the hottest examples. We started a survey of white dwarfs with HST – in modest numbers, about 20. Observed abundances of Fe and Ni are shown in figure 9, alongside radiative levitation predictions. This idea doesn't work: the predicted abundances of these materials are higher than the ones we observe. Qualitatively, the radiation levitation theory works very nicely – white dwarfs with heavy elements exist at the expected temperatures – but the observed abundances don't match the theory. This is a puzzle that I have been trying to solve for about 15 years.

Circumstellar discs

In parallel with this, a lot of work was going on looking at cool white dwarfs. Some key infrared surveys including the WISE survey (Wright *et al.* 2010) came on line, and latterly NASA's Spitzer Space Telescope was launched, making spectroscopic observations possible at these wavelengths. Surprisingly, a number of white dwarfs were found to have infrared excesses. We had already imaged a number of these white dwarfs, looking for cool companions, but had not detected any; the infrared excesses are certainly not stellar. The implication of these observations is that many white dwarfs, particularly cool hydrogen-rich DA white dwarfs, have circumstellar discs of gas and dust surrounding them (figure 8).

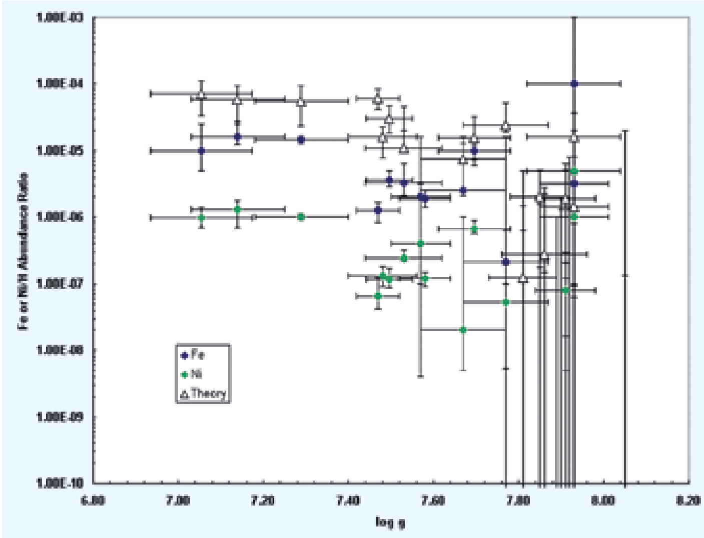
A particular example is white dwarf GD65. There is a bump in the infrared spectrum that is indicative of dusty material, while the visible light spectrum shows absorption from heavy elements at blue wavelengths. There is a build-up of evidence that, where infrared emission from dust is present, metals absorbed by the atmosphere of the white dwarf are also detected. The idea arose that the disc material is perhaps being accreted onto the white dwarfs observed. We see signs of the dust arriving in the atmosphere and, because it is continually resupplied, the signal does not diminish as material sinks into the white dwarf atmosphere.

The Far Ultraviolet Spectroscopic Explorer (FUSE), which flew for about 10 years from the late 1990s to the late 2000s, provided a really important probe of this process. FUSE observed white dwarfs largely as tools for other studies; they provided background sources for studying the interstellar medium and observations of deuterium in the ISM. So, for the first time, we had a relatively unbiased sample of white dwarfs from the ultraviolet part of the spectrum. The FUSE stars were drawn from several programmes, giving broad temperature coverage across a sample of about 90 stars with good signal-to-noise ratios in the far UV. Within this sample we detect a number of species, including nitrogen, oxygen, silicon, phosphorus and sulphur. Importantly, we detect some of them in excited states in this part of the spectrum, such as C III, Si IV, P V and S IV. Ground state transitions can originate in the ISM, but these lines can only be seen in hot and dense material, i.e. material that is in the stellar atmosphere.

The FUSE sample demonstrates that a high proportion of stars show heavy elements in their atmosphere, across the entire temperature range from about 20 000 K up to 70 000 K. The proportion declines at lower temperatures, which would be expected as radiation levitation forces diminish, but if radiative levitation were the only mechanism, the number of stars showing metals should decline much more steeply. And below about 35 000–40 000 K we should stop seeing those metals – but they are still observed.

Measurements of the carbon abundance as a function of effective temperature of the white dwarf lie well below predictions from radiative levitation models. For silicon we find a similar effect, although silicon behaves slightly differently under radiative levitation. Again, there is no correlation between predictions and observations. However, the ratio of silicon to carbon shows material depleted of carbon, in most cases, indicative of rocky material. The majority of measurements for the FUSE white dwarfs sit between the chondrite and bulk Earth abundances. Again the data bear no resemblance to the predictions of the radiative levitation model – indeed they are completely anti-correlated.

These data together demonstrate that we are seeing material accreted from extrasolar planetary debris, from dust discs and material from fragmented asteroids or planets. More recently we have seen some very direct evidence of this, where transits of dusty material in discrete pieces have been observed, in front of white dwarf stars (Vanderburg *et al.* 2015). This puts the icing on the cake.



9 The measured abudances of nickel (green diamonds) and iron (blue). The unfilled triangles are the predictions of radiation theory.

Cosmological significance

Finally, I would like to touch on the significance of white dwarfs for cosmology. A few years ago, John Barrow suggested to me that white dwarf spectra could be used to study fundamental constant variation in strong gravity. We put together a project to measure the potential variations in the fine structure coupling constant, α, that characterizes the strength of the electromagnetic interaction. In some cosmological models α is not constant with time but also does not necessarily remain constant in varying gravitational fields. In a strong gravitational field, such as that around a white dwarf, there may be changes that would manifest themselves as very small but potentially detectable shifts in wavelength for a particular series of atomic transitions. The effect is larger for higher atomic mass ions such as iron or nickel. Those white dwarf stars in which we observe high levels of iron and nickel are prime objects to test this idea.

"We have shown the potential for white dwarf data to probe fundamental physics"

One particular white dwarf, G191B2B, could demonstrate a small but measurable change in the spectrum if α does depend on the gravitational field. We measured the sensitivity parameter and found a trend in the difference between the predicted and measured wavelength for the iron lines; we also found a trend in the nickel lines, but it was in the opposite sense. A real effect of this type would affect both iron and nickel in the same way; what this work has done is to determine an upper limit for any such effect. However, we have demonstrated the potential for using white dwarf data to probe fundamental physics (Berengut *et al.* 2013). We now have support from the Leverhulme Trust to reduce the systematic errors in the analysis and to refine the measurements – maybe we will then detect something. It would be wonderful if we could, but nevertheless a refined upper limit will provide an important contribution to understanding our cosmology.

Conclusion

I hope that the examples I have discussed here demonstrate that, in the 160 years or so that they have been known, white dwarfs have played key roles in astrophysics – and that they still do so. In that time we have learned a lot, but there remain problems to be solved. The mass–radius relation remains important but, despite our efforts, it is proving to be a difficult problem to resolve. If we do not understand it, how can we believe all the measurements that we make that depend upon it, such as the age of the galactic disc, and ages of stellar clusters?

We have also found out new things about white dwarfs in recent years. Surprises are still there. The presence of metals in some white dwarfs at all effective temperatures, which indicates accretion of rocky planetary debris, is to me particularly exciting because it allows us to go back to these stars and take more observations to probe potential variability and try to refine the accretion and abundance histories so that we can begin to understand perhaps differential compositions in different parts of the galaxy. Finally, a new and significant angle is using white dwarfs as laboratories for studying variations of α in strong gravity. ●

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