The Importance of White Dwarf Stars as Tests of Stellar Physics and Galactic Evolution

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Introduction

Every star will meet one of three ends as it approaches the limits of its evolution. If the star is massive, the events triggered by the exhaustion of nuclear fuel in the stellar core will lead to a black hole. If the star is of intermediate mass, the product will be a neutron star. If the star is low mass, the end product will be an electron-degenerate white dwarf. The overwhelming majority of all stars formed in previous stellar generations, those currently on the main sequence including our Sun, and stars born in the future have or will end their lives as white dwarfs.

White dwarfs are structurally simple objects. Ninety nine percent of a white dwarf's mass is contained in an electron-degenerate core. High surface gravities (log g $\sim$ 8 in cgs) and efficient chemical diffusion/gravitational settling produce atmospheres composed predominantly of either hydrogen (DAs) or helium (DBs). DA white dwarfs comprise 80% of the total population and helium dominant DBs the remaining 20%. Evidence provided by ultraviolet and asteroseismological investigations increasingly supports the idea that DAs and DBs follow separate evolutionary paths. We now believe that once DAs emerge onto the white dwarf cooling track (with hydrogen layer masses between $M_H \sim 10^{-7} M_*$ and $M_H \sim 10^{-4} M_*$), they remain DAs as they cool (Bergeron 1995)). DBs are not as numerous as DAs and consequently are more difficult objects to study. Fundamental questions about their atmospheres, origins, and evolution remain (Bergeron 2011).

White dwarfs are rich forensic laboratories that provide links between the history and future evolution of the Milky Way Galaxy. The structure and composition of white dwarfs contain the records of the final stages of stellar evolution. As a newly forming white dwarf evolves through the planetary nebula phase, large quantities of processed material are injected into the interstellar medium. The chemical evolution of the Galaxy is traced through subsequent generations of stars formed from this contaminated material. The current temperature and/or luminosity distribution of Milky Way white dwarfs constrains models of galactic and cosmological evolutionary history. Type I supernovae, in which an accreting white dwarf undergoes a thermonuclear event, are used as distance indicators demonstrating the acceleration of the universe. Underlying all these studies is the theoretical mass-radius relation for electron degenerate matter. An important consequence of this relation is the existence of a limiting mass for white dwarf stars.

UV astronomy is particularly important for the study of white dwarf stars. A significant fraction of white dwarf emergent flux appears in the UV, especially for the hotter stars. In addition, traces of elements heavier than hydrogen or helium are, in general, only detected in this waveband or at shorter wavelengths that are also only accessible from space. In the following, we will broadly outline the importance of the white dwarf mass-radius relation, the white dwarf luminosity function, and white dwarf spectroscopy in understanding important cosmological questions, including questions of stellar physics in extreme conditions, galactic evolution, stellar formation and evolution, and the chemical distribution of material in our galaxy. We will conclude by demonstrating the importance of UV observations of white dwarf stars in advancing our understanding of these questions.

The White Dwarf Mass-Radius Relation

The theoretical mass-radius relation for electron degenerate matter is a generally accepted underlying assumption in all studies of white dwarfs and their properties. In turn, these studies, including the white dwarf mass distribution and luminosity function, are foundations for such fields as stellar evolution, galactic formation and Type 1a supernovae. The relation predicts the radius of a white dwarf of given mass and interior composition, usually assumed to contain a mixture of carbon and oxygen. An important consequence of the mass-radius relation is the limiting mass for white dwarfs (Chandrasekhar 1933), above which an object cannot be supported by electron degeneracy.

One would like to assume that as fundamental a theory as the white dwarf mass-radius relation rests on solid observational grounds. However, we have complete observational data for only 3 stars (40 Eri B, Procyon B, and Sirius B). Each of these objects is a member of a binary system, giving us the ability obtaining independent dynamical information on the white dwarf mass from its orbital parameters. In addition, the stellar distances are known, allowing for an independent determination of stellar radii (Figure 1). The source of difficulties for single white dwarfs is the need for determinations of masses and radii in ways that do not invoke the mass-radius relation.

The most general method used to determine white dwarf masses, and the single technique capable of inferring the masses of solitary white dwarfs, is the comparison of observed spectra with the predictions of model atmospheres. This comparison produces estimates of surface gravity (log *g*) and effective temperatures by matching the widths of line profiles. Precise surface gravities are essential, as the uncertainty in log *g* translates directly into the mass uncertainty. However, surface gravity is a function both of mass and of radius. Most field white dwarfs do not have the accurate parallax measurements necessary for deriving precise independent radii. In addition, surface temperature can be influenced by trace elements, most of which are only detected in the UV wavelength range. In most cases, to determine stellar mass one must assume an underlying mass-radius relation for a given core composition, usually chosen to be carbon. It is therefore difficult to prove the validity of the mass-radius relation without assuming its existence (Provencal 2002).

The White Dwarf Luminosity Function

White dwarf evolution is dictated by cooling. White dwarfs contain no energy sources, and cool by emitting residual energy. As any white dwarf cools, its surface temperature decreases and its luminosity decreases. White dwarfs have very small surface areas, so they cool very gradually over billions of years. The basic analytical model of white dwarf cooling was developed by Mestel in 1952.

The observed white dwarf luminosity function (WDLF) is defined as the number of white dwarfs as a function of their intrinsic luminosity (Figure 2). The WDLF is a convolution of the star formation history of the Galaxy, the cooling physics of white dwarfs, and the evolution of the white dwarf progenitors. As such, it is a valuable diagnostic of the age of the galactic disk and the history of stellar formation in the Galaxy. Detailed knowledge of the white dwarf cooling can provide a valuable cosmic

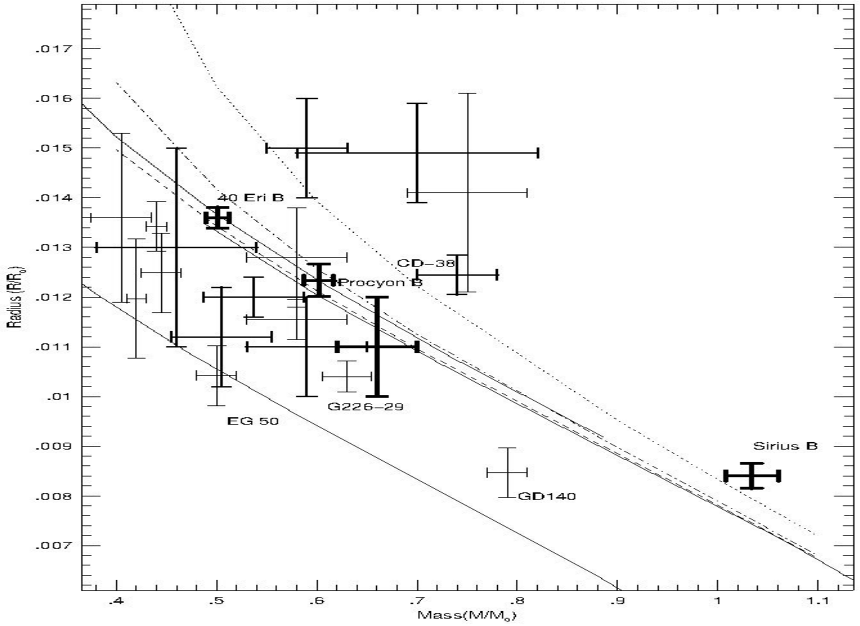

Figure 1: Current observational support. Positions of the visual binaries Procyon B, Sirius B, 40 Eri B, and Stein 2051B (extra-thick error bars), common proper motion systems (thick error bars), and field white dwarfs (thin error bars) are shown (from Provencal et al. 2002).

clock to determine the ages of individual white dwarfs, the ages of open and globular clusters, and age of the galactic disk.

Upcoming as well as ongoing surveys (SDSS, LSST) will greatly improve the white dwarf sample and hence the empirical luminosity function. We will require detailed observational support for these new objects. In particular, the hotter and cooler ends of the WDLF contain few objects. This can be attributed to the difficulty in identifying the coolest white dwarfs, and the relative rarity of hot white dwarfs. UV observations will be particularly important for the hotter objects.

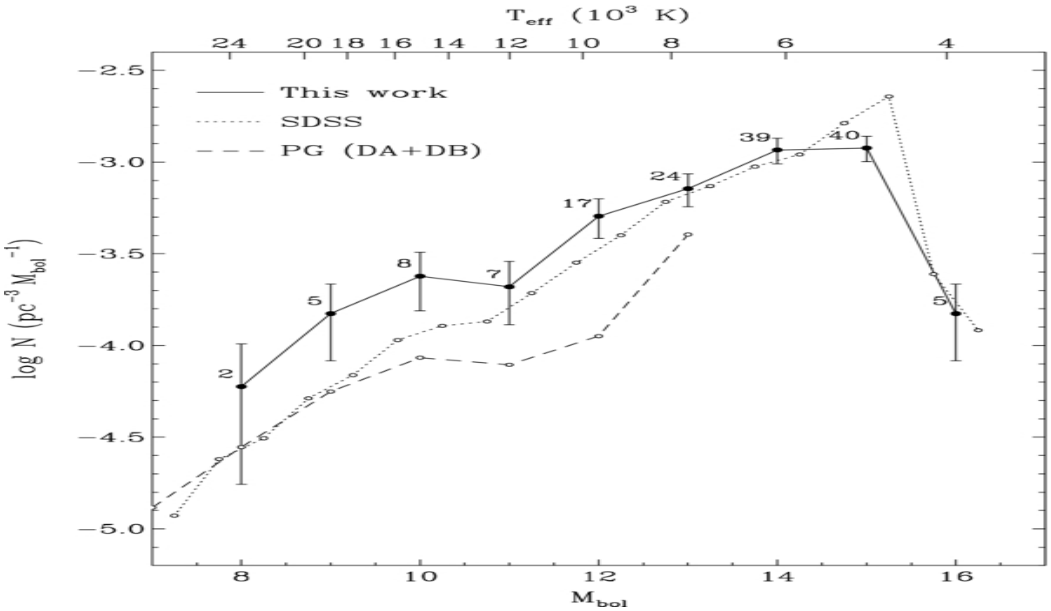

Figure 2: Luminosity function (solid line) from Giammichele et al. (2012), compared to the luminosity functions obtained from the SDSS (Harris et al. 2006) (dotted line) and the PG survey (dashed line, Bergeron et al. 2011) for the DA and DB stars in the PG survey (dashed line). The temperature scale assuming M= 0.6 is also shown at the top of the figure.

Photospheric Composition of White Dwarf Atmospheres and the Interstellar Medium

It is well established that some white dwarfs, particularly the hotter objects, possess significant abundances of elements heavier than helium in their atmospheres. Given the high surface gravities and short diffusion timescales, the favored origin for these trace elements is accretion from the interstellar medium. In addition, the lack of hydrogen in most DB white dwarfs, which have been immersed in the hydrogen dominated interstellar medium, is an unresolved question. Finally, white dwarfs are important probes of the structure and composition of the local interstellar medium. Lehner et al. (2009) present detailed results of a survey of the local interstellar medium using 31 white dwarfs observed with the FUSE satellite.

The Importance of UV Observations of White Dwarf Stars

We now arrive at the primary motivation for this discussion: our continuing need for UV observations of white dwarf stars to address problems of importance to a wide range of astronomical fields. Direct imaging in the UV is an significant method of discovering new objects, especially including white dwarfs in binary systems. As an example, a major result of the EUV sky surveys was the discovery of many unresolved binary systems containing white dwarfs and companions with spectral types ranging from A to K (see for example Barstow et al. 1994). In optical wavelengths, the presence of a companion of spectral type earlier than mid-K will swamp the white dwarf, making it undetectable. In the EUV, the companion flux is generally negligible, and the white dwarf stands out very clearly. The UV wavelength range is an even more efficient way of searching for these binaries, as the interstellar opacity is much lower than in the EUV and the GALEX sky survey is finding many examples.

Ultraviolet spectroscopic observations have played an essential role by providing access to absorption features from elements heavier than He. These features are not usually present in optical or infrared data except where photospheric abundances are unusually high. Typical detection limits in the UV are two orders of magnitude lower. Therefore, the most important and useful transitions, particularly many resonance lines of elements heavier than H and He, lie in the far-ultraviolet (far-UV, 1000-2000Å).

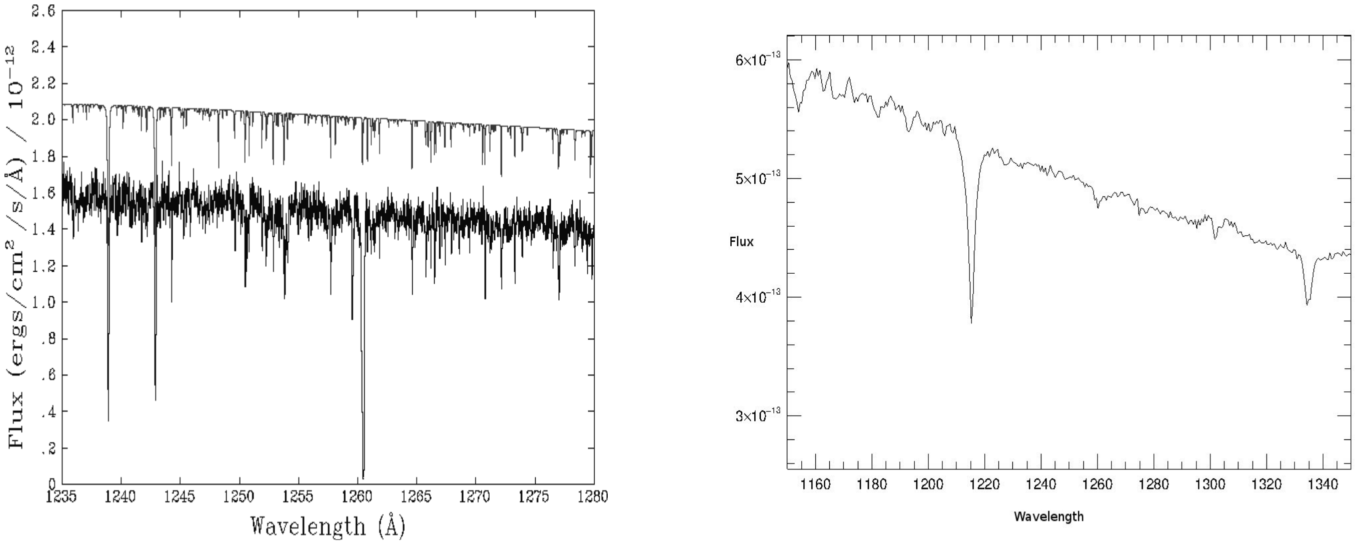

Figure 3: Left: STIS spectrum of REJ0558-373, showing photospheric absorption lines of NV (1238.821/1242.804Å) and large numbers of Ni lines. The best-fit synthetic spectrum is shown offset for clarity. The strong line near 1260Å,

present in the observation but not in the model, is interstellar SiII (from Barstow et al. 2003). Right: STIS spectrum of GD358, showing Lyman α, and CII at 1335 Å.

However, since the lines are expected to be weak and narrow, they are only normally visible at high resolution (R>20,000). An example is given by the hydrogen atmosphere white dwarf REJ0558-373. Fig. 3 shows the high-resolution spectrum obtained with the Space Telescope Imaging Spectrograph onboard *HST*, which includes the interstellar 1260.4 Å line of SiII together with photospheric NV. A second example is given by the helium atmosphere DB GD358, which shows absorption features of CII.

Determinations of the physical properties of white dwarf stars such as temperature and surface gravity is severely hampered by the large errors associated with optical spectroscopic determinations, especially for hotter white dwarfs and helium atmosphere objects (DBs). Most of this error is not due to failings of the optical spectroscopic observations and resulting model fits, but rather to the high temperatures of the objects. For example, optical spectroscopy of helium white dwarfs with temperatures cover regions far out on the Rayleigh-Jeans tail of the energy distribution. This creates difficulties in properly defining the observed continuum (Figure 4, left). In addition, in this temperature range, optical helium lines are insensitive to changes in temperature (Fig. 3, right). Finally, trace amounts of hydrogen and other elements particularly affect the DB temperature scale. Beauchamp et al. (1999) show fitting a pure helium model to a star containing traces of hydrogen (H/He ~10^{-4}-10^{-5}) can produce changes in effective temperatures as large as 3000 K. Upper limits on hydrogen abundances do exist (Bergeron et al. 2011), but detection of trace amounts in DB white dwarfs is notoriously difficult at optical wavelengths.

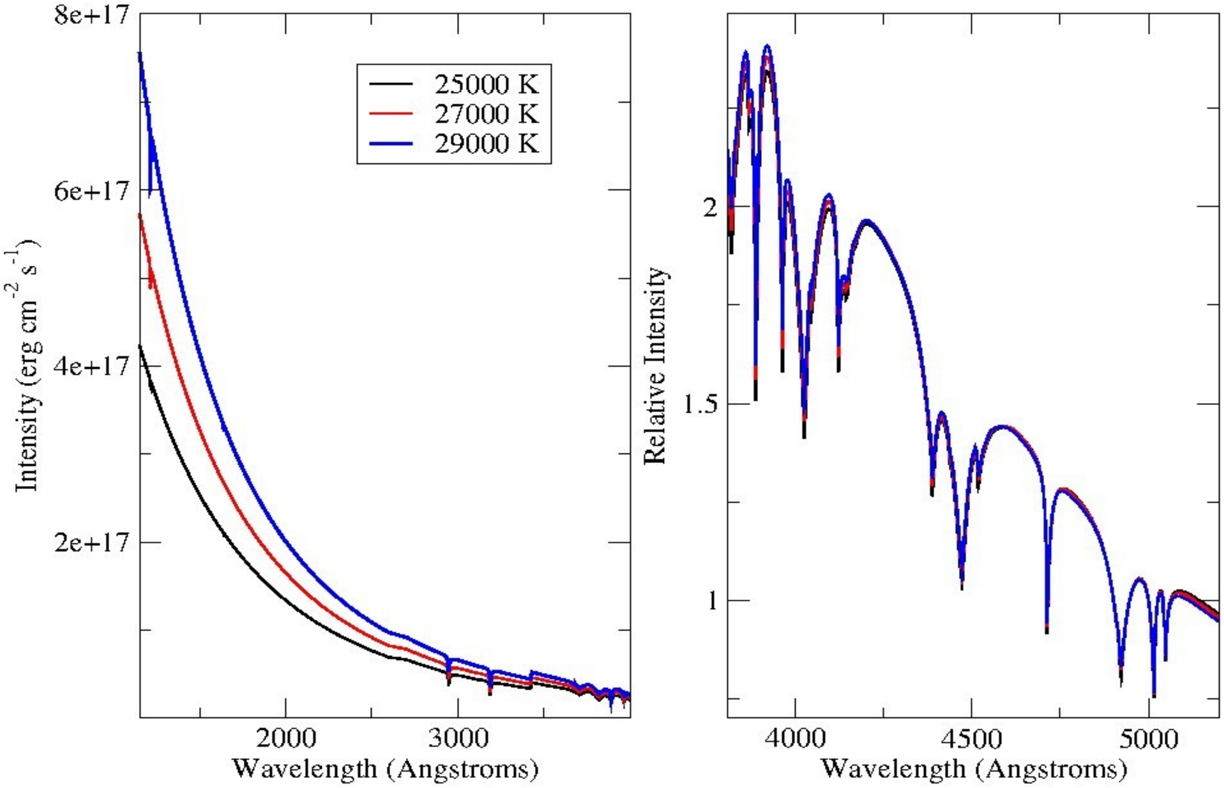

Figure 4: Synthetic spectra of pure helium DB models (log g = 8 and ML2) at 25000, 27000, and 29000 K. The left panel shows the effects of increasing temperature on the slope shortward of 3000 Å, while the right panel shows the

insensitivity of optical helium lines to changes in effective temperature.

Finally, the hottest white dwarfs, the PG1159 stars, are rare objects. Only a select few have been studied in detail in the ultraviolet. High-resolution UV observations are essential, because most diagnostic metal lines observed in these extremely hot stars are located in this wavelength region. The wide spread in element abundances, as well as the observed iron-deficiency and neon- and fluorine-overabundances show that PG1159 stars have a large, and unique, potential to study mixing and fusion processes whose consequences are usually unobservable in other stars. As a consequence of a late He-shell flash, PG1159 stars exhibit intershell matter that normally remains hidden in the stellar interior. In contrast to cooler white dwarfs, the observed element abundances in PG1159 stars are not affected by gravitational settling, hence, abundance patterns still do reflect the history of these stars.

Conclusions

White dwarfs represent a significant contribution to the galactic stellar population and are significant indicators of the evolutionary history of the Galaxy. It is critical to understand the white dwarf population as fully as possible. This is only possible through a continued program of observations in the far ultraviolet waveband. Given the current and upcoming survey projects, our principal need is for high resolution spectroscopy, but diffraction limited imaging is also of importance.

The situation regarding continued access to the far UV after HST is overshadowed by complex programmatic and political issues which make it difficult to plan ahead. Currently, no space agency has any plans for a HST (or larger) class UV telescope. To achieve this in a relatively short timescale requires the use of existing technology, but given that HST itself is “old” technology, it should be possible to provide an instrument with enhanced sensitivity through avoidance of complex relay optics and significantly improved grating and detector technology. A 2-m class telescope would be able to address many of the science goals relating to observation of white dwarfs in our own galaxy if the following technical capabilities are achieved:

- Galactic white dwarf spectroscopic survey
    - λ~912-3000Å, R~50,000-100,000, V_{lim}~20
- Astrometric white dwarf masses
    - Diffraction limited imaging to V~20

For a larger 4-6 m telescope, white dwarf research would be greatly advanced by these key requirements:

- Globular cluster/Magellanic Cloud white dwarf surveys
    - Integral field spectroscopy λ~912-1300Å, R~1000, V_{lim}~28
    - Wide field imaging (10 arcmin) to V~35

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