

STRUCTURE AND EVOLUTION OF WHITE DWARFS AND THEIR INTERACTION WITH THE LOCAL INTERSTELLAR MEDIUM

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Abstract: The development of far-UV astronomy has been particularly important for the study of hot white dwarf stars. A significant fraction of their emergent flux appears in the far-UV and 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. Although white dwarfs have been studied in the far-UV throughout the past ~25 years, since the launch of *IUE*, only a few tens of objects have been studied in great detail and a much larger sample is required to gain a detailed understanding of the evolution of hot white dwarfs and the physical processes that determine their appearance. We review here the current knowledge regarding hot white dwarfs and outline what work needs to be carried out by future far-UV observatories.

Key words: ultraviolet astronomy; space missions; white dwarfs

1. INTRODUCTION

1.1 White dwarf stars and the local interstellar medium in astrophysics

Many white dwarfs are among the oldest stars in the Galaxy. Their space and luminosity distributions help map out the history of star formation in the Galaxy and can, in principle, determine the age of the disk, by providing an

important lower limit to the age of the Universe. Recently, it has been suggested that cool white dwarfs may account for a substantial fraction of the missing mass in the galactic halo (Oppenheimer et al. 2001). White dwarfs are also believed to play a role in the production of type Ia supernovae, through possible stellar mergers or mass transfer. Although no candidate precursor system has yet been found, they are used as “standard candles” to measure the distances of the most remote objects in the Universe and to imply a non-zero value for the cosmological constant. It is intriguing that such local, low luminosity objects as white dwarf stars play a key role in some of the most important cosmological questions of our day, concerning the nature and fate of the Universe. To understand and calibrate cosmologically important aspects of white dwarfs, such as their cooling ages, masses and compositions we require a thorough understanding of how their photospheric compositions evolve. Atmospheric metal abundances affect cooling rates and bias the determination of temperature and surface gravity. Reliable masses can only be derived from accurate effective temperature and surface gravity measurements. Importantly, metals are difficult to detect in cool white dwarfs but still play an important role in cooling. Therefore, abundances measured in hotter stars provide important data as to what species may be present and in what quantities.

Interstellar gas is a fundamental component of the Milky Way and other galaxies. The local interstellar medium (LISM) is particularly important because it is close enough to us for detailed examination of its structure. Indeed, it is the only part of the Universe, apart from the solar system, that we can study directly, from the penetration of neutral particles through the heliopause. Study of the composition of the local interstellar gas tells us about the evolution of the Universe and our galaxy. While modified considerably since the formation of the solar system, the processes that have shaped the ISM must have also affected the solar system and possibly even the evolution of life. For example, the local radiation field and gas properties of the LISM set the boundary conditions for the heliosphere. Therefore, it regulates the properties of the interplanetary medium and the cosmic ray fluxes through the solar system (see Frisch et al. 2002), which may affect the terrestrial climate (Mueller et al. 2003).

The relationship between white dwarfs and the LISM is intimate. The process of producing white dwarfs in the disk substantially enriches the content of the local ISM (Margio 2001) and white dwarfs contribute significantly to the total cosmic abundance of metals (Pagel 2002). They also provide a significant fraction of the total flux of ionizing radiation within the LISM and will affect the ionization state of the interstellar gas, even if the LISM is not in ionization equilibrium. At the same time, white dwarfs may be accreting material from the denser clouds in the ISM, which will modify

their photospheric abundances. Finally, white dwarfs are ideal background sources for direct study of the LISM

1.2 Physical structure and classification of white dwarfs

Astronomers have known about the existence of white dwarf stars for 150 years, since the discovery of a companion to the brightest star in the sky, Sirius. Studying the regular wave-like proper motion of Sirius, F.W. Bessel revealed the presence of a hidden companion, with the pair eventually resolved by A.G. Clark in 1862 and the orbital period revealed to be 50 years. Later, the first spectroscopic study of the system by W.S. Adams revealed a great enigma. While the temperature of Sirius B was found to be higher than Sirius A, it was apparently 1000 times less luminous. This result could only be explained if Sirius B had a very small radius, $1/100R_{\odot}$ and similar to that of the Earth. However, with a known mass of $\sim 1M_{\odot}$ for Sirius B, the implied density of $1400 \text{ Tonnes m}^{-3}$ was well above that of any form of matter known to 19th and early 20th century physicists. Within a number of years, a handful of stars similar to Sirius B were found, mostly in binaries. The term “white dwarf” was coined later, on the basis of the visual colour and small size, when compared to other stars.

The answer to the riddle of their structure stems from the development of the quantum statistical theory of the electron gas by Enrico Fermi and Paul Dirac. When atoms in a material are sufficiently close together, their most weakly bound electrons move freely about the volume and can be considered to behave like a gas. Almost all the electrons in the gas will occupy the lowest available energy levels. Any states with the same energy are said to be “degenerate”. Hence, this gas is known as the “degenerate electron gas”. Under conditions of extreme pressure the electrons are forced to occupy space much closer to the nuclei of the constituent atoms than in normal matter, breaking down the quantised structure of the energy levels. However, according to the Pauli Exclusion Principle, no two electrons can occupy the same quantum state, which has a finite volume in position-momentum space, so there is a limit where a repulsive force arising from this, the “electron degeneracy pressure”, resists further compression of the material. Fowler (1926) showed that this pressure could support a stellar mass against gravitational collapse and proposed that this might explain the existence of white dwarfs. Combining this insight with the equations of stellar structure, Chandrasekhar (1931, 1935) determined the mass-radius relation for white dwarfs and the maximum mass ($1.4M_{\odot}$) that electron degeneracy pressure could support against gravity, the Chandrasekhar limit. As this Nobel Prize winning work has been extended by subsequent developments, the basic

ideas remain unchanged. However, importantly, they have also hardly been tested by direct observation.

Theoretical and observational study of stellar evolution has placed white dwarfs as one possible end point of the process. In general terms, all stars with masses below about eight times that of the Sun will pass through one or more red giant phases before losing most of their original mass to form a planetary nebula. The remnant object, a white dwarf, is the core of the progenitor star. In the absence of any internal source of energy, the temperature of a white dwarf, after its birth, is determined by how rapidly stored heat is radiated into space. Estimates of white dwarf cooling times indicate that it will take several billion years for the stars to fade to invisibility. Hence, white dwarfs are among the oldest objects in the galaxy. Since, the galaxy is younger than the cooling timescales; the lowest temperature (oldest) white dwarfs yield a lower limit to its age.

The basis for understanding the nature of most stars is analysis of their optical spectra and classification according to the characteristics revealed. A number of physical processes can alter the atmospheric composition of a white dwarf as it cools. As noted by Schatzmann (1958), the strong gravitational field ($\log g \sim 8$ at the surface) causes rapid downward diffusion of elements heavier than the principal H or He component. Hence, Schatzmann predicted that white dwarf atmospheres should be extremely pure. Consequently, the spectra should be devoid of most elements, showing signatures of only hydrogen and, possibly, helium. White dwarfs are thus divided into two main groups according to whether or not their spectra are dominated by one or other of these elements. The hydrogen-rich stars are given the classification DA, while the helium-rich white dwarfs are designated DO if HeII features are present (hotter than about 45000K) and DB if only HeI lines are visible. Small numbers of hybrid stars exist, with both hydrogen and helium present. In these cases, two classification letters are used, with the first indicating the dominant species. For example, DAO white dwarfs are mostly hydrogen but exhibit weak HeII features.

The above classification scheme applies only to white dwarfs with temperatures above $\sim 10000\text{K}$, when the H and He energy levels are sufficiently populated above the ground state to produce detectable features at visual wavelengths. At lower temperatures, although H and/or He may be present these elements are no longer directly detectable. Cool white dwarfs are divided into three main groups. DC white dwarfs have continuous, completely featureless spectra; DZ white dwarfs are He-rich and have only metal lines visible; DQ white dwarfs show carbon features. Figure 1 summarises the current thoughts regarding the relationships between the hot white dwarf groups along with the principal mechanisms that provide evolutionary routes between them.

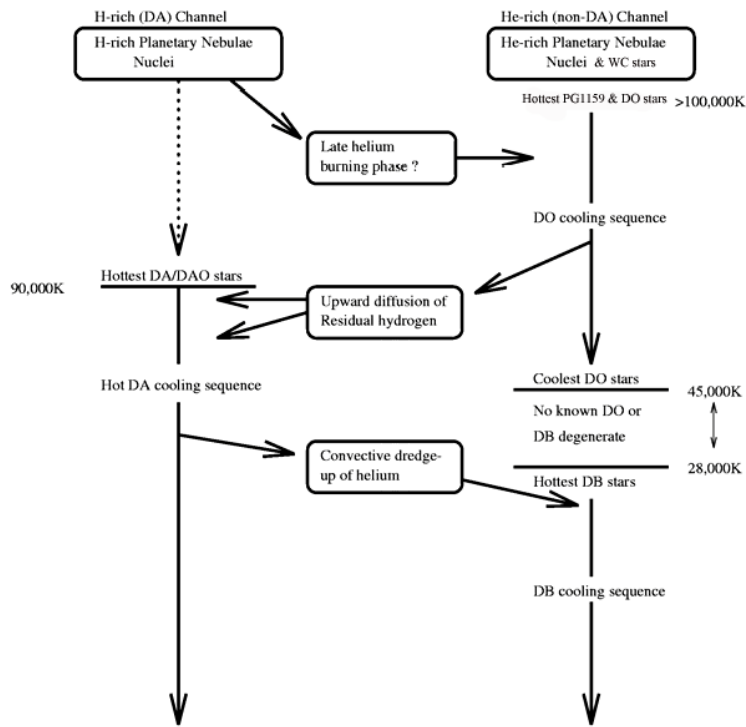


Figure 1. Schematic description of the production of H-rich and He-rich branches of white dwarf evolution

Gravity is not necessarily the only influence on photospheric composition. It can be countered by radiation pressure which acts outward to support heavy elements in the atmosphere, a process termed “radiative levitation”. Another mechanism that can mix elements that have settled out in the stellar atmosphere is convection. If the convective zone reaches down to the base of the atmosphere then heavy elements can be dredged back up into the outer atmosphere. A further complication is that material can also be accreted from the interstellar medium.

1.3 The structure of the local interstellar medium

The Sun is embedded in the Local Interstellar Cloud (LIC), a warm ($T \sim 10,000\text{K}$), low-density ($n \sim 0.1\text{cm}^{-3}$) region, which is observed in projection toward most, but not all, nearby stars. Models of the LIC (Redfield &

Linsky, 2000) show the Sun located just inside the edge of the LIC in the direction of the Galactic Center and toward the North Galactic Pole (NGP). The LIC is surrounded by a hot 10^6K substrate and appears to be part of the expanding cloud complex representing the Loop I radio shell, which is either a supernova remnant or a wind blown shell from the Sco-Cen Association (Fig. 2). Indeed, evidence for shocks in the LIC within the past 2 Myr is supported by EUV observations of ionized interstellar HeII (Lyu & Bruhweiler 1996; Barstow et al. 1997). Also, surrounding the LIC is the low density Local Bubble with dimensions of $> 200\text{pc}$. Soft X-ray and OVI observations imply this region is largely filled with a hot ($T \sim 10^6\text{ K}$), extremely low-density ($n \sim 10^{-2}\text{ cm}^{-3}$) plasma. Frisch (1995) and Bruhweiler (1996) discuss possible origins of Loop I and the Local Bubble, but we need to resolve two key questions. What is the geometry of the Local Bubble? What are the distribution, physical conditions, and kinematics of clouds in the Local Bubble? The answers to these questions also bear directly on whether interstellar accretion is possible in specific white dwarfs.

2. THE COMPLEX NATURE OF THE DA WHITE DWARF POPULATION

2.1 Composition and structure of the stellar photospheres from UV spectroscopy

The emergence from the Asymptotic Giant Branch (AGB) of the two H- and He-rich groups, is qualitatively understood to arise from differences in precise evolutionary paths. The He-rich group undergoes a late helium shell flash, which causes convective mixing of the outer envelope. Hydrogen is ingested and burnt or diluted by this process (e.g. Herwig et al. 1999). The majority of young white dwarfs are of DA type, outnumbering the He-rich objects by a ratio of $\sim 7:1$ (Fleming et al. 1986; Liebert, Bergeron & Holberg 2005). The more recent, deeper, Sloan Digital Sky Survey appears to yield an even higher value of 9:1 for the ratio of DAs to the total number of DO and DB white dwarfs (Kleinman et al. 2004). However, the complex relationships between these groups and a demonstrable temperature gap in the He-rich cooling sequence cannot yet be readily explained. For example, the ratio of H-rich to He-rich progenitors (4:1) is lower than that of the white dwarfs into which they evolve (Napiwotzki 1999). Furthermore, a gap in the He-rich sequence, between ~ 45000 and 30000K , separating the DO and DB white dwarfs (Wesemael, Green & Liebert 1985; Liebert et al. 1986;

Dreizler & Werner 1996) implies that He-rich white dwarfs must temporarily be seen as DA stars due to some physical process.

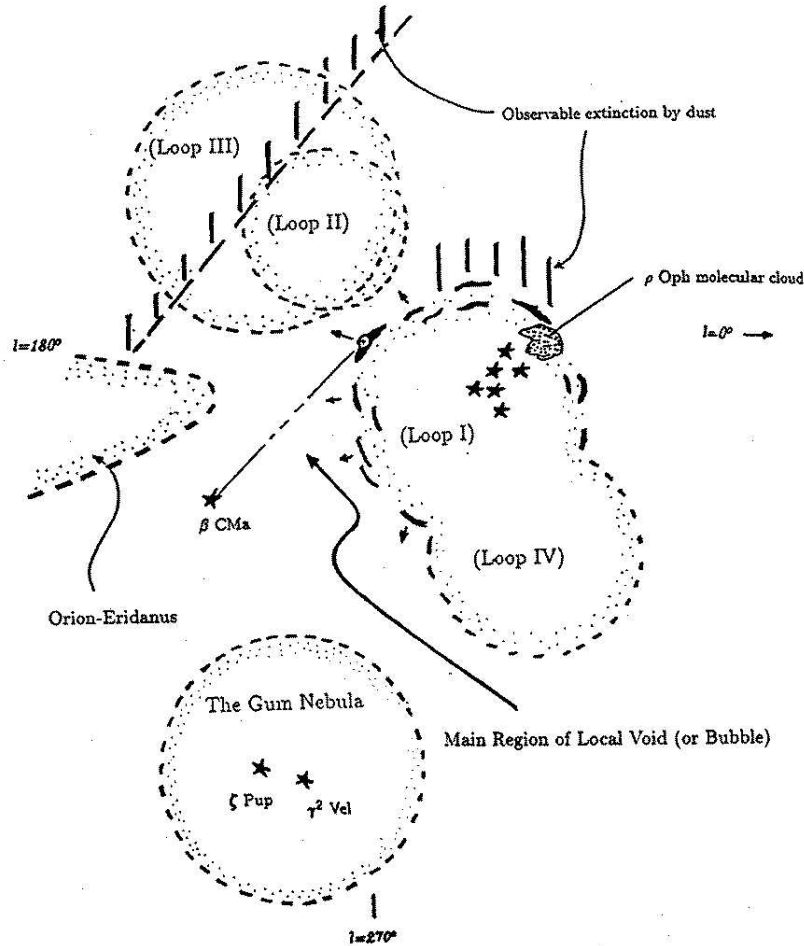


Figure 2. View of the LISM within 400 pc of the Sun. The Sun is located at the end of the dashed line extending from the star β CMa. The dashed line is ~ 200 pc in length. The region of the Local Void or Local Bubble is denoted. Most of the volume of the LISM is composed of very low-density gas. The radio loop structures are further indicated. The stars of Sco-Cen are interior to Loop I. Regions of high dust extinction, regions where dense clouds are found, are also marked. From Bruhweiler (1996).

It is well established that the hottest ($T \sim 50,000\text{K}$) white dwarfs possess significant abundances of elements heavier than He in their atmospheres. Typical ranges are shown in table 1 for the most important elements. Mass

fractions are given, with respect to H for DAs and He for DOs, since they are essentially independent of nuclear burning, if the element does not participate in the process. Observed abundances may vary considerably with temperature, as discussed later. Hence, we list typical values and comment on the possible ranges in each white dwarf pathway. Studying how photospheric abundance patterns change as these stars cool can delineate the evolutionary pathways followed by white dwarfs. For example, abundance enhancements in C, N and O may be a sign of near exposure of the C-O core during the AGB phase or of a late He-shell burning episode.

Table 1. Abundances of important heavy elements observed in DA and DO white dwarfs. Note that the values are much more uncertain for the less well-studied DO stars.

Element	DA		DO	
	Typical value	Comment	Typical value	Comment
C	10^{-6} to 10^{-5}	zero in coolest	3×10^{-3}	
N	10^{-6}	From zero to 10^{-2} at extremes	5×10^{-5}	In a few cases
O	10^{-4}	zero in coolest	10^{-5}	
Si	10^{-4}	Seen at most temps down to 10^{-8}	10^{-4}	
Fe	$2-5 \times 10^{-4}$	zero in coolest	-	Not detected in any DOs
Ni	$1-2 \times 10^{-5}$	zero in coolest	10^{-4}	

Focused spectroscopic studies of the hottest white dwarfs have begun to establish the general pattern of abundance with respect to evolutionary status. Ultraviolet observations have played an essential role by providing access to absorption lines of elements heavier than H or He. Such features are not present in optical or IR data except where photospheric abundances are unusually high. Indeed, He is also hard to detect, requiring abundances in excess of a few times 10^{-3} in the visible band. 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). 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 a small section of the high-resolution spectrum of the DA white dwarf REJ0558-373, recorded with the Space Telescope Imaging Spectrograph (STIS) onboard *HST* (figure 3),

which shows the interstellar 1260.4Å line of SiII together with photospheric NV.

A survey of 25 hot DA white dwarfs, based on IUE and HST data (Barstow et al. 2003b), shows that, while the presence or absence of heavy elements largely reflects what would be expected if radiative levitation were the supporting mechanism, the measured abundances do not match predicted values very well. These and earlier results are forcing us to confront complexities in the real physical structure of the stars. For example, it has become clear that the shape and strength of the Balmer line profiles, from which T_{eff} and $\log g$ (and, indirectly, mass) are measured, are dependent on the stellar photospheric abundances, requiring a self-consistent analysis of each individual star based on data acquired at all wavelengths (Barstow et al. 1998). Furthermore, we now have direct observational evidence (Barstow et al. 1999; Dreizler & Wolff 1999) that photospheric heavy elements are not necessarily homogeneously distributed (by depth) and that more complex stratified structures must be considered. While almost all stars hotter than $\sim 50,000\text{K}$ contain heavy elements, as expected, there is an unexplained dichotomy at lower temperatures, with some stars having apparently pure H atmospheres and others detectable quantities of heavy elements (Barstow et al. 2003b, e.g. figure 4). In many of these objects the photospheric opacity does not reveal itself in EUV photometric or spectroscopic observations, implying that the observed material resides in a thin layer in the uppermost region of the photosphere (see Holberg et al. 1999, Barstow et al. 2003b). The effect of this stratification can be observed directly with high resolution UV spectroscopy. Figure 5 shows the HST/STIS spectrum of the white dwarf REJ1032+532, compared to that predicted by a homogeneous model stellar atmosphere. The NV line profiles in the model have significantly broader wings than are observed, while a stratified model (not shown) gives a much better match to the data.

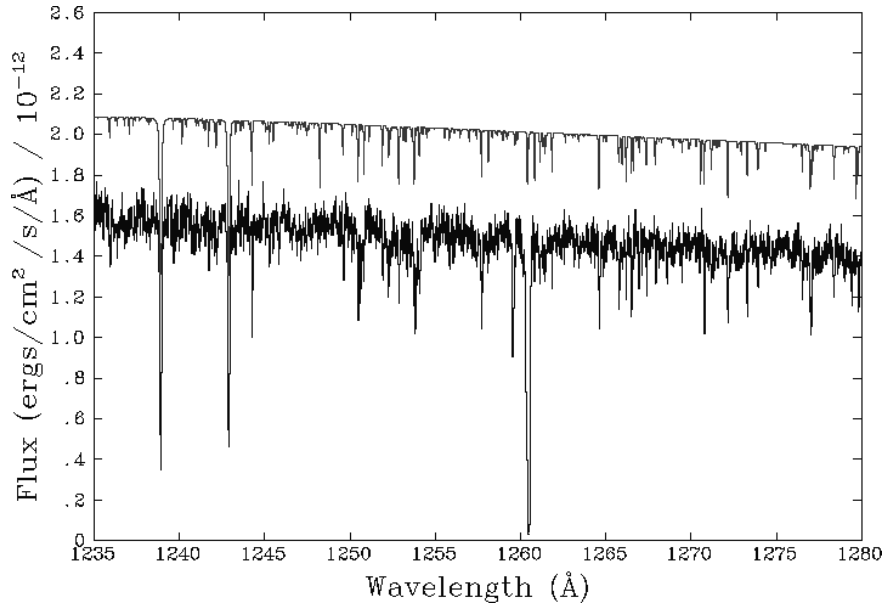


Figure 3. 1230Å to 1280Å region of the STIS spectrum of REJ0558-373, showing photospheric absorption lines of NV (1238.821/1242.804Å) and large numbers of Ni lines. The best-fit synthetic spectrum is shown offset for clarity. The strong line near 1260Å, present in the observation but not in the model, is interstellar SiII (from Barstow et al. 2003b).

Recently, important progress has been made in incorporating radiative levitation and diffusion self-consistently into the atmosphere calculations (Dreizler & Wolff 1999; Schuh et al. 2002). This work reconciles the overall spectral distribution across the soft X-ray, EUV and far-UV bands with the models (a problem with homogeneously distributed elements) and explains the level of stratification inferred for various elements. However, the abundance predictions do not match observations for the known gravity of each star observed, and agreement requires a higher surface gravity than allowed by the optical data. In particular, we cannot account for the large observed compositional differences between stars with identical temperature and surface gravity.

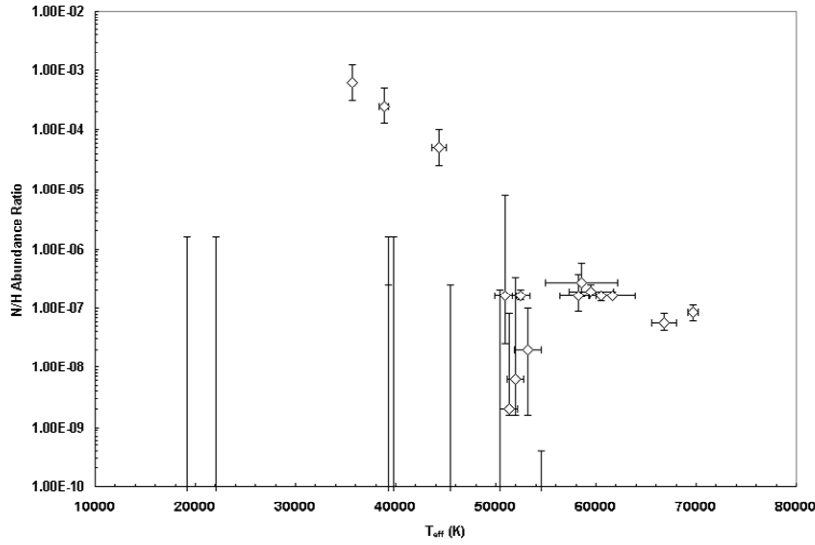


Figure 4. Measured abundances of nitrogen (number ratio with respect to hydrogen) as a function of T_{eff} for a sample of 25 DA white dwarfs (from Barstow et al. 2003b).

In almost all the hot DA white dwarfs observed, the high ionization resonance lines arising from photospheric heavy elements have blue-shifted components, indicating that there is some circumstellar gas present (Bannister et al. 2003). Whether or not this material is a remnant of the planetary nebula or due to ongoing mass-loss is unresolved. This has important consequences for our basic understanding of stellar composition. The effects of mass-loss, in the form of weak winds ejecting material into the local ISM, and direct accretion of material from the ISM are likely to be of great importance in providing a plausible framework that can explain measured abundances.

Hot He-rich DO white dwarfs are the progeny of stars which constitute an interesting spectral class. Much of the detailed physics involved in studying their atmospheres is similar to that of the DA white dwarfs. However, the levitation of heavy elements in these objects is far from understood. The DO progenitors are the so-called PG1159 stars, hot hydrogen-deficient objects, some of which represent the hottest white dwarfs known, while others are still burning helium in a shell.

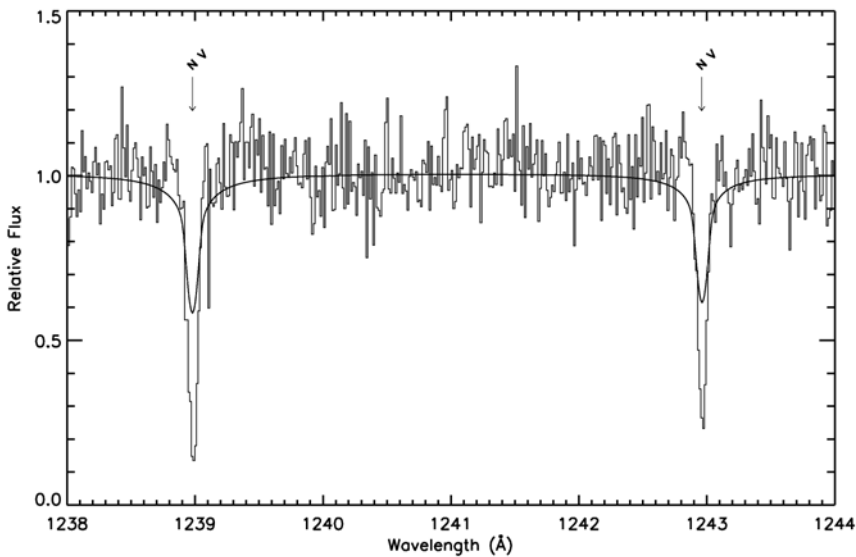


Figure 5. The STIS E140M spectrum of REJ1032+532 in the region of the N V resonance doublet (histogram), compared to the predicted line profiles from a homogeneous model atmosphere calculation (from Holberg et al. 1999).

Optical and UV spectral analyses have shown that the effective temperatures of PG1159 stars range between 75000 K and 200000 K and the derived surface gravities are between $\log g=5.5$ and 8 (Werner 2001). They are probably the outcome of a late helium-shell flash, a phenomenon that drives the fast evolutionary rates of three well-known objects (FG Sge, Sakurai's object, V605 Aql). Flash-induced envelope mixing produces a H-deficient stellar surface (Herwig et al. 1999). The He-shell flash transforms the star back to an AGB star ("born-again AGB star") and the subsequent, second post-AGB evolution explains the existence of Wolf-Rayet central stars of planetary nebulae (spectral type [WC]) and their successors, the PG1159 stars. The photospheric composition then essentially reflects that of the region between the H- and He-burning shells in the precursor AGB star. It is dominated by He, C, and O. Typical values are He=33%, C=50%, O=17% (by mass), however, a considerable spread of abundance patterns is observed, pointing to complicated processes in the stellar interiors. Few stars show traces of nitrogen (1%) or considerable amounts of residual hydrogen (about 25%).

PG1159 stars provide the unique possibility of studying the chemistry in the intershell region between the H- and He-burning shells that is created after complicated and still poorly understood burning and mixing processes during the AGB phase. Usually the intershell material remains hidden within

the stellar interior. During the third dredge-up on the AGB, however, intershell material can get mixed into the convective surface layer and appears on the stellar surface, though in rather diluted abundances. Nevertheless, this process defines the role of AGB stars as contributors of nucleary processed matter to the Galaxy. The motivation to study PG1159 stars is based on the fact that these objects *directly* display their intershell matter. It can be expected that gravitational settling is not affecting the composition, because of ongoing mass-loss and convective motions. However, the quantitative interpretation of the abundance analyses is still premature because evolutionary calculations through a final He-shell flash including a full nuclear network are not available, yet.

High-resolution UV spectroscopy was crucial in making surprising discoveries which provide essential constraints to calibrate theoretical modeling of stellar evolution. Generally, UV spectra of PG1159 stars show only few photospheric (absorption) lines, mainly from He II, C IV, O VI, and Ne VII. Some of them display shallow N V lines and in many of them we see sulfur. The S VI 933/944 Å doublet in K1-16, for example, suggests a solar abundance, what is in line with the expectation that S is not affected by nuclear processes. Silicon was also identified in some objects (Reiff et al. 2005), but detailed abundance analyses remain to be done.

A very surprising result of UV spectroscopy was the detection of a significant iron deficiency (1-2 dex) in the three best studied PG1159 stars (Miksa et al. 2002). Obviously, iron was transformed to heavier elements in the intershell region of the AGB star by n-captures from the neutron source $^{13}\text{C}(\alpha, n)^{16}\text{O}$ (Herwig et al. 2003). Subsequently, several other studies have also revealed an iron-deficiency in [WC]-type central stars, which matches our picture that these stars are immediate PG1159 star progenitors. Another important result was accomplished by the identification of one of the strongest absorption lines seen in FUSE spectra of most PG1159 stars, located at 973.3 Å. It is a Ne VII line (figure 6) that allowed us to assess the neon abundance in a large sample of objects (Werner et al. 2004). It turns out that neon is strongly overabundant, (2%, i.e., 20 times solar). This result clearly confirms the idea that PG1159 stars indeed exhibit intershell matter. Neon is produced in the He-burning environment by two α -captures of nitrogen, which itself resulted from previous CNO burning: $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(e^+ \nu)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$.

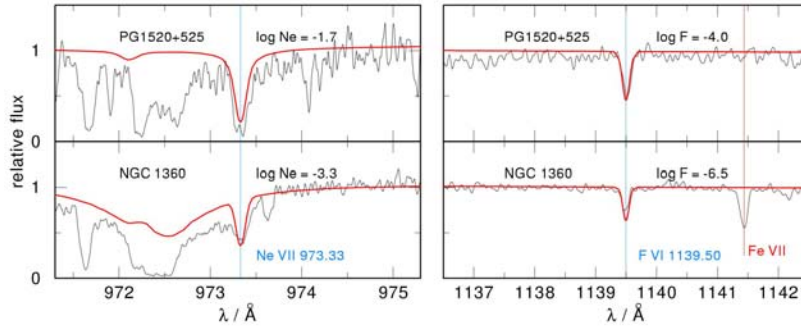


Figure 6. Discovery of a neon line (left panels) and a fluorine line (right panels) in the hydrogen-deficient PG1159-type central star PG1520+525 (top panels) and in the hydrogen-normal central star of NGC 1360 (bottom panels). The neon and fluorine abundances in the PG1159 star (given as mass fractions in the panels) are strongly enhanced, namely 20 times and 250 times solar, respectively, whereas they are solar in NGC 1360. Note the strong Fe VII line (not included in the models) at 1141.4Å in NGC 1360, which indicates a solar iron abundance (Hoffmann et al. 2005). It is not detectable in the PG1159 star, probably due to a subsolar Fe abundance (Werner et al. 2004).

There are still many photospheric lines in UV spectra of PG1159 stars which remain unidentified. Some of them may stem from yet unknown Ne VII lines, or even of elements which have not been detected in these stars at all. The latest identification is that of a feature at 1139.5Å, which appears rather strong in some objects. It is a line from highly ionized fluorine (figure 6) and large overabundances (up to 250 times solar) were derived for a number of PG1159 stars. This line was also identified in “normal” hydrogen-dominated central stars and, in contrast, solar fluorine abundances were found (Werner et al. 2005). This again is a clear proof that we see intershell matter on PG1159 stars. According to recent calculations by Lugaro et al. (2004), their stellar models show an effective fluorine production and storage in the intershell, leading to abundances that are comparable to the observed PG1159 abundances of fluorine. The general problem for fluorine production is that ^{19}F , the only stable F isotope, is rather fragile and readily destroyed in hot stellar interiors by hydrogen via $^{19}\text{F}(p,\alpha)^{16}\text{O}$ and helium via $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$. The nucleosynthesis path for F production in He-burning environments of AGB and Wolf-Rayet stars is $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(p,\alpha)^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$.

All this underlines that AGB stars which dredge up material from the intershell are contributing to the Galactic fluorine content (together with Wolf-Rayet stars and type II SNe). This is completely in line with the detected fluorine overabundances (up to 30 times solar) found from IR spectra in AGB stars (Jorissen et al. 1992). To what extent PG1159 stars themselves return F to the ISM remains to be estimated. The life time of a

born-again AGB star is short in comparison to a usual AGB star, however, the fluorine fraction in the mass lost by a wind of the former is much higher.

2.2 White dwarf masses and radii and the role of UV imaging observations

Two of the most important physical parameters that can be measured for any star are the mass and radius. They determine the surface gravity by the relation $g=GM/R^2$. Hence, if $\log g$ is measured the mass can be calculated provided the stellar radius is known. One outcome of Chandrasekhar's original work on the structure of white dwarfs was the relationship between mass and radius, arising from the physical properties of degenerate matter. Further theoretical work yielded the Hamada-Salpeter zero-temperature mass-radius relation (Hamada and Salpeter 1961). However, white dwarfs do not have zero temperature, indeed many are very hot. Hence, the Hamada-Salpeter relation is only a limiting case and the effects of finite temperature need to be taken into account. Evolutionary calculations, where the radius of a white dwarf of given mass decreases as the star cools, have been carried out by Wood (1992, 1995), Blöcker (1995) Blöcker et al. (1997) and others.

Measurements of the surface gravity of samples of white dwarfs show that the distribution of $\log g$ values and, therefore, of mass is very narrow (e.g. Bergeron et al. 1992; Napiwotzki et al. 1999), with a peak mass of $\sim 0.6M_{\odot}$. This is a direct consequence of the evolution of single stars, with masses from $1M_{\odot}$ up to $\sim 8M_{\odot}$. While the details of the relationship between the initial mass of the progenitor star and the final white dwarf mass are not particularly well understood, it is clear that the small dispersion in the white dwarf masses is related to a similarly small range of stellar core masses and the fact that most of the outer stellar envelope is expelled through several phases of mass loss along the AGB. Importantly, any white dwarf with masses outside the approximate range $0.4-1.0M_{\odot}$ cannot arise from single star evolution and must have an origin in a binary, where mass exchange has taken place.

The basic model of the white dwarf mass-radius relation, is often used to derive masses from the spectroscopic measurements of effective temperature and surface gravity (e.g. Bergeron et al. 1992; Napiwotzki et al 1999). While this is not in serious doubt, opportunities for direct observational tests of the work are rare. This is particularly true of models that take into account the finite stellar temperature and details of the core/envelope structure, discussed above. Varying the assumed input parameters in these models can lead to quite subtle, but important differences in the model predictions. To test these

requires independent measurements of white dwarf mass, which can be compared with the spectroscopic results. Such information can be obtained spectroscopically by measuring the gravitational redshift of absorption lines in the white dwarf atmosphere ($V_{\text{gr}} [\text{km s}^{-1}] = 0.636M/R$, M & R in Solar units), but this is only possible if the systemic radial velocity is known as a reference point. Generally, this is only the case if the white dwarf is part of a binary system and then there is also the possibility of obtaining independent dynamical information on the white dwarf mass from the system orbital parameters. An additional important constraint is knowledge of the stellar distance.

The four best white dwarf mass determinations, where we have the most complete and accurate information, are for 40 Eri B, Procyon B, V471 Tauri B and Sirius B, where we can combine the assembled data with the *Hipparcos* parallax to test the mass radius relation (figure 7). While there is good agreement between the observation and theory, there nevertheless remains a high degree of uncertainty in the mass determinations. As a result, for example, it is not possible to distinguish between different models, such as those with “thin” or “thick” H envelopes.

We have such complete data (dynamical masses, gravitational redshifts and accurate parallaxes) for only a very few white dwarfs. Therefore, it is important to extend the sample of white dwarfs for which we have to more objects and, possibly, explore a wider range of masses and temperatures. The role of direct imaging in the UV as means of discovering new systems is particularly important. For example, a major result of the EUV sky surveys was the discovery of many unresolved binary systems containing white dwarfs and companion spectral types ranging from A to K (e.g. Barstow et al. 1994; Burleigh, Barstow & Fleming 1997; Vennes, Christian & Thorstensen 1998). In visible light the presence of a companion of spectral type earlier than mid-K will swamp the signature of the white dwarf making it undetectable. In the EUV, where the companion flux is generally negligible, 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.

The large difference in the visual magnitudes makes these systems generally impossible to resolve with ground-based observations. However, in the UV where the contrast is far better it is possible to measure their separations, or at least provide improved constraints. HST Wide Field Planetary Camera 2 images of 18 binary systems have resolved 9 objects (Barstow et al. 2001a). Figure 8 shows one of the most interesting examples, 56 Per, a known binary in which each component has been resolved into a pair, making it a quadruple star system. The white dwarf is a companion to 56 Per A and is labeled 56 Per Ab in the image. At a distance of 42pc, the

measured 0.39 arcsec separation indicates a binary period of ~ 50 years for the Aa/Ab system. Therefore, the orbital motion of the two stars should be readily apparent with repeated exposures on timescales $\sim 1-2$ years, from which a dynamical white dwarf mass can ultimately be obtained. This is clearly demonstrated in figure 8 which shows a zoomed view of the Aa/Ab pair from the main image and, on a similar, scale a second image obtained ~ 18 months after the first. Continued monitoring of systems like 56 Per will eventually yield the orbital parameters and dynamical determinations of the component masses. This requires continued access to UV imaging.

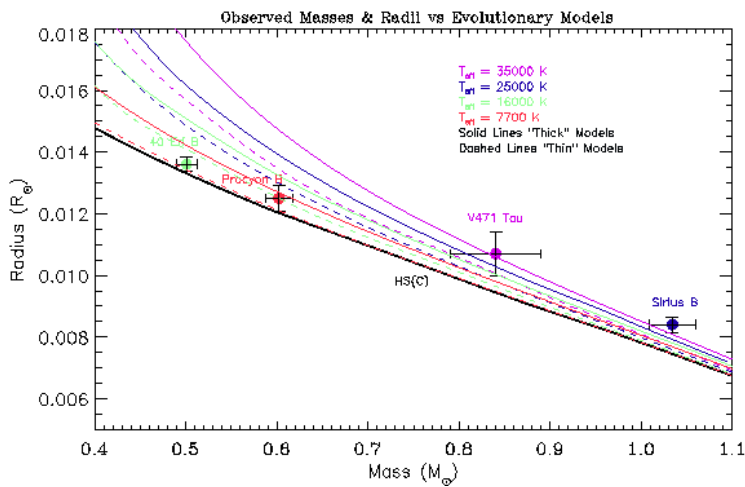


Figure 7. Comparison of mass estimates for 40 Eri B, Procyon B, V471 Tau B and Sirius B with the evolutionary models of Wood (1995), displayed at various temperatures and with “thin” and “thick” H envelopes. The solid limiting curve represents the Hamada-Salpeter zero temperature relation for a carbon core (figure produced by Jay Holberg).

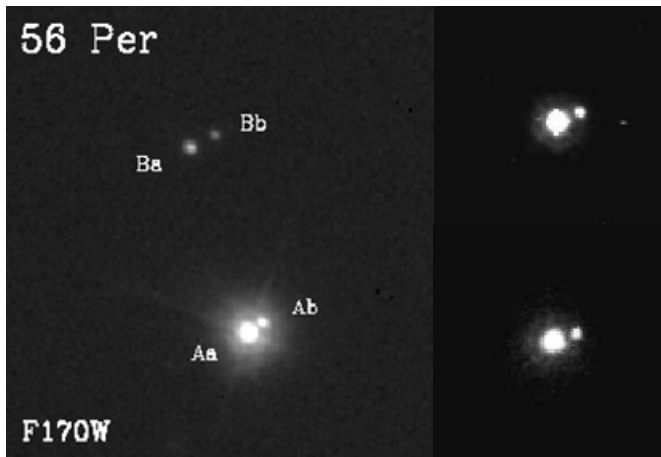


Figure 8. Wide Field Planetary Camera image of the binary 56 Per, where each component (A & B) is itself resolved into a pair (left). (right) Successive images of the Aa/Ab pair taken ~18 months apart clearly show the orbital motion of the system.

3. PROBLEMS OF WHITE DWARF EVOLUTION

Clearly significant progress has been made in the study of white dwarf stars through ultraviolet observations. However, these have not yet given us access to a detailed understanding of the important physics because they have been limited in scope. First the total number of objects studied with the necessary spectral resolution and signal-to-noise is small. Therefore, we do not know how representative of the general population individual objects or small groups of objects may be. This is exacerbated by the fact that there are strong selection effects present within the existing samples. For example, most hot DA white dwarfs have been observed because of expectations that significant quantities of heavy elements were present in their photospheres, and, as a result are mostly stars with temperatures above 50,000K. Therefore, a number of significant questions regarding the evolution of white dwarfs remain to be solved:

- What is the origin of the DO-DB gap and the relationship between the H- and He-rich white dwarf branches? For example, do DO white dwarfs appear as DAs through float up of residual H?
- What mechanisms determine the compositions of the DA white dwarfs as they cool? Radiative levitation and gravitational

diffusion are clearly important, but why do some stars of the same apparent temperature and gravity have widely differing compositions? Is accretion (from the ISM or a companion) an important mechanism? Do the abundance differences reflect differences in progenitor composition/prior evolution of the progenitor?

- What are the metal abundances in the He-rich white dwarfs? Are the PG1159 stars and DOs part of a single sequence or do they represent the separate progenitor evolutionary paths. Do all hot He-rich white dwarfs eventually become DBs?
- What is the 3-D structure of the local ISM? How do white dwarfs interact with it and exchange material. Does mass-loss continue beyond the planetary nebula phase? Is apparently circumstellar material detected in some of the hottest white dwarfs evidence of such mass-loss or merely the residual signature of PN material?
- What is the initial-final mass relation for both H- and He-rich white dwarfs and what is the upper limit on the possible progenitor mass? Does the theoretical mass-radius relation for white dwarfs stand up to close scrutiny? Do the most massive white dwarfs have exotic core compositions beyond the C/O product of helium burning?

All white dwarfs that have ever been studied in the UV reside within our own galaxy and must have emerged from stellar populations with different ages and environments. To solve the outstanding problem and make significant further progress in the study of white dwarfs requires a substantial enlargement of the sample, to properly examine the full range of temperatures, gravities and possible environmental conditions.

- Expand the number of galactic white dwarfs by a factor 10 for which high resolution/high signal-to-noise UV spectra are available.
- Increase by a factor 10 the number of binary systems with white dwarf components for which astrometric masses can be obtained.
- Be able to study uniform, co-eval populations of white dwarfs in globular clusters, the Magellanic Clouds and nearby galaxies.

4. FUTURE WHITE DWARF RESEARCH IN THE FAR ULTRAVIOLET

4.1 White dwarfs in the galaxy

A large-scale survey of the hot white dwarfs in the galaxy will provide observations which can simultaneously address two broad areas of astrophysics: the local interstellar medium, its composition, ionization and structure; and the degenerate stars, their origin and evolutionary history as well as the detailed modeling of critical physical processes in their photospheres. The primary broad scientific objectives would be:

- Define the evolutionary history of the hot white dwarf stars through detailed modeling of their photospheric composition and structure.
- Study the occurrence of circumstellar material surrounding the white dwarfs and their interaction with the ISM.
- Map out the 3-D structure of the local interstellar medium (LISM) and determine its composition and ionization state.
- Use the morphology of the LISM and the estimated elemental diffusion (gravitational settling) times for white dwarf photospheres to provide a crucial test of the ability of interstellar accretion processes to explain abundance patterns in cooler white dwarfs.
- Identify and characterise new non-interacting white dwarf binary systems.
- Carry out a long term astrometric programme to determine white dwarf masses.

4.1.1 White dwarf composition

Although there is a qualitative understanding of how the abundance patterns vary across the hot white dwarf population, the detailed picture is quite confused and some very important questions need to be answered. The observed abundances will reflect the balance of several processes, including mass loss, radiative levitation, gravitational settling and accretion from the LISM. DA white dwarfs have been selected for follow-up UV studies mainly on the basis of their EUV fluxes, low values indicating the presence of

photospheric metals. Thus, the existing observational sample is strongly biased towards such stars. Few stars having apparently pure-H atmospheres have been observed. In addition, the existing data are highly non-uniform in wavelength coverage, signal-to-noise and spectral resolution, which yield non-uniform detection criteria for spectral features. Therefore, the apparent absence of metals may be as much a function of the weak detection limits and too few observations of appropriate stars than a real lack of metals. Hence, we have no idea whether the small group of heavy element-rich stars (see figure 4) are typical of the cooler group below 50,000K, or whether they are truly unusual. Are there really two distinct groups of stars with and without metals? Or, is this an artifact of the small sample and in reality compositions range between the two extremes? It is hard to explain why any DA would have no heavy elements at all. Thus, establishing the frequency of pure-H envelopes is an important component of providing an answer to this problem. In particular, we need to properly sample the lower temperature white dwarfs, especially within the 20,000 – 35,000 K region, which are not well represented in earlier studies and existing data.

PG1159 stars are rare objects, about 40 are known. Only a few of them have been studied in detail in the UV. 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 DA and DO 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.

4.1.2 Circumstellar material

What appears to be circumstellar gas has been detected in most of the white dwarfs observed in high resolution HST spectra. What is the nature of this material? Is it present in all white dwarfs with photospheric metals or is there a temperature cut-off? A lower temperature (greater age) limit would imply that we are looking at a nebular remnant, which disperses with time. Apportioning unresolved lines to circumstellar and photospheric components for the whole sample of stars is essential for correct atmospheric abundance measurements. For example, when observed by HST, the photospheric C

abundance of G191-B2B was really found to be a factor 5 lower than the value obtained by IUE (see Barstow et al. 2003b).

4.1.3 3-D structure of the ISM

High-resolution spectra of LISM absorption lines from abundant ionic species (C II, C II*, N I, O I, Si II-III, S II, Fe II, Zn II, Cr II, MgI-II) will provide several quantitative measurements of nearby interstellar gas. We will be able to measure the line-of-sight densities and composition of the LISM, derive velocities, to probe the gas kinematics, and determine the ionization of the gas. It is important that the chosen white dwarf sample includes enough different lines-of-sight to provide a true 3-D picture. The high resolution of the echelle data for these white dwarfs will be instrumental in resolving the inherent complex velocity structure seen even in the very local gas within 15 pc (e.g. Lallement et al. 1986, Sahu et al. 2000), and provide the means to obtain reliable ionic column densities for the individual velocity components in the LISM. Does a single bulk velocity vector fit all the lines of sight through a particular cloud, or is the gas fragmented into filamentary structures more characteristic of low velocity shocks? An adequate sample of white dwarfs will provide extensive sampling for distances out to 50–100 parsecs.

The problem of the variability of the D/H ratio in the LISM appears to be on the way to resolution, but there are many details that still need to be addressed (Moos et al. 2002; Sahu et al. 2002). Specifically, obtaining reliable D/H ratios is not easy. Extreme care must be taken in data reduction and calibration and accounting for multiple velocity components along the line of sight. One must look at the heavy ions to determine what velocities are present, because they can be easily masked in the intrinsically broader profiles of light H I and D I.

Column densities, measured from high resolution far-UV spectra, will be useful for determining chemical abundances in the LISM clouds. Comparing the LISM abundances with those of Savage & Sembach (1996) would determine if the cloud has abundances and depletions similar to warm partially ionized gas observed in the more distant ISM.

Examination of the white dwarf data has revealed an unrecognized problem, namely the frequent occurrence of interstellar Si III λ 1206 in many lines-of-sight. This is difficult to reconcile, since this ion has a high charge-exchange rate with neutral hydrogen. Its presence suggests substantial amounts of warm ionized gas have been unaccounted for in the LISM. It is intriguing that low ionization species seen in G191-B2B (Sahu et al. 2000) are close to the velocity of interstellar Si III. An examination of S II/H I and C II/H I ratios compared to those found for the LIC at 19.3 km/s, suggests

the H ionization fraction is near 0.7 for the 8.6 km/s gas. Another problem is that the shortward “circumstellar” components of C IV in G191-B2B also have a close velocity coincidence with the Si III and the 8.6 km/s low ionization species. Photoionization calculations find no way to have all of these ions in the same gas. High resolution ($R \sim 50,000$ - $100,000$) data for other sightlines should be able to determine the origin of the Si III.

4.1.4 Interstellar accretion

For the cooler DAZ stars ($6,000 < T_{\text{eff}} < 12,000 \text{K}$) the existence of heavy elements such as Ca, Mg and Fe has traditionally been attributed to interstellar accretion (e.g. Dupuis et al. 1993). For DA stars at intermediate temperatures ($20,000 \text{K} < T_{\text{eff}} < 25,000 \text{K}$) the presence of heavy elements poses a dilemma.

In DAZ stars the retention times for high Z elements in the observable photospheres, while substantial (i.e. $\sim 10^4$ yr), remains short compared to the thermal (cooling) time scale of the photospheres. It is possible to imagine that DAZ white dwarfs represent stars passing through, or recently passed through, a diffuse interstellar cloud and having accreted heavy elements. As long as the fraction of DAZ stars remained small it was possible to entertain such views since the number of these stars were the result of infrequent encounters between diffuse clouds and white dwarfs. However, Zuckerman et al. (2003) have shown that the occurrence of cool DAZ stars approaches 25%, which is well in excess of the fraction that might be attributed to ISM accretion. Likewise, other possible explanations involving intrinsically rare events such as comet impacts are equally untenable. Yet, Zuckerman et al. were able to demonstrate a correlation between the presence of low mass companions and the DAZ phenomena.

Thus, some form of ongoing circumstellar accretion appears necessary to explain the bulk of the DAZ stars. Typically the DAZ stars are too faint and too cool to search for the UV presence of heavy elements. However, it is possible to investigate the DAZ phenomena in a hotter class of DA stars at UV wavelengths. In earlier work, there has been little evaluation of the actual conditions of the interstellar medium along the lines of sight to the known DAZ white dwarfs. Nevertheless, knowledge of the morphology of the LISM is necessary to evaluate and critically test the accretion model, since the local distribution of interstellar clouds directly determines the efficiency of interstellar accretion. In general, interstellar features can be distinguished from stellar features on the basis of velocity and the presence of excited fine-structure lines. We can use the several density sensitive

indicators to probe the gas phase density of any accreting medium in the vicinity of the star. For example, an important diagnostic tool is the presence of the collisionally excited C II* $\lambda 1335$ line, from which estimates of the ambient electron density can be determined (Holberg et al. 1999). The presence of ground state and excited C I lines indicate the presence of a medium, which is sufficiently dense to be effectively self-shielding with respect to UV radiation shortward of the C I ionization limit. Even if excited lines are not detected, the mere presence of significant column density, as evidenced by strong IS absorption is important.

4.1.5 White dwarfs in binaries

Many new white dwarf binaries with main sequence companions are being discovered by the GALEX UV sky survey. In these systems the presence of the companion obscures the white dwarf at long wavelengths. Hence, for these objects, far-UV spectroscopy is essential to determine the basic physical parameters of the white dwarfs. For example, temperature and surface gravity can be determined from model atmosphere analyses of the hydrogen Lyman series lines (e.g. Barstow et al. 2003a), while photospheric composition can be determined from any heavy element lines present, as discussed above. Since many of the brighter companions will be members of the Hipparcos catalogue, and therefore have well-determined distances, the sample of binary white dwarfs can be used to study the mass-radius relation and the initial-final mass relation. The latter is extremely uncertain and is important in validating potential models for type Ia supernovae progenitors.

Only about half a dozen of the known binary systems have sufficiently short orbital periods for astrometric information to be obtained on sensible timescale. A subset of any newly discovered binaries will also fall into this group. Thus far astrometric orbits and directly determined masses are only available for three white dwarfs, Sirius B, 40 Eri B and Procyon B. All other WD masses are based on gravitational redshifts or spectroscopic $\log g$ determinations, which require theory-dependent assumptions, or on generally uncertain measurements of interacting close binaries. Knowledge of the masses is, in turn, vital in testing the theory of WD structure (e.g., the mass-radius-core composition relation), understanding the history of star formation in the solar neighbourhood, and setting limits on the age of the Galaxy.

4.2 White dwarfs outside the galactic disk

Imaging surveys of white dwarfs have been carried out in globular clusters, but most of the individual stars are only characterized by broad band photometry. This provides almost no information on the white dwarf masses and weak temperature constraints. Knowledge of the white dwarf masses is essential for determining the cooling age of individual stars and interpretation of the observed luminosity functions. Study of white dwarfs in globular clusters yields a number of advantages compared to the galactic population.

- All the stars lie at the same, known distance.
- The stars are co-eval.
- The stars are all descendents of a uniform population.

Knowledge of white dwarf temperature and gravity (and, therefore mass) in globular clusters will provide a direct calibration of the initial-final mass relation. In particular, the upper limit of the progenitor mass will be reliably established for the first time, which has important implications for models of SNIa systems. In the galaxy most of white dwarf progenitors for stars in the disk will probably have had population I metallicities. With all progenitors in a globular cluster being population II, the metallicity and, as result, their prior evolution will be well determined. Since post-main sequence evolution is affected by stellar metallicity, in particular in establishing core He burning, we would expect the resulting white dwarf population to have different characteristics to those in the galaxy.

5. THE FUTURE NEED FOR FAR UV MISSIONS

In section 4 we have outlined in detail the scientific goals for future studies of white dwarfs. This wealth of science is only possible through a programme of observations in the far ultraviolet waveband. The principal need is for high resolution spectroscopy, but diffraction limited imaging is also of importance. During the past 15 years, these joint capabilities have been provided by the Hubble Space Telescope, following on from 18 years of operations with IUE. Although of great importance, the relatively small aperture of IUE limited high resolution studies of white dwarfs to a handful of the brightest examples. Using a variety of instruments HST has provided us with a flow of high signal-to-noise and resolution ($R \sim 50,000-100,000$) spectra of white dwarfs and the first diffraction limited imaging of white dwarfs in binary systems. However, HST time has had to be shared across a wider range of wavelengths including the visible and IR bands. Since 1999,

this has been complemented by the availability of the FUSE mission, working down to shorter wavelengths than HST (912Å cf. 1050Å), but with more modest spectral resolution ($R \sim 20,000$). Sadly, the STIS instrument on HST failed in August 2004, ending the UV spectroscopic capability for the foreseeable future. Also, FUSE is probably nearing the end of its lifetime. While operations have been maintained through the heroic efforts of the FUSE team, continued degradation of its attitude control system (through gyroscope and reaction wheel failures) will eventually lead to its termination. Within current mission plans access to far UV spectroscopy is likely to end soon with no prospect of any replacement. It is astounding that, at a time when GALEX is opening up the discovery space in UV astronomy in a major way, that we will have no way of adequately following up its surveys.

The current situation regarding continued access to the far UV is full of complex programmatic and political issues which are making it difficult to plan ahead. For example, a shuttle mission to HST could carry out the installation of the Cosmic Origins Spectrograph (COS), which will operate in the far UV with $R \sim 20,000$, and (possibly) repair STIS. However, this is currently ruled out on safety grounds. A robotic alternative is being studied as an extension to the attachment of the de-orbit module (which must be carried out to control HST re-entry). If successful, any HST repair/servicing would resurrect the far UV capability and extend the mission lifetime to ~ 2012 . Alternatively, a new mission called the Hubble Origins Probe (HOP) is being studied as a way of placing COS into orbit (with the Wide Field Camera 3) using a new telescope and spacecraft.

Whatever is finally decided regarding HST and COS, the result will not be ideal. HST operations will still have a limited life and COS does not operate at the spectral resolution needed for the work proposed here. Furthermore, with its multi-waveband capability, HST has never provided as much UV observing time as is really needed. Therefore, there remains the problem of future provision for far UV spectroscopy. This can be divided into two: the replacement of 2-m class access to high resolution spectroscopy for the ~ 2010 -2015 period and the long term provision of a larger scale (4 to 6-m) facility beyond 2015.

There is an urgent need to provide a dedicated far UV mission to follow HST. To achieve this in a relatively short timescale requires the use of existing technology, but within these constraints it should be possible to provide an instrument with enhanced sensitivity through avoidance of complex relay optics and improved (but still current) 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, provided the following technical capabilities are achieved:

- Galactic white dwarf spectroscopic survey
 - $\lambda\lambda\sim 912\text{-}3000\text{\AA}$, $R\sim 50,000\text{-}100,000$, $V_{\text{lim}}\sim 18$
- Astrometric white dwarf masses
 - Diffraction limited imaging to $V\sim 18$

The World Space Observatory (WSO, see e.g. Barstow et al. 2003c) is an example of a mission that could meet these aims on the necessary timescale. Plans for WSO have been developed over several years and phase A studies of the concept and key instruments have been carried out. There is a good prospect that this mission will go ahead under the leadership of the Russian Space Agency, with contributions from many other countries.

In contrast, provision of a large (4 to 6-m) UV telescope is not in the plans of any space agency. Some US studies have been carried out on a large UV/optical space telescope but no concrete plans have yet emerged. However, as agencies begin to plan their programmes for the time-frame beyond 2015, it is absolutely essential that these should include a large UV facility. It would be preferable that such a telescope should be UV only, but it may be inevitable that this would need to be UV/optical mission on cost grounds. For white dwarf research, the key requirements are for:

- Globular cluster/Magellanic Cloud white dwarf surveys
 - Integral field spectroscopy $\lambda\lambda\sim 912\text{-}1300\text{\AA}$, $R\sim 1000$, $V_{\text{lim}}\sim 28$
 - Wide field imaging (10 arcmin) to $V\sim 35$

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