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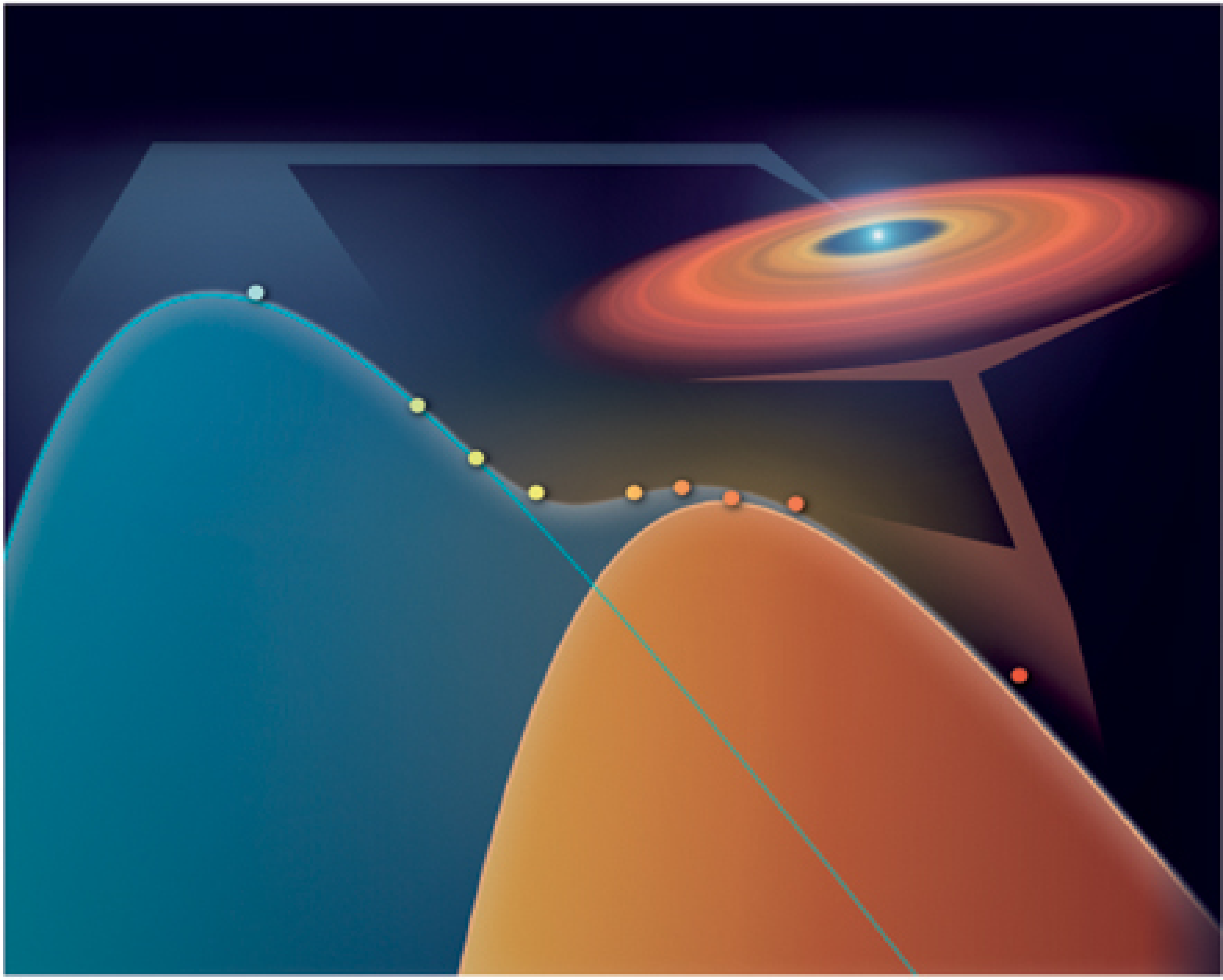

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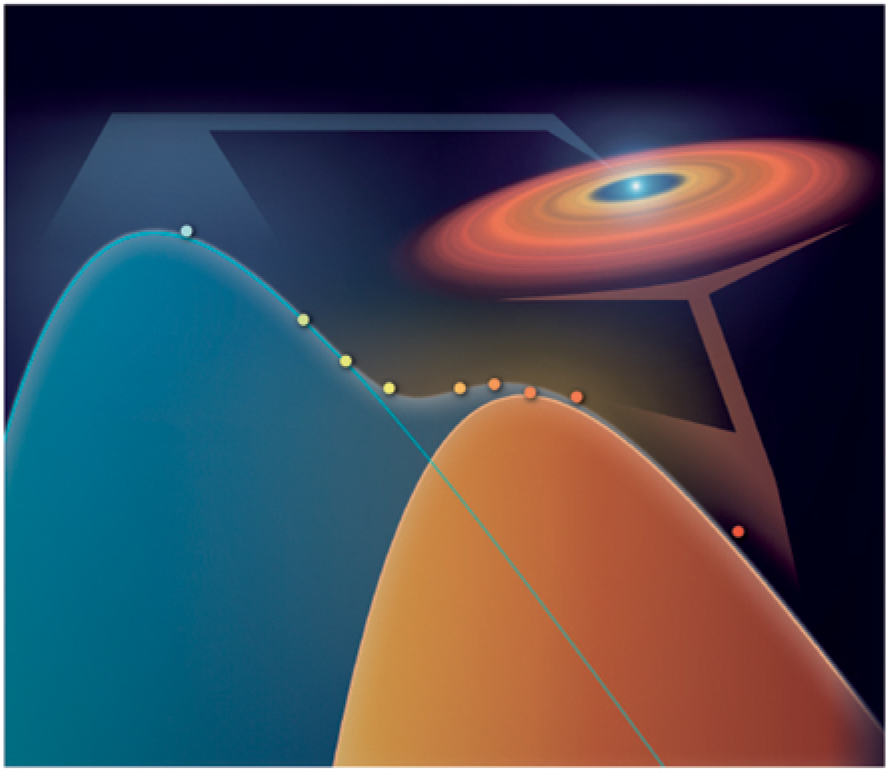

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D. W. Hoard

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Where are the stars, pristine as great ideas? Behind clouds
the heavens saturate with luminous dust…

(“Where Are The Stars Pristine” from Palladium by Alice Fulton. Copyright 1987 by Alice Fulton. Used with permission of the University of Illinois Press.)

Preface

White dwarf stars play a key role in a wide variety of astrophysically important scenarios. They not only provide a glimpse into the distant future of our own Sun, but are the evolutionary endpoints of the majority population of low mass stars in the Galaxy. As relic cores of normal stars, white dwarfs provide insights into stellar evolution, and expose material created during a stellar lifetime of nuclear burning to direct examination. Binary stars containing white dwarfs are linked to the chemical enrichment of the interstellar medium (via nova explosions), and are laboratories to probe the processes of mass transfer and accretion that power the central engines of quasars and govern the formation of stars and planetary systems. Type Ia supernovae, used as standard candles for measuring cosmological distances, are believed to result from accretion onto white dwarfs and/or white dwarf-white dwarf collisions.

In many ways, white dwarfs are relatively “simple” and well understood objects: partially crystallized balls of mostly electron-degenerate carbon and oxygen, with the mass of a sun packed into the volume of an earth.1) They do not produce any new energy, but slowly radiate away the trapped energy of billions of years of nuclear fusion. We can “listen” to the ringing of acoustic waves in their interiors, and produce physically realistic model spectra that are almost indistinguishable from the real thing. However, in recent years, new discoveries have made it clear that the immediate environments of white dwarfs, from their photospheres out, can be – and often are – as interesting as the white dwarfs themselves. The flotsam and detritus surrounding white dwarfs, largely undetectable or overlooked during most of the last 100 years of astronomical observations of white dwarfs, turn out to have their own tales to tell about the past, present, and future of these objects.

During approximately the last decade, advances in observational techniques and detector technology have opened up new regimes of wavelength and sensitivity to the study of white dwarfs. In particular, satellite observatories such as the Hubble and Spitzer Space Telescopes have enabled dramatic new discoveries about white dwarfs. For example, observations with Spitzer have shown that the presence of dusty debris disks around white dwarfs, which can often only be detected in the mid-infrared, is fairly common. Meanwhile, ever more sophisticated model atmosphere calculations have enabled the increasingly realistic generation of white dwarf synthetic spectra that can be used as diagnostic comparisons with observations.

The tale of Subrahmanyan Chandrasekhar is well known among those astronomers who study white dwarfs: as a 19-year-old student, on a long sea voyage to England in 1930 to begin his graduate studies at Cambridge University, he whiled away his time by modifying a theory proposed by his soon-to-be graduate advisor, the British astronomer Ralph Fowler, to include special relativistic effects. By combining quantum mechanics and Einsteinian relativity, Chandra determined that the mass of a star that can end its life as a white dwarf (and, hence, the mass of a white dwarf itself) has an upper limit, which is now named in his honor. In part for this work, Chandra was awarded the Nobel Prize in Physics in 1983 (shared with William A. Fowler) “for his theoretical studies of the physical processes of importance to the structure and evolution of the stars.”2) The preparation of this book coincided with the 100th anniversary of both the birth of Chandra and the classification of the first white dwarf, 40 Eridani B – auspicious omens for a book about white dwarf stars.

The chapters in this book will *not* present detailed treatises on the formation or internal structure of white dwarfs themselves, topics which have been extensively covered in other works (from Chandra onward). Nor will they focus on white dwarfs as members of detached or interacting binary star systems. Instead, the focus of this book is shifted somewhat away from the white dwarfs themselves, and onto the relatively new and fascinating topics of peculiar atmospheric compositions and the dust, nebulae, and (potentially) planets that surround white dwarfs. We will start in the geometrically thin, nondegenerate atmospheres of the white dwarfs and move outward into their circumstellar environs.

Acknowledgments

The cover of this book shows the spectral energy distribution of the dusty white dwarf GD 16 from the optical to the mid-infrared, illustrating the infrared excess, along with a depiction of the white dwarf and its circumstellar disk. Robert Hurt (Spitzer Science Center) kindly made some minor modifications to the original image from the Spitzer press release sig09-002 by Jay Farihi[3] for use on this cover. The original image is courtesy of NASA/JPL-Caltech.

The rapid pace of advances in the understanding of white dwarf stars and their circumstellar environments, especially over the course of the last ten years, would not have been possible without the contributions of many theorists and researchers, as well as the availability of data from numerous surveys and data archives. On behalf of myself and the other authors, I would like to acknowledge the following facilities that have been of particular (although not exclusive) usefulness in exploring the atmospheres and circumstellar environments of white dwarfs as discussed in this book (listed in order by wavelength regime, from short to long):

1. The NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer, FUSE, which was operated for NASA by the Johns

Hopkins University under NASA contract NAS5-32985.

2. The NASA Galaxy Evolution Explorer, GALEX, which is operated for NASA by the California Institute of Technology under NASA contract NAS5-98034.

3. The International Ultraviolet Explorer satellite, which was a collaboration among three groups: NASA, the European Space Agency (ESA), and the United Kingdom's Science and Engineering Research Council (SERC; now called the Particle Physics and Astronomy Research Council, PPARC).

4. The NASA/ESA Hubble Space Telescope, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

5. The Digitized Sky Surveys, which were produced at the Space Telescope Science Institute under US Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions. The National Geographic Society – Palomar Observatory Sky Atlas (POSS-I) was made by the California Institute of Technology with grants from the National Geographic Society. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The UK Schmidt Telescope was operated by the Royal Observatory Edinburgh, with funding from the UK Science and Engineering Research Council (later the UK Particle Physics and Astronomy Research Council), until 1988 June, and thereafter by the Anglo-

Australian Observatory. The blue plates of the southern Sky Atlas and its Equatorial Extension (together known as the SERC-J), as well as the Equatorial Red (ER), and the Second Epoch [red] Survey (SES) were all taken with the UK Schmidt.

6. The Sloan Digital Sky Surveys, SDSS and SDSS-II. Funding for the SDSS and SDSS-II was provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS was managed by the Astrophysical Research Consortium for the Participating Institutions.

7. The Two Micron All Sky Survey, 2MASS, which was a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

8. The Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Pasadena, California, 2011

D. W. Hoard

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1) This is an extreme physical situation that was eloquently described by Arthur Stanley Eddington in a lecture transcribed in his 1927 book *Stars and Atoms* (Oxford: Clarendon Press, p. 50), as “a density much transcending our terrestrial experience” and, somewhat more pithily, “a tight squeeze”. Eddington also relates the initial reaction to the inferred physical properties of the second known white dwarf, Sirius B: “We learn about the stars by receiving and interpreting the messages which their light brings to us. The message of the Companion of

Sirius when it was decoded ran: ‘I am composed of material 3000 times denser than anything you have ever come across; a ton of my material would be a little nugget that you could put in a matchbox.’ What reply can one make to such a message? The reply which most of us made in 1914 was – ‘Shut up. Don’t talk nonsense.’”.

2) http://nobelprize.org (15 June 2011)

3) http://www.spitzer.caltech.edu/images/2054-sig09-002-Emission-from-the-White-Dwarf-System-GD-16 (9 May 2011)

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Chapter 1

Hot White Dwarfs

Edward M. Sion

1.1 Introduction

Research on hot white dwarfs during the past 30 years has greatly expanded, as many new discoveries and the new questions they raise have emerged from increasingly larger, deeper surveys conducted with multimeter class ground-based telescopes, the International Ultraviolet Explorer (IUE), the Hubble Space Telescope (HST), the Extreme Ultraviolet Explorer (EUVE), and the Far Ultraviolet Spectroscopic Explorer (FUSE). This review will focus on white dwarfs ranging in temperature from 20 000 up to 200 000 K and higher, which are the hottest white dwarf stars known. Since the mid-twentieth century, the earliest spectroscopic surveys of white dwarf candidates from the proper motion selected samples of Willem Luyten and Henry Giclas were carried out by Jesse Greenstein, Olin Eggen, James Liebert, Richard Green, and others. The selection criteria employed in many of these surveys did not reveal a large number of hot white dwarfs because the surveys lacked ultraviolet sensitivity and also missed objects with low flux levels in the optical. Nevertheless, the earliest surveys quickly revealed that white dwarfs divide into two basic composition groups with hydrogen-rich (the DA stars) and helium-rich atmospheric compositions (the DB and other non-DA stars). The origin of this dichotomy still represents a major unsolved problem in stellar evolution, although theoretical advances in late stellar evolution made starting in the 1980s, as well as advances in modeling envelope physical processes and mass loss, have shed important new light on this puzzle (Chayer *et al.*, 1995; Fontaine and Michaud, 1979; Iben, 1984; Iben *et al.*, 1983; Schoenberner, 1983; Unglaub and Bues, 1998, 2000; Vauclair *et al.*, 1979).

The spectroscopic properties of white dwarfs are determined by a host of physical processes which control and/or modify the flow of elements and, hence, surface abundances in high gravity atmospheres: convective dredge-up, mixing and dilution, accretion of gas and dust from the interstellar medium and debris disks, gravitational and thermal diffusion, radiative forces, mass loss due to wind outflow and episodic mass ejection, late nuclear shell burning and late thermal pulses, rotation, magnetic fields, and possible composition relics of prior pre-white dwarf evolutionary states. Virtually all of these processes and factors may operate in hot white dwarfs, leading to the wide variety of observed spectroscopic phenomena and spectral evolution.

The basic thrust of research on hot white dwarfs is three-fold: (i) to elucidate the evolutionary links between the white dwarfs and their pre-white dwarf progenitors, whether from the asymptotic giant branch (AGB), the extended horizontal branch, stellar mergers, or binary evolution; (ii) to understand the physics of the different envelope processes operating in hot white dwarfs as they cool; and (iii) to disentangle and elucidate the relationships between the different spectroscopic subclasses and hybrid subclasses of hot white dwarfs as spectral evolution proceeds. This includes the source of photospheric metals, the chemical species observed, and the measured surface abundances in hot degenerates.The evolutionary significance of certain observed ion species is complicated by the role of radiative forces and weak winds in levitating and ejecting elements at temperatures >20 000 K.

1.2 Remarks on the Spectroscopic Classification of Hot White Dwarfs

Before discussing the hot white dwarfs, a brief discussion of their spectroscopic classification is appropriate. The non-DA stars fall into six subclasses, including the PG 1159 stars (75 000 K<T_{eff}<200 000 K); DO (45 000 K<T_{eff}<120 000 K), and DB (12 000 K<T_{eff}<45 000 K). The remaining three subclasses, which are too cool (T_{eff}<12 000 K) to show helium, are DC (pure continuum, no lines), DQ (helium-dominated but with carbon molecular bands and/or atomic carbon dominating the optical spectrum), and DZ (helium dominated with lines of accreted metals and sometimes H). The three cool spectral subgroups, as well as the PG 1159 stars, are discussed elsewhere in this volume (see Chapters 2 and 3 by M. Kilic and P. Dufour), and are not covered here. For convenience, Table 1.1 lists the various primary white dwarf spectroscopic classification symbols, any of which can also be assigned as a secondary symbol to form hybrid spectral classes. For example, the identified classes of hot, hybrid composition degenerates are predominantly DBA, DAB, DAO, and DOA.

Table 1.1 Definition of primary spectroscopic classification symbols.

Spectral type	**Characteristics**
DA	Only Balmer lines; no He I or metals present
DB	He I lines; no H or metals present
DC	Continuous spectrum, no lines deeper than 5% in any part of the electromagnetic spectrum
DO	He II strong; He I or H present

Spectral type	**Characteristics**
DZ	Metal lines only; no H or He lines
DQ	Carbon features, either atomic or molecular in any part of the electromagnetic spectrum
P	magnetic white dwarfs with detectable polarization
H	magnetic white dwarfs without detectable polarization
X	peculiar or unclassifiable spectrum
E	emission lines are present
?	uncertain assigned classification; a colon (:) may also be used
V	optional symbol to denote variability

The DA stars are much easier to classify because the Balmer lines of hydrogen are detectable across a vast range of T_{eff}, from 4000 up to 120 000 K and higher. Figure 1.1 shows representative optical spectra of several DA white dwarfs. Hot DA stars that contain detectable helium are classified as DAO if He II is present and DAB if He I is present. Because of the importance of temperature as a direct luminosity and age indicator in white dwarfs, and the fact that white dwarfs span enormous ranges of T_{eff} (e. g., the H-rich white dwarfs span a temperature range from 4500 to 170 000 K!), a temperature index was introduced by Sion *et al.* (1983) defined as $10\times\theta_{\mathrm{eff}}$ (=50 400 K/T_{eff}). Thus, for the hot DA and non-DA stars, their spectral types can be expressed in half-integer steps as a function of temperature; for example, the DA sequence extends from DA.5, DA1, DA1.5, DA2, DA2.5, …, DA13. A DA2 star has a temperature in the range 22 400–28 800 K, while a DA2.5 has T_{eff} in the range 18 327–22 400 K. Similarly, the sequence of DB stars extends from DB2, DB2.5, DB3, DB3.5, and so on. A DB2 star has a temperature in the range 22 400–28 800 K, while a DB2.5 has T_{eff} in the range 18 327–22 400 K. Figure 1.2 shows representative optical spectra of several DB white dwarfs. For the hot DA stars (T_{eff}>20 000 K), the temperature index ranges are given in Table 1.2. A similar range of temperature index is defined for the hot non-DA stars.

Figure 1.1 Spectra and model fits of three hot DA white dwarfs, (a) G191-B2B, (b) GD 53, and (c) GD 71, that are used as primary flux calibration standards for HST. Absorption lines of the hydrogen Balmer series are prominent in the spectrum of each star. The fluxes are in f_λ units, normalized to have a median value of one in the range 3850–5400 Å (a–c). Panel (d) shows the model fit for GD 71 when the continuum shape is rectified. Note that the spectra and model fits are essentially indistinguishable in the plots.

From Allende Prieto et al. (2009), reproduced with the permission of Wiley-Blackwell.

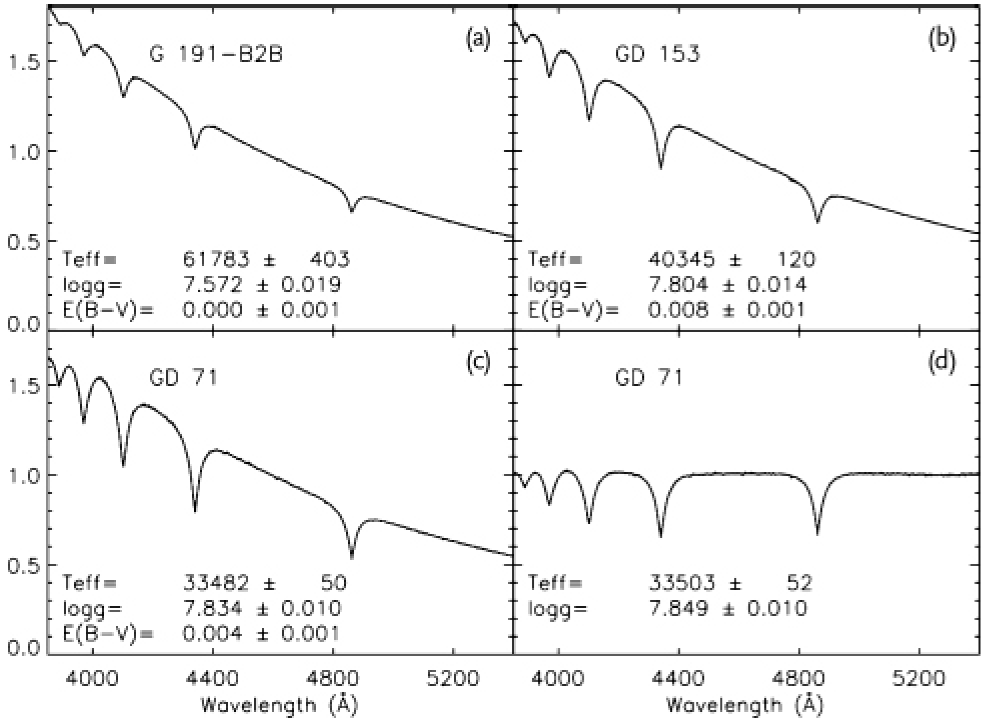

Figure 1.2 Spectra and model fits (smooth lines) of six hot DB white dwarfs, with temperatures in the range 30 000–45 000 K. The prominent absorption features in each spectrum are lines of He I.

From Eisenstein et al. (2006b), reproduced by permission of the AAS.

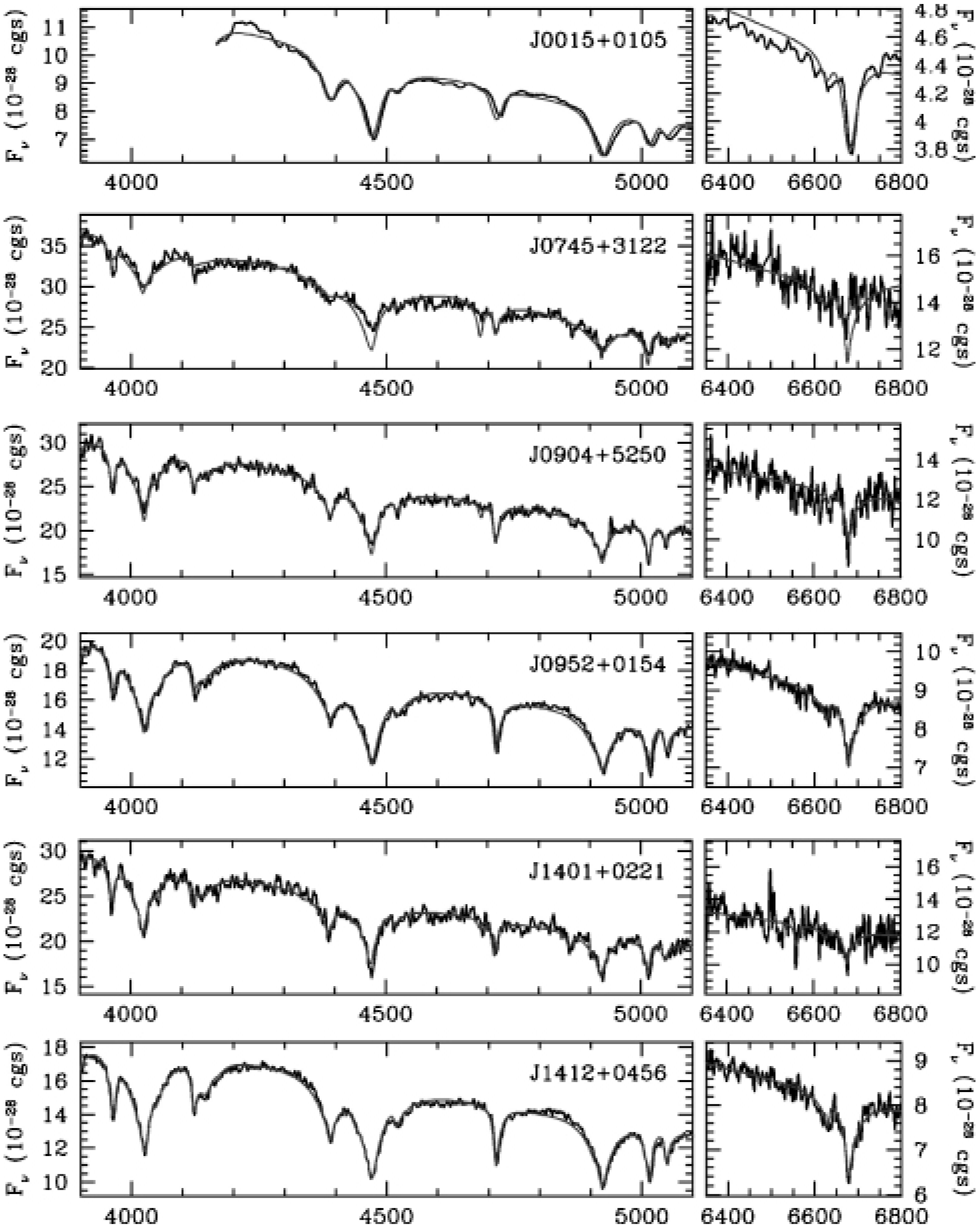

Table 1.2 Temperature index ranges for hot DA stars.

Spectral type	T_{eff} Range (K)	$10\times\theta_{\mathrm{eff}}$ Range
DA.25	200 000	–
DA.5	100 800	–
DA1	40 320–67 200	1.25–0.75
DA1.5	28 800–40 320	1.75–1.25
DA2	22 400–28 800	2.25–1.75
DA2.5	18 327–22 400	2.75–2.25

The spectroscopic appearance of the DO and DB subclasses is determined by the ionization balance of He I and He II. The DO white dwarfs show a pure He II spectrum at the hot end, and a mixed He I and He II spectrum at the cool end. However, the hottest non-DA stars are problematic to classify because (1) many are planetary nebula nuclei and isolated post-AGB stars sharing the hallmark spectroscopic characteristics of the PG 1159 degenerates, though with gravities lower than *logg* = 7, which is traditionally adopted as the minimum defining gravity for classification as a white dwarf star (versus a high gravity subdwarf; Greenstein and Sargent, 1974); and (2) the assignment of the primary spectral class for a white dwarf is determined by the element represented by the strongest absorption features in the optical spectrum. However, by this criterion, the PG 1159 stars, for which either oxygen (e. g., O VI) or carbon (e. g., C IV) are the strongest optical lines (with He II features weaker), should be classified as DZQO or DQZO depending upon whether O VI or C IV are strongest, respectively. Since many of these objects have atmospheric compositions which are not completely helium-dominated (cf., Werner and Heber, 1991; Werner *et al.*, 1991), it is inappropriate to assign spectral type DO on the Sion *et al.* (1983) scheme since the primary O-symbol denotes a helium-dominated composition. Hence, the primary spectroscopic type is adopted here as the atom or ion with the strongest absorption features in the *optical* spectrum, where applicable (for example, it is possible that the strongest absorption feature may lie in the ultraviolet). This is the scheme used for classifying the hottest degenerates.

In practice, a degenerate classification is withheld for any PG 1159 star with *logg*<7. However, these objects are designated PG 1159 as given by Werner and Heber (1991) and Werner *et al.* (1991), and subsequently used by Napiwotzki and Schoenberner (1991) and Dreizler *et al.* (1995). These designations are: E for emission, lgE for low gravity with strong central emission, A for absorption, E_p for emission/peculiar, and E_H, lgE_H or A_H for hybrid PG 1159 stars that have detectable hydrogen. The temperature index would differentiate the hot C-He-O stars from the well-known, much cooler DZ and DQ degenerates below 10 000 K. For example, PG 1159 itself ($logg = 7, T_{eff} = 110\ 000$ K, C IV absorption as the strongest optical lines) would be classified as DQZO.4. The obvious disadvantage is the inevitable confusion with the cool DQ and DZ degenerates in cases for which the temperature index is missing or there are no He II absorption features (e. g., H 1504; Nousek *et al.*, 1986). In a case like H1504, where no helium is detected, $T_{eff} = 170\ 000$ K, and $logg = 7$, the classification DZQ.3 is assigned.

The hot DQ stars are an entirely new subclass of hot white dwarfs. Unlike the previously known, and cooler, DQ white dwarfs which have helium-dominated atmospheres, the hot DQ stars have atmospheres that are dominated by carbon! These hot DQs probably evolve from a different progenitor channel than the cool DQs. While the temperature index can be used to distinguish these C-dominated objects from the cooler He-dominated DQ stars, their uniqueness suggests a special classification designation as “hot DQ” stars defined by the dominant presence of C II features in their optical spectra. There is certainly a precedent for having a special designation for this unique class of C-dominated white dwarfs. The PG 1159 stars merited their own special designation, rather than classifying them as DZ, DQ, or DO based upon whether O, C, or He features dominated their optical spectra. The designation PG 1159 is widely used to distinguish these unique, exotic objects from helium-dominated DO stars at lower temperatures. See Chapter 3 by P. Dufour for details of the hot DQ white dwarfs.

1.3 The Hot DA Stars

The total number of hot (T_{eff}>20 000 K) DA white dwarfs has increased enormously, largely due to the Sloan Digital Sky Survey (SDSS; Eisenstein *et al.*, 2006a; York *et al.*, 2000) but also to smaller surveys such as the Supernova Progenitor SurveY (SPY) project (Koester *et al.*, 2001; Napiwotzki *et al.*, 2003), and the Hamburg–Schmidt (Hagen *et al.*, 1995; Homeier, 2003) and Montreal–Cambridge–Tololo surveys (Demers *et al.*, 1986; Lamontange *et al.*, 1997). Follow-up high quality ground-based spectroscopy of survey objects yield large samples of hot DA white dwarfs with precise temperatures and gravities. Only one of many such examples is the Koester *et al.* (2009) analysis of 615 DA white dwarfs from the SPY project.

When the Balmer lines are extremely weak due to ionization, it is difficult to determine accurate temperatures for the hottest DA white dwarfs. While the Lyman series can be used to measure T_{eff} and estimate *logg* in the far-ultraviolet with Orfeus (e. g., Dupuis *et al.*, 1998), the Hopkins Ultraviolet Telescope (HUT; e. g., Kruk *et al.*, 1997), and FUSE (Sahnow *et al.*, 2000), there are two different widely known discrepancies that plague the reliable determination of hot DA physical parameters: (1) an inability to fit all of the Balmer lines simultaneously with consistent atmospheric parameters (the so-called Napiwotzki effect; cf. Gianninas *et al.*, 2010, and references therein); and (2) the disagreement between the parameters derived from fitting optical spectra and those derived from fitting far-ultraviolet spectra (e. g., Finley *et al.*, 1997, and references therein). The Napiwotzki effect has been resolved by adding metals (not detected in the optical spectra) to the model atmospheres, which provides a mild back-warming effect. The fact that the analysis of far-ultraviolet spectra from the FUSE archive reveals a correlation between higher metallic abundances and instances of the Balmer line problem strongly supports this scenario (Gianninas *et al.*, 2010).