White Dwarfs and Hot Subdwarfs as Seen from FUSE

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Abstract.

We present a small collection of FUSE spectra representative of the main spectral classes found in white dwarf stars. In addition, we also discuss another family of hot evolved stars, that of the hot subdwarfs. Both families belong to the chemically peculiar stars, and it is thought that a complex interplay of competing processes such as gravitational settling, ordinary diffusion, radiative levitation, weak stellar winds, and accretion is responsible for the rich variety of atmospheric compositions observed in those objects. FUSE is playing a key role in the current quest for establishing a coherent theory of the spectral evolution of these stars as it allows the determination of the patterns of heavy element abundances at a significantly higher level of accuracy than has been possible before on the basis of optical or UV observations. We also briefly present some fascinating FUV light curves of a handful of pulsating subdwarf B stars, thus illustrating the unique potential of FUSE for asteroseismological studies, a potential which has not been exploited yet.

1. Introduction

Despite their intrinsic faintness, white dwarfs and hot subdwarfs are routinely used as “lamps” that provide light along lines of sight in studies of the ISM, and they are also used during calibration exercises for many space experiments. This is because their spectra are relatively simple, owing to the fact that their atmospheres show a high degree of purity, not seen elsewhere in astrophysics. This is particularly true for white dwarfs, examples of which can show essentially pure H atmospheres or pure He atmospheres. This purity is understood as the result of gravitational settling in the intense gravitational field that characterizes white dwarfs. Under its influence, all elements heavier than the dominant atmospheric constituent (either H or He) rapidly sink below the photosphere and remain out of sight.

However, the record shows that white dwarf atmospheres, although highly pure, are not perfectly pure in most cases. And indeed, white dwarf atmospheres are generally polluted by small traces of heavy elements, particularly at both the high and low effective temperature ends of the white dwarf cooling sequence. For example, above 30,000 K, it is generally believed that radiative levitation as well as residual stellar winds can compete efficiently and selectively against gravitational settling to produce an amazing variety of atmospheric chemical
compositions. On the other hand, below 20,000 K or so, episodic fractionated accretion from the ISM is believed to be a temporary source of heavy metal pollutants that are often detected in the atmospheres of the cooler white dwarfs.

The competition between gravitational settling, thermal diffusion, ordinary diffusion, radiative levitation, weak stellar winds, superficial convection, and accretion produces a bewildering variety of trace element pollutants along the white dwarf cooling sequence. To a lesser extent, this is also true of the hot subdwarfs which are also, as a rule, chemically peculiar stars showing very intriguing atmospheric compositions. In fact, it could be argued that white dwarfs and hot subdwarfs constitute the most fascinating of all chemically peculiar stars. Hence, beside their usefulness as calibrators and lamps for ISM studies, white dwarfs and hot subdwarfs are certainly of high intrinsic interest.

The theory of the spectral evolution of white dwarfs and hot subdwarfs aims at explaining in a coherent way the puzzling variety of surface abundances observed in such stars. This implies detailed studies of the complex interplay between the various competing mechanisms that are mentioned just above, mechanisms that are believed to be at work in those stars. This also implies the establishment of observed element patterns from which one can make some sense and test the theory.

It is here that FUSE is playing its unique role in this particular endeavor. And indeed, FUSE allows us to detect a full host of traces of metals in the atmospheres of white dwarfs and hot subdwarfs, traces that are more often than not invisible in the optical, and that would remain undetected otherwise. FUSE observations in conjunction with model atmosphere and spectral synthesis techniques are being used to establish more firmly than before the patterns of heavy element abundances in white dwarfs and hot subdwarfs. Already, some very interesting results have been obtained as reported in these Proceedings. Some of these results challenge our current understanding of the formation of white dwarf and hot subdwarf spectra. In a broader context, FUSE is also helping us in refining our detailed understanding of the evolution of white dwarfs, a necessary step if white dwarf cosmochronology – i.e., the use of white dwarfs as independent age indicators – is to reach its potential.

2. White Dwarf Stars

White dwarfs, as is well known, represent the endpoint of the evolution for the vast majority of stars. It is indeed believed that more than 97% of the stars in our galaxy (those with initial masses less than about 8 $M_\odot$ on the main sequence) end up as white dwarfs. Most of them descend from post-AGB evolution and are former nuclei of planetary nebulae. They have run out of thermonuclear fuel, and they consist mainly of C and O, the products of H and He burning. White dwarfs are thus cooling bodies in hydrostatic equilibrium provided by the balance between gravity and the pressure of degenerate electrons. They shine through the slow leakage of thermal energy coming from the nondegenerate ions. White dwarfs have a stratified configuration with a C/O core surrounded by a thin He mantle ($M(\text{He})/M_* \sim 10^{-2}$) itself surrounded by an even thinner H outermost layer ($M(\text{H})/M_* \sim 10^{-4}$). Some 20% of the white dwarfs, however, have lost their H layer as they were formed through the so-called born-again
AGB mechanism (a late He flash that destroys the outermost H layer). Hence, from a spectroscopic point of view, white dwarfs come in two main “flavors”, the H-dominated atmosphere (DA) or the He-dominated atmosphere (non-DA) stars.

A total of about 2200 white dwarfs have been cataloged so far. The average visual magnitude of those is $<V> \simeq 15.5$. They are found over the full range of effective temperatures in the HR diagram, from 200,000 K for the hottest and youngest stars, down to 3000 K for the coolest ones known. They show a narrow mass distribution centered on 0.6 $M_\odot$. This corresponds to a typical radius of about 0.01 $R_\odot$, a surface gravity of $\log g \sim 8$, and a mean density of $<\rho> \sim 10^6$ g cm$^{-3}$. The white dwarfs of spectral type DA are found over almost the full range of effective temperatures, while the non-DA stars take on the spectral type name PG1159, DO, DB, DQ, or DC depending on their values of $T_{\text{eff}}$.

As an example, Figure 1 shows the FUSE spectrum (upper panel) of GD 394, a $T_{\text{eff}} = 39,000$ K DA white dwarf. The spectrum is dominated by the Lyman series of H. The spectral lines are very broad, which is the signature of the high pressures encountered in the high-gravity atmospheres characterizing white dwarf stars. The atmosphere of GD 394 is, however, clearly polluted by traces of heavy elements. Indeed, a zoom on the narrow spectral window shown in the lower panel indicates the presence of several metals, including P, Si, and Fe. In this context, it is well to remember here that without competition, gravitational settling would have left a completely pure H atmosphere in that star.

Figure 2 shows examples of FUSE spectra for two cooler DA white dwarfs, one around 30,000 K and the other at 20,000 K. Notice how the width of the Lyman lines increases considerably with decreasing $T_{\text{eff}}$. In fact, H lines reach
their maximum strength at still lower $T_{\text{eff}}$ in DA white dwarfs, around 12,000 K. The higher lines of the series become essentially fused together as can be seen, corresponding physically to their disappearance in a very high pressure environment. Also, the spectra shown in Figure 2 show some very interesting features for experiments in atomic physics. And indeed, the structures identified as $\text{H}_2^+$ correspond to collision-induced quasi-molecular absorption features whose existence was predicted by Nicole Allard in France. The features detected by FUSE provide new testing grounds for atomic theory.

Examples of non-DA spectra are provided in Figure 3. In the top panel, we show the spectrum of the prototype of the PG1159 class. Note that the H Lyman lines seen in the spectrum are interstellar in origin here. In this very hot atmosphere, residual winds prevent settling from operating efficiently, and the chemical composition is believed to reflect the composition produced immediately after the born-again AGB phase. It is mostly a mixture of He, C, and O with traces of several other elements. In the paper presented by Klaus Werner in these Proceedings, one can learn more about these extremely hot and fascinating objects.

In the lower panel of Figure 3, we show an example of a DO spectrum, a much cooler star, believed to have descended directly from the PG1159 phase. In the DO phase of the evolution, residual winds have decreased considerably in intensity, the stars are much older than in the PG1159 phase, and settling is winning its battle. That is, the atmosphere of a DO star is now dominated by He. The spectrum shows mostly the relatively strong lines of the Balmer series of HeII.

In the top panel of Figure 4, we again show the spectrum of the DO white dwarf HZ 21. This is to contrast with its future spectral state in the lower
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Figure 3. Upper panel: FUSE spectrum of the PG1159 white dwarf PG1159−034 ($V = 14.87$). Lower panel: FUSE spectrum of the DO white dwarf HZ 21 ($V = 14.22$).

Figure 4. Upper panel: FUSE spectrum of the DO white dwarf HZ 21 ($V = 14.22$). Lower panel: FUSE spectrum of the DB white dwarf BPM170 88 ($V = 14.07$).

panel, represented here by the 23,000 K DB star BPM17088. The spectrum of the latter is rather interesting. Disregarding the interstellar H lines, it is basically featureless except for some prominent C lines and very little else! According to the theory of the spectral evolution of white dwarfs, a DB star should have a
perfectly pure He atmosphere, yet this is not the case here as C is an obvious pollutant. In this respect, we draw attention to the interesting contribution by Petitclerc et al. (these Proceedings) where the authors discuss this C pollution problem in BPM17088 and other hot DB white dwarfs.

3. Hot Subdwarf Stars

Most hot subdwarfs belong to spectral type sdB and are evolved, compact stars that populate the extreme horizontal branch (EHB). They surely evolved from the RGB, but we still do not know the details of their formation process, and this constitutes one of the last frontiers of stellar evolution theory. The sdB stars have atmospheric parameters in the range of temperatures from about 20,000 K to upward of 40,000 K, and in the range of gravities from \( \sim 5.0 \) to \( \sim 6.2 \) in \( \log g \). They are believed to be core He-burning objects with masses in a very narrow range centered around 0.5 \( M_\odot \). Their residual H-rich envelopes are too thin to sustain significant H-shell burning during core He-burning (EHB) evolution. Their envelopes are also too thin to prevent sdB stars from reaching the AGB after core helium exhaustion, and they become sdO stars instead (\( T_{\text{eff}} \sim 45,000 \) K and \( \log g \sim 5.4 \)) in their post-EHB, He shell-burning phase. After a few \( 10^8 \) yr of evolution near the EHB, hot subdwarfs ultimately collapse into low-mass white dwarfs, but provide a mere 2% of the white dwarf population.

Hot subdwarf stars are all chemically peculiar. For instance, He is typically underabundant by 1 to 2 orders of magnitude in sdB stars, and heavy elements have unusual and puzzling abundances (as inferred from optical, IUE, EUVE, HST, and FUSE observations). Diffusion processes (gravitational settling, ordinary diffusion, radiative levitation) are believed to be at work in competition with weak stellar winds. Hot subdwarfs (sdB, sdO) dominate the brighter end of surveys for faint blue stars down to \( V \sim 16 \). They are the most numerous objects found in shallow surveys for faint blue stars such as the PG, EC, and MCT surveys (e.g., there are more than 300 hot subdwarfs brighter than \( V \sim 14.3 \) in the PG survey). They are the main sources of ultraviolet light in old populations such as elliptical galaxies and some globular clusters (the so-called UV-upturn phenomenon).

One of the current problems in subdwarf B star research is to seek for an explanation for the observed coexistence of short-period pulsating and nonpulsating stars in the same region of the \( \log g - T_{\text{eff}} \) diagram. The variable sdB stars of interest show multiperiodic luminosity variations with periods in the range \( 100-500 \) s, which are caused by pressure-mode pulsational instabilities. Pulsation calculations have shown that nonradial mode instabilities can be triggered through the so-called kappa-mechanism associated with a local overabundance of iron in the envelope of models of pulsating sdB stars provided the Fe abundance is large enough. Hence, an obvious test of this idea is to search for a spectral signature for the pulsations, Fe being the key element.

Along with several collaborators, we have used FUSE to carry out such a test. It is important to realize that, in order to obtain a meaningful result, it is necessary to minimize the complicated dependences of the Fe abundance on \( \log g \) and \( T_{\text{eff}} \) in presence of radiative levitation by comparing the spectrum of a pulsating star with that of a nonpulsating object with very similar values of
their atmospheric parameters. So far, we have obtained results for one such a pair of pulsating/nonpulsating stars, and their FUV spectra are shown in Figure 5.

![Figure 5](image)

Figure 5. Upper panel: FUSE spectrum of the pulsating sdB star Feige 48 ($V = 13.48$). Lower panel: FUSE spectrum of the nonpulsating sdB star PG1206+165 ($V = 13.75$). Both stars have similar values of log $g$ and $T_{\text{eff}}$, yet one pulsates and the other does not.

While the overall spectra of the two objects are quite similar – consistent with the fact that they have similar values of log $g$ and $T_{\text{eff}}$ – it turns out that the pulsating star has a much higher atmospheric abundance of Fe than the nonpulsating star. This is best seen in Figures 6 and 7, which show a portion of the spectrum where prominent Fe lines can be seen. We find, quantitatively, that the Fe abundance in the pulsating star Feige 48 is more than two orders of magnitude larger than in its nonpulsating counterpart PG1206+165, in line with the expectations of pulsation theory. While extremely encouraging, this result, obtained so far for a single pair of pulsating/nonpulsating stars, must be confirmed by observing further suitable pairs. We hope to be able to do that in the future.

4. FUSE as a FUV Photometer for Asteroseismological Studies

Our interests in pulsating white dwarfs and hot subdwarfs have led us to investigate the potential of FUSE as a FUV photometer. One of the key ingredients in the asteroseismological process is to identify a pulsation mode in terms of its radial order $k$ (corresponding to the number of nodes of the eigenfunction in the radial direction) and of its degree index $\ell$ (corresponding to the azimuthal wave number associated with the spherical harmonic function which describes the angular geometry of the mode). The pulsation frequency (period) of a mode depends on these two “quantum” numbers for spherically symmetric stel-
Figure 6. Portion of the FUSE spectrum of the pulsating sdB star Feige 48 showing prominent Fe lines.

Figure 7. Similar to Figure 6, but for the nonpulsating sdB star PG1206+165.

lar models. Theory shows that the ratio of the amplitudes of a given pulsation mode in two different wavebands is, in a first approximation, independent of the unknown intrinsic amplitude and of the unknown viewing aspect. This ratio, however, does depend on the index $\ell$, thus allowing, in principle, for its empirical determination. For hot stars, calculations clearly indicate that the relative mode amplitudes as seen in the optical and in the FUV strongly discriminates between values of the degree $\ell$, allowing these to be easily determined. Such constraints on the mode identification are otherwise very difficult to obtain from optical multicolor photometry alone, as the discrimination between different $\ell$ values is weak when confined to this bandpass. The principle is illustrated in Figure 8, as appropriate for a typical sdB star model with $T_{\text{eff}} = 30,000$ K and log $g = 5.5$. 
The figure shows the relative monochromatic amplitude ratio as a function of $\ell$ and wavelength for nonradial modes of degree $\ell = 1, 2, 3, \text{ and } 4$.

![Graph showing relative monochromatic amplitude ratio as a function of \( \ell \) and wavelength for nonradial modes of degree \( \ell = 1, 2, 3, \text{ and } 4 \) in a typical sdB model.]

With these considerations in mind, we investigated the potential of FUSE as a FUV photometer for such experiments using data on pulsating sdB stars obtained previously in program B033 (PI: G. Fontaine). This was possible as these observations were all gathered in TTAG mode, with a frequency resolution of 1 Hz. To increase the S/N ratio we integrated over the full FUSE bandwidth to produce a single FUV “color”, and we binned the data in 10 s bins, a sampling time more than adequate for the periods involved. With the help of B. Godard, we were thus able to produce the light curves shown in Figure 9. Given the relative faintness of our target stars and the small aperture of FUSE, these light curves are, in our view, nothing short of amazing! They establish, above all, that FUSE can indeed be used as a useful tool for asteroseismological studies.

As a comparison, we show, in Figure 10, the corresponding optical light curves, all obtained in “white light” at the 3.6 m CFHT telescope. There is already a strong hint that the pulsation amplitudes are larger, as expected, in the FUV than in the optical domain, but caution should be taken here because the FUV and optical light curves have not been taken at the same epoch. Indeed, it is well known that pulsating hot subdwarfs (and white dwarfs) are multiperiodic pulsators with highly variable mode amplitudes from season to season. The proper way to use FUSE as an asteroseismological tool is to gather contemporaneous FUV and optical observations, and integrate over a sufficient period of time in order to reach a suitable time resolution in the Fourier domain. The issue of temporal resolution is essential to be able to isolate individual frequency peaks (pulsation modes) in that domain. For each of these modes, the amplitude ratio $A(\text{FUV})/A(\text{optical})$ would constrain its $\ell$ value.
Figure 9. FUV light curves of four pulsating sdB stars as obtained by FUSE; from top to bottom: PG1219+534 ($V = 13.24$), Feige 48 ($V = 13.48$), KPD2109+4401 ($V = 13.38$), and PG1605+072 ($V = 12.92$). The light curves are expressed in terms of percentage of residual amplitude relative to the mean brightness of the star. Each plotted point represents a sampling time of 10 s. The curves have been shifted by arbitrary amounts in the vertical direction away from the zero point for visualization purposes.

Figure 10. Similar to Figure 9, on the same scale and for the same stars, but in the optical regime. Here the data are “white light” light curves gathered at the CFHT with the Montréal 3-channel photometer LAPOUNE.