PHOTOSPHERIC METALS IN THE FUSE SPECTRUM OF THE SUBDWARF B STAR PG0749+658

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ABSTRACT

We present an abundance analysis of the far-ultraviolet (905–1187 Å) spectrum of the subdwarf B star PG0749+658, obtained by the Far Ultraviolet Spectroscopic Explorer (FUSE). The data have a resolution of about R = λ/Δλ = 12000–15000 (20–25 km/s). We determine C, N, Si, P, S, Cr, Mn, Fe, Co, and Ni abundances, and upper limits on the abundance of Cl and V, using a grid of synthetic spectra based on a LTE stellar atmosphere model. He, C, N, Si, and Cl are depleted by a factor of ≥10 with respect to solar, while P, S, and Fe are diminished by less than a factor of 10. We measure a solar abundance of Cr, Mn, and Co and a Ni enhancement of ≈0.6 dex. We compare these values to predictions based on radiative levitation theory. The radial velocity of the foreground interstellar material has one dominant component and coincides with that of the photospheric lines.

Subject headings: stars: abundances — stars: horizontal branch — stars: individual (PG0749+658)

1. INTRODUCTION

PG0749+658 was discovered by the Palomar-Green survey as an ultraviolet-excess object (Green, Schmidt, & Liebert 1986) and classified as a subdwarf B star (sdB). In their study of sdB candidate stars found in the Palomar-Green survey, Saffer et al. (1994) measured the star’s effective temperature, gravity, and He abundance (Table 1). With an effective temperature of 24,600 K, PG0749+658 is near the cool end of the sdB population.

SdBs lie on the extreme horizontal branch (EHB) of the HR diagram and are progenitors of low-mass white dwarfs (Dorman, Rood, & O’Connell 1993). They are core He-burning stars with high effective temperatures (20,000 K ≤ Teff ≤ 40,000 K) and gravities (log g ≳ 5–6), and small H-rich envelopes (Menv < 0.05M⊙) (see, e.g., Saffer et al. 1994 and references therein). Precisely how EHB stars evolve to their location on the HR diagram is controversial. Proposed binary scenarios draw on mass loss (Mengel, Norris, & Gross 1976) or mergers (Iben 1990). Single star theories involve heavy mass loss on the red giant branch (RGB), leaving the star on the zero age HB with a low Menv and high Teff (see, Yi, Demarque, & Oemler 1997 and references therein). This interpretation invokes mass loss on the RGB that is a sensitive function of metallicity.

Although the evolutionary path followed by the progenitors of sdB stars is unclear, sdBs are important to understanding the late stages of stellar evolution, with implications for the evolution of galaxies. Early vacuum ultraviolet observations of E/S0 galaxies and the bulges of spiral galaxies revealed that these old populations, which were thought to harbor no significant number of stars hotter than their main-sequence turn-offs (Teff ≳ 5,500 K), are copious UV emitters (see O’Connell 1999 for a review). For the leading theories which address the “UV excess” (e.g., Yi, Demarque, & Oemler 1997), sdB stars represent only one candidate for the source of the emission. However, sdBs have lifetimes much longer than other EHB stars, and dominate the UV excess (Dorman, Rood, & O’Connell 1993; Brown et al. 1997).

Some sdB stars, named for the prototype EC14026, are observed to pulsate (Kilkenny et al. 1997). At present, 14 sdB pulsators have been discovered and all show multi-periodic, high-frequency luminosity variations with typical periods of ∼100–300 sec and amplitudes of <1–25% (see, e.g., Koen et al. 1998, O’Donoghue et al. 1999, and Billeres et al. 2000). The peculiar iron abundance profile, produced in these high gravity stars by diffusion processes, is thought to play an important role in the pulsation mechanism (Charpinet et al. 1996 and 1997). Although PG0749+658 is not expected to pulsate because its effective temperature is somewhat low (G. Fontaine 2000, private communication), the study of its FUV spectrum provides an opportunity to test the diffusion theory, which is one of the major ingredients in explaining the pulsation of sdB stars. Understanding the pulsation mechanism can potentially be used to shed light on the interior of sdB stars and, thus, their evolutionary status.

Abundance anomalies are observed in the atmospheres of sdB stars. Low resolution optical spectroscopy reveals that the abundance of helium in sdB stars is typically a factor of ten smaller than the solar abundance (see, e.g., Moehler, de Boer, & Heber 1990). On the other hand, high resolution optical and UV spectra show that elements heavier than He may or may not be underabundant. For instance, C and Si are underabundant in sdB stars, while the N abundance is nearly solar over the effective temperature range covered by sdB stars (Lamontagne, Wesemael, Fontaine, & Sion 1985; Heber 1991). The processes of gravitational settling, radiative levitation, and mass loss are thought to be responsible for the observed abundance anomalies in these EHB stars, which have gravities larger than those of main sequence stars (Michaud et al. 1985; Bergeron et al. 1988; Fontaine & Chayer 1997; Unglaub & Bues 1998).
We present the far-ultraviolet (FUV; 905–1187 Å) spectrum of PG0749+658 obtained by the Far Ultraviolet Spectroscopic Explorer (FUSE). This is the first high-resolution spectrum of a sdB shortward of Lyα. In this paper we perform an abundance analysis and we compare our results with radiative levitation theory. Furthermore, this study is a test case in support of future FUSE subdwarf observations.

2. OBSERVATIONS AND DATA REDUCTION

The FUSE mission and instrument performance are covered by Moos et al. (2000) and Sahnow et al. (2000), respectively.

This spectrum was obtained as a part of In-Orbit Check-out program 1904 on 9 November 1999 using the high-throughput apertures (30′′ × 30′′; LWRS) on all four spectrograph channels and recorded in “histogram” mode for a total exposure time of 17,616 sec. On 7 January 2000, six additional exposures were obtained in “time tag” mode for a total of 9,409 sec, but only data from the LiF1 and LiF2 channels were usable. The spectra were processed by the FUSE pipeline (version number 1.6.8). No flat-fielding was performed, and the dominant statistical uncertainty is the fixed pattern noise associated with the detectors. Astigmatism and dead-time corrections were not applied, but rough photometric and wavelength calibrations were performed. For this analysis, we co-added individual exposures to increase the signal-to-noise ratio and corrected the photometry and wavelength calibrations for a total exposure time of 17,616 sec. We detect one radial velocity component of the foreground interstellar medium and many interstellar H₂ and metal lines are present.

Selection of the FUSE channel used for fitting a given photospheric line was based on the local data quality (i.e., the signal-to-noise ratio and the presence of artifacts). A wavelength solution has been applied to the data, but it is inaccurate on small scales (< 0.1 Å). Before fitting each stellar line, we created a local wavelength solution over ∼ 6–10 Å by linearly interpolating between the known locations of interstellar features and the photospheric lines of interest. These local corrections to the wavelength scale greatly improved the fit used to determine abundance (Section 3).

The uncertainty in the absolute wavelength calibration dominates the error in the measurement of radial velocity. However, measurements of the relative locations of photospheric and interstellar lines indicate that the radial velocity of PG0749+658 and the dominant component of the foreground interstellar medium are essentially equal, within the uncertainty set by local distortions in the wavelength scale (< 30 km/s). This makes the interstellar lines useful for correcting the wavelength scale, but it is harder to disentangle blends of interstellar and photospheric lines.

3. RESULTS

We computed a stellar model under the assumption of local thermodynamic equilibrium (LTE), and a pure H and He composition using the stellar atmosphere code TLUSTY (Hubeny & Lanz 1995) and parameters derived by Saffer et al. (1994) (Table 1). Using this model, we generated a grid of synthetic spectra for each photospheric line using the SYNSPEC code (I. Hubeny) and atomic data provided by R. L. Kurucz. The grid covered a range in metal abundance and local instrument resolution. We then fit each line individually using a chi-square minimization technique, where, for a given wavelength range, the abundance, resolution, and normalization were optimized.

To fit each line, we modeled a ∼ 6–10 Å range in the spectrum centered on the feature of interest. We chose spectral features based on the strength of the transition, the local data quality, and the presence of “contaminating” interstellar absorption lines. We then checked that the derived abundance reproduced other lines of the element observed elsewhere in the spectrum. The abundances by number with respect to H are listed in Table 2 for all of the photospheric lines detected in the FUSE spectrum. A model spectrum using all of our determined abundances is shown in Figure 1.

The formal, 1σ uncertainties associated with the output of the fitting process are much lower than the systematic errors: The uncertainties in the flux and wavelength calibrations, errors in the oscillator strength used to calculate our synthetic spectra, uncertainty in the atmospheric parameters (Table 1), and the potential blending of the photospheric lines with interstellar absorption features represent significant sources of systematic error. Furthermore, we neglect non-LTE effects in the calculation of our model atmosphere, which may also contribute to this error. Studies examining departure from LTE indicate that the impact on our model line profiles is probably not critical to this abundance analysis for this cool sdB (Baschek et al. 1982; Heber et al. 1984). We neglect microturbulence in our abundance analysis. We estimate the combined systematic errors to impact our abundance measurements on about the ±0.3 dex-level.

The photospheric abundances and the predictions of radiative levitation theory are listed in Table 2. The predicted equilibrium abundance for a given element is computed within the framework of the radiative levitation theory developed by Chayer et al. (1995a, 1995b). The computations are performed at the Rosseland optical depth, \( \tau_{\text{Ross}} = 2/3 \), for a hydrogen-rich stellar atmosphere model with \( T_{\text{eff}} = 24,600 \) K and \( \log g = 5.5 \). The equilibrium abundance was calculated only for the elements available in the TOPBASE data bank (i.e., those with cosmic abundances by number greater than \( \sim 10^{-6} \) relative to H; Cunto & Mendoza 1992). These theoretical values are also plotted for comparison to the observed PG0749+658 photospheric and solar abundances in Figure 2. The solar abundances are from Anders & Grevesse (1989).

4. DISCUSSION

The FUV spectral analysis of PG0748+658 is summarized in Figure 2, where the observed, predicted and solar abundances are compared. All of the elements are depleted with respect to solar, except Cr, Mn, Co, and Ni. Among those that are depleted, He, C, N, Si, and Cl are diminished by a factor of \( \gtrsim 10 \), while P, S, and Fe are depleted by less than a factor of 10. We observe an enhancement of Ni of \( \sim 0.6 \) dex. We do not measure over-abundances of P and Cl, as reported by Baschek & Sargent (1976) and Heber (1991), respectively, in their studies of cooler HB stars of spectral type B (HB3).

The measured abundances are generally consistent with predictions based on radiative levitation theory, except for
He and Si. The under-abundance of He is not explained by this theory alone. On the other hand, Fontaine & Chayer (1997) and Unglaub & Bues (1998) suggest that an outward velocity field, created by a weak stellar wind, may support significant amounts of He in the photosphere of sdB stars.

The observed Si abundance falls below that expected from theory by about two orders of magnitude. This result is consistent with that of Bergeron et al. (1988), who show that radiative levitation theory does not predict the observed under-abundance of Si in sdB stars. Calculations by Michaud et al. (1985) indicate that this anomaly may be explained by the presence of a weak stellar wind.

The predicted and observed Fe abundance agree well, which supports the application of radiative levitation theory toward predicting the amount of Fe in the atmospheres of hot subdwarfs.

Lamontagne et al. (1987) observed PG0342+026 with IUE and determined C, N, and Si abundances. This star and PG0749+658 have very similar atmospheric parameters. Averaging the parameters obtained by Lamontagne et al. (1987), Moehler, de Boer, & Heber (1990), and Saffer et al. (1994) gives $T_{\text{eff}} = 24,800$ K, $\log g = 5.3$, and $\log \text{He}/\text{H} = -2.6$ for PG0342+026. The C and Si abundances of the two stars are in good agreement. However, the N abundance is about 1.7 dex higher for PG0342+026, but the uncertainties in the measurements for both stars are large.

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### Table 1
**Target Summary for PG0749+658**

| Quantity     | Value       | ref |
|--------------|-------------|-----|
| Spectral Type| sdB         | 1   |
| $V$          | 12.121      | 2   |
| $B - V$      | −0.106      | 2   |
| $V - R$      | 0.021       | 2   |
| $R - I$      | 0.072       | 2   |
| $T_{\text{eff}}$ | 24,600 K   | 3   |
| log $g$      | 5.5         | 3   |
| log He/H     | −2.4        | 3   |
| $V_{\text{rad}}$ | $-27.3 \pm 6.9$ | 4   |

**References.**—(1) Green, Schmidt, & Liebert 1986; (2) Allard et al. 1994; (3) Saffer et al. 1994; (4) Saffer, Livio, & Yungelson 1998.
| Ion  | $\epsilon^a$ (observed) | $\epsilon^a$ (predicted) |
|------|-------------------------|-------------------------|
| C II | 6.59                    | 6.78                    |
| C III| 7.08                    | 6.78                    |
| N III| 6.93                    | 6.20                    |
| Si III| 5.16                  | 7.30                    |
| Si IV| 5.46                    | 7.30                    |
| P III| 4.69                    | ...                     |
| S II | 6.00                    | 6.23                    |
| S III| 6.76                    | 6.23                    |
| S IV | 6.55                    | 6.23                    |
| Cl III| < 3.5                  | ...                     |
| V III| < 4.0                   | ...                     |
| Cr III| 5.37                   | ...                     |
| Mn III| 5.29                   | ...                     |
| Fe III| 7.32                    | 7.26                    |
| Co III| 4.65                   | ...                     |
| Ni III| 6.88                    | ...                     |

$^a \epsilon = 12 + \log([N(A)/N(H)]).$
Fig. 1.— *FUSE* spectrum (solid line) 1120–1130 Å and model using all of the observed metal abundances given in Table 2 (dotted line). Lines with equivalent widths larger than 20 mÅ are identified above the spectrum. The vertical lines below the spectrum mark the location of interstellar Fe II absorption features.

Fig. 2.— Comparison of the observed and expected abundances of elements found in the photosphere of the sdB star PG0749+658. Systematic errors for both the observed and predicted abundances are about ±0.3 dex. The data place stringent upper limits on the abundances of Cl and V (arrows). The predicted abundances were computed for elements available in the TOPBASE data bank, i.e., He, C, N, Si, S, and Fe. Where multiple species are available for a given element, the average of the derived abundances is shown. The He abundance is from Saffer et al. (1994).
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