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THE DISCOVERY OF Mg II λ4481 IN THE WHITE DWARF EG 102: EVIDENCE FOR ONGOING ACCRETION

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ABSTRACT

Recent optical spectra of the DA3 white dwarf EG 102 clearly show a feature due to Mg II λ4481. This is the first spectroscopic detection of Mg in a DA star at a temperature of 20,000 K. The presence of this ion in the stellar photosphere poses a severe dilemma for the theory of radiative levitation, which predicts a vanishingly small equilibrium abundance of Mg in a star such as EG 102. Ongoing accretion must to be the source of this ion. An accretion rate of $1.6 \times 10^{-16}\ M_{\odot}\ \mathrm{yr}^{-1}$ is implied by the short timescale (3.3 days) for the diffusive loss of Mg from the photosphere. Such a rate could be supplied by the interstellar medium, if EG 102 is embedded in a diffuse interstellar cloud. Alternately, EG 102 may possess a very low mass companion, which is transferring material onto the white dwarf. Finally, we use an *IUE* echelle spectrum to demonstrate the presence of photospheric Si in this star. We find respective abundances of log (Mg/H) = −5.3 and log (Si/H) = −7.0 for EG 102.

Subject headings: stars: abundances — stars: individual (EG 102) — stars: white dwarfs

1. INTRODUCTION

The existence of trace levels of heavy ions in the otherwise pure-hydrogen photospheres of DA white dwarfs is of considerable interest. In the hotter DA white dwarfs, these heavy elements are now known to be responsible for the high levels of EUV and soft X-ray opacity frequently seen in these stars. The presence of such elements is also one of the few observational clues we have to probe the structure and chemical history of white dwarf atmospheres. In the absence of other processes, the high gravitational fields of white dwarfs will result in a rapid settling of heavy elements below photospheric levels. It is, however, theoretically possible (Vauclair, Vauclair, & Greenstein 1979) for radiative forces to levitate selected ions at atmospheric levels in hot ($T_{\mathrm{eff}} > 20{,}000$ K) DA white dwarfs. Although this mechanism often fails to predict observed abundances accurately, it does account for some of the more general aspects of the observed patterns of heavy elements in DA white dwarfs. Radiative levitation results in equilibrium abundances for specific ions that depend primarily on the effective temperature and gravity of the star. Chayer et al. (1995) have published explicit abundance predictions for a number of elements in white dwarfs. It is clear from this work that radiative levitation ceases to be effective for all heavy elements below 20,000 K. The fact that observed abundances are often quite different from predictions and that similar stars often have quite different abundances has led to the suggestion that other processes are important, in particular mass loss. Indeed, there do exist examples of DA stars (Holberg, Bruhweiler, & Andersen 1995b; Holberg et al. 1995a) that possess circumstellar gas containing heavy elements and that may represent examples of a mass-loss phenomenon.

A second mechanism that is frequently invoked to explain the presence of species such as Ca, Mg, and Fe in much cooler ($T_{\mathrm{eff}} \sim 10{,}000$ K) white dwarfs, including a few DA stars, is accretion from the interstellar medium (ISM). Since the primary observed species are depleted in the ISM, it is presumed (Wesemael & Truran 1982) that they are derived from interstellar dust grains. As with mass loss, accretion is capable of producing nonequilibrium abundances; until now, however, no clear examples of accretion have existed for DAs above 15,000 K.

EG 102 (WD 1337+705, GW +70°5824, LTT 18341, G238-044, PG 1337+705) is a bright ($V = 12.77$), apparently isolated, DA3 white dwarf. From Bergeron, Saffer, & Liebert (1992) and others, it has an accurately known effective temperature (20,230 K) and gravity ($\log g = 7.90$). EG 102 is also a familiar standard star, frequently used for both photometric and spectrophotometric calibration (Turnshek et al. 1990). In all known respects, it very closely resembles the DA star Wolf 1346, which has recently been demonstrated to contain a significant abundance of photospheric Si (Holberg et al. 1996). Vennes, Thjell, & Shipman (1991, hereafter VTS) have previously noted the presence of the excited Si II λλ1264, 1265 lines in EG 102 and calculated a Si abundance based on the assumption that the lines are photospheric. However, they possessed no independent estimate of stellar velocity with which to verify this assumption.

In this Letter we present optical and UV data on EG 102 that demonstrate the presence of photospheric Mg II and Si II. In the optical, a single Mg II feature is seen at λ4481. This is unique in that it is the first spectroscopic detection of Mg in a hot DA white dwarf. It also represents a rare detection in the optical (as opposed to the UV) of an element heavier than He

[1] Observations reported here have been obtained in part with the Multiple Mirror Telescope, a joint facility of the University of Arizona and Smithsonian Institution.

in a moderate temperature DA white dwarf. We also present a rediscussion of the single archive *IUE* echelle spectrum of EG 102 and demonstrate that the excited Si II features, first noted by VTS, are also photospheric in origin. An accurate stellar radial velocity determined from the H I Balmer lines is found to be in good agreement with the velocity of the optical Mg II feature and the UV Si II lines. We additionally derive estimates of the Mg and Si abundances in EG 102 and compare these with predictions based on radiative levitation.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Optical and UV Spectra*

EG 102 was observed on June 26 with the MMT Blue Channel Spectrometer and Loral 3072 × 1024 CCD, as part of a program to obtain accurate radial velocities for a selected set of white dwarfs. A single spectrum of 360 s duration (S/N = 18) was obtained using the 832 line mm^{-1} grating in second order, with $CuSO_4$ and UV-36 blocking filters, and a 1″.25 slit. Spectra cover the 3920–5010 Å region at ~1 Å resolution, although only the central 950 Å are usable. HeAr arc lamps of 60 s duration were taken immediately before and after each program star. Standard IRAF routines were used to perform the bias subtraction, flat-fielding, cosmic-ray removal, and wavelength calibration. The IRAF task FXCOR was used to cross-correlate the observed continuum-subtracted spectrum with a synthetic white dwarf spectrum corresponding to the temperature and gravity of EG 102, using only wavelength regions near Hβ, Hγ, and Hδ. The resulting heliocentric velocity of the Balmer lines in EG 102 is $+0.7 \pm 1.9$ km s^{-1}, where the uncertainty is an internal estimate based on cross-correlations using various Fourier filters, the reproducibility of other white dwarf spectra, and the observed centroid of the Hg I λ4358 night-sky line. We can estimate an external error of ~4.8 km s^{-1} in our EG 102 result by considering two other white dwarfs observed on the same night and that have independent *IUE* and *HST* velocity measurements.

Given the surprising presence of the 4481 Å feature in a much observed standard star, we examined the spectral image and are able to rule out an instrumental artifact. We also reexamined a lower resolution (~2.5 Å) spectrum of EG 102 obtained on 1991 May 27 by Kidder (1991) using the Steward Observatory 2.3 m telescope on Kitt Peak. Both spectra clearly show the same feature at similar strengths. In Figure 1 we show both the MMT and 2.3 m spectra. From the MMT spectrum, we find a radial velocity of -0.2 ± 3 km s^{-1} and an equivalent width of 126 ± 15 mÅ for the Mg II feature. The Mg II λ4481 line is doublet (λλ4481.327, 4481.130) having an excited lower level and therefore cannot arise in the interstellar medium.

The *IUE* archives contain a single echelle image (SWP 17182) of EG 102 obtained by F. C. Bruhweiler on 1982 June 10. This spectrum (see Fig. 2) is rather noisy and contains relatively few clearly identifiable stellar or interstellar features. In Table 1 we identify four interstellar and four stellar features present in SWP 17182. The respective mean velocities of these two components are -10.5 km s^{-1} and -5.2 km s^{-1}. These velocities are similar enough that it can be difficult to distinguish between these two alternatives for any single line. However, the four photospheric Si II lines in Table 1 are all excited transitions with lower levels ~0.036 eV above ground, which excludes an interstellar origin. These lines are also seen in other white dwarfs, where they are associated with photospheric features (Wolf 1346; Holberg et al. 1996) and circumstellar gas (CD −38°10980; Holberg et al. 1995b).

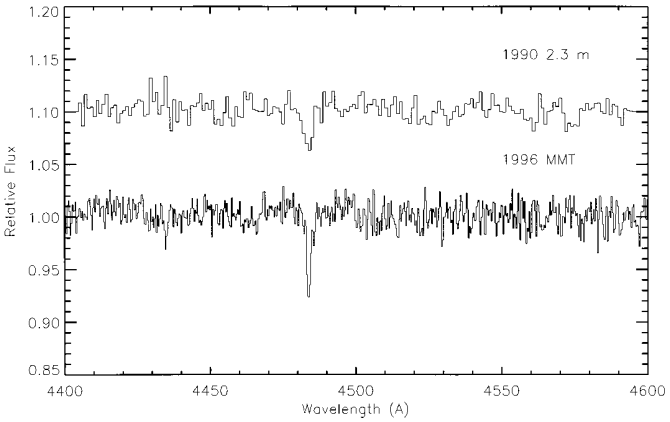


FIG. 1.—Spectra of EG 102 showing the presence of the Mg II λ4481 doublet. The top plot shows a spectrum obtained at the Steward Observatory 2.3 m telescope in 1991 May. The bottom plot shows a single spectrum obtained in 1996 June with the MMT Blue Channel.

The velocity of the optical and UV stellar features differ by ~5.4 km s^{-1}. However, considering the 3 km s^{-1} internal uncertainty of the *IUE* velocity and the possible offset resulting from the placement of the star in the *IUE* slit and uncertainties in our Balmer line velocity, the agreement between the optical and *IUE* velocities must be considered good. We therefore identify the Si II lines as originating in the stellar photosphere. In the case of the Si II λλ1260 and 1526 ground-state transitions in Table 1, these are almost certainly a blend of stellar and interstellar lines. The nature of the excited C II λ1335 is more difficult to judge. VTS apparently used this line to estimate a C abundance for EG 102 based on the assumption that it is was stellar. We find its velocity significantly closer to the ISM velocity than that of the stellar features, but we note, however, that if the C II line is, indeed, a stellar feature, then the mean velocity of the ISM and stellar components would become nearly identical. We also note that, although the weakly excited C II λ1335 line is frequently seen in the ISM spectra of other white dwarfs, its strength in EG 102 is exceptional, however, nearly an order of magnitude stronger then average. It is also possible that the C II feature could be circumstellar, as is observed in the 25,000 K DA CD −38°10980 (Holberg et al. 1995b). Improved UV spectra will be required to resolve the status of this line. In addition to Si II and C II, we find very strong (100–200 mÅ) features due to Al II λ1670.787 and Al III λλ1854.716, 1862.784 to be also present in SWP 17182. These lines are consistent with the stellar velocity, although the Al II line is also frequently seen in the ISM. The stellar signal is very weak in this region and no attempt has been made to estimate a photospheric Al abundance from these features.

2.2. *Heavy Element Abundances in EG 102*

We have used the advanced non-LTE code TLUSTY developed by Hubeny (1988) and improved by Hubeny & Lanz (1992, 1995) to calculate models appropriate to EG 102. Theoretical equivalent widths are determined from detailed model spectra calculated using the SYNSPEC program (Hubeny, Lanz, & Jeffery 1994). From the observed equivalent width of 126 ± 15 mÅ we estimate a Mg abundance of log (Mg/H) = −5.35 ± 0.10. To estimate the Si abundance we

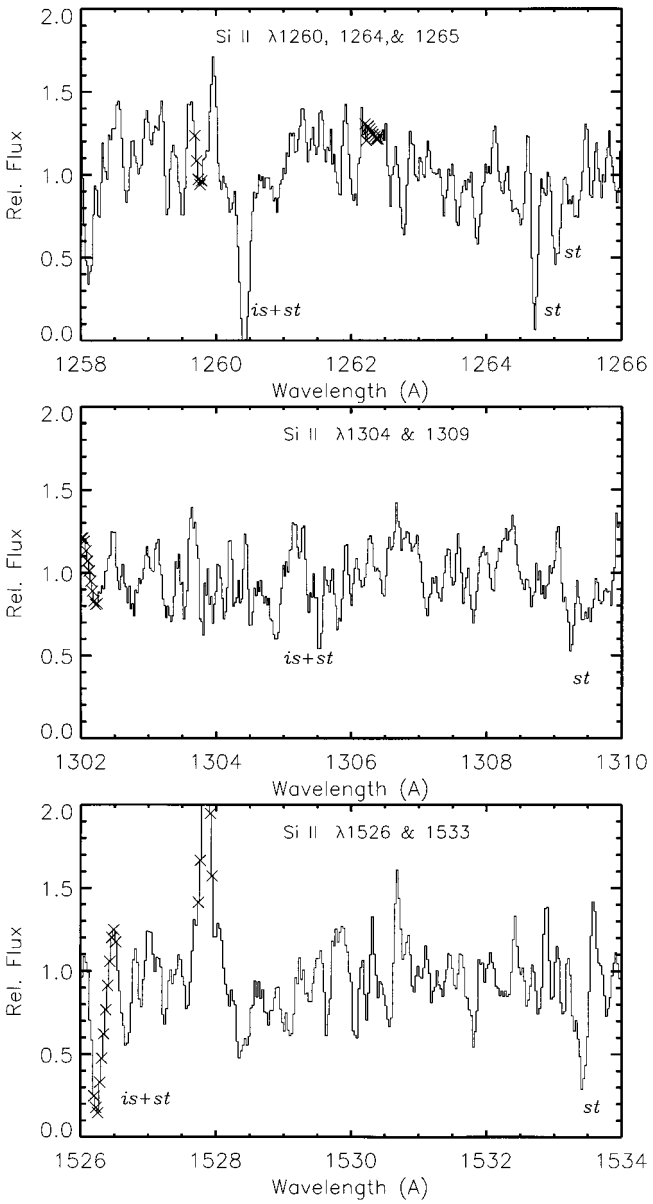


FIG. 2.—*IUE* echelle spectrum of EG 102 showing the stellar Si II features in the regions of the Si II features at 1262, 1306, and 1520 Å. The data have been smoothed over three points.

follow the procedure of Holberg et al. (1996) used with Wolf 1346 and avoid the use of the Si II λ1264 and λ1265 lines owing to concern about their published f-values. In place of these lines, we use the previously unreported λ1309 and λ1533 lines. From those we obtain log (Si/H) = −7.0 ± 0.1. We also make a similar estimate for the C II λ1335 line, on the assumption that it is photospheric rather than interstellar or circumstellar, and find log (C/H) = −5.65 ± 0.20. These estimates can be compared with earlier estimates of log (Si/H) = −7.1 and log (C/H) = −5.8 from VTS. The predicted (Chayer et al. 1995) log Si and C abundances due to radiative levitation are −7.9 ± 0.2 and <−9.0, respectively.

3. DISCUSSION

The presence of Mg in EG 102 is very surprising and provides a new insight into the origin of heavy elements in hot DA stars. In dramatic contrast to Si and C, which may be radiatively supported in a 20,000 K DA star such as EG 102, this explanation is not feasible for Mg. The results of Chayer et al. (1995) clearly show that Mg begins to achieve a significant equilibrium abundance only at temperatures above 40,000 K. The presence of Mg in EG 102 thus requires an external source. The source of the accreting matter could be the ISM in the vicinity of EG 102, if it is dense enough, or an unseen low-mass companion could be transferring matter onto the white dwarf.

While Mg I and Mg II features have previously been noted in cooler ($T_{\rm eff} < 15{,}000$ K) DZ and DA stars (Sion, Kenyon, & Aannestad 1990), this element has not previously been spectroscopically detected in hotter DA stars. In the DZ stars, the presence of Mg and Ca is attributed to the accretion of interstellar matter (Koester & Chanmugam 1990). Existing computations of diffusion times (Paquette et al. 1986) and predicted heavy-element abundances due to accretion (Dupuis et al. 1993) have focused on those He-rich stars and cool DA stars where the convective zone is near the surface and with effective temperatures too low for radiative levitation to be effective. J. Dupuis (private communication) has computed the e-folding time for the diffusive loss of Mg from the photosphere of EG 102 using the formalism of Dupuis et al. (1993) and finds a residence time of only ∼3.3 days. Thus, the Mg in EG 102 cannot be the remnant of a past encounter with a dense interstellar cloud, as has been postulated for DZ stars, but must represent a current equilibrium between accretion and gravitational settling. From Dupuis et al., the total accretion rate (assuming solar abundance) necessary to produce the observed photospheric Mg abundance is $\sim 1.6 \times 10^{-16}\, M_\odot\, {\rm yr}^{-1}$. Using Bondi's (1952) expression for accretion, such rates

TABLE 1

FEATURES PRESENT IN THE SWP SPECTRUM OF EG 102

Ion	Lab (Å)	Observed (Å)	Velocity (km s^{-1})	E.W. (mÅ)
C II.....	1335.7077	1335.637	−15.87	191.7 ± 20
Si II.....	1260.4221	1260.397	−5.97	190.8 ± 20
Si II.....	1526.7066	1526.647	−11.70	68.4 ± 10
S II	1259.519	1259.483	−8.57	25.3 ± 20
.....	...	...	$\langle V_{\rm ISM}\rangle = -10.5 \pm 2$	...
Si II.....	1264.738	1264.697	−9.72	87.8 ± 10
Si II.....	1265.002	1265.017	+3.56	59.7 ± 10
Si II.....	1309.276	1309.228	−10.99	46.5 ± 10
Si II.....	1533.431	1533.413	−3.52	35.3 ± 10
.....	...	...	$\langle V_{\rm PHOT}\rangle = -5.2 \pm 3$	...

could be achieved by a white dwarf moving at 20–40 km s^{-1} with respect to an interstellar cloud of respective densities of $n_H = 1$–10 cm^{-3}. This would constitute a relatively dense interstellar cloud. Little is known concerning the interstellar line of sight to EG 102; however, it does not appear to be unusually dense. Our single *IUE* spectrum shows relatively strong Si II features, but these almost certainly contain significant contributions from the stellar photosphere. A weak S II λ1259 feature appears to be present, but the normally prominent N I triplet at 1200 Å is remarkably weak, if present at all.

An alternate possibility is that EG 102 possesses an unseen companion of very low mass that is transferring material on to the white dwarf, perhaps through thermal evaporation. Probst (1983) included EG 102 in his infrared survey of white dwarfs to search for companions but detected no IR excess. He did note the possible presence of several late-type common proper-motion candidates, but these are too distant to be involved in mass transfer. We can use Probst's *K*-band magnitude of 13.46 ± 0.08 to estimate limits on a possible late-type companion to EG 102. From Bergeron, Wesemael, & Beauchamp (1995), we obtain a predicted value of $V - K = -0.705$ for a DA white dwarf similar to EG 102. Using the observed *V* magnitude, we obtain a predicted value of $K = 13.48$ for EG 102. Allowing for a 3 σ uncertainty in Probst's *K* magnitude, we estimate a limiting excess of 14.92 in the *K* band due to any companion. From the trigonometric parallax for EG 102 (van Altena, Lee, & Hoffleit 1991), this corresponds to $M_K = 12.95$, which effectively rules out any main-sequence companion. A close binary system containing a substellar secondary, however, remains a possibility.

Given that Mg is being accreted, it is natural to consider the possibility that the Si observed in EG 102 is also accreted along with other elements such as Ca, Fe, and O. Spectral features due to Ca are prominent, along with Mg, in many DZ optical spectra; therefore, Ca lines, in particular the H and K lines, might be expected in EG 102. Our present spectra do not usefully extend to the Ca H and K lines, but we have used SYNSPEC to estimate that a Ca abundance of log (Ca/H) > -5.4 would be necessary to produce features with equivalent widths in excess of 0.1 Å; the Ca lines could therefore have been overlooked as was the case for the Mg line. Clearly, additional high S/N UV and optical spectra of EG 102 are called for.

The primary significance of the presence of Mg in EG 102 is that there now exists an example of a DA star, with evidence of ongoing accretion, in the temperature regime where radiative levitation is effective for several heavy elements. If this accretion is interstellar, the possibility of accretion must be considered along with mass loss as a process that can lead to observed abundances that differ from equilibrium predictions. Indeed, accretion may explain superabundances of certain ions such Si in GD 394 (Barstow et al. 1996), while mass loss may be responsible for underabundances observed in other stars such as GD 659 (Holberg et al. 1995a).

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Note added in proof.—D. Koester, J. Provencal, and H. L. Shipman (in White Dwarfs, ed. J. Isern, M. Hernanz, & E. Garcia-Berro [Dordrecht: Kluwer], in press [1996]) have recently discovered a relatively strong Ca II absorption line in the spectra of the cool (11,600 K) DA white dwarf G29-38. They speculate that the presence of metals and the well-known infrared excess in this star can be explained by the accretion of dusty material near the star.