

*Letter to the Editor***The EUV spectrum of the unique bare stellar core H1504+65***Klaus Werner¹ and Burkhard Wolff²¹ Institut für Astronomie und Astrophysik, Universität Tübingen, D-72076 Tübingen, Germany² Institut für Theoretische Physik und Astrophysik, Universität Kiel, D-24098 Kiel, Germany

Received 25 May 1999 / Accepted 5 June 1999

Abstract. We performed a spectral analysis of the EUVE spectrum and ROSAT data of the unique object H1504+65, which is an extremely hot post-AGB star entering the white dwarf cooling sequence. It is the only pre-white dwarf known, whose surface is free of hydrogen and helium, hence, it represents the bare core of a former AGB star. The EUV spectrum (75–150 Å) is dominated by strong O VI lines and we can identify a number of Ne VII lines.

EUVE and ROSAT data can be fitted with models between $T_{\text{eff}}=170\,000\text{ K}$ and $200\,000\text{ K}$. We derive an extraordinarily high neon abundance (2%–5% by mass, i.e. 20–50 times solar) which we confirm by an optical Ne VII line detected in a Keck HIRES echelle spectrum. This abundance is expected for 3α processed matter and corroborates our understanding of H1504+65 as a C-O stellar core which has lost its entire H- and He-rich envelopes.

Key words: stars: abundances – stars: atmospheres – stars: evolution – stars: AGB and post-AGB – stars: white dwarfs – stars: individual: H1504+65

1. Introduction

The optical counterpart of the soft X-ray source H1504+65 was detected by Nousek et al. (1986) and spectroscopy revealed the unique nature of this object. From the spectroscopic signatures it belongs to the PG 1159 stars, which are very hot ($T_{\text{eff}}=75\,000\text{--}180\,000\text{ K}$) hydrogen-deficient pre-white dwarfs ($\log g = 5.5\text{--}8$, cgs-units). But in contrast to all other PG 1159 stars it appeared to be also helium-deficient, which was later confirmed by model atmosphere analyses of optical spectra (Werner 1991) and FUV spectroscopy with the *Hopkins Ultraviolet Telescope* (Kruk & Werner 1998). Detailed NLTE line profile fitting revealed that H1504+65 is the most massive PG 1159 star, having the highest surface gravity, and that it is among the hottest of this group

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* Based on observations with the Extreme Ultraviolet Explorer (EUVE) and ROSAT. Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated by the California Institute of Technology and the University of California.

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($M/M_{\odot} = 0.86 \pm 0.15$, $\log g = 8.0 \pm 0.5$, $T_{\text{eff}}=170\,000\text{ K} \pm 20\,000\text{ K}$; Werner 1991).

H1504+65 is one of the brightest sources in the EUV and an early attempt to understand its spectrum recorded with the *Extreme Ultraviolet Explorer* (EUVE) failed in several respects, particularly the model flux was overestimated by an order of magnitude, however, it became obvious that the spectral appearance is dominated by strong lines of O VI (Barstow et al. 1995). Since that time considerable progress was made in NLTE modeling of stellar atmospheres so that a new attempt to analyze these data together with soft X-ray ROSAT observations and new optical Keck spectra seemed promising.

2. Observations and data reduction

The EUVE spectrum of H1504+65 was retrieved from the public archive. The exposure lasted 38 000 seconds, starting on Dec. 5, 1993. It was reduced (including flux calibration and subtraction of higher order contributions) with the standard procedures of the IRAF/EUV software package (Version 1.6.2). H1504+65 is only detected in the EUVE short wavelength spectrometer because of its relatively high interstellar column density. The observed spectrum covers the range 75–150 Å at a resolution of 0.5 Å .

A useful complement are X-ray ROSAT PSPC data, which were retrieved from the public archive. The observation lasted 4882 seconds, beginning on July 18, 1990. A pulse height distribution was extracted by using the MIDAS-EXSAS software. Source flux is detected in the range 30–120 Å (100–420 eV).

We have performed optical spectroscopy of H1504+65 at the 10m Keck I telescope on July 20, 1998, under excellent weather conditions. We have taken two spectra, which were later co-added, with a total of 6000 seconds exposure time, using the high resolution echelle spectrograph (HIRES) and the blue cross disperser. For details on data reduction see Zuckerman & Reid (1998). The spectrum covers the full wavelength region between 3600 Å and 5100 Å at a resolution of 35 000.

3. Model atmospheres and spectral fitting

We have computed a grid of non-LTE model atmospheres with different input parameters (T_{eff} , $\log g$, element abundances).

The models include the most abundant elements, C and O, as well as Ne and He self-consistently and they are plane-parallel and in radiative and hydrostatic equilibrium. The computer code is based on the Accelerated Lambda Iteration method and is described in detail by Werner & Dreizler (1999).

Let us present the atomic input data at some length, because this is the first detailed analysis of an EUV spectrum of a PG 1159 star with data of this good quality. We note in passing that similar models were applied only in the case of one other PG 1159 star (PG 1520+525; Werner et al. 1996a) from which a useful spectrum could be taken by EUVE. However, the S/N was much worse in that case.

3.1. Potential spectral lines and absorption edges in the EUVE spectrum of H1504+65

No features of He II and C IV are located in the 75–150 Å spectral range, however, C IV absorption edges at longer wavelengths are important because they contribute strongly to the background opacity in the EUVE region. Although C V is the dominant ionization stage of carbon we do not expect to see any of its spectral lines because temperatures are too low to populate excited C V levels. On the other hand, we know from previous studies that the C V ground state edge (31.6 Å) almost completely blocks the flux (Werner et al. 1996b) in a PG 1159 stellar atmosphere. This has no observable influence for the EUVE range, but is important in order to interpret correctly the ROSAT PSPC data.

The strongest opacity source is oxygen. O VI is most important: In the spectral range in question we find two absorption line series arising from the ground state and the first excited state. The respective absorption edges are located at 89.8 Å and 98.3 Å (see Fig. 1, top panel), the latter one causes the flux to drop at $\lambda < 100$ Å. Absorption edges of O V are weaker (because O VI is more populated), but they are more numerous so that their combined opacity is important for the overall flux distribution (Fig. 1). These edges arise from the six lowest O V levels, where we have accounted for the possibility that from any 2s2p configuration either the 2p or 2s electron can be ionized, leaving behind an O VI ion in the ground state or first excited state, respectively; therefore two edges appear at different locations in the spectrum. Spectral lines of O V are less important because of the weak population of this ion and because the line profiles are intrinsically less broad than those of the O VI lines (quadratic vs. linear Stark effect, see below).

Many lines from Ne VII are located in the 80–140 Å range, as well as numerous absorption edges from Ne IV to Ne VII. The edges turned out to be very weak as compared to oxygen, which is of course a consequence of the lower Ne abundance.

Primary source for the used level energies is Bashkin & Stoner (1975). Carbon and oxygen oscillator strengths for spectral lines as well as bound-free cross-sections for photon and electron collisional ionization were largely provided by K. Butler (priv. comm.). Oscillator strengths for Ne VII lines were retrieved from the Opacity Project data base (Seaton et al. 1994), and bound-free cross-sections were computed hydrogen-like (the Ne model atom is essentially identical to that of Werner &

Rauch 1994). Alternatively we have also used Opacity Project photon ionization cross-sections for all species, but the consequences are not relevant for our present study.

Finally we note that helium, for which an upper limit of 1% by mass was derived, does not at all affect the EUV spectrum.

3.2. Line broadening and pressure ionization

Line broadening is a problem which can be tackled only approximately at best, particularly in the most important case, the O VI lines. O VI is a hydrogenic ion. Its energy levels with equal principal quantum number are closely spaced but not degenerate. As a consequence, line broadening ranges between the linear and quadratic Stark regimes. We faced the same problem for optical lines in previous analyses and we refer to Werner et al. (1991) for details on the approximative approach which we apply here, too. For O V and Ne VII lines we assume quadratic Stark broadening, which is reasonable except for the highest members of the O V line series in our synthetic spectra, because linear Stark effects could become important here, too.

Another problem is posed by the numerical treatment of the bound-free photon cross-sections. It is clear from the outset that absorption edges in a stellar spectrum are not really sharp. Pressure effects lower the atomic ionization potential and tend to smear them out (see Fig. 1, top panel). We account for this effect by an occupation probability formalism (Hummer & Mihalas 1988) which was generalized to NLTE conditions by Hubeny et al. (1994). We use essentially their numerical treatment, but two details demand special attention in our case. First, the perturber particles, which impose an electric microfield at the location of the radiating atom, are not protons (as it is the case in atmospheres with solar composition), but highly charged particles (mostly C V and O VII). Consequently the critical field strength β_c as given in Hubeny et al. (1994; their Eq. A.2) needs to be scaled by $C^{1/3}$, where C is the ratio of the total ion density to the electron density, n_{Ion}/n_e . And second, the plasma correlation parameter a , which is defined as the ratio of the mean distance of ions to the Debye length, needs to be scaled, so that we have instead of their Eq. A.4:

$$a = 0.09 \frac{n_e^{1/6}}{\sqrt{T}} \left(1 + \sum_i Z_i^2 N_i / n_e \right)^{1/2} \left(\sum_i N_i / n_e \right)^{-1/3}$$

where N_i and Z_i are the number density and charge of the i -th ion, respectively, and n_e and T are the electron density and temperature. This procedure is formulated strictly for hydrogenic ions only and, hence, applicable for O VI, but we also treat the O V edges in this way, because we lack any better approach. But since the O V edges are weak, this uncertainty is not important for our analysis.

To summarize, the most severe uncertainty in the synthetic spectrum calculations is the lack of a satisfactory treatment of O VI line broadening, because strong O VI line merging has a significant effect on the overall shape of the EUV spectrum. Theoretical line broadening data exist for only few of the O VI

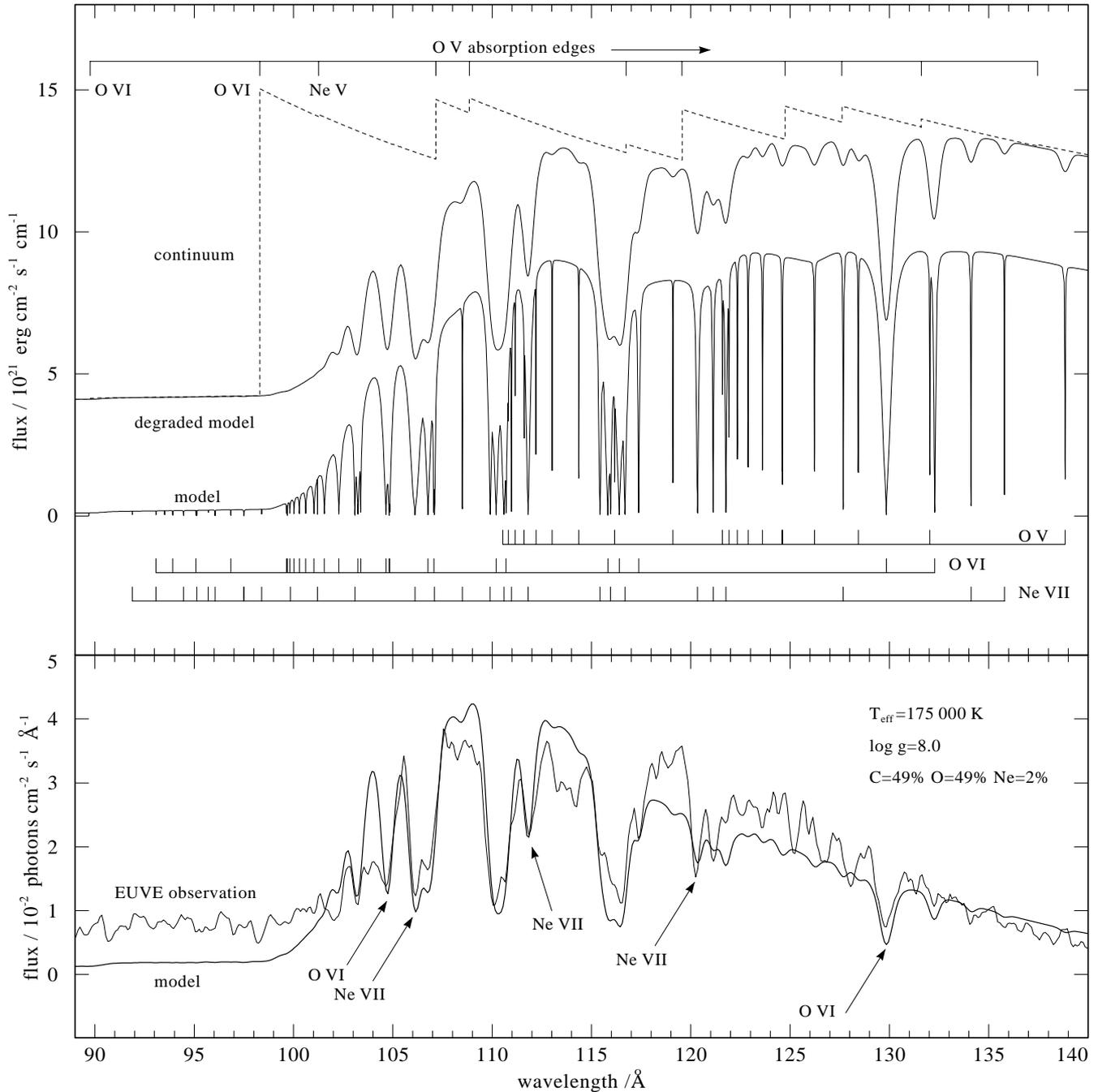


Fig. 1. *Top panel:* Emergent flux of a model with $T_{\text{eff}}=175\,000\text{ K}$, $\log g=8$. Shifted upward is the same model spectrum but degraded with a 0.5 \AA FWHM Gaussian. Overplotted (dashed line) is the continuum flux computed without occupation probabilities in order to display the position of the absorption edges. They are smeared out by atomic level dissolution and broad absorption lines. The spectrum is dominated by strong and broad O VI lines and less prominent O V and Ne VII lines. *Bottom panel:* Comparison of the observed EUVE spectrum with this model (attenuated by an interstellar column density $N(\text{H I}) = 5.1 \cdot 10^{19}\text{ cm}^{-2}$ with $\text{He II}/\text{H I} = 0.068$ and $\text{He I}/\text{H I} = 0.052$)

lines relevant here, but these do not account for linear Stark effects (Dimitrijevic & Sahal-Brechot 1992).

3.3. Iron group elements

EUVE spectra of hot hydrogen-rich white dwarfs are completely dominated by iron and nickel lines and bound-free continua

(e.g. Wolff et al. 1998), hence, it was felt mandatory to check the relevance of these opacities in the case of H1504+65. Model calculations show that effects of the iron group elements (with a solar abundance fraction) are not detectable at the resolution and S/N level of the present EUVE spectrum. Continuous opacities of the Fe group are negligibly small compared to the dominant species. On the other hand, our model predicts that a large num-

ber of lines should be detectable in future observations with the Chandra X-ray observatory, which will be able to provide spectra with higher resolution and better S/N.

3.4. Treatment of interstellar absorption in synthetic spectra

EUV and soft X-ray spectra are very sensitive to absorption from interstellar hydrogen and helium. For the EUVE spectrum this attenuation was calculated according to the model of Rumph et al. (1994). The interstellar column density of neutral hydrogen ($N(\text{H I})$) enters as a free parameter. It was chosen so that the observed flux could be reproduced at $\lambda \gtrsim 130 \text{ \AA}$. The column densities of He I and He II were fixed relative to hydrogen using the mean values of $\text{He I}/\text{H I} = 0.068$ and $\text{He II}/\text{H I} = 0.052$ from Wolff et al. (1999).

For the ROSAT PSPC pulse height distribution we have also used fixed relative abundances for helium (see Jordan et al. (1994) for details of the analysis). Since different spectral regions are used to determine the interstellar absorption the $N(\text{H I})$ values from the ROSAT and EUVE analyses differ.

4. Results and discussion

In the top panel of Fig. 1 we display a model spectrum for H1504+65. The numerous O and Ne lines are identified and close inspection shows that the O VI lines are strongest. Line blending with O V and Ne VII occurs at many locations and the degraded spectrum (shifted upward in the Figure) which simulates the EUVE resolution of 0.5 \AA demonstrates that disentangling of single lines becomes difficult. However, it is possible to identify a few isolated lines or line cores of O VI and Ne VII which are indicated by arrows in the lower panel of Fig. 1. The roll-over of the flux towards shorter wavelengths is caused by the strong absorption edge of the first excited level of O VI at 98 \AA , which can be seen by the dashed line in the top panel of Fig. 1 which represents the continuum flux of the model. As already mentioned, the sharp absorption edge is strongly smoothed out by pressure effects as well as the converging absorption line series. For the same reason all other absorption edges which are indicated in Fig. 1 cannot be recognized in the final model spectrum.

4.1. Effective temperature

The best fitting model was found by taking models with different T_{eff} and keeping fixed $\log g = 8$ and the abundance ratio $\text{C}/\text{O}=1$. The latter two parameters, when varied within the limits of the optical line analysis, affect the model spectrum much less than T_{eff} . The model flux is normalized to the observed visual magnitude ($V=16.24$, Nousek et al. 1986) and the interstellar column density, which is responsible for the roll-off at the long wavelength end of the spectrum, is treated as a free parameter. The neon abundance can be estimated from the Ne VII line near 106 \AA which is observed to have a deeper core than the blending O VI lines near 107 \AA .

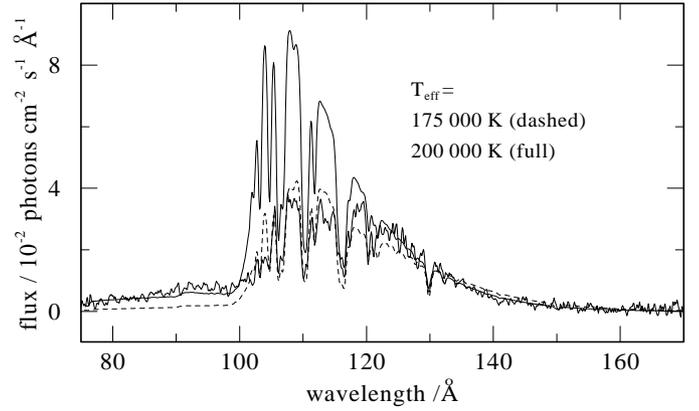


Fig. 2. EUVE spectrum as compared to two models with different T_{eff} : 175 000 K (dashed line) and 200 000 K (full line). The hot model fits the flux at $\lambda < 100 \text{ \AA}$, but overestimates the maximum flux by a factor of two. Interstellar columns are $N(\text{H I}) = 5.1 \cdot 10^{19} \text{ cm}^{-2}$ and $6.0 \cdot 10^{19} \text{ cm}^{-2}$, respectively. Other model parameters as in Fig. 1

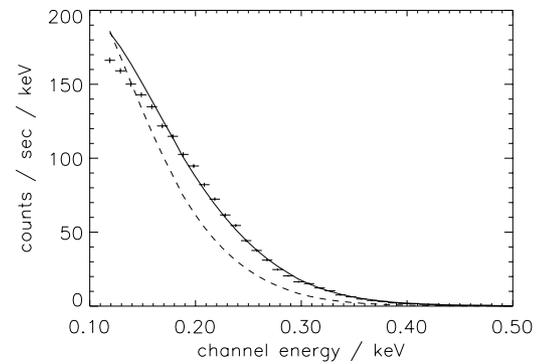


Fig. 3. The same models which were fitted to the EUVE spectrum in Fig. 2 are here compared to the ROSAT PSPC pulse height distribution. The 175 000 K model (dashed line) cannot fit the data but the 200 000 K model (full line) does, except for the softest channels (see text for discussion). Interstellar columns are $N(\text{H I}) = 5.75 \cdot 10^{19} \text{ cm}^{-2}$ and $9.5 \cdot 10^{19} \text{ cm}^{-2}$, respectively

The best fit is displayed in the bottom panel of Fig. 1, with model parameters as indicated. The overall fit is satisfactory. The strongest O VI and Ne VII line features can be identified and the model can fit them. The absolute flux level at the flux maximum and at longer wavelengths is matched by the model with $T_{\text{eff}}=175 \text{ 000 K}$. Models with T_{eff} less than 170 000 K can be clearly ruled out, because the O V absorption edges become too strong. On the other hand, T_{eff} higher than 180 000 K causes a strong flux excess in the region of the observed flux maximum.

However, in one respect this model fails to fit the observation. Its flux is distinctly too low at $\lambda < 100 \text{ \AA}$. This could in principle be improved with a hotter model (200 000 K, along with a higher column density to fit the spectrum at long wavelengths), but the flux exceeds the maximum by a factor of two in the range $100\text{--}120 \text{ \AA}$ (Fig. 2). This is the range where strong O VI line merging occurs and it is conceivable that, in case that we underestimate the O VI line broadening, stronger line wings can effectively block more flux in this region. Alternatively, yet

unidentified opacity sources of other light metals may be responsible (e.g. Mg might be as abundant as Ne, and many Mg v and Mg vi lines are located in the EUV), but any progress must await data with better spectral resolution.

Another argument that speaks for T_{eff} slightly higher than 175 000 K is the strength of the optical Ne VII 3644 Å line (the very strong EUV lines of Ne are much less temperature sensitive). A better fit is obtained at 200 000 K, although still, the equivalent width is too weak (Fig. 4). This can be improved by reducing $\log g$ to 7.5 and/or increasing the Ne abundance (see below).

As one can expect from the EUVE flux below 100 Å, the ROSAT PSPC pulse height distribution (120–30 Å) cannot be matched by the “cool” 175 000 K model (Fig. 3). A model with $T_{\text{eff}}=200\,000\text{ K}$ is needed to obtain a satisfactory fit (where we accept a model flux excess at the softest energies, which might be caused by the underestimated flux blocking in the 100–120 Å range as mentioned above).

To summarize, we estimate $T_{\text{eff}}=170\,000\text{--}200\,000\text{ K}$ from the EUV and X-ray data, which compares reasonably well with the range obtained previously from the optical spectra ($T_{\text{eff}}=150\,000\text{--}190\,000\text{ K}$). This indicates that H1504+65 approaches or even exceeds the temperature of the hottest known PG 1159 star ($T_{\text{eff}}=180\,000\pm 20\,000\text{ K}$; RX J0122.9–7521; Werner et al. 1996b).

4.2. Neon abundance

The EUV spectrum indicates a high neon abundance (2%), which is a factor of 20 higher than the solar value. We estimate a possible error of a factor of three, which is caused by the S/N of the data and the fact that the strong Ne VII lines are saturated. Our first detection of the Ne VII 3644 Å line in the Keck spectrum of H1504+65 (a previous attempt with the 3.5m Calar Alto telescope failed) indicates, that the actual abundance might be even higher. Fig. 4 shows several model fits to this line. Even under the assumption of a lower gravity ($\log g=7.5$), which represents the lower limit of the optical analysis and which results in a stronger line, the relatively strong observed profile suggests an abundance of the order 5%. We successfully detected this line earlier in three other PG 1159 stars (Werner & Rauch 1994) and, as discussed in detail in that paper, the derived Ne abundance (2%) can be expected in matter processed by 3α burning. This high abundance can be rated as an indication that the stars have lost their H- and He-rich envelopes, with H1504+65 being the most extreme case.

We have already speculated that the He-deficiency in H1504+65 points at the possibility that the star has burned carbon in previous evolutionary stages (Werner 1991). Hence, it might have been one of the “heavyweight” intermediate-mass stars ($8M_{\odot} \lesssim M \lesssim 10M_{\odot}$) which form white dwarfs with electron-degenerate O-Ne-Mg cores resulting from carbon burning. The extraordinarily high Ne abundance found in the present study and the unusually high mass of H1504+65 corroborate this speculation. In any case, the Mg and Na abundances can be as high as the Ne abundance (Iben et al. 1997),

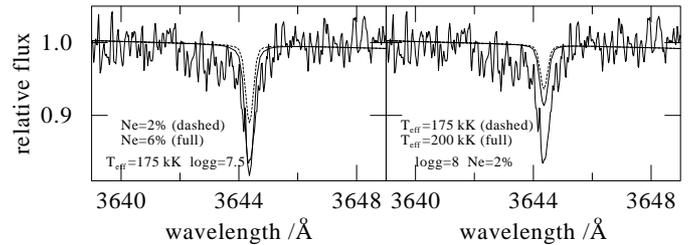


Fig. 4. The Keck spectrum shows the Ne VII 3644 Å line and its strength confirms the high neon abundance deduced from the EUV lines. *Left panel:* Profiles from the two models fitted to EUVE and ROSAT data in Figs. 2 and 3. With Ne=2% (20 times solar value) the profiles are still too weak, however, they are also gravity dependent, as can be seen in the *right panel* ($\log g$ decreased from 8 to 7.5). It suggests that the Ne abundance might be even higher than 2%

so that better EUV spectra, which can be provided by the future Chandra mission, should be used for further studies in this direction with a possible identification of other metal lines.

Acknowledgements. Keck data were taken in collaborative observations with I.N. Reid. A travel grant from the DFG (We 1312/21-1) to the Keck Observatory is gratefully acknowledged. ROSAT data analysis in Tübingen and Kiel is supported by the DLR under grants 50 OR 97055 and 50 OR 96173, respectively. Correspondence with I. Hubeny on occupation probabilities was helpful.

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