Discovery of photospheric Ca X emission lines in the far-UV spectrum of the hottest known white dwarf (KPD 0005+5106)*

K. Werner1, T. Rauch1, and J. W. Kruk2

1 Institut für Astronomie und Astrophysik, Kepler Center for Astro and Particle Physics, Eberhard-Karls-Universität, Sand 1, 72076 Tübingen, Germany. e-mail: werner@astro.uni-tuebingen.de
2 Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

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ABSTRACT

For the first time, we have identified photospheric emission lines in the far-UV spectrum of a white dwarf. They were discovered in the Far Ultraviolet Spectroscopic Explorer spectrum of the hot (Teff ≈ 200 000 K) DO white dwarf KPD 0005+5106 and they stem from extremely highly ionized calcium (Ca X λλ 1137, 1159 Å). Their photospheric origin is confirmed by non-LTE line-formation calculations. This is the highest ionisation stage of any element ever observed in a stellar photosphere. Calcium has never been detected before in any hot white dwarf or central star of planetary nebula. The calcium abundance determination for KPD 0005+5106 (1-10 times solar) is difficult, because the line strengths are rather sensitive to current uncertainties in the knowledge of effective temperature and surface gravity. We discuss the possibility that the calcium abundance is much lower than expected from diffusion/levitation equilibrium theory. The same emission lines are exhibited by the [WCE]-type central star NGC 2371. Another Ca X line pair (λλ 1461, 1504 Å) is probably present in a Hubble Space Telescope spectrum of the PG1159-type central star NGC 246.

Key words. Stars: abundances – Stars: atmospheres – Stars: evolution – Stars: AGB and post-AGB – White dwarfs

1. Introduction

Observations of hot (pre-) white dwarfs with the Far Ultraviolet Spectroscopic Explorer (FUSE) have revealed a large number of chemical elements that were never detected before in these objects. Their abundances can be used either to probe interior processes in previous stellar evolution phases or to test predictions from theories for element destruction or to test predictions from theories for element destruction.

We have recently identified Ne viii lines in the hottest (Teff ≥ 150 000 K) non-DA (pre-) white dwarfs, i.e. objects of spectral type PG1159, DO, and [WCE] (Werner et al. 2007). The discovery of these lines in the hottest known DO white dwarf KPD 0005+5106 was particularly surprising, because this proves that its effective temperature must be much higher than previously thought (200 000 K instead of 120 000 K).

KPD 0005+5106 was frequently observed by FUSE as a calibration target over its entire lifetime. We have co-added all available spectra and obtained datasets with very high S/N ratio. A careful inspection of spectra taken with different detectors revealed the presence of two hitherto unidentified emission lines. While there is still a large number of unidentified absorption lines present in FUSE spectra of hot white dwarfs (WDs), the discovery of emission features is unique and was completely unexpected. In this Letter we identify them as Ca X lines and present results of non-LTE modeling in order to confirm their photospheric origin and to perform an abundance determination.

We present observations and line identifications in Sect. 2 and describe the modeling in Sect. 3. The results from line-profile fits are presented in Sect. 4. We conclude with Sect. 5.

* Based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer. FUSE is operated for NASA by the Johns Hopkins University under NASA contract NAS5-32985.
Fig. 1. The two Ca X emission lines discovered in KPD 0005+5106 (thin graphs). Overplotted is the spectrum from a model with \( T_{\text{eff}} = 200,000 \) K, log \( g = 6.2 \), and solar Ca abundance. The model was convolved with a Gaussian with FWHM = 0.05 Å in order to match the instrumental resolution.

**Fig. 2.** Grotrian diagram of our Ca X model ion. Lines discussed in the text are caused by transitions between \( n = 4 \) sublevels. The 4p\(^{-}\)4d transition causes the observed UV emission lines.

aboard the *Hubble Space Telescope* (*HST*) was retrieved from the MAST archive.

In the *FUSE* spectrum of KPD 0005+5106 we detected two emission lines, located at photospheric rest wavelengths \( \lambda \lambda 1136.5, 1159.2 \) Å (Fig. 1), radial velocity +35 km \( s^{-1} \); Werner et al. 1996). We identify these lines as due the 4p\(^{-}\)2S – 4d\(^{-}\)2P\(^{o}\) transition in the Ca X ion (Fig. 2). Compared to the Ritz wavelengths in the NIST\(^1\) database, both observed lines are located at wavelengths shorter by 0.3 Å. Their NIST \( gf\)-values are \( \log gf_{ik} = 0.23 \) and 0.46, respectively. The third line component of this transition is located at \( \lambda 1161.4 \) Å according to NIST, so that in reality we expect it to be found at \( \lambda 1161.1 \) Å. Its \( gf\)-value, however, is much smaller (\( \log gf_{ik} = -0.47 \)) explaining the fact that we cannot detect it in the observation. (This is confirmed by our line-formation calculations.)

We searched for the two Ca X lines in other hot DO white dwarfs and PG1159 stars, but to no avail. As we will demonstrate below (Sect. 4), this is a consequence of the extremely high \( T_{\text{eff}} \) of KPD 0005+5106 combined with a relatively low surface gravity. However, these lines are seen in the very hot, early-type Wolf-Rayet central star NGC 2371 (Fig. 3). For this object we did not attempt to fit these lines with our (static) model atmospheres, because the profiles might be affected by the stellar wind.

In the course of our model calculations we found that further Ca X lines might be detectable in other wavelength regions. The 4s–4p transition gives rise to a line doublet at \( \lambda \lambda 1461.8, 1503.8 \) Å. Our models predict only marginal emission features for KPD 0005+5106, which cannot be detected in archival spectra taken with the *Faint Object Spectrograph* aboard *HST* and high-resolution spectra from the *International Ultraviolet Explorer*. However, for NGC 246 our models predict absorption lines that are possibly present in a *HST/STIS* spectrum (Fig. 4). The positions of the tentatively identified absorption features in NGC 246 differ from the NIST wavelengths by −0.7 and −0.2 Å, respectively.

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\(^1\) http://physics.nist.gov/PhysRefData/ASD/index.html
From NIST level energies one expects the two strongest lines of yet another transition of Ca X (4d–4f) to be located in the optical UV at λλ 3478, 3492 Å, respectively. A high-resolution spectrum of NGC 246 taken with ESO’s Very Large Telescope and the UVES spectrograph as part of the SPY survey (Napiwotzki et al. 2003) reveals no line features there. Our model for NGC 246 predicts absorption lines with a depth of only 5% relative to the continuum. The relatively fast rotation (v sin i = 70 km s\(^{-1}\)) smears the line features considerably, and they remain hidden in the noise. Similar weak absorption profiles for these lines are predicted for KPD 0005+5106, but no appropriate observations are available.

3. Model atmospheres and calcium line-formation

We have designed a calcium model atom for NLTE line-formation calculations. These were performed using and keeping fixed the physical structure (temperature, densities) of line-blanketed NLTE model atmospheres which are described in detail in Werner et al. (2004). In short, they are plane-parallel and in hydrostatic and radiative equilibrium. The models are composed of He, C, O, and Ne. For KPD 0005+5106, we assumed helium-dominated atmospheres with admixtures of C=0.003, O=0.0006, Ne=0.01 (mass fractions). The high neon abundance was derived from Ne vii lines (Werner et al. 2007). The C and O abundances are uncertain, because they were derived in earlier work that assumed that KPD 0005+5106 is relatively cool (T\(_{\text{eff}}\) = 120 000 K; Werner et al. 1996). We verified that varying the C and O abundances within reasonable limits does not change the Ca X lines significantly. A series of models with various T\(_{\text{eff}}\) and log g values was computed to study the dependency of the Ca X lines on these parameters (see Sect. 2). For NGC 246 we adopted T\(_{\text{eff}}\) = 150 000 K, log g = 5.7, and the composition He/C/O/Ne=0.62/0.30/0.06/0.02 (Werner et al. 2007).

The Ca model atom considers the ionization stages viii–xii, represented by 1, 15, 25, 4, 1 NLTE levels, respectively, plus a number of LTE levels. In the ions Ca_x–xii we include 23, 126, and 2 line transitions, respectively. Atomic data were taken from the NIST, Opacity (Seaton et al. 1994), and ISON (Hummer et al. 1993) Projects databases (TIPTOPbase 4). Fine-structure splitting is accounted for in the final formal solution for the synthetic line-profile computation, distributing the level populations among sublevels assuming LTE. For all lines we assumed quadratic Stark broadening for the profile calculation.

http://cdsweb.u-strasbg.fr/topbase/

2 http://cdsweb.u-strasbg.fr/topbase/

3 http://www.g-vo.org
4 http://astro.uni-tuebingen.de/~rauch/ TMAD/ TMAD.html

Fig. 4. HST/STIS spectrum of the PG1159-type central star NGC 246 and computed profiles for the 4s–4p doublet of Ca X. Their shape reflects the stellar rotation of v sin i = 70 km s\(^{-1}\). The observation was smoothed with a Gaussian with FWHM=0.03 Å.

Fig. 5. Ionization fraction of calcium as a function of atmospheric depth in the model with T\(_{\text{eff}}\) = 200 000 K, log g = 6.2, and solar Ca abundance.

Particularly for the Ca X λλ 1137, 1159 Å lines the values of the oscillator strengths differ between the OP and NIST databases. We use the OP values for our NLTE level population iterations, because they are complete, in contrast to the NIST database. For the final line-profile calculation we prefer the NIST values, which are higher than the OP values by ∼25%. The differences do not affect our conclusions.

Photoionization cross-sections are taken from the Opacity Project database when available or, otherwise, computed in a hydrogen-like approximation. Electron collisional rates were calculated with the usual approximation formulae. The Ca model atoms that were used for this analysis have been developed in the framework of the German Astrophysical Virtual Observatory (GAVO) project and are provided within the Tübingen Model-Atom Database TMAD 4.

4. Results

Figure [1] shows a fit to the Ca X emission lines in KPD 0005+5106 with a model T\(_{\text{eff}}\) = 200 000 K, log g = 6.2, and a solar Ca abundance (log Ca = −4.22, mass fraction; Asplund et al. 2005). In Fig. 5 we show the ionization structure of Ca throughout this model atmosphere. Within the entire line-forming region Ca xii is dominant, followed by Ca x. In order to achieve the observed emission strength in a model with this temperature and Ca abundance, the surface gravity must be that low (log g = 6.2). This is 0.3 dex lower than what is preferred from the He ii line spectrum (Werner et al. 2007). We will show, however, that the fit to the Ca X lines can be achieved with more than one parameter set.

The occurrence of this line emission can be understood when the non-LTE departure coefficients b\(_{ij}\) = n\(_{i}^{\text{NLTE}}\)/n\(_{i}^{\text{LTE}}\) for the populations n\(_{i}\) of the involved atomic levels and the line source function S\(_{i}\) are inspected (Fig. 6). The line source function is determined by the ratio of the departure coefficients of the higher and lower levels (i, j) and can be written as S\(_{ij}\) = [exp(hν\(_{ij}\)/kT) − 1]/[(b\(_{ij}\)/b\(_{ji}\)) exp(hν\(_{ij}\)/kT) − 1], where b\(_{ij}\) is the Planck function. An overpopulation of the upper level relative to the lower (i.e. S\(_{ij}\)/B\(_{ij}\) > 1) may lead to line emission. In fact, this condition is fulfilled in the line-forming region (Fig. 6), although both levels are underpopulated (i.e. b\(_{ij}\) < 1).
We have computed a small grid of models with different $T_{\text{eff}}$ and log $g$ (representing the uncertainties with which these parameters are known) and Ca abundances. The results are presented in Fig. 7. Generally, high $T_{\text{eff}}$ and low log $g$ is necessary in order to bring this line into emission (left and right upper panels). If $T_{\text{eff}}$ decreases (and/or log $g$ increases), the lines first turn from emission into weak absorption features and then disappear at about 140,000 K. This explains why other DOs do not exhibit these lines: they are significantly cooler and have higher gravities compared to KPD 0005+5106.

The sensitivity of these emission lines to the calcium abundance is complicated and depends on $T_{\text{eff}}$ and log $g$ of the atmosphere (Fig. 2 left and right lower panels). Increasing the Ca abundance over the solar value can strongly increase the emission height (model $T_{\text{eff}}=200,000$ K, log $g=6$) or decrease it (model $T_{\text{eff}}=200,000$ K, log $g=6.5$). For KPD 0005+5106 we achieved a good fit at $T_{\text{eff}}=200,000$ K, log $g=6.2$, and solar Ca abundance. As mentioned, however, our previous analysis favors a gravity higher by 0.3 dex. Increasing the gravity to log $g=6.5$ makes the emission weaker, but this can be compensated by simultaneously increasing the Ca abundance to 3 times the solar value and $T_{\text{eff}}$ to 220,000 K. A much higher abundance, as predicted by diffusion theory, can be excluded. We have calculated models with 70 times solar Ca abundance. The emission line peak heights hardly change in the $T_{\text{eff}}=200,000$ K, log $g=6.2$ model when Ca is increased from solar to 70 times solar; however, detailed inspection of the relative strength of both lines shows that it is not in agreement with the observation. In the observation as well as in the ≈ solar Ca abundance models the 1159 Å emission is stronger than the 1137 Å emission, as can be expected from the $gf$-value ratio. In the 70 times solar models the emission strength ratio is reversed, in contrast to the observation.

Concerning PG1159 stars, the behaviour of these Ca lines is rather similar and therefore not shown in detail here. There are seven objects that are hot enough and for which $FUSE$ spectroscopy is available. These are the low-gravity central stars of planetary nebulae K1-16, Longmore 4, RXJ2117.1+3412, NGC246 ($T_{\text{eff}}=140,000–170,000$ K, log $g≈5.5$–6), the higher-gravity objects PG1520+525 and PG1144+005 ($T_{\text{eff}}=150,000$ K, log $g=6.5$–7), as well as the peculiar H1504+65 ($T_{\text{eff}}=200,000$ K, log $g=8$). Model calculations were performed for all of these models with solar Ca abundance (diffusion is not at work in these objects’ atmospheres; see Unglaub & Bues 2000). They exhibit the expected from the 1159 Å emission is stronger than the 1137 Å emission, as can be seen. However, detailed inspection of the relative strength of both lines shows that it is not in agreement with the observation. In the 70 times solar Ca abundance models the 1159 Å emission is not possible. A comparison of this result with predictions from radiative levitation/gravitational diffusion equilibrium theory is difficult because $T_{\text{eff}}$ and log $g$ of KPD 0005+5106 are outside of the range considered by Chayer et al. (1995; their Fig. 20). For the closest parameters ($T_{\text{eff}}=130,000$ K, log $g=7$) a huge overabundance is predicted (2500 times solar). Our estimate for log $g$ is smaller (6.2–6.5) which would result in an even higher overabundance. On the other hand it is impossible to make a solid estimate for the effect of the higher $T_{\text{eff}}$ (200,000–220,000 K) on the behaviour of the Ca equilibrium abundance, because the dominant ionisation stage in KPD 0005+5106 is Ca x, while it is Ca viiii in the hottest Chayer et al. model ($T_{\text{eff}}=130,000$ K, log $g=7.5$). Looking at the behaviour of other elements (S, Ar), namely how their equilibrium abundance changes when their (respective isoelectronic) ionisation stages increase (with increasing $T_{\text{eff}}$), it is suggestive that the Ca abundance at $T_{\text{eff}}=200,000$ K is lower than at 130,000 K, but not by orders of magnitude. Although detailed calculations are required.

**Fig. 6.** Left: Departure coefficients $b_i$ for the 4p and 4d levels that cause the Ca X emission lines. Right: Ratio of 4p–4d line source function $S_i$ to Planck function $B_e$ at line centre. The thick horizontal lines near log $m=0$ denote the line formation region. Dashed lines correspond to the LTE case ($b_i=1$ and $S_i/B_e=1$). Model parameters as in Fig. 5.

**Fig. 7.** Profile shapes of the Ca X λλ 1137, 1159 Å lines as a function of $T_{\text{eff}}$, log $g$, and Ca abundance, as given by the labels.
for a definitive statement, we conclude that the atmosphere of KPD 0005+5106 is probably not in levitation/diffusion equilibrium. This is confirmed by the diffusion/mass-loss calculations of Unglaub & Bues (2000) which suggest that KPD 0005+5106 has yet to cross the wind-limit on its evolutionary track, meaning that mass-loss is large enough to prevent both gravitational settling and the accumulation of radiatively supported heavy elements. In this case, KPD 0005+5106 is not a descendant of the PG1159 stars. An evolutionary link to the He-dominated central stars of spectral type O(He) and to the RCrB stars has been suggested (Werner et al. 2008).

If unaffected by diffusion processes, then the photospheric composition of KPD 0005+5106 is the consequence of previous evolutionary phases. In contrast, the presence of Ca in the atmospheres of cooler white dwarfs (spectral types DAZ and DBZ, with low-ionisation optical Ca absorption lines) requires on-going accretion of circumstellar matter, because gravitational settling rapidly removes heavy elements from the photosphere (e.g. Koester & Wilken 2006).

The non-detection of the Ca X λλ 1137, 1159 Å lines in the hottest PG1159 stars is explained by undetectably weak absorption line features in the models. Another Ca X line pair (λλ 1462, 1504 Å) is possibly present in absorption in NGC 246 and suggests a roughly solar Ca abundance. The only other object in which we discovered the Ca X λλ 1137, 1159 Å emission lines is the [WCE]-type central star NGC 2371. This corroborates the extraordinarily high effective temperature of this object.

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