Observational constraints on the evolutionary connection between PG 1159 stars and DO white dwarfs

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Abstract. The Sloan Digital Sky Survey has provided spectra of a large number of new PG 1159 stars and DO white dwarfs. This increase in known hot H-deficient compact objects significantly improves the statistics and helps to investigate late stages of stellar evolution. We have finished our analyses of nine PG 1159 stars and 23 DO white dwarfs by means of detailed NLTE model atmospheres. From the optical SDSS spectra, effective temperatures, surface gravities, and element abundances are derived by using our new automated $\chi^2$-fitting in order to place the observed objects in an evolutionary context. Especially the connection between PG 1159 stars and DO white dwarfs has been investigated.

1. Introduction

PG 1159 stars are evolutionary transition objects between the hottest post-AGB and WD phases. The Palomar Green (PG) survey put forth the prototype of this spectroscopic class, PG 1159-035 (Green et al. 1986). It shows a spectrum without detectable hydrogen lines and is instead dominated by He \textsuperscript{II} and highly ionised carbon and oxygen lines. PG 1159 stars display a characteristic broad absorption trough around 4670 \AA\ composed of He \textsuperscript{II} 4686 \AA\ and several C \textsuperscript{IV} lines, suggesting high effective temperatures. Spectral analyses yield $T_{\text{eff}} = 75\,000 - 200\,000$ K and surface gravities of $\log g = 5.5 - 8.0$ (Werner et al. 1991; Dreizler et al. 1994; Werner et al. 1996). Of the 29 PG 1159 stars known prior to the SDSS, ten are low-gravity (subtype lgE, Werner 1992) stars, placing them in the same Hertzsprung-Russell-Diagram (HRD) region as the hot central stars of planetary nebulae (CSPNe), while the others are more compact objects with surface gravities of WDs (subtype A or E). Due to their rarity, the majority of the known PG 1159 stars were discovered in large surveys (Palomar Green, Hamburg Schmidt (HS), Hagen et al. 1995). The most recent and only discovery
Within the last 10 years, besides those from the SDSS (Werner et al. 2004), was an object from the Hamburg ESO (HE) survey (Wisotzki et al. 1996). The SDSS thus offers a new and currently unique opportunity to increase the number of known PG 1159 stars.

White dwarfs can be separated into two distinct spectroscopic classes, DA and non-DA white dwarfs. The former show a pure hydrogen spectrum and can be found over the entire WD cooling sequence. The latter fall into three subclasses: DO (45,000 K < \( T_{\text{eff}} \) < 120,000 K), DB (11,000 K < \( T_{\text{eff}} \) < 30,000 K), and DC / DQ / DZ white dwarfs (\( T_{\text{eff}} \) < 11,000 K; pure continuum / carbon / metal lines present). The classification of white dwarfs of subtype DO and DB is determined by the ionisation balance of He \( \text{i} \) and He \( \text{ii} \). DO white dwarfs show a pure He \( \text{ii} \) spectrum at the hot end and a mixed He \( \text{i} \)/He \( \text{ii} \) spectrum at the cool end. The transition to the cooler DB dwarfs, characterised by pure He \( \text{i} \) spectra, is interrupted by the so-called “DB-gap” (Liebert et al. 1986). In the HRD region of white dwarfs with 30,000 K < \( T_{\text{eff}} \) < 45,000 K, no objects with H-deficient atmospheres have been observed to date. However, Eisenstein et al. (2006a) describe over 25 objects taken from SDSS DR4 data which likely fall in that temperature region. These new objects might increase our knowledge of the spectral evolution of He-rich white dwarfs considerably.

The region in the HRD occupied by the PG 1159 stars overlaps with that of the DO white dwarfs. Therefore, it is assumed that gravitational settling of the heavier elements in the atmosphere of the PG 1159 stars leads them to transition towards DO white dwarfs. Diffusion calculations by Unglaub & Bues (2000) support this assumption. They show that the decrease of winds from PG 1159 stars leads to a rapid settling of the CNO elements.

2. Models and fitting

For the PG 1159 stars in our sample, we calculated NLTE model atmospheres with TMAP, the Tübingen NLTE Model Atmosphere Package (Werner et al. 2003; Rauch & Deetjen 2003), using detailed H – He – C – N – O model atoms. The model grid ranges from \( T_{\text{eff}} = 55,000 \) – 150,000 K and \( \log g = 5.5 \) – 7.8. The abundances are fixed to values He/H = 100 and C/He = 0.01 – 0.11 (in steps of 0.02), 0.20, 0.30, or 0.60 (number ratio). We have a nearly complete model grid with \( T_{\text{eff}} = 55,000 \) – 110,000 K in steps of 5,000 K, \( \log g = 6.4 \) – 7.8 in steps of 0.2 dex, and C/He = 0.01 – 0.11 in steps of 0.02. Complete coverage of the whole parameter space is not yet available due to the high computational time required to compute the model atmospheres. However, the majority of the analysed PG 1159 stars are covered by our nearly complete model grid. Best-fit models for PG 1159 star candidates were calculated with an oxygen abundance following the typical PG 1159 abundance-scaling ratio O/C \( \approx C/\text{He} \). However, variations in the oxygen abundance do not produce a significant effect on the other stellar parameters. The nitrogen abundance is kept fixed at N/He = 0.01 by number which is a typical upper limit for PG 1159 stars.

Detailed H – He atomic models (Dreizler & Werner 1990) were used to calculate our NLTE model atmospheres for the DO white dwarfs. The model grid ranges from \( T_{\text{eff}} = 40,000 \) – 120,000 K in steps of 2,500 K, \( \log g \) ranges from 7.0 to 8.4 in intervals of 0.2 dex. The helium abundance is fixed to He/H = 99.
In order to derive a best-fit model we applied a \( \chi^2 \)-analysis. The noise level \( \sigma \) of the observed spectrum has been determined using a Savitzky-Golay smoothing filter (Savitzky & Golay 1964). The observation was then normalised to unity with the help of the normalised model spectrum. Given the continuum points from the model, we fitted a third order polynomial through the double-logarithmic flux-wavelength data of the observation, which have a linear relation in good approximation. This is due to the fact that the optical SDSS spectra of hot WDs are dominated by the Rayleigh-Jeans tail of the flux distribution, which behaves as \( F_\lambda \sim \lambda^{-4} \). Dividing the spectrum by the polynomial yields the normalised data which can now be compared to the synthetic spectrum. We have done this consistently for all spectra in order to reduce errors introduced by the individual normalisation of the observation. For the determination of the \( \chi^2 \) value we selected lines and regions that are essential for the quality of the fit.

3. Results

In our two spectral analyses papers (Hügelmeyer et al. 2005, 2006), we have presented the atmospheric parameters of our programme stars and plots of observed spectra and best-fit models. Here we now want to compare SDSS results to previous work and go more into detail on the transition of PG 1159 stars towards DO white dwarfs.

PG 1159 stars

Our analyses added eight new PG 1159 stars to the sample of 29 known objects of this spectral type. Comparing the atmospheric parameters of the new SDSS objects to the literature values of previously known PG 1159 stars (see e.g. the review of Werner & Herwig 2006), it becomes obvious that our results diverge from earlier ones. While the prototype PG 1159−035 yields \( T_{\text{eff}} = 140000 \) K, \( \log g = 7.0 \), and \( \text{C/He} = 0.60 \), and the other PG 1159 stars scatter around these values, seven out of the eight new SDSS PG 1159 stars have \( T_{\text{eff}} \approx 100000 \) K, \( \log g \approx 7.5 \), and a carbon abundance of \( \text{C/He} = 0.05 - 0.30 \). The only new object that deviates from this average SDSS PG 1159 star is SDSS 0016 51.42−011329.3 (Hügelmeyer et al. 2005) with \( T_{\text{eff}} = 120000 \) K, \( \log g = 5.5 \), and \( \text{C/He} = 0.30 \) and is therefore of subtype lgE. The reason why most of the SDSS PG 1159 stars are found in the low temperature and high surface gravity part of the PG 1159 star domain is easily explained by the fact that the evolutionary time scales are much longer in this part of the post-AGB sequence than in the earlier low gravity part. Therefore, the SDSS objects show what we would expect from the theory. We should find even more objects in this late stage of PG 1159 star evolution, however, the SDSS is only complete to \( \sim 30\% \) (Eisenstein et al. 2006b) and therefore misses more than half of these objects. Since 14 PG1159s have been found because they are CSPNs and the three hottest objects have been detected in X-ray surveys, the fact that preferably hotter and less compact – i.e. less evolved – PG 1159 stars have been discovered before the large SDSS survey is no surprise.

One object from the SDSS sample shows lines of ultra-high excitation ions (UHEI) such as C vi, N vi, N vii, O vii, O viii, and even Ne x. It is the first PG 1159 star to do so among several known DO and DAO white dwarfs presented.
Hügelmeyer et al. in Dreizler et al. (1995) and Werner et al. (1995). Since the UHEI lines are blue shifted and since they have an extreme triangular shape it is believed that they originate in a hot and fast wind while the underlying star shows He II and C IV lines that are too strong to be fitted with our model spectra. An explanation for this phenomenon has not been found to date.

DO white dwarfs

In contrast to the SDSS PG 1159 stars, the analysed DO white dwarfs from this survey cover the whole known temperature range and even extend this to a new lowest value of $T_{\text{eff}} = 40{,}000$ K placing it in the “DB-gap”. This is in agreement with the work of Eisenstein et al. (2006a) who find four DO white dwarfs from the SDSS that are close to the suggested lower “DB-gap” temperature boundary of $T_{\text{eff}} = 45{,}000$ K and six DB just below $T_{\text{eff}} = 40{,}000$ K. Three of these four DOs have also been analysed in Hügelmeyer et al. (2005, 2006) and we found temperatures agreeing with those of Eisenstein et al. (2006a) by about $\sim 2{,}500$ K using our NLTE models while the latter authors employed LTE synthetic spectra. Two DOs from our sample show UHEI lines (first classified by Krzesiński et al. 2004) and three have M-star features in their spectra. Of the latter three, we believe that two are part of a physical binary system.

Even though the SDSS DOs cover the expected parameter ranges for this type of object, the mass distribution is shifted towards higher masses by $0.10 M_\odot$ to $M = 0.69 M_\odot$ (not taking binary WDs into account) compared to earlier analyses (Dreizler & Werner 1996). This effect can also be seen by the relatively high log $g$ values of the SDSS DOs in Fig. We believe that the increase in log $g$ and mass, respectively, most likely results from an incorrect calibration of SDSS hot WD spectra since Kleinman et al. (2004) also observe a deviation from expected values by comparing fitted DA parameters from SDSS spectra to literature values of the observed stars. Their work shows an overestimation of effective temperature for stars with $T_{\text{eff}} \lesssim 30{,}000$ K which is compensated by their fitting routines by also increasing log $g$. This problem is discussed in more detail by Eisenstein et al. (2006a).

4. Discussion

We have placed the PG 1159 stars and DO white dwarfs from the SDSS and previous analyses in an evolutionary context depicted in Fig. Along with post-AGB and WD tracks, we have plotted equidistant time marks of $10^6$ years. Despite the increasing number of hot H-deficient (pre-)WDs, we are still dealing with low number statistics. The time marks can though give a rough estimate on the age distribution of He-rich WDs. We can see that the age bins above $T_{\text{eff}} > 45{,}000$ K are quite equally populated if we only regard DO white dwarfs. The new results of Eisenstein et al. (2006a) show that there is a continuation of H-deficient white dwarfs towards lower temperatures than $T_{\text{eff}} = 45{,}000$ K. These hot DBs on average have lower surface gravities than the hotter DOs. If this is a real effect or a result of the application of LTE models to these hot objects remains to be seen.

Concerning the transition between PG 1159 stars and DO white dwarfs, we have plotted the wind limits for PG 1159 stars calculated by Unglaub & Bues
Evolutionary connection between PG 1159 stars and DO white dwarfs

Figure 1. PG 1159 stars (diamonds) and DO white dwarfs (triangles) compared to evolutionary tracks from Blöcker (1995) and Schönberner (1983) (dashed-dotted lines), Wood & Faulkner (1986, solid lines), and Wood (1995, dashed lines). The black symbols come from our analyses of SDSS spectra and the grey ones from literature values (Werner & Herwig 2006; Dreizler & Werner 1996). The black asterisks are hot DB white dwarfs in the “DB-gap” (Eisenstein et al. 2006a). The dotted lines are the wind limits for PG 1159 stars calculated by Unglaub & Bues (2000), where the grey line represents the limit calculated for a mass loss rate ten times lower than for the black line. The thick grey lines are equidistant time marks of $10^6$ years. Labels are given in $M_\odot$.

Because of different initial compositions, PG 1159 stars have different mass loss rates assuming that $\dot{M}$ depends on the composition. Therefore the rapid depletion of the CNO elements predicted by Unglaub & Bues (2000) takes place at different positions in the HRD. There are still a few DOs beyond either of the wind limits but none of the PG 1159 stars from the SDSS, even though they are quite evolved compared to previous analyses, has crossed the wind limit. Therefore, we can say that the wind limit is a strict lower limit for PG 1159 star – DO white dwarf transitions.

The low carbon abundances observed in five of the eight new PG 1159 stars from the SDSS (C/He = 0.03 – 0.05 by number, Hügelmeyer et al. 2006) can also be explained by the diffusion calculations of Unglaub & Bues (2000). Even though the gravitational settling of the CNO elements sets in quite abrupt, the metal abundances are already reduced by a factor of two compared to the initial chemical composition at temperatures of the low-abundance SDSS PG 1159 stars. Therefore, these stars can already be considered transition objects.

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