MULTIWAVELENGTH OBSERVATIONS OF THE HOT DB STAR PG 0112+104*

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ABSTRACT

We present a comprehensive multiwavelength analysis of the hot DB white dwarf PG 0112+104. Our analysis relies on newly acquired FUSE observations, on medium-resolution FOS and GHRS data, on archival high-resolution GHRS observations, on optical spectrophotometry both in the blue and around Hα, as well as on time-resolved photometry. From the optical data, we derive a self-consistent effective temperature of 31,300 ± 500 K, a surface gravity of log g = 7.8 ± 0.1 (M = 0.52 M☉) and a hydrogen abundance of log N(H)/N(He) < −4.0. The FUSE spectra reveal the presence of C ii and C iii lines that complement the previous detection of C i transitions with the GHRS. The improved carbon abundance in this hot object is log N(C)/N(He) = −6.15 ± 0.23. No photospheric features associated with other heavy elements are detected. We reconsider the role of PG 0112+104 in the definition of the blue edge of the V777 Her instability strip in light of our high-speed photometry and contrast our results with those of previous observations carried out at the McDonald Observatory.

Key words: white dwarfs

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1. ASTROPHYSICAL CONTEXT

The DB stars constitute the subgroup of helium-atmosphere white dwarfs whose optical spectrum is dominated by the transitions of neutral helium. Their effective temperatures extend from roughly 13,000 K upward to ~40,000 K. The lower boundary is imposed by the visibility of the He i lines, that become very weak and disappear near that effective temperature, while the upper boundary is the effective temperature near which the smooth merging occurs between the DB sequence and the sequence of the hotter DO stars, whose spectrum is characterized by lines of ionized helium. Some filling-in of the region between 30,000 K and 40,000 K, previously thought to be devoid of helium-atmosphere white dwarfs (Wesemael et al. 1985) and known as the “DB gap” (Liebert et al. 1987), has been accomplished with the recent observation by Eisenstein et al. (2006) of several fainter hot DB stars in the Sloan Digital Sky Survey (SDSS).

While the idea of a true gap in the cooling sequence of the helium-atmosphere white dwarfs has now been abandoned, Eisenstein et al. (2006) argue nevertheless for the presence of a residual imbalance in the relative numbers of DA and DB stars, in the sense that the DA/DB number ratio is ~2.5 times larger at 30,000 K than it is at 20,000 K. This result is interpreted in terms of a transformation of ~10% of the DA stars observed at 30,000 K into DB stars by the time these objects cool down.

Based on observations with the FUSE satellite, which is operated by the Johns Hopkins University under NASA contract NAS 5-32985; with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under the NASA contract NAS 5-26555; and with the Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
constrain effectively its atmospheric properties and to try to shed light on its nature. In addition, the status of PG 0112+104 as a non-variable star has recently been challenged (Shipman et al. 2002; Provencal et al. 2003) so we take advantage of this study to reconsider the issue of the variability of this critical object.

We present the observational material on which this investigation is based in Section 2 and discuss some issues related to the modeling of DB stars in Sections 3 and 4. Our re-analysis follows in Section 5, while our conclusions are presented in Section 6.

2. OBSERVATIONAL MATERIAL

2.1. FUSE Data

The FUSE detectors span the ultraviolet region between 905 and 1187 Å, a region where numerous transitions associated with heavy elements are located. The spectroscopic observations of PG 0112+104 were secured in the TTAG mode through the high-throughput low-resolution (LWRS) aperture, which provides high-resolution ultraviolet spectra with throughput low-resolution (LWRS) aperture, which provides

| Program ID | Date       | Grating | R = λ/Δλ | Wavelength (Å) | Exp. Time (s) | Instrument |
|------------|------------|---------|----------|----------------|---------------|------------|
| C0260301   | 2004 Jan 2 | ...     | 18000    | 905–1187       | 22899         | FUSE       |
| M1020101   | 2004 Dec 19| ...     | 18000    | 905–1187       | 4250          | FUSE       |
| Z3EU0106P  | 1996 Nov 15| G140L   | 2000     | 1136–1422      | 653           | GHRS       |
| Z3EG0207T  | 1996 Dec 2 | G160M   | 15000    | 1196–1234      | 5658          | GHRS       |
| Z3EG0205M  | 1996 Nov 14| G160M   | 17000    | 1316–1353      | 3699          | GHRS       |
| Z3EU0107P  | 1996 Nov 15| G140L   | 2300     | 1389–1676      | 1197          | GHRS       |
| Y3EU0103P  | 1996 Nov 15| G190H   | 1300     | 1571–2311      | 480           | FOS        |
| Y3EU0104P  | 1996 Nov 15| G270H   | 1300     | 2222–3277      | 160           | FOS        |
| ...        | 1996 Nov 23| G140L   | 700      | 3750–5100      | 2100          | FOS        |
| ...        | 1997 Sep 29| KPC 18C | 1300     | 3200–5300      | 1200          | FOS        |
| ...        | 2000 Feb 24| KPC 18C | 2200     | 5600–7400      | 2400          | FOS        |

Figure 1. FUSE spectrum of PG 0112+104. The spectrum is obtained by merging the SiC1B, LiF1A, SiC2B, LiF2A, and LiF1B segments. The interstellar H ii, N i, O i, Si ii, Ar i, and Fe ii lines are labeled, as are the observed photospheric C ii and C iii transitions. The symbol “″ indicates geocoronal emission lines, except for the C ii line at 977 Å, which originates from scattered solar emission.

Segments covering a given spectral region is a function of wavelength.

When searching for additional stellar lines, such as C iii 9777 and potential O i, N i, and N ii transitions, it is necessary to extract the night-only data because these lines can be blended with strong emission lines coming from the terrestrial day airglow (see Feldman et al. 2001). The night-only data are obtained by reprocessing the raw data with the keyword DAYNIGHT set to NIGHT. In this way, the FUSE pipeline processes only data that were taken during the night. That subset amounts to 66% of the original data secured.

2.2. FOS and GHRS Data

Medium-resolution FOS red digicon data of PG 0112+104 can, when combined with medium-resolution GHRS data, be used to construct an energy distribution that replaces the low S/N data secured many years ago with the IUE satellite and
repeatedly analyzed since (Liebert et al. 1986; Thejll et al. 1991; Castanheira et al. 2006).

The FOS data were acquired through the large (3′7 × 1′3) aperture with the red G190H and G270H dispersers, and cover the region between 1571 and 2311 Å, and between 2222 and 3277 Å at a resolution λ/Δλ = 1300. This corresponds to ~1–2 Å through our wavelength range. These data were complemented with medium-resolution GHRs data secured through two exposures with the G140L grating and acquired at a spectral resolution of ~0.65 Å (image number z3eu0106p in the 1136–1422 Å range and z3eu0107p in the 1389–1675 Å range). At λ, our GHRs data are of lower quality than those secured at better spectral resolution (~0.08 Å) by Provencal et al. (2000). These data, a log of which is given by Provencal et al. (2000), were retrieved from the MAST archives. The concatenated medium-resolution data are displayed in Figure 2.

2.3. Optical Spectrophotometry

Two blue optical spectra of PG 0112+104 were secured over a time span of 18 yr (see Table 1 for a summary of our observations). PG 0112+104 initially belonged to a sample of over 100 DB stars observed over several years in the blue optical region at the Steward Observatory 2.3 m Bok Telescope. This sample formed the observational basis for the work of Beauchamp (1995). The instrumental setup includes a Boller & Chivens Spectrograph, a 4′.5 slit, and a 600 l mm−1 grating in first order. Together with a 800 × 800 TI or a 1200 × 800 Loral CCD, this combination provides coverage of the ~5600–7400 Å region at an intermediate resolution of ~6 Å. The PG 0112+104 spectrum was characterized by an S/N ratio of 120. More recently, a new observation of PG 0112+104 with the same telescope was secured specifically for this paper. The new data are entirely consistent with the older spectrum secured in 1991 and have the added feature that an annoying instrumental glitch present in the older data near 3950 Å has been removed.

PG 0112+104 was also included in the sample of stars observed at Hα and analyzed by Hunter et al. (2001). The red spectroscopy was secured during two runs at the KPNO 4 m Mayall telescope equipped with the Ritchey–Chretien Focus Spectrograph, UV Fast Camera, and T2KB CCD. The data from both runs were later combined. Coverage extends approximately from 5600 Å to 7400 Å, at a resolution of ~3 Å. An S/N ratio of ~90 was achieved. The blue and red spectra are displayed together in Figure 3.

2.4. High-speed Photometry

High-speed photometry was obtained by G.F. and Charpinet on 2002 July 14 UT with LAPOUNE, the portable Montréal three-channel photometer on the Canada–France–Hawaii Telescope (CFHT) 3.6 m reflector. The instrument uses three Hamamatsu R647-04 photomultiplier tubes to measure simultaneously the target star, a reference star, and the sky. The light curve of slightly over an hour long (3650 s) was obtained under excellent photometric conditions and consists of 365 points sampled every 10 s. Our light curve is shown in Figure 4.

3. MODEL ATMOSPHERE AND SYNTHETIC SPECTRUM CALCULATIONS

Our analysis is based on our updated grid of white dwarf models described in Tremblay & Bergeron (2009) in which
we have incorporated the improved Stark profiles of neutral helium of Beauchamp et al. (1997). In the context of DB stars, these models are comparable to those described by Beauchamp (1995) and Beauchamp et al. (1996), with the exception that at low temperatures \( T < 10,800 \text{ K} \), we now use the free–free absorption coefficient of the negative helium ion of John (1994), but this should have no effect on the analysis of PG 0112+104 (as discussed further below). Our models are in LTE and include convective energy transport within the mixing length theory. As in the analysis of Beauchamp et al. (1999), we use here the parameterization described as \( \text{ML2}/\alpha = 1.25 \). Synthetic spectra based on these models were used for the \( \text{L}_\alpha \) and optical spectra analyses.

In addition, several calculations were also carried out with TLUSTY and SYNSEP, the publicly available model atmosphere codes developed by Hubeny and one of us (T.L.; e.g., Hubeny & Lanz 1995), which were also used in the analysis of Provencal et al. (2000). Specifically, we used these codes for the determination of the carbon abundance and to set the upper limits on other heavy elements (see Section 5.5 below) as well as to reassess the importance of NLTE effects in DB stars (see Section 4 below). While the standard parameterization of the convective efficiency within the mixing length theory included in TLUSTY corresponds to that described by Mihalas (1978), we have modified our version to be able to consider alternative efficiencies.

4. THE IMPORTANCE OF NLTE EFFECTS IN DB STARS

In their analysis of HST observations of helium-atmosphere white dwarfs, Provencal et al. (2000) suggest that NLTE effects in the continuum of DB stars might be significant and deserve consideration in their analysis. Their Figure 3 shows, in particular, deviations at the level of 9% near 1500 Å, and at the level of 4% near 4000 Å, between emergent fluxes from an LTE model and those of an NLTE model, both computed with TLUSTY at \( T_{\text{eff}} = 25,000 \text{ K} \). This comes a bit as a surprise since the early investigations of both Kudritzki (1976) and Wesemael (1981) suggested that NLTE effects in the continuum were negligible even at effective temperatures considerably higher than that of Provencal et al. (2000). Dreizler & Werner (1996) also justified an LTE analysis of the DB stars on the basis of the complete absence of NLTE effects in the He I line spectrum at \( T_{\text{eff}} = 40,000 \text{ K} \); NLTE effects in the lines can persist even when continuum NLTE effects are completely negligible (a case in point would be the sharp \( \text{H}_\alpha \) core in cool DA stars). Even more recently, in a reanalysis of hot SDSS DB white dwarfs in the DB-gap, Hugelmeyer & Dreizler (2009) concluded that LTE is a valid assumption for objects with effective temperature below 45,000 K. The result of Dreizler & Werner (1996) and Hugelmeyer & Dreizler (2009) thus appears to confirm the earlier assessment that NLTE effects are negligible for the analysis of DB stars.

Intrigued by the Provencal et al. (2000) claim, which is based on TLUSTY models, we have computed our own NLTE models of DB stars with TLUSTY. The input parameters are identical to those of Provencal et al. (2000), namely \( T_{\text{eff}} = 25,000 \text{ K} \), \( \log g = 8.0 \), \( \log N(\text{C})/N(\text{He}) = \log N(\text{H})/N(\text{He}) = -5.0 \), and the parameterization of Mihalas (1978) for the convective flux within the mixing-length theory. We find no observable NLTE effects in the ultraviolet and optical continua at that effective temperature. Furthermore, additional tests suggest that no NLTE effects are apparent in the optical He I line spectrum at 40,000 K and 30,000 K, the highest temperature we considered. This is in complete agreement with the result of Dreizler & Werner (1996) and Hugelmeyer & Dreizler (2009). However, we find NLTE effects within \( \pm 2.5 \text{ Å} \) of the core of the \( \text{L}_\alpha \) line, which is formed high in the photosphere. We have explicitly checked that these effects have no significant impact upon the analysis we carry out, given that the saturated interstellar profile at \( \log N_{\text{HI}} = 19.4 \) dominates the core of the observed \( \text{L}_\alpha \) profile. We also explicitly verified that the models calculated with small traces of carbon are identical to those without carbon. The abundance of carbon needs to be several orders of magnitude higher, which is ruled out by spectroscopic observations, to have any detectable effect on the thermodynamic structure. Therefore, classical LTE DB atmosphere models are sufficient for determining the effective temperature and the surface gravity of PG 0112+104 from the optical spectra.

5. ANALYSIS

5.1. Determination of the Atmospheric Parameters from Optical Data

The analyses of Beauchamp (1995) and Beauchamp et al. (1999) show that the effective temperature determined from the optical spectrum of hot DB stars depends on the hydrogen abundance adopted for the atmosphere, despite the fact that hydrogen may not be directly visible. This is why two effective temperatures, which differ by 200–4000 K, are listed by Beauchamp et al. (1999) for the majority of DB stars: the hotter one was obtained under the assumption of a completely hydrogen-free atmosphere and the cooler one was obtained under the assumption that hydrogen is present at an abundance slightly below that at which the \( \text{H}_\beta \) line would become visible. In general, thus, the fits to the \( \text{He}_\text{i} \) lines in the optical provide a locus of optimal effective temperatures as a function of assumed hydrogen abundance.

The constraints that can be placed on the photospheric hydrogen abundance thus represent important ingredients in the analysis of hot DB stars. These can be obtained by searching either the \( \text{H}_\alpha \) transition in the red or the \( \text{L}_\alpha \) transition in the ultraviolet. Both techniques have well-known advantages and disadvantages. In rare cases, for example for bright or important objects, both sets of data are available. This is the case for PG 0112+104.

The fits to the older blue optical spectrum of PG 0112+104 by Beauchamp et al. (1999) yielded \( T_{\text{eff}} = 31,500 \text{ K} \), \( \log g = 7.82 \) for a pure helium composition, and \( T_{\text{eff}} = 28,300 \text{ K} \), \( \log g = 7.76 \) for a composition with \( \log N(\text{H})/N(\text{He}) = -3.0 \). This representative abundance was chosen at the time on the basis of a quick look at the newly acquired GHRS data which appeared to show a fairly strong \( \text{L}_\alpha \) profile. Of course, the profile has since been shown by Provencal et al. (2000) to have a substantial interstellar contribution, and their derived photospheric hydrogen abundance, namely \( -4.0 < \log N(\text{H})/N(\text{He}) < -3.5 \), is consequently somewhat lower than the nominal value used by Beauchamp et al. (1999).

As an internal check of our updated model grid discussed in Section 3, we analyzed this older spectrum using our fitting technique that relies on the nonlinear least-squares method of Levenberg–Marquardt (Press et al. 1986), which is based on a steepest descent method. The model spectra (convolved with a Gaussian instrumental profile) and the optical spectrum are first normalized to a continuum set to unity; this continuum is set in a fashion similar to that described in detail in Liebert et al. (2005) for DA stars. The calculation of \( \chi^2 \) is then carried out.
in terms of these normalized line profiles only. Atmospheric parameters—\(T_{\text{eff}}\), \(g\)—are considered free parameters in the fitting procedure; in the case of PG 0112+104, we assume a given value of the hydrogen abundance and compare the predicted \(H\alpha\) profile with the observations to set a limit on the hydrogen abundance (see below). Our atmospheric parameters with this old spectrum yield \(T_{\text{eff}} = 31,600\) K and \(g = 7.85\) under the assumption of a pure helium composition, in excellent agreement with the values reported by Beauchamp et al. (1999), which suggests that both model grids for DB stars are entirely consistent.

Since the analysis of Beauchamp et al. (1999), a new blue spectrum as well as spectra covering \(H\alpha\) has been secured. Our analysis of this blue spectrum using our pure helium grid yields \(T_{\text{eff}} = 31,590\) K and \(g = 7.82\), in almost perfect agreement with the results obtained with our old spectrum. Our procedure is then to fit this spectrum assuming various hydrogen abundances and compare the predictions at \(H\alpha\) with our red spectrum. These comparisons are shown in the inset of Figure 3 for \(\log N(H)/N(\text{He}) = -4.0\) (31,320 K, 7.82; this is almost identical to our pure helium solution), -3.5 (30,780 K, 7.81), and -3.0 (29,140 K, 7.78). Since \(H\alpha\) is clearly not detected in our red spectrum, we adopt as our final solution \(T_{\text{eff}} = 31,300 \pm 500\) K, \(g = 7.8 \pm 0.1\), and \(\log N(H)/N(\text{He}) \leq -4.0\), a hydrogen abundance limit that is not grossly inconsistent with the result of Provencal et al. (2000) based exclusively on the \(L\alpha\) profile. Our adopted solution is superposed in Figure 3 on top of the blue and red spectra.

5.2 Constraint on the Hydrogen Abundance from the \(L\alpha\) Profile

When \(L\alpha\) observations are available, the contribution of both the geocoronal feature and the interstellar medium (ISM) absorption must be allowed for. As shown by Provencal et al. (1996, 2000) in their pioneering analyses of the \(L\alpha\) profile in PG 0112+104, GD 190, and in the prototypical V777 Her star GD 358, this can be done successfully when the saturated core and the broad wings are considered separately. For nearby objects, this allows limits on the photospheric hydrogen content to be placed.

The values of the atmospheric parameters we have secured on the basis of the optical data in the preceding section are likely to be the most reliable in terms of the assumptions underlying our analysis. Nevertheless, other spectral ranges, perhaps less amenable to detailed analyses, can contribute to the overall self-consistency of the analysis. In this spirit, we have investigated the consistency of the \(L\alpha\) profile, following the method and technique outline by Provencal et al. (2000) in their original analysis, with our optical determination of the atmospheric parameters of PG 0112+104. The saturated part of the profile suggests a fairly well-constrained interstellar hydrogen column density of \(\log N_H = 19.4 \pm 0.1\), a value consistent with the results of the initial analysis. The resulting photospheric hydrogen abundance depends on the assumed effective temperature, and—given the importance assumed by the interstellar core—a two-dimensional fit would likely not be significant. We plot, in Figure 5, the match to the overall ISM+photospheric \(L\alpha\) profile secured with models at our optically determined effective temperature and gravity. This is done for values of the hydrogen abundance for \(\log N(H)/N(\text{He}) = -3.0, -4.0,\) and -5.0. The two panels display matches secured with values bracketing the optimal column density determined above. The theoretical profiles become less sensitive to the hydrogen abundance for \(\log N(H)/N(\text{He}) < -4.0\), and an accurate determination of the hydrogen content from the \(L\alpha\) profile seems hardly possible. Suffice it to be said that the value we derive from the optical spectrum is consistent with the limit set from the \(HST\) data.

5.3. Transitions of \(\text{He}\) i and \(\text{He}\) ii

Our FOS data show several members of the \(\text{He}\) i far-ultraviolet series originating on the \(2^3S\) lower level at \(E = 159,850\) cm\(^{-1}\). Prominent among these are the first members at 3187.74 Å (\(2^3S - 4^3P\)), 2945.10 Å (\(2^3S - 5^3P\)), and 2829.07 Å (\(2^3S - 6^3P\)). These transitions can be faintly seen in some of the better exposed IUE LWR spectra of DB white dwarfs (Holberg et al. 2003). As was done with the \(L\alpha\) profile, we can investigate here the rough consistency of our atmospheric parameters with those new features, amenable to a preliminary analysis. In Figure 6, we plot the observed FOS data together with a synthetic spectrum generated with SYNSPEC at the values of the atmospheric parameters determined above. While the match to the first two transitions appears quite good, it worsens as we move up the series. This is undoubtedly due to a combination of factors, namely, the lack of tabulated electron impact widths for the higher line members and the omission, within SYNSPEC, of detailed treatment of the level dissolution as we approach the series limit near 2644 Å.
The S/N ratio of the medium-resolution GHRS data around the He ii λ1640 transition is unfortunately too low to provide a useful check on the atmospheric parameters of PG 0112+104. Our synthetic spectra do predict a weak He ii λ1640 transition at this effective temperature, but no meaningful confrontation with the data is possible.

5.4. Energy Distribution

The spectral energy distribution of the star provides an additional piece of information. While its slope is, for classical hot DB stars, relatively insensitive to the photospheric hydrogen content and to the surface gravity, it displays some sensitivity to the effective temperature, especially when the energy distribution can be sampled as far as possible in the ultraviolet. We can exhibit many of the photospheric carbon features previously uncovered and equivalent widths measured in the ultraviolet range. For the other carbon features associated with C ii, C iii, N i, N ii, O i, Si ii, and Fe ii, the FUSE spectra of PG 0112+104 exhibit many of the photospheric carbon features previously seen in other hot DB stars by Petitclerc et al. (2005) and Desharnais et al. (2008). Five transitions were observed: the C ii λ1010 triplet, the C ii λ1036 and λ1066 doublets, and the C iii λ977 line and λ1175 complex. Among those, the two components of the C ii doublet, λ1036.337 and λ1037.018, are split since the doublet originates on levels of low excitation energy (ground-state for the blue component and 63.4 cm$^{-1}$ above the ground state for the red component). Both doublet components thus exhibit well-separated contributions originating in the photosphere and in the ISM. For the other carbon features observed, the energy of the lower levels is high enough to guarantee a photospheric origin. Table 2 lists the transitions uncovered and equivalent widths measured in the FUSE spectra of PG 0112+104. Among the DB stars previously studied with FUSE, EC 20058–5234—with its effective temperature near 28,000 K—is the closest analog to PG 0112+104: in that object, Petitclerc et al. (2005) reported the C ii λ1010 and λ1036 doublets, as well as the C iii λ1175 complex. The C ii λ1066 doublet was not observed. In addition, the reanalysis by Dufour et al. (2002) of the GHRS spectra of PG 0112+104 secured by Provencal et al. (2000) had shown the presence of the C ii λ1335 doublet in those data.
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Figure 8. Fits to the carbon transitions observed in the FUSE and GHRS range. The C ii λ1036 and λ1335 features, which originate on low-lying levels, both exhibit a contribution formed in the ISM. Two interstellar O i and Ar i lines are also labeled.

Table 2

| Ion | λ (Å) | log gf | \( g_\ell \) | \( E_\ell (\text{cm}^{-1}) \) | E.W. (mÅ) | Abundance | Instrument |
|-----|-------|--------|-------------|-----------------|-----------|-----------|------------|
| C iii | 977.020 | −0.120 | 1.0 | 0.000 | 165.8 ± 13.2 | −5.85 ± 0.13 | FUSE |
| C ii | 1009.858 | −0.457 | 2.0 | 43003.300 | 135.3 ± 12.2 | −6.13 ± 0.08 | FUSE |
|      | 1010.083 | −0.156 | 4.0 | 43025.300 |           |           |            |
|      | 1010.371 | 0.200 | 6.0 | 43053.600 |           |           |            |
| C ii | 1036.337 | −0.611 | 2.0 | 0.000 | 63.7 ± 4.7 | −6.03 ± 0.12 | FUSE |
|      | 1037.018 | −0.310 | 4.0 | 63.420 | 82.1 ± 6.2 |           |            |
| C iii | 1065.891 | 0.001 | 6.0 | 74930.100 | 23.5 ± 4.9 | −6.22 ± 0.14 | FUSE |
|      | 1065.920 | −0.952 | 4.0 | 74932.620 |           |           |            |
|      | 1066.133 | −0.255 | 4.0 | 74932.620 |           |           |            |
| C iii | 1174.933 | −0.468 | 3.0 | 52390.750 | 289.4 ± 19.0 | −6.54 ± 0.10 | FUSE |
|      | 1175.263 | −0.565 | 1.0 | 52367.060 |           |           |            |
|      | 1175.590 | −0.690 | 3.0 | 52390.750 |           |           |            |
|      | 1175.711 | 0.009 | 5.0 | 52447.110 |           |           |            |
|      | 1175.987 | −0.565 | 3.0 | 52390.750 |           |           |            |
|      | 1176.370 | −0.468 | 5.0 | 52447.110 |           |           |            |
| C iii | 1323.862 | −1.296 | 6.0 | 74930.100 | ... | ... | GHRS |
|      | 1323.906 | −0.342 | 4.0 | 74932.620 | ... | ... |            |
|      | 1323.951 | −0.150 | 6.0 | 74930.100 | ... | ... |            |
|      | 1323.995 | −1.297 | 4.0 | 74932.620 | ... | ... |            |
| C iii | 1334.532 | −0.597 | 2.0 | 0.000 | 81.4 ± 8.1 | −6.14 ± 0.15 | GHRS |
|      | 1335.663 | −1.295 | 4.0 | 63.420 | 119.7 ± 9.8 |           |            |
|      | 1335.708 | −0.341 | 4.0 | 63.420 |           |           |            |

We have redetermined individual carbon abundances on the basis of the six transitions of C ii and C iii observed in the ultraviolet spectra of PG 0112+104. The results are summarized in Table 2 and shown in Figure 8. Our analysis differs little
from those carried out earlier (Dufour et al. 2002; Petitclerc et al. 2005; Desharnais et al. 2008). We abstained from carrying out a detailed analysis of the interstellar components in the C\(	ext{II}\) doublets. In the case of the C\(\text{III}\) \(\lambda 877\) line, we analyzed the night-time data of the SiC channels in order to avoid the scattered solar emission contribution. For each transition, the individual uncertainty on the carbon abundances range from \(\pm 0.08\) dex to \(\pm 0.15\) dex. The uncertainties on the carbon abundances take into account uncertainties on the quality of the fit, uncertainties on the oscillator strengths, and uncertainties on the atmospheric parameters (\(\Delta T_{\text{eff}} = 500\) K, \(\Delta \log g = 0.1\) dex, and \(\Delta H/He = 0.3\) dex). Table 2 shows that the carbon abundances vary from \(\log N(C)/N(He) = -5.85\) to \(-6.54\). These two extremes come from the two C\(\text{III}\) \(\lambda 877\) and \(\lambda\lambda 1175\) lines. Considering all carbon abundances, we obtain a mean carbon abundance of \(\log N(C)/N(He) = -6.15 \pm 0.23\), where the uncertainty is the standard deviation of the measurements. This abundance is consistent with that obtained by Provencal et al. (2000) on the basis of the C\(\text{II}\) doublet in their GHRS data, \(\log N(C)/N(He) = -5.8 \pm 0.3\) (determined for a slightly cooler effective temperature near 30,000 K), and with the value estimated by Dufour et al. (2002) from the same data, \(\log N(C)/N(He) = -6.0\) (for the same effective temperature near 30,000 K).

We inspected the \emph{FUSE} spectrum in detail to search for the presence of other elements in the atmosphere of PG 0112+104. No photospheric lines other than carbon were detected. Given that the \emph{FUSE} wavelength range is rich in resonance lines or strong transitions, we were able to estimate abundance upper limits of a dozen elements. Table 3 summarizes our results and shows the lines that we used for determining the upper limits. The upper limits correspond to abundances that are 3\(\sigma\) above the lowest detectable abundances. We measured upper limits of six light elements (N, Si, P, S, Cl, and Ar), five iron peak elements (V, Cr, Mn, Fe, and Co), and one element beyond the iron peak (Pb). The upper limits range from \(-7.0\) to \(-8.7\). Elements such as oxygen and calcium do not have strong lines in the \emph{FUSE} pass band for a star like PG 0112+104, so no upper limits could be set for these elements.

The problem posed by the presence of carbon in hot, classical DB stars such as GD 358, EC 20058–5234, or PG 0112+104 was addressed by Desharnais et al. (2008), who used the carbon abundance value published by Provencal et al. (2000; \(\log N(C)/N(He) = -5.8 \pm 0.3\)) in their discussion. Our updating of the carbon abundance in PG 0112+104 does little to alleviate the problems discussed there and in Petitclerc et al. (2005): “hot” DB stars are too cool for significant radiative element support, but too hot for significant dredge-up or accretion from the ISM.

Fontaine & Brassard (2005) have proposed an attractive scenario to account for the presence of carbon in DB stars above 23,000 K. In their view, the observed carbon abundances result from the competition in hot DB stars of efficient downward gravitational settling with a weak stellar wind left over from previous evolution. While there is currently no direct evidence for this wind, its existence is not unreasonable given that signs of mass loss are observed in the PG 1159 progenitors of hot DB stars. The investigation of winds along the cooling track performed by Fontaine & Brassard (2005) is based on fully evolutionary models which include a linear relationship between mass loss and age, with the wind turning off completely by the time a star reaches \(T_{\text{eff}} = 20,000\) K. For the hot DB stars, the resulting carbon abundance depends mainly on the mass loss rate and is not strongly dependent on the structural parameters of the star (for example, on the helium layer thickness). To account for the abundances summarized by Desharnais et al. (2008), the rates invoked are on the order of a few \(10^{-13}\) M\(_\odot\) yr\(^{-1}\).

Large amounts of carbon are also found in the so-called hot DQ white dwarfs (Dufour et al. 2007, 2008). These carbon-dominated atmosphere white dwarfs are believed to be the offsprings of DB white dwarfs with very thin helium layers that have experienced a convective mixing episode with the underlying carbon envelope. However, the hot DQ stars are all found at a much lower effective temperatures (~18,000–24,000 K) than PG 0112+104. It thus appears very unlikely that the carbon observed in the atmosphere of this hot DB white dwarf could be the result of a similar convective transformation caught in its early phase.

### Table 3

| Ion | \(\lambda\) (Å) | \(\log gf\) | \(g_i\) | \(E_2\) (cm\(^{-1}\)) | \(\log N(X)/N(He)\) |
|-----|-----------------|------------|------|----------------|---------------------|
| N\(\text{III}\) | 991.511 | -1.317 | 4 | 174.400 | < -7.0 |
| N\(\text{III}\) | 991.577 | -0.357 | 4 | 174.400 | < -7.0 |
| Si\(\text{III}\) | 1113.174 | -1.356 | 5 | 531.150 | < -8.7 |
| Si\(\text{IV}\) | 1113.204 | -0.186 | 5 | 531.150 | < -8.7 |
| Si\(\text{III}\) | 1113.230 | 0.564 | 5 | 531.150 | | |
| P\(\text{III}\) | 1003.600 | -0.400 | 4 | 559.140 | < -7.8 |
| S\(\text{IV}\) | 1072.996 | -0.829 | 4 | 951.100 | < -7.2 |
| Cl\(\text{III}\) | 1015.022 | 0.050 | 4 | 0.000 | < -8.3 |
| Ar\(\text{II}\) | 932.054 | 0.120 | 4 | 1431.580 | < -7.4 |
| V\(\text{III}\) | 1149.945 | 0.068 | 10 | 583.800 | < -7.6 |
| Cr\(\text{III}\) | 1033.232 | -0.197 | 9 | 576.080 | < -7.2 |
| Cr\(\text{III}\) | 1033.433 | -0.259 | 8 | 356.550 | |
| Cr\(\text{III}\) | 1033.680 | -0.245 | 7 | 356.550 | |
| Mn\(\text{III}\) | 1108.164 | -0.057 | 16 | 26824.400 | < -7.4 |
| Mn\(\text{III}\) | 1111.104 | -0.169 | 16 | 26851.100 | |
| Mn\(\text{III}\) | 1113.186 | -0.293 | 8 | 26859.900 | |
| Fe\(\text{III}\) | 1122.526 | 0.149 | 9 | 0.000 | < -7.4 |
| Co\(\text{III}\) | 939.062 | -0.047 | 10 | 0.000 | < -7.2 |
| Pb\(\text{III}\) | 1048.877 | 0.114 | 1 | 0.000 | < -8.7 |

### 5.6. Is PG 0112+104 a True V777 Her Variable?

PG 0112+104 had generally been considered a constant star on the basis of high-speed photometry carried out by Robinson & Winget (1983) and Kawaler et al. (1994). Its effective temperature has generally been located in the 27,000–30,000 K range (Liebert et al. 1986; Beauchamp et al. 1999; Provencal et al. 2000; Castanheira et al. 2006), although Thejell et al. (1991) quote a temperature as low as 24,300 K.

Because its effective temperature placed it early on near the blue edge of the instability strip of the V777 Her variables, high-speed photometry of PG 0112+104 has been carried out on several occasions to search for the non-radial pulsations that characterize the V777 Her stars. Only upper limits on variations were reported. Thus, Robinson & Winget (1983) list maximum semi-amplitudes of 0.30% in the 10–50 s window, of 0.21% in the 50–200 s window, and of 0.29% in the 200–1200 s window, while Kawaler et al. (1994) report upper limits on the amplitude of brightness variations of 0.34%, the latter being based on UV data where the amplitudes are expected to be even larger than in the optical.

More recently, however, Shipman et al. (2002) and Provencal et al. (2003) have reopened the debate and suggested, on the basis of 30 hr of observing carried out in 2001 October at the McDonald observatory 2.1 m telescope, that the object might be variable, with two periods tentatively identified: \(P = 168.98\) s,
Figure 9. Fourier transform of the light curve of PG 0112+104. No peak higher than 0.08% of the mean brightness is observed in the period window from 20 s to 1800 s.

with an amplitude of 0.083% and $P = 197.76$ s, with an amplitude of 0.087%. The noise level in the Fourier amplitude spectrum is $\sim 0.018\%$. The periods they infer are consistent with those that characterize known V777 Her stars (100–1100 s), but the reported amplitudes are considerably lower than those observed up to now even in the lowest-amplitude V777 Her pulsators, which are $\sim 4.6\%$ (for PG 1351+489 and PG 2246+121).

If the pulsations observed by Shipman et al. (2002) in PG 0112+104 are real, it is unclear to what extent the driving mechanism—and its associated instability strip—inferred for the regular V777 Her stars may be relevant to the variations they observed. While the Shipman et al. (2002) and Provençal et al. (2003) data were considered preliminary, their potentially crucial importance within the context of pulsation theory prompted us to observe PG 0112+104 as a back-up object during one of our high-speed photometry run at the CFHT.

As shown in Figure 9, white light brightness variations with amplitudes greater than 0.08% of the mean brightness of the star can be ruled out in the period window from 20 s to 1800 s, a range that includes all known periodicities in DBV variables. With a noise level on the order of twice that of Shipman et al. (2002), we see no structure at the frequency (5.06 mHz) corresponding to the 198 s period, while a noise peak might be present at the frequency (5.92 mHz) corresponding to the 169 s period detected by Shipman et al. (2002). Our upper limits on the brightness variations in PG 0112+104 are comparable to (even slightly lower than) the variations reported by Shipman et al. (2002), so we cannot confirm their suggested detection. We note in this context that had PG 0112+104 been a normal V777 Her variable, our observations would have revealed it easily.

What is, then, the status of the variations observed by Shipman et al. (2002)? To our knowledge, neither was their preliminary report published in a referred journal nor was their claim withdrawn. It is assuredly of some significance that PG 0112+104 was not considered a V777 Her star in Section 5.6 underscores the fact that, even for the brightest members, a complete picture of these complex objects is only slowly developing. There are still many aspects about the evolution of helium atmosphere white dwarf that are not completely understood yet, for instance, the observed carbon and hydrogen abundance patterns and the exact location of the instability strip. This study brings much needed empirical knowledge about these issues but more work on helium-rich white dwarfs will be needed for a complete understanding of these objects to emerge.

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6. CONCLUSIONS

We have provided a comprehensive multiwavelength analysis of the hot DB white dwarf PG 0112+104 based on data largely unexploited up to now. Our analysis yields the following parameters: $T_{\text{eff}} = 31,300 \pm 500$ K, $\log g = 7.8 \pm 0.1$ ($M = 0.52 M_\odot$), a hydrogen abundance of $\log N(\text{H})/N(\text{He}) < -4.0$, and an improved carbon abundance of $\log N(\text{C})/N(\text{He}) = -6.15 \pm 0.23$. Since the discovery of several hot DB stars within the SDSS has contributed to the demise of the idea of a true DB gap along the white dwarf cooling sequence, the individual modeling of a single “hot” DB white dwarf may have lost some of its luster. Nevertheless, at $V \sim 15.4$, PG 0112+104 remains one of the few hot DB stars currently amenable to a detailed analysis of the type completed here. PG 0112+104 represents our best object near the transition from nonpulsator to pulsator and our reevaluation of the status of PG 0112+104 as a V777 Her star in Section 5.6 underscores the fact that, even for the brightest members, a complete picture of these complex objects is only slowly developing. There are still many aspects about the evolution of helium atmosphere white dwarf that are not completely understood yet, for instance, the observed carbon and hydrogen abundance patterns and the exact location of the instability strip. This study brings much needed empirical knowledge about these issues but more work on helium-rich white dwarfs will be needed for a complete understanding of these objects to emerge.

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