A NON-LTE ANALYSIS OF THE HOT SUBDWARF O STAR BD+28°4211. I. THE UV SPECTRUM

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ABSTRACT

We present a detailed analysis of the UV spectrum of the calibration star BD+28°4211 using high-quality spectra obtained with the Hubble Space Telescope and Far-Ultraviolet Spectroscopic Explorer satellites. To this aim, we compare quantitatively the observed data with model spectra obtained from state-of-the-art non-LTE metal line-blanked model atmospheres and synthetic spectra calculated with TLUSTY and SYNSPEC. We thus determine in a self-consistent way the abundances of 11 elements with well-defined lines in the UV, namely those of C, N, O, F, Mg, Si, P, S, Ar, Fe, and Ni. The derived abundances range from about solar to 1/10 solar. We find that the overall quality of the derived spectral fits is very satisfying. Our spectral analysis can be used to constrain rather tightly the effective temperature of BD+28°4211 to a value of $T_{\text{eff}} = 82,000 \pm 5000$ K. We also estimate conservatively that its surface gravity falls in the range $\log g = 6.2^{+0.3}_{-0.1}$. Assuming that the Hipparcos measurement for BD+28°4211 is fully reliable and that our model atmospheres are reasonably realistic, we can reconcile our spectroscopic constraints with the available parallax measurement only if the mass of BD+28°4211 is significantly less than the canonical value of 0.5 $M_{\odot}$ for a representative post-extended horizontal branch star.

Key words: stars: abundances – stars: atmospheres – stars: fundamental parameters – stars: individual (BD+28°4211) – subwarfs

Online-only material: color figures, extended figure

1. INTRODUCTION

BD+28°4211 is a hot subdwarf O (sdO) star whose brightness, high effective temperature, and relatively simple spectrum have made it a standard star in the optical domain as well as a calibration star for UV space missions such as IUE, Hubble Space Telescope (HST), and FUSE. Its status of standard star implies that some of its observational properties are very well known. For example, high precision $UBVRI$ magnitudes have been presented by Landolt & Uomoto (2007). In addition, its parallax measurement in the Hipparcos catalog places the star at 92 ± 11 pc. While studying BD+28°4211 as a spectrophotometric standard, Massey & Gronwall (1990) found it to have a faint red companion at a separation of 2′.8. Moreover, BD+28°4211 has been extensively observed in the UV range by the missions mentioned above and there are highly valuable data available on that star. Ultraviolet spectra are precious tools for studying the chemical composition via the numerous metallic lines present in this wavelength range. It could be thought that with this privileged status, BD+28°4211 would have been thoroughly studied and its physical parameters would be accurately known, but this is not exactly the case. In this connection, it has to be mentioned that because of its high effective temperature (around 80,000 K), the local thermodynamic equilibrium (LTE) approximation is inappropriate for model atmospheres intended to represent the star. Instead, the more sophisticated and realistic approach of non-LTE (NLTE) has to be used. Given the physical and technical difficulties associated with that approach, however, more efforts remain to be made along that avenue in order to characterize better the atmosphere of this star.

The first determination of the effective temperature of BD+28°4211, using quantitative spectroscopy, has been made by Napwiwotzki (1993) who estimated it to be around 82,000 K. He determined this value by comparing the Balmer lines of the star with those of NTLE model atmospheres with a variable H/He ratio (but with no metals) for different effective temperatures and surface gravities. This method is now largely used and its ability to give reliable fundamental parameters ($T_{\text{eff}}$, log $g$, and sometimes also N(He)/N(H)) for white dwarfs and hot subdwarf B stars has already been demonstrated (Bergeron et al. 1992; Saffer et al. 1994). However, this method is rather tricky in the case of BD+28°4211 because, like others sdO stars and white dwarfs that have high temperatures, the model spectra used generally suffer from the so-called Balmer line problem. That is, the observed lines cannot be simultaneously matched with a unique model spectrum. In other words, each line needs a model of different effective temperature in order to be well reproduced. Usually, the lowest lines in the series (like Hα and Hβ) need a lower temperature, while the highest ones are better reproduced at higher temperatures. In the case of BD+28°4211, to give the “extreme” values, He was best reproduced at $T_{\text{eff}} \approx 50,000$ K and Hα at around 85,000 K (Napiwotzki 1993). The author also found a log $g$ value of 6.2 and a solar helium abundance to be appropriate values for BD+28°4211. His best estimate of the effective temperature of ~82,000 K was subsequently confirmed by Dreizler & Werner (1993) who checked that parts of the IUE UV spectrum of BD+28°4211, showing Fe vi and Fe vii lines, are properly reproduced at around 82,000 K. This time, the NLTE model atmospheres they used included metals, namely carbon, oxygen, nitrogen, and iron group elements, that were grouped together into six model atoms (one for each ionization stages between iii and viii). With similar models, and on the basis of the same IUE spectrum, Haas et al. (1996) estimated the abundance of iron to be about 10 times subsolar while nickel was found to be nearly solar. According to them, oxygen and nitrogen also have abundances near the solar value. The improved UV spectra taken with Space Telescope Imaging Spectrograph (STIS) on board the HST allowed us to derive a solar abundance of manganese, while a sole line of chromium indicated an abundance between two and four times the solar value (Ramspeck et al. 2003).
The inclusion of metallic elements in NLTE model atmospheres, though costly in terms of computation time and complexity, allows not only for more realistic models, but also permits to solve, at least in part, the Balmer line problem (Werner 1996). We will address this issue in more details in the second paper of this series (M. Latour et al. 2013, in preparation). The optical spectrum of BD+28\(^{\circ}\)4211 is rather featureless in comparison to its rich UV spectrum. Except for the Balmer and He \(\text{II}\) lines, nothing else is seen at medium resolution in the optical range. Because of this, BD+28\(^{\circ}\)4211 was chosen to be part of an investigation of diffuse interstellar bands in OB stars given its uncomplicated spectrum. However, the high resolution HIRES spectra of the star obtained for this investigation at the Keck I telescope show a lot of narrow absorption lines as well as a handful of emission lines (Herbig 1999). The sharpness of the absorption lines allowed to set an upper limit on the star’s rotational velocity, \(v \sin i \lesssim 4 \text{ km s}^{-1}\), which is quite slow.

As for the high-quality \textit{FUSE} spectrum of BD+28\(^{\circ}\)4211, it has only been used to study interstellar abundances in the line of sight of the star (Sonneborn et al. 2002). To our knowledge, this data set has not been exploited so far to better characterize the star. Although we have a general idea of its atmospheric chemical composition, no comprehensive or systematic studies were made on that star. With high-quality data available from \textit{HST} and \textit{FUSE} in particular, we felt we should exploit them in order to reexamine the chemical composition of BD+28\(^{\circ}\)4211 and also try to constrain better its effective temperature and surface gravity by studying the ionization equilibrium of some metallic elements. Getting a portrait of the chemical composition of BD+28\(^{\circ}\)4211 should also be a first step in studying the optical spectrum of the star, with appropriate model atmospheres, for the Balmer line problem.

In the second section of this paper we describe our model atmospheres. This is followed by a short description of the observational material we used and of our abundance analysis in Section 3. We then discuss our attempts at constraining the effective temperature and the surface gravity by using the ionization equilibrium of metals in the UV range as well as the parallax distance in Section 4. Finally, we present a discussion and conclusion in Section 5.

2. MODEL ATMOSPHERES

2.1. Characteristics of Our Model Atmospheres

We have developed the capacity to compute large grids of NLTE metal line-blanketed model atmospheres over reasonable timescales (days to weeks) with our parallel versions of TLUSTY and SYNSPEC that run on a dedicated cluster of computers (currently containing 320 processors). Our setup is described in more details in Latour et al. (2011) and has not changed since, apart from the increase in the number of processors we have available. Our final fully blanketed model atmospheres for BD+28\(^{\circ}\)4211 include the following ions (besides those of \(\text{H}\) and \(\text{He}\)): \(\text{C}\) \(\text{II}\) to \(\text{C}\) \(\text{V}\), \(\text{N}\) \(\text{II}\) to \(\text{N}\) \(\text{V}\), \(\text{O}\) \(\text{II}\) to \(\text{O}\) \(\text{VII}\), \(\text{Si}\) \(\text{III}\) to \(\text{Si}\) \(\text{V}\), \(\text{P}\) \(\text{IV}\) to \(\text{P}\) \(\text{VI}\), \(\text{S}\) \(\text{III}\) to \(\text{S}\) \(\text{VII}\), \(\text{Fe}\) \(\text{IV}\) to \(\text{Fe}\) \(\text{VIII}\), and \(\text{Ni}\) \(\text{III}\) to \(\text{Ni}\) \(\text{VII}\). The highest ionization stage of each element is taken as a one-level atom. More information on the model atoms we used can be found on TLUSTY’s Web site\(^3\) and in Lanz & Hubeny (2003, 2007). Since our thorough examination of BD+28\(^{\circ}\)4211’s UV spectrum revealed also lines of argon, magnesium and fluorine, we needed to construct additional model atoms in order to study the abundance of these extra elements. This was done with the MODION program\(^4\) which uses the TOPBASE data (Lanz et al. 1996). This program allows the user to choose the explicit energy levels and also build superlevels that are included in the model atom. We thus constructed in this way model atoms for the following ions: \(\text{F}\) \(\text{III}\) with 9 levels and 5 superlevels, \(\text{F}\) \(\text{IV}\) with 11 levels and 5 superlevels, \(\text{F}\) \(\text{V}\) with 19 levels and 3 superlevels, \(\text{F}\) \(\text{VII}\) with 12 levels and 5 superlevels, \(\text{Mg}\) \(\text{III}\) with 37 levels and 3 superlevels, \(\text{Mg}\) \(\text{IV}\) with 29 levels and 5 superlevels, \(\text{Mg}\) \(\text{V}\) with 18 levels and 2 superlevels, \(\text{Ar}\) \(\text{IV}\) with 39 levels, \(\text{Ar}\) \(\text{V}\) with 25 levels, \(\text{Ar}\) \(\text{VI}\) with 20 levels, and \(\text{Ar}\) \(\text{VII}\) with 18 levels. All transitions (bound-bound and bound-free) between these levels are thus considered when the ions are included in a model atmosphere.

Since Werner (1996) underlined the importance of using Stark profiles for CNO lines when modeling atmospheres of hot stars such as BD+28\(^{\circ}\)4211, we inspected our different model atoms to check what kinds of profiles were used. We found that the strongest transitions (often resonance lines) of each ion are treated with Stark profiles while the weaker ones are represented by Doppler profiles. We then examined a synthetic spectrum that could represent BD+28\(^{\circ}\)4211 and identified its most prominent lines and made sure they were described with a Stark profile in the corresponding atomic model. This way we added a classic Stark profile to a few more lines of some elements, namely \(\text{C}\) \(\text{IV}\), \(\text{N}\) \(\text{IV}\), \(\text{O}\) \(\text{IV}\) and \(\text{O}\) \(\text{V}\), \(\text{Si}\) \(\text{IV}\), and \(\text{P}\) \(\text{V}\). A striking effect that Werner (1996) noticed when including Stark profiles was the disappearance of a high-temperature bump around log \(m\) of \(-3\) \(\text{g cm}^{-2}\) which was present when using Doppler profiles only (see his Figure 1). Since this bump is not seen either in our models (see our Figure 1), we believe that our atomic data are appropriate for the study of BD+28\(^{\circ}\)4211 or other hot stars. Note that, even without modifying the original model atoms used by Lanz & Hubeny (2003, 2007), our temperature structures do not present this bump (see Figure 4 of Latour et al. 2011).

The inclusion of our metallic elements must be done “step by step” if we want to ensure the convergence of our models. Too drastic changes in the physical parameters of the model atmosphere used as input and the one we want to compute will prevent the latter from converging. Thus, when constructing a grid of these line-blanketed models, we end up with a number of “subgrids” including only some of the elements mentioned above. In the case of BD+28\(^{\circ}\)4211, we built five “subgrids” in order to end up with our final fully blanketed one. For example, we have a grid including only \(\text{C}\), \(\text{N}\), and \(\text{O}\) in solar abundances, from which comes one of the models plotted in Figure 1.

In Figure 1, we show the temperature stratification for models with \(T_{\text{eff}} = 82,000\) K, log \(g = 6.2\), and having a solar helium abundance culled from three of our grids. These estimates of the atmospheric parameters come from the work of Napliwotski (1993). The first model is a “classical” pure \(\text{H}+\text{He}\) NLTE model that shows the well-known outwardly rise of temperature near the surface (dotted curve). The second one includes \(\text{C}\), \(\text{N}\), and \(\text{O}\) (solid curve), while the third one includes all the elements of our final model (see above) besides nickel (dashed curve). At this point, all our elements have a solar abundance (Grevesse & Sauval 1998). Though we plotted only three models in the figure, we examined the ones (having the same parameters) from our other grids and concluded that adding \(\text{S}\), \(\text{P}\), and \(\text{Si}\) to the \(\text{C}\), \(\text{N}\), \(\text{O}\) only induces a minor drop of the temperature in the outer layers (log \(m < -2\)). When we add nickel to models

\(^3\) http://nova.astro.umd.edu/Tlusty2002/tlusty-frames-data.html

\(^4\) http://idlastro.gsfc.nasa.gov/ftp/contri/varosti/modion/README
Figure 1. Temperature stratification and monochromatic optical depth $\tau_\nu = 2/3$ as functions of depth, where $m$ is the column density, for NLTE models defined by $T_{\text{eff}} = 82,000$ K, $\log g = 6.2$, and $\log N(\text{He})/N(\text{H}) = -1.0$. The temperature structure is shown for models including H and He only (dotted curve), H, He, and CN in solar abundances (solid curve), and H, He, and CNOSiPSFe in solar abundances (dashed curve). The $\tau_\nu = 2/3$ curve is from the latter model and shows part of the FUSE and STIS wavelength range in the UV.

(A color version of this figure is available in the online journal.)

already including C, N, O, Si, P, S, and Fe, the changes in the temperature structure are unnoticeable on a graph like Figure 1. The cooling of the outer layers is thus mostly done by the inclusion of C, N, and O elements; adding more metals does not cool anymore the surface. As for the inner layers, their heating comes essentially from the presence of C, N, and O, as well as Fe that was included afterward in the third model depicted in the figure.

It is easy to see from the temperature stratification that metallic elements, though they are not the dominant ones in the atmosphere, have an important effect on the thermodynamic structure at the surface of the star. Via their important opacity, they block a non-negligible part of the flux in the UV range, thus raising the continuum in the optical range. The presence of metals also causes a heating of the inner layers of the atmosphere, while it cools the outer layers. These changes in the atmospheric structure influence the emergent spectrum of the star, and thus the Balmer lines themselves. This is why their presence is an essential ingredient in the solution of the Balmer line problem (Werner 1996).

The other curve featured in Figure 1 shows the optical depth $\tau_\nu = 2/3$ as a function of the column density $m$. It allows us to locate where the continuum and different lines are formed. The most opaque features, formed very near the surface, are the core of the resonance doublets of S vi, O vi, and N v as well as the O v line at 1371 Å. As for the broadest lines, they are either hydrogen or helium ii ones. Depending on where a line is formed in the atmosphere, it might be affected differently by a change of the temperature structure.

In a model atmosphere with fundamental parameters like those of BD+28° 4211, some of the atomic species have a sole ion which dominates the atmosphere while the other ionization degrees have populations that are lower by orders of magnitude. This is the case for carbon, silicium, and phosphorus, where ions in a noble gas configuration (C v, Si v, and P vi) are the ones that contribute the most to the thermodynamic structure of the atmosphere. The population of the other elements is dominated by ions of different ionization degrees depending on the depth in the atmosphere. We show the ionization equilibria of nitrogen and iron in Figure 2 for models including all the elements mentioned at the beginning of this section and having an effective temperature of $T_{\text{eff}} = 82,000$ K (solid lines) and $T_{\text{eff}} = 92,000$ K (dashed lines), a surface gravity $\log g = 6.2$, and a solar helium content. The temperature is also shown
in black for each model. Though the equilibrium changes as function of depth, N v is dominant in the line forming region (around log \( m = -1 \)) while Fe vi and viti are in comparable proportions in this region for the model at 82,000 K. However, when the temperature is raised to 92,000 K, Fe viti becomes more dominant.

2.2. A Word on the Inclusion of Metallic Elements

By self-consistently including each element we want to study in our models, we allow it to influence the thermodynamical structure of the atmosphere. This is crucial if we want to get the right ionization equilibria and populations for our different ions. Dreizler & Werner (1993) show that large discrepancies can arise in the strength of iron lines in a synthetic spectrum, depending on whether or not iron is included in a NLTE and self-consistent way. The inconsistent approach uses LTE statistics to obtain iron populations and ignore the back-reaction of the element on the atmospheric structure. The discrepancies increase between the two methods as the NLTE effects increase (as well as the abundance of the element in question), which means in our case, when the effective temperature increases.

For BD+28\(^{\circ}\)4211, it is essential that the elements we want to fit be consistently included in the models.

The TLUSTY package allows to add new elements afterward in the synthetic spectrum computed by SYNSPEC. Even though it is an inconsistent approach, we tried it just to take a look at some lines of additional elements we did not plan to include in our models because of their expected low abundances and the lack of model atoms, as well as the limit on the number of atomic levels and transitions the code can handle without becoming unstable. Even though for some atomic species we could easily make model atoms with the TOPBASE data, they are not present in TOPBASE (except for iron) and their data (for iron and nickel) come from the Kurucz atomic data sets. Building model atoms for other elements of the iron peak would be a far more complex task than what was done for magnesium, fluorine, and argon. That being said, we added a solar amount of manganese, cobalt, and chromium in SYNSPEC to an already line-blanketed model atmosphere computed without these elements. When the resulting spectrum was compared with observations, it immediately appeared that there was a problem with the ionization equilibrium. Both Mn and Cr show lines of two different ions (v and vi); lines corresponding to the higher ionization degree were well reproduced by our model while the ones from the lower degree were not correctly matched. In order to illustrate this, we included nickel in our synthetic spectrum with the determined abundance of this element (see Section 4.1) and compared the result with our final model, which included nickel in the model atmosphere. We show in Figure 3 two regions of the STIS spectrum featuring some Ni v and viti lines. The two upper panels show the comparison between the observed spectrum of BD+28\(^{\circ}\)4211 and the synthetic one obtained by adding nickel (log \( N(Ni)/N(H) = -6.0 \)) in SYNSPEC only. The lower ones show the result of adding the same amount of nickel this time directly in the model atmosphere. In the case of nickel, Ni viti lines are definitely not strong enough in the upper panels, which is consistent with the observations of Lanz & Hubeny (2003) that NLTE effects favor higher ionization degree due to the strong radiation field coming from the hotter and deeper layers that causes overionization. In the other hand, the Ni v line shows in the second portion of the spectrum, as well as the few other we examined, remain quite unaffected by the difference in the inclusion method.

3. ABUNDANCE ANALYSIS

3.1. Observational Material

3.1.1. FUV and UV Observations

A wealth of FUV and UV observations of BD+28\(^{\circ}\)4211 has been gathered over the years. As we have mentioned earlier, BD+28\(^{\circ}\)4211 has been used as a calibration star by several space observatories. In order to find all the FUV and UV observations of BD+28\(^{\circ}\)4211, we carefully searched the Mikulski Archive for Space Telescopes (MAST).\(^5\) Spectroscopic observations of BD+28\(^{\circ}\)4211 have been obtained not only with space observatories such as IUE, FUSE, and HST, but also with instruments such as the Orbiting Retrievable Far and Extreme Ultraviolet Spectrometers and the Hopkins Ultraviolet Telescope that flew on space shuttle missions. Moreover, the HST spectroscopic observations include observations obtained with the Goddard High-Resolution Spectrograph and STIS. After retrieving the

\(^5\) http://archive.stsci.edu/index.html
Figure 3. Comparison between portions of the observed STIS spectrum of BD+28°4211 and synthetic spectra. The two upper panels show the synthetic spectra obtained when nickel is included in the spectrum only, thus in an inconsistent manner. In the lower panels, nickel was included from the beginning in the model atmosphere. It is possible to see the differences arising from the two ways of treating the presence of nickel in the models.

(A color version of this figure is available in the online journal.)

BD+28°4211 data from MAST and looking at the available data, we selected the FUSE and STIS observations in order to carry out our spectroscopic analysis. The choice of these spectroscopic data is based on the wide wavelength range covered by both instruments, and on their higher resolution and higher signal-to-noise ratio (S/N) than the data obtained by other instruments. The next two sections describe in detail the FUSE and STIS data that we selected for our analysis.

3.1.2. FUSE Observations

FUSE covers a wavelength range of 905 Å to 1187 Å with a resolution of about $R = \lambda / \Delta \lambda \approx 20,000$. For more information about the design of the instrument and the spectroscopic data products, see Moos et al. (2000), Sahnow et al. (2000), and Dixon et al. (2007). During the lifetime of the FUSE mission, several observations of BD+28°4211 have been carried out under three calibration programs. The first FUSE observation of BD+28°4211 was obtained through the program M108 in order to establish the suitability of the star to the calibration program, given that its FUV flux was close to the bright limit of the FUSE detectors. Subsequently, BD+28°4211 was observed under the program M104 to test the use of the focal plane splits (FP splits) in order to mitigate the fixed-pattern noise, and therefore to increase the S/N of the final spectrum. This technique consisted in taking a series of exposures at different focal plane assembly positions. In this way, the corresponding spectra were shifted along the dispersion direction and exposed on different portions of the detectors. The fixed-pattern noise was therefore reduced by co-aligning and co-adding all the spectra. The M104 observations consisted of exposures using the LWRS and MDRS apertures. Finally, two series of short observations taken through the LWRS, MDRS, and HIRES apertures were carried out under the M103 program, which monitored the photometric stability of the FUSE instrument.

We selected the M1080901, M1040101, M104105, M1031201, and M1031204 observations. All these observations were taken through the LWRS aperture and recorded in spectral image mode, or histogram (HIST) mode. We considered 66 exposures with an average exposure time of about 485 s, such that the total exposure time amounts to about 32,000 s. The eight FUSE segments, LiF1A, LiF1B, LiF2A, LiF2B, SiC1A, SiC1B, SiC2A, and SiC2B, were cross-correlated and co-added.
All LiF1B exposures show a depression in flux between 1130 Å and 1170 Å. This depression in flux is caused by an electron repeller wire grid that can cast shadows on the detectors. The LiF1B data in this wavelength range were not considered. A final co-added FUSE spectrum was obtained by considering and merging the following spectral regions: SiC1B (905–990 Å), LiF1A (990–1080 Å), SiC2B (1080–1090 Å), LiF2A (1090–1180 Å), and LiF1B (1180–1187 Å). The final spectrum has a signal-to-noise ratio S/N ∼ 68 at 950 Å, S/N ∼ 130 at 1050 Å, and S/N ∼ 89 at 1150 Å.

The FUSE spectrum displays many interstellar and stellar absorption lines. The most prominent stellar lines are the Lyman series of hydrogen starting from Lyβ up to Ly-8. There are followed by the He ii lines that involve transitions between energy levels n_f = 2 → n_a = 4 up to 13. Transitions with upper even numbers produce, however, lines that are blended with the hydrogen Lyman lines. The strongest metal lines are the O vi λ1031.91 and 1037.61 resonance lines that have equivalent widths of about 400 mÅ each. It is interesting to note that the O vi doublet does not display any P Cygni profile characteristic, which suggests that no stellar wind expanding away from BD+28° is observed in the FUSE spectrum. The most prominent stellar lines are the Lyman, Lyβ = 1031.91 and 1037.61 resonance lines that have equivalent widths of about 400 mÅ each. It is interesting to note that the O vi doublet does not display any P Cygni profile characteristic, which suggests that no stellar wind expanding away from BD+28° is observed in the FUSE spectrum.

### Table 1

| Dataset            | Grating | λ_cen (Å) | Range (Å) | Exp. Time (s) |
|--------------------|---------|-----------|-----------|---------------|
| E140M-1425_0202050_50710-53135 | E140M   | 1425      | 1140–1729 | 20607         |
| E140H-1416_0202050_50812-53135 | E140H   | 1416      | 1316–1517 | 15311         |
| E230M-1978_0202050_50710-53135 | E230M   | 1978      | 1607–2365 | 9510          |
| E230H-2263_0202050_50812-53135 | E230H   | 2263      | 2128–2396 | 22962         |
| E230H-2513_0202050_52461 | E230H   | 2513      | 2386–2639 | 2674          |
| E230M-2707_0902050_50678-53135 | E230M   | 2707      | 2629–3118 | 22547         |

3.1.3. STIS Observations

Since the installation of STIS on board HST in 1997, BD+28°4211 has been observed to monitor the sensitivity of each Multi-Anode Microchannel Array (MAMA) echelle grating mode. Although STIS suffered a major failure in 2004 August, it returned to science operations after being repaired during the fourth HST servicing mission in 2009 May. To this date about 206 observations of BD+28°4211 have been carried out with the echelle gratings E140M and E140H FUV-MAMA, and the E230M and E230H NUV-MAMA. Specifically, BD+28°4211 has been observed with the following echelle grating setups: E140M (central wavelength of spectrum λ_cen = 1425 Å; wavelength range 1140–1729 Å), E140H (1416 Å; 1316–1517 Å), E230M (1978 Å; 1607–2365 Å), E230H (2263 Å; 2128–2396 Å), E230H (2514 Å; 2385–2650 Å), and E230M (2707 Å; 2275–3118 Å). Therefore the spectroscopic coverage ranges from 1140 Å to 3118 Å. The resolution R = λ/Δλ for the E140M and E230M is ∼45,800, and it is ∼114,000 for the E140H and E230H. All the observations were carried out by using the 0′.2 × 0′.2 aperture. The exposure times for the individual observations are on average ∼360 s and ∼500 s for the E140M and E230M observations, and they are ∼1000 s and ∼1500 s for the E140H and E230H observations.

Instead of using all the STIS observations of BD+28°4211 that are available at MAST, we opted to retrieve the observations from StarCAT, which is a STIS echelle spectral catalog of stars that Ayres (2010) created based on observations of high-resolution spectra. StarCAT contains all the echelle high-resolution spectra of BD+28°4211 that were collected from 1997 to the failure of STIS in 2004. Given that BD+28°4211 has been observed frequently, Ayres (2010) cross-correlated and co-added all the BD+28°4211 spectra in order to achieve a high S/N. We retrieved six datasets from Ayres’s (2010) StarCAT. The properties of the datasets are summarized in Table 1. The table gives the name of the dataset, the grating that was used with its setting λ_cen, the wavelength range, and the total exposure time in seconds that is the sum of all the exposures. The resulting S/N for the observations taken with the E140M at λ_cen = 1425 Å is S/N ∼ 180 at 1250 Å and S/N ∼ 145 at 1500 Å. The observations performed with the E230H at λ_cen = 2513 Å has the shortest exposure time and consequently has the lowest signal-to-noise ratio with S/N ∼ 30 at 2500 Å. The remaining observations have S/Ns greater than 100. The resulting STIS spectra of BD+28°4211 with their high S/N and large spectral coverage are FUV and UV data of outstanding quality.

As in the case of the FUSE data, the STIS data show a large number of absorption lines. The greatest number of lines are observed between 1140 Å and ∼1475 Å. Beyond 1475 Å, the intensity and the number of lines decrease dramatically. On the short wavelength side, absorption lines of high-ionization species such as Fe v, Fe vi, Fe vii, Co v, Ni v, and Ni vi are the most numerous. The equivalent widths of these absorption lines vary from a few mÅ to ∼75 mÅ. The strongest line observed in the STIS spectrum is Lyα. In fact, most of the absorption at Lyα comes from the interstellar H i along the line of sight of BD+28°4211. Sonneborn et al. (2002) measured a H i column density of log N(H i) = 19.842 in the direction of BD+28°4211, and showed that the stellar H i component is much fainter than the interstellar absorption. The second strongest observed line is the He ii λ1640 line (n_f = 2 → n_a = 3) that has an equivalent width of about 1200 mÅ. The line shows broad wings that extend

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6 http://archive.stsci.edu/prepds/starcat/
to about 4.5 Å from the center of the line, and it shows a shallow core. Interestingly, the He η line series \( n_f = 3 \rightarrow n_u = 6 \) up to 11 is observed at longer wavelengths. The wings of these He η lines are also broad, but the lines show a much shallower core than the He η 1640 line. The N ν λλ 1238, 1242 lines and O ν λλ 1371 line are the strongest metal lines observed in the STIS spectrum. The lines have equivalent widths of about 770 mÅ, 482 mÅ, and 574 mÅ. The total equivalent widths of the Si iv λλ 1393, 1402 lines and C iv λλ 1548 and 1550 lines have equivalent widths of about 125 mÅ and 340 mÅ.

Even though we have identified most stellar and interstellar absorption lines in the STIS spectrum of BD+28°4211, there are still about 260 lines that do not have any identification. The equivalent widths of these lines range from a few mÅ to a few ten of mÅ. The total approximate number of lines with no identification in both FUSE and STIS spectra is around 410 lines. We extended our search of metal lines to elements beyond Zn. For instance, O’Toole & Heber (2006) and Chayer et al. (2006) observed strong absorption lines of heavy elements such as Ga, Ge, Zr, Sn, and Pb in FUSE and STIS spectra of sdB stars, while Vennes et al. (2005) and Chayer et al. (2005) observed Ge and Sn in a handful of hot DA white dwarfs, and Ge, As, Se, Br, Sn, Te, and I in two cool DO white dwarfs. Werner et al. (2012) added the discovery of Kr and Xe in the atmosphere of the DO white dwarf RE 0503−289 to the list of heavy elements detected in the atmospheres of compact stars. We looked for these heavy elements in both FUSE and STIS spectra by using the wavelengths of the high-ionization species. We also added Mo to our search. Unfortunately, no lines from heavy elements are observed. There is an absorption feature around 987.6 Å that could correspond to the As ν λ 987 line, but no absorption feature matches the second component of the As ν doublet at 1029.48 Å adequately. As we have concluded in the previous section, the non-identification of many absorption features in the FUSE and STIS spectra of BD+28°4211 illustrates the lack of atomic data of high-ionization species.

### 3.2. Fitting Technique and Resulting Abundances

Our fitting technique consists in minimizing a \( \chi^2 \)-type value defined as the sum of the squared difference between the model and observed fluxes over a given range of wavelength. Our free parameters are the solid angle and, obviously, the abundance of the fitted element. It is also possible to add a trend (linear or quadratic) if the continuum in the range of interest needs one, which was sometimes useful since the normalized UV spectra are not always as flat as they should.

The method used to determine the abundance is a partial iterative one. First of all, from the work of Napiwotzki (1993), the temperature and gravity of our models are held fixed at \( T_{\text{eff}} = 82,000 \) K and \( g = 6.2 \), and the helium abundance is fixed at the solar value. Most of our metal grids consist of six or seven different abundances centered around the solar one and varying in steps of 0.5 dex. For example, in the case of oxygen (whose solar abundance is log \( N(O)/N(H) = -3.3 \)), its grid covers a range from log \( N(O)/N(H) = -2.0 \) to \( -4.5 \) in steps of 0.5 dex. Since we have a better idea of the iron and nickel abundances (thanks primarily to the work of Ramspeck et al. (2003)), their grid meshes are narrower; between one-tenth and one times solar for iron, and centered around the solar value for nickel, but this time varying only in steps of 0.2 dex. In the first step of the procedure, we used models including C, N, O, and Fe in solar abundances initially and then varied the abundances of these four elements, one at a time. We then used these improved models to build the grids for silicon, sulfur, and phosphorus. We were then able to obtain a first estimate of the abundances for these seven elements. The number of lines fitted for each element is given in Table 2. We carefully chose lines that are reasonably well isolated in regions of the spectrum not too crowded with blends or interstellar lines. Our second step was to redo our grids for each element, this time including the previously found abundances for the other elements. At this point, when redoing our fitting procedure, the values found for individual lines sometimes changed a little, but the mean abundances stayed roughly the same.

### Table 2

| Element (Ions) | No. of Intervals (No. of Lines) | Mean Abundance \( \log N(X)/N(H) \) (dex) | Standard Deviation (dex) | Total Uncertainty (dex) |
|---------------|-------------------------------|------------------------------------------|--------------------------|-------------------------|
| C (iv)        | 3 (3)                         | −4.48                                    | 0.16                     | 0.46                    |
| N (iv, v)     | 4 (8)                         | −4.23                                    | 0.19                     | 0.78                    |
| O (iv, v, vi) | 10 (15)                       | −3.38                                    | 0.15                     | 0.46                    |
| F (iv, v, vi) | 1 (1)                         | −8.00                                    | ...                      | 0.50                    |
| Mg (v)        | 7 (7)                         | −4.57                                    | 0.12                     | 0.45                    |
| Si (iv)       | 3 (3)                         | −4.95                                    | 0.06                     | 0.30                    |
| P (v)         | 2 (2)                         | −7.45                                    | 0.29                     | 0.52                    |
| S (v, vi)     | 8 (8)                         | −5.53                                    | 0.18                     | 0.47                    |
| Ar (v, vii)   | 2 (2)                         | −5.53                                    | 0.04                     | 0.43                    |
| Fe (v, vii)   | 11 (33)                       | −5.08                                    | 0.12                     | 0.32                    |
| Ni (v, vii)   | 7 (17)                        | −6.04                                    | 0.21                     | 0.48                    |

**Notes.**

a. Fluorine was not formally fitted, we visually examined some lines in order to estimate an abundance. See the text for more details.

The first column shows the different elements as well as the ionic species present in our sample of fitted lines. The second column gives the number of intervals (like the six ones presented in the previous paragraph) which was sometimes useful since the normalized UV spectra are not always as flat as they should.
Figure 4. Sample of our fitted spectral intervals from the STIS spectrum. The red curve shows the result of the fitting procedure for the element mentioned at the bottom of each panel, where the resulting abundance for the interval is expressed as log $N(X)/N(H)$. All our models have $T_{\text{eff}} = 82,000$ K, log $g = 6.2$, and log $N(\text{He})/N(H) = -1.0$. Interstellar features are visible in some spectral chunks, such as a strong Si ii line beside Ar vi $\lambda$ 1303 and shortward-shifted C iv and Si iv lines. 

(A color version of this figure is available in the online journal.)

Table 3
Chromium, Manganese, and Cobalt Estimated Abundances (LTE)

| Element (ions) | No. of Intervals (No. of Lines) | Mean Abundance log $N(X)/N(H)$ | Standard Deviation (dex) | Total Uncertainty (dex) |
|---------------|--------------------------------|-------------------------------|-------------------------|------------------------|
| Cr (vi)       | 4 (4)                          | $-6.17$                       | 0.31                    | 0.41                   |
| Mn (vi)       | 5 (6)                          | $-6.71$                       | 0.21                    | 0.32                   |
| Co (vi)       | 5 (11)                         | $-6.71$                       | 0.12                    | 0.25                   |

Figure 4) and the total number of lines (from the element of interest) included in those intervals. The third column presents the mean abundance of the analyzed ranges while the fourth one gives the standard deviation associated with the previous column. Finally, the last one gives the total uncertainty of our abundances, which will be discussed in the next subsection.

We tentatively tried to formally fit some fluorine lines, but since they were either too faint, or blended the results were not conclusive. Our result is thus based on a sole isolated line, F iv $\lambda$ 1059.719, for which we visually estimated an abundance of log $N(F)/N(H) = -8.0$ to be appropriate. The resulting comparison can be found in the last panel of Figure 9 in the online version. This result is compatible with the other lines we checked ($\lambda\lambda$ 1082.345, 1088.400 and 1139.523), although these lines are either blended or in a noisy region of the spectrum for which their faintness does not help.

For the sake of completeness, we also examined the chromium, manganese and cobalt lines visible in our spectra and estimated their abundances. This time we had to add these elements afterward in the synthetic spectrum (as explained in Section 2.2) where their populations were computed assuming LTE. The model atmosphere used as input for the spectra computation included our main metallic elements (C, N, O, Si, P, S, Fe, and Ni). The abundances of the three studied elements were in turn varied in the synthetic spectra and then fitted the same way we did for the other elements. In order to avoid the ionization problem discussed in Section 2.2, we fitted only lines coming from the dominant ionization stage, which is vi for these three iron-peak elements. As for the previously fitted elements, the uncertainties include the standard deviation as well as effects from a change of temperature and surface gravity in the input model atmosphere. Despite the fact that our resulting abundances presented in Table 3 are only rough estimates, obtained with an approximate method, our values for Cr and Mn are in good agreement with the ones found by Ramspeck et al. (2003), which were around $-5.88$ for Cr and $-6.62$ for Mn.

Figures 4 and 5 show a sample of our fitted intervals taken from the STIS (Figure 4) and FUSE (Figure 5, except the top
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Figure 5. Same as Figure 4 but for parts of the FUSE spectrum, except for the first interval, showing He ii λ1640, which comes from the STIS spectrum. Note the He ii line which is particularly well reproduced with the assumed fundamental parameters. There is a lot more interstellar lines in the FUSE wavelength range. We notice in this figure, among others, C ii λ1036.3, O i λλ1039.19, 921.82, and C i λ945.15.

(A color version of this figure is available in the online journal.)

left panel) spectra. The abundance resulting from the fitting procedure of the featured region is given as log N(X)/N(H). We show here the final step of our fitting method, so the elements included, besides the fitted one, have abundances corresponding to the ones presented in Table 2. The totality of our fitted spectral chunks are available in the online journal.

Some of our intervals include important interstellar lines, such as O i, N i, C i, H i, and H_2. Interstellar shortward-shifted C iv and Si iv components are also seen for both doublet lines (one of which is shown in Figure 4). These features are thought to originate from a circumstellar cloud or shell near the star (Bruhweiler & Dean 1983). Since BD+28°4211 has some similarities with central stars of old planetary nebulae in its spectrum as well as in its fundamental parameters, this could be some sort of old planetary nebula remnant. When strong interstellar medium lines are present in our fitted intervals, we exclude them from our minimization procedure by iteratively rejecting wavelength points of the observed spectrum too far from the model’s ones.

We carefully inspected each fitted range to make sure the resulting model was appropriate, the continuum was at a satisfactory level, and to notice any discrepant lines. Our checkup highlighted some points we found worth mentioning.

First of all, if we consider the most prominent features (i.e., resonance and strong lines), they are all well reproduced. The only exception is the O vi doublet (λλ933, 944), in S vi λ11117.76 and in O v λ1371.3. We have to mention here that the analysis of Rauch et al. (2007) has been a useful reference to us on this particular account. They analyzed STIS and FUSE spectra of a star (LS V +46°21) whose fundamental parameters (T_{eff} = 95,000 K and log g = 6.9) give it a spectrum quite similar to that of BD+28°4211, in the sense that both star show lots of common lines. It allows us to compare some of our fits with theirs. This way, we noticed that they reported the same effect of too strong cores in resonance lines of their star, letting us know the issue is not only about our own model atmospheres.

Secondly, when choosing our sample of lines to be fitted, a few lines gave inconsistent results or could not be matched in any way whatsoever. For instance, our attempt to fit the O iv structure around 1081 Å was not conclusive enough to be included in our final sample because the core of the central component at 1080.97 Å was too strong in our models. The N iv triplet between 1225 and 1226 Å required a much higher abundance (log N(N)/N(H) = −3.2) than our other lines of nitrogen, so we did not include it our sample. The same thing happened for O v λ968.9, but this time we suspect this line to be blended with interstellar H_2 lines at 968.997 and/or 969.07 Å. This possibility is supported by the few H_2 lines present in the vicinity of the oxygen line.

Finally, some odd lines of oxygen appear in our models, whereas there is no sign of them in the observed spectrum. We noticed O iii λ1153.775 and two O iv lines at 1076.06 and 1294.065 Å. A too-strong oscillator strength value might be
the cause of their presence. We should also mention four other lines, among which three of them appear also too strong in our final model, namely Fe \textsc{v} 1393.072 and Fe \textsc{vii} 1154.990, 1180.827. As for the last one, Ni \textsc{i} at 1204.078 Å is too faint in our models and was excluded from our fitted nickel sample. However, these lines also appear too strong (or too faint for the nickel one) in the final model of Rauch et al. (2007), so there is a strong chance that the oscillator strengths of the lines are involved here.

3.3. Evaluation of the Abundance Uncertainties

Hot stars sometimes “become” hotter with time, in the sense that their estimated effective temperature tend to be revised upwards. For example, the DAO white dwarf LS V +46°21, has seen its estimated effective temperature go from 83,000 K in Napiwotzki (1999) to 95,000 K in the thorough study of Rauch et al. (2007). In a most extreme case, the white dwarf KPD 0005+5106 was shown to be the hottest known DO in Werner et al. (1994) with an estimated value of $T_{\text{eff}} = 120,000$ K, but a subsequent analysis of better spectroscopic data found lines of highly ionized metals (Ne \textsc{viii} and Ca \textsc{x}), thus needing the star to have an effective temperature of at least 180,000 K (Wassermann et al. 2010). With these rather extreme cases in mind, we wanted to have an idea of how our abundances would change if the effective temperature or the surface gravity of BD+28°4211 end up being different from our assumed values.

Therefore, we redid a part of our abundance analysis, using in a first step models with an effective temperature of 92,000 K, and then models at log $g = 6.6$. To do this for all the atomic species studied in the previous section would require computing twice as many grids as we did for determining the abundances themselves. We therefore decided to do this exercise for three elements only, namely nitrogen, silicon, and iron. The resulting abundances are presented in Table 4, which gives, for each model considered, the abundance and standard deviation obtained for the indicated element. The first column specifies the model used in our fitting procedure by indicating the parameter that has been changed with respect to the ones used in the previous section. The first quoted model is our reference model at $T_{\text{eff}} = 82,000$ K and log $g = 6.2$. One thing to note here is that a change in the effective temperature of the models of the magnitude considered here induces a larger change in the determined abundance than a change in log $g$. Another interesting thing to look at is the value of $\sigma$, the standard deviation of the different spectral chunks we fitted. In the case of iron and nitrogen, this value is larger for $T_{\text{eff}} = 92,000$ K and 72,000 K, meaning the abundances obtained from each interval agree less with each other than in the reference case. The results for silicon are somewhat different because there is only three fitted lines, produced by a sole ion (Si \textsc{iv}), whereas nitrogen and iron have lines produced by two and three ions. Silicon is thus less expected to show larger discrepancies between its fitted lines at different atmospheric parameters. The behavior of the standard deviation (for nitrogen and iron) with the temperature can be taken at a reassuring sign pointing towards 82,000 K to be a good value for the star’s effective temperature. About the two additional log $g$ values, their standard deviation for iron is a bit larger than the one found in the previous section, but as a whole, they are nevertheless quite similar to the ones obtained with models at log $g$ of 6.2.

We used the abundance differences between different models in the calculations of the uncertainties reported in Table 2. We wanted our chemical composition, within the given uncertainties, to be able to stand a potential change in the fundamental parameters of BD+28°4211. By using the abundances found at $T_{\text{eff}} = 92,000$ K and log $g = 6.6$, our determined values should remain appropriate for changes of $\pm 10,000$ K and $\pm 0.4$ dex, assuming the errors should be symmetrical in $T_{\text{eff}}$ and log $g$. Although we also have abundances for 72,000 K and log $g$ of 5.8 we prefer not to include them in our uncertainty calculations because they are less likely to be realistic values for BD+28°4211. This will be discussed in the next section. That being said, our final uncertainties are the sum of three components:

$$\sigma = \sqrt{(\sigma_{\text{fit}})^2 + (\sigma_{T_{\text{eff}}})^2 + (\sigma_{\log g})^2},$$

where $\sigma_{\text{fit}}$ is the standard deviation of the fitted chunks, $\sigma_{T_{\text{eff}}}$ is the difference between the abundances at $T_{\text{eff}} = 92,000$ K and 82,000 K, whereas $\sigma_{\log g}$ is the difference between the results at log $g$ of 6.6 and 6.2. For the elements besides nitrogen, silicon, and iron, $\sigma_{T_{\text{eff}}}$ and $\sigma_{\log g}$ were taken as the mean values of the three determined ones.

4. CONSTRAINING THE ATMOSPHERIC PARAMETERS

4.1. With the Metal Lines

As mentioned in the Introduction, finding out the effective temperatures and surface gravities of hot stars is not straightforward and standard methods used on cooler stars do not work very well. A more reliable approach in this case is to look at the metal lines visible in the UV spectrum of the star. A change of temperature will modify the ionization equilibrium of the atomic species present in the photosphere, as shown previously in Figure 2, and this will result in changes of the spectral lines strength. The exercise done in the last subsection, when fitting iron and nitrogen with models having different parameters, favors the models at $T_{\text{eff}} = 82,000$ K. The standard deviations of the fitted intervals are smaller with this temperature and moreover, the ionization equilibrium of iron lines cannot be correctly reproduced neither with the hotter or cooler models. This is what is shown in Figure 6, where the two left panels feature an interval of the STIS spectrum including three ionization stages of iron and three model spectra having different temperatures. Fe \textsc{vi} lines do not change much with the effective temperature, but Fe \textsc{v} and \textsc{vii} lines are more sensitive and become quite stronger with, respectively, a lower and higher temperature. The changes are easily seen, even with a difference of 5000 K between models. Thus, when trying to do a fit of the iron lines, at hotter or cooler temperatures, it is impossible to simultaneously match the lines coming from the three ionization degrees. Indeed, the four fits shown in Figure 6 (middle and right panels) are rather poor. Therefore, when looking at iron lines as a temperature indicator, it appears clearly that the temperature of the star must be quite close to 82,000 K.
Figure 6. Comparison of iron lines with models having different temperatures. The temperature and the abundance of iron are indicated on each panel. The two left panels present a comparison of three model spectra with the spectrum of BD+28°4211 over a range featuring lines from three ionization stages of iron. The standard model at $T_{\text{eff}} = 82,000$ K and log $g = 6.2$ is represented by the red line, the hotter ones (92,000 K in the top panel and 87,000 K in the bottom one) are in blue, while the cooler models (72,000 K in the top panel and 77,000 K in the bottom one) are in green. It can be seen that with a fixed abundance, a change in the temperature, even of only 5000 K, leads to a poorer agreement between the observed lines and the modeled ones. The two middle panels show the result of a fitting procedure, over the same wavelength range, with hotter and cooler models, while the right panels also show a fit of iron lines, but over two other spectral ranges.

(A color version of this figure is available in the online journal.)

Figure 7 shows the same kind of plots as Figure 6, except that this time we changed the value of the surface gravity between log $g$ of 6.6 and 5.8 while the temperature was fixed at $T_{\text{eff}} = 82,000$ K. Like the temperature, the gravity also affects the iron lines, but to a lesser extend, at least in the ranges investigated. With a higher log $g$ it is still possible to represent correctly the lines shown in the two right panels, but the fits lead to abundances that are different by 0.45 dex, which is larger than the difference of 0.12 dex obtained with our models at log $g = 6.2$ (see panel (g) in the online version of Figure 9). When fitting our principal range of interest, 1330–1333 Å, with models having different log $g$, we do not obtain a match as good as with our reference grid. Indeed, when looking at the standard deviations for the iron fits found in Table 4 for the various log $g$, the agreement is better with the reference model, but $\sigma$ is not much higher in the two other cases. In the case of nitrogen, the standard deviations of the various log $g$ do not obviously support a specific gravity. That being said, when considering iron lines, the surface gravity we assumed for our analyses (log $g = 6.2$) seems to be right.

4.2. With the Parallax Distance

Another method that can be used to place constraints on the parameters of BD+28°4211 is to compare its spectroscopic distance with the one determined by parallax measurements, which is between 81 and 106 pc according to the latest reduction of the Hipparcos catalog (van Leeuwen 2007). The idea here is to compute the absolute magnitude of a model atmosphere and combine it with the apparent magnitude of the star (recently measured by Landolt & Uomoto 2007) to obtain the distance. In order to do that, some other quantities are required.

First of all, at these distances, reddening must be considered, and we thus computed theoretical, unreddened ($B - V$) color indices for several relevant model spectra. We used the flux calibration of Holberg & Bergeron (2006) to find the absolute $B$ and $V$ magnitudes. By considering six models (with $T_{\text{eff}} = 82,000$ K and log $g = 6.2, 6.4, \text{and} 6.6$), we derived an average representative color index $(B - V)_n = -0.3831 \pm 0.0018$ showing a very small dispersion (which is, of course, not surprising for a star as hot as BD+28°4211). This is to be compared with the accurate observed value of $(B - V) = -0.3410 \pm 0.0018$ obtained by Landolt & Uomoto (2007), leading immediately to a rather precise reddening index of $E(B - V) = 0.042 \pm 0.003$ for BD+28°4211. Combined with the extinction law proposed by Seaton (1979), this leads to an absorption coefficient in the V band of $A_V = 0.135 \pm 0.008$. We note that this value is quite compatible with the overall absorption coefficient of $A_V = 0.3$ along the line-of-sight in the direction of BD+28°4211 as obtained from the Infrared Science Archive7 using data from Schlegel et al. (1998).

7 http://irsa.ipac.caltech.edu/applications/DUST/
Figure 7. Comparisons of iron lines with models at different log g. This figure is very similar to Figure 6, but for different values of log g while the temperature is kept at 82,000 K. The two left panels show the observed spectrum and three models with different surface gravity, having a fixed iron abundance. Models in the upper panel have gravities that change by 0.4 dex with log g = 6.2 as a middle value, while the changes are of 0.2 dex in the lower panel. The spectrum with the highest value is in blue, the middle one in red, and the lowest one in green. The two middle panels show the results of the fits with the two extreme values of log g, while the right panels show different ranges, fitted with models at log g of 6.6.

(A color version of this figure is available in the online journal.)

Another parameter needed in the computation of the spectroscopic distance is the mass of the star, which allows us to find its radius given the surface gravity. Unfortunately, that parameter is largely unknown, except to say that BD+28°4211 must be either a post-asymptotic giant branch (AGB), a post-extended horizontal branch (EHB), or maybe a post-red giant branch (RGB; though this is less likely because of the relatively short timescale of this evolutionary path). Constraints on the mass can then be derived from model calculations of these late evolutionary phases. For instance, according to the evolutionary tracks of Schoenberner (1983, post-AGB), Dorman et al. (1993, post-EHB), and Driebe et al. (1998, post-RGB) and the approximate position of BD+28°4211 in the log g–T\text{eff} plane, it would appear that its mass should be around 0.5 \( M_\odot \) and could hardly be higher than 0.6 \( M_\odot \) or lower than 0.4 \( M_\odot \). Plots of post-AGB and post-EHB tracks can be found in Figure 1 of Haas et al. (1996), while post-RGB tracks are shown in Figure 10 of Stroeer et al. (2007). However, this is probably not the full story because we know of post-EHB stars with masses less than 0.4 \( M_\odot \), one of which not known to be part of a close binary system (Heber et al. 2005; Randall et al. 2007; For et al. 2010; Fontaine et al. 2012). We cannot therefore exclude a mass for BD+28°4211 less than 0.4 \( M_\odot \) and, as an extreme limit, we will also consider a value as low as 0.3 \( M_\odot \).

Finally, the surface gravity and the effective temperature of a given model atmosphere influence directly the absolute magnitude determined in a given bandpass and, thus, the inferred distance. Since the effective temperature of BD+28°4211 appears to be well constrained by the pattern of iron lines, this parameter was initially fixed at \( T_{\text{eff}} = 82,000 \) K and we computed the spectroscopic distance of the star for different combinations of mass and surface gravity. This was done by comparing the computed absolute visual magnitude \( M_V \) with the well-measured reddened apparent magnitude of \( V = 10.509 \pm 0.0027 \) provided by Landolt & Uomoto (2007).

Our results are presented in Table 5, where, for each combination of mass and gravity, we computed two distances, with and without the reddening. The comparison of our computed spectroscopic distances and the measured one favors a surface gravity higher than 6.2 and/or a low mass for BD+28°4211. If we were to insist that the mass of BD+28°4211 is a representative post-EHB star value, 0.5 \( M_\odot \), say, then our optimal spectroscopic model—characterized by \( T_{\text{eff}} = 82,000 \) K and log g = 6.2—would lead to a distance of 157 pc, in apparent conflict with the parallax measurement of 81–106 pc. This is very

| Mass/log g | 0.3 \( M_\odot \) | 0.4 \( M_\odot \) | 0.5 \( M_\odot \) | 0.6 \( M_\odot \) |
|------------|----------------|----------------|----------------|----------------|
| log g = 6.2 | 129/122 | 150/140 | 167/157 | 183/172 |
| log g = 6.4 | 103/97 | 119/111 | 133/125 | 145/136 |
| log g = 6.6 | 81/77 | 94/88 | 105/99 | 115/108 |
Figure 8. Summary of the determined chemical composition of BD+28°4211. The top panel shows the absolute abundances relative to hydrogen (log N(X)/N(H)) and the horizontal lines indicate the solar one for each element (Asplund et al. 2009). The bottom panel shows this time the abundances relative to the solar value.

reminiscent of the situation encountered by Rauch et al. (2007) in the case of the hot DAO white dwarf LS V +46°21 where the authors estimated the unknown mass by interpolating in a given set of evolutionary tracks. With a fixed value of 0.55 M☉, they found a discrepant spectroscopic distance of 224±46−58 pc compared to a ground-based parallax measurement giving 129±6 pc.

If we take the parallax measurement of BD+28°4211 at face value, then the surface gravity has to be pushed above log g ∼ 6.5 for our spectroscopic distance to become compatible with that measurement, again assuming that the mass of the star is 0.5 M☉. However, such large values of the surface gravity are now in conflict with the iron line profiles depicted in Figure 7. It may thus be preferable to think in terms of a low mass for BD+28°4211 for the time being. This may also be an option in the case of LS V +46°21 (Rauch et al. 2007).

Finally, we also checked what would be the effect of a change in the temperature of our model spectra and we thus computed a table similar to Table 5, except that all models were characterized by T_eff = 87,000 K instead of 82,000 K. We found that the spectroscopic distance increases by only 2 to 6 pc, depending on the parameters mass and gravity, compared to the entries of Table 5. Hence, within an uncertainty of 5000 K (which seems to be a reasonable range according to the result of the previous section), the conclusions of this subsection are practically not dependent on the effective temperature.

5. DISCUSSION

In spite of the huge progress made in the model atmosphere modeling field in the last two decades, the analysis of hot stars still remains a challenge. In this paper, we have presented the first part of our analysis of BD+28°4211, which consists in the study of its UV spectrum. Our work made use of high-quality spectra from the HST and FUSE satellites combined with state-of-the-art NLTE line-blanketed model atmospheres and synthetic spectra computed with TLUSTY and SYNSPEC.

To our knowledge, the FUSE data available on that star have not been exploited previously in the context of an atmospheric abundance analysis. The abundances of eleven elements have been determined, namely those of C, N, O, F, Mg, Si, P, S, Ar, Fe, and Ni. Our abundance analysis was made in a self-consistent way, meaning that the element analyzed contributed to the thermodynamical structure of the model and its populations were explicitly calculated in NLTE during the computation of the model atmosphere. We also made sure that the models used for fitting elements always included, besides the fitted element, at least the atomic species that most contribute to the thermodynamical structure, that is to say helium, carbon, nitrogen, oxygen, and iron. For a star as hot as BD+28°4211, we stress that it is crucial to compute NLTE populations of the studied elements in order to get realistic abundances. Even with the thermodynamical structure of a NLTE line-blanketed model atmosphere, the LTE ionization equilibrium is likely to be wrong, thus preventing a simultaneous fit of absorption lines originating from different ionization stages of a given atomic species. We illustrated this effect in Figure 3, with an example of nickel lines computed in both the NLTE self-consistent way and with LTE populations. In addition to the elements mentioned above, the UV spectrum of BD+28°4211 shows lines of chromium, manganese, and cobalt (and probably those of other species as well). We tentatively tried to fit these three elements by using the LTE approximation, because of the lack of proper model atoms that could be used in our NLTE models. We analyzed only lines originating from the dominant ionization stage (vi) and we got abundances surprisingly similar to the ones Ramspeck et al. (2003) derived (for Cr and Mn) using the “generic ion” approach in NLTE model atmosphere.

Our resulting chemical composition is summed up in Figure 8 and the entire sample of our NLTE fitted lines is shown in the online version of Figure 9. We found the overall quality of our fits very satisfying. When comparing the abundances of BD+28°4211 with those of the Sun, it appears that...
none of the elements studied with self-consistent NLTE models has an abundance higher than solar (the only exceptions being the LTE estimated abundances of chromium and cobalt). Instead, our derived abundances are all between one and 1/10 of the solar ones (Asplund et al. 2009). The most depleted species is carbon with $\log N(C)/N(C_\odot) = -0.91 \pm 0.46$, followed by phosphorus with $\log N(P)/N(P_\odot) = -0.86 \pm 0.52$. It turns out that these two elements, as mentioned in Section 2.2, are present in the photosphere mainly as C $\text{v}$ and P $\text{v}$, which are in a noble gas configuration. This kind of ion usually has its resonance lines in the extreme UV (EUV) or even in the X-ray domain because of the large energy gap between their ground and first excited levels. Therefore, they are less sensitive to radiative levitation, since the EUV and X-ray fluxes of stars are usually lower than the flux at larger wavelengths. This might explain why carbon and phosphorus are the most depleted elements, since their resonance lines are respectively around 40 Å and 90 Å. Even if BD+28°4211 is a hot star, its flux at these extreme wavelengths remains quite low. For its part, even though our abundance of fluorine is at best an estimation based on a sole line, its value around $\log N(F)/N(F_\odot) = -0.56 \pm 0.50$ still suggests that this element is not enriched in BD+28°4211. This is in line with the findings of Werner et al. (2005) who found an important enrichment of fluorine in a number of PG1159 stars, while its abundance remains around or slightly lower than solar in their sample of H-rich central stars of planetary nebulae, the latter being a family of stars having similar evolutionary paths than BD+28°4211. As for iron, our results indicate that $\log N(Fe)/N(Fe_\odot) = -0.58 \pm 0.32$, while they indicate $\log N(Ni)/N(Ni_\odot) = -0.26 \pm 0.48$ for nickel. Both results are compatible with the findings of Ramspeck et al. (2003) which suggest a depleted value of iron by about an order of magnitude (formally, from their Table 1, $\log N(Fe)/N(Fe_\odot) = -0.82 \pm 0.15$), and a solar abundance for nickel.\footnote{Our derived abundances $\log N(Ni)/N(Ni_\odot) = -0.06 \pm 0.78$ and log $N(O)/N(O_\odot) = -0.17 \pm 0.46$ are equally compatible with the work of Haas et al. (1996) who deduced about solar abundances for those two elements.} We thus find a ratio $N(Fe)/N(Ni) \approx 9.1$, which is about half of the solar value. An even more depleted ratio was first suggested by Haas et al. (1996) in BD+28°4211 and is particularly interesting because it connects well with the work of Werner & Dreizler (1994) who found a similar trend in four hot DA white dwarfs. This trend may possibly be explained through the combined effects of radiative levitation and residual stellar winds (see, e.g., the work of Chayer et al. 1994). It must be kept in mind that with an effective temperature of 82,000 K, the abundance pattern of BD+28°4211 is strongly affected by radiative levitation. We made sure that the uncertainties on our determined abundances were computed in a way that includes the effects of a change in the temperature and the gravity of our model atmospheres. Therefore, our abundances should remain fairly reliable even if the effective

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9}
\caption{Totality of our fitted spectral intervals for all the atomic species. The fits were done with models having $T_{\text{eff}} = 82.000$ K, log $g = 6.2$, and log $N(\text{He})/N(\text{H}) = -1.0$. The red curve shows the result of the fitting procedure for the element mentioned on each panel and the abundance obtained is expressed as $\log N(X)/N(H)$. (a) The fit shown in the lower left panel was not included in our mean abundance for nitrogen. Second online panel: the O $\text{iv}$ line at 1338.6 Å is fitted twice because each line comes from two different STIS orders. They were both included in the mean abundance. The lower right panel shows a view of He $\text{ii}$ at 1226 Å, an element not included in our model atmospheres. (An extended, color version of this figure is available in the online journal.)}
\end{figure}
temperature or the surface gravity are revised upward or downward by some 10,000 K or 0.4 dex, respectively.\footnote{After our complete analysis, it appears that a \pm 10,000 K margin of error on the effective temperature is twice our adopted value. Thus, the uncertainties on our abundances are a bit generous.}

Even if we took the fundamental parameters of BD+28°4211 from the literature (Napiwotzki 1993), we nevertheless checked the validity of the assumed effective temperature and surface gravity. To carry out that task, we first redid our fits for nitrogen, silicon, and iron (used as proxy elements) by constructing additional model atmospheres having different parameters. The standard deviation of the sample of fitted intervals for an element gives us an idea of how well the different abundances agree internally with each other. A small value of $\sigma$ indicates that all intervals lead to similar abundances, which is a good thing in our case. By examining the standard deviations obtained when the temperature of the models is changed, we found the results to be in better agreement when the effective temperature of our models is near 82,000 K, which is the assumed one. As for the standard deviations obtained with various log $g$ values, they do not point toward a favored value of the surface gravity. Instead, we have to look at a comparison of observed and synthetic spectra over a wavelength range featuring iron lines originating from three ionization stages, namely Fe v, vi, and vii to have an indication of the better value for the surface gravity (see Figure 7). This figure suggests the assumed value of 6.2 dex to be the one giving the best simultaneous match of the iron lines over the selected range. The differences between our model spectra at different log $g$ are not as striking as the one we obtained with different $T_{\text{eff}}$ (see Figure 6), but they are nevertheless significant.

We also exploited the availability of an \textit{Hipparcos} parallax measurement for BD+28°4211 and compared the inferred distance with spectroscopic distances estimated from several model spectra. In a first step, we were able to derive an accurate determination of the reddening between Earth and BD+28°4211, $E(B-V) = 0.042 \pm 0.003$, thanks to the high-precision optical photometry of Landolt & Uomoto (2007). Several spectroscopic distances (with and without reddening correction) were derived as indicated in Table 5. A comparison with the parallax distance implies a relatively large value of the surface gravity and/or a small mass for BD+28°4211. We can reconcile our spectroscopic constraints with the available parallax measurement only if the mass of BD+28°4211 is significantly less than the canonical value of 0.5 $M_\odot$ for a representative post-EHB star. Assuming that the \textit{Hipparcos} measurement for BD+28°4211 is fully reliable and that our model atmospheres are reasonably realistic, we must conclude that BD+28°4211 is likely less massive than could have been expected on the basis of standard evolutionary tracks.

Our analysis has allowed us to get a good idea of the atmospheric chemical composition of BD+28°4211. Its main constituents, in terms of atomic species, have been analyzed and we were able to get abundances for eleven elements, including the ones that influence the most the thermodynamical structure, i.e., carbon, nitrogen, oxygen, and iron. This now allows us to compute more realistic NLTE model atmospheres including the appropriate line blanketing for BD+28°4211. The value of 82,000 K for the effective temperature of the star now seems quite robust and realistic uncertainties are likely less than $\pm 5000$ K. The case of the surface gravity is somewhat more difficult, but we estimate conservatively that log $g = 6.2^{+0.3}_{-0.1}$ for BD+28°4211. This information should be a good starting point for the study of the optical spectrum of the star. This will follow in an upcoming paper.

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REFERENCES

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, \textit{ARA&A}, 47, 481
Ayres, T. R. 2010, \textit{ApJS}, 187, 149
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, \textit{ApJ}, 394, 228
Bruhweiler, F. C., & Dean, C. A. 1983, \textit{ApJL}, 274, L87
Chayer, P., Fontaine, M., Fontaine, G., Wesemael, F., & Dupuis, J. 2006, \textit{BaltA}, 15, 131
Chayer, P., LeBlanc, F., Fontaine, G., Wesemael, F., & Vennes, S. 1994, \textit{ApJL}, 436, L161
Chayer, P., Vennes, S., Dupuis, J., & Kruk, J. W. 2005, \textit{ApJL}, 630, L169
Dixon, W. V., Sahnow, D. J., Barrett, P. E., et al. 2007, \textit{PASP}, 119, 527
Dorman, B., Rood, R. T., & O’Connell, R. W. 1993, \textit{ApJ}, 419, 596
Dreizler, S., & Werner, K. 1993, \textit{A&A}, 278, 199
Driebe, T., Schoenberner, D., Bloecher, T., & Herwig, F. 1998, \textit{A&A}, 339, 123
Fontaine, G., Brassard, P., Charpinet, S., et al. 2012, \textit{A&A}, 539, A12
For, B.-Q., Green, E. M., Fontaine, G., et al. 2010, \textit{ApJ}, 708, 253
Grevesse, N., & Sauval, A. J. 1998, \textit{SSRv}, 85, 161
Haas, S., Dreizler, S., Heber, U., Jeffery, S., & Werner, K. 1996, \textit{A&A}, 311, 669
Heber, U., Drechsel, H., Karl, C., et al. 2005, in ASP Conf. Ser. 334, 14th European Workshop on White Dwarfs, ed. D. Koester & S. Moehler (San Francisco, CA: ASP), 357
Herbig, G. H. 1999, \textit{PASP}, 111, 1144
Holberg, J. B., & Bergeron, P. 2006, \textit{AJ}, 132, 1221
Landolt, A. U., & Uomoto, A. K. 2007, \textit{AJ}, 133, 768
Lanz, T., & Hubeny, I. 2003, \textit{ApJS}, 146, 417
Lanz, T., & Hubeny, I. 2007, \textit{ApJS}, 169, 83
Lanz, T., Hubeny, I., de Koter, A. 1996, \textit{PhilST}, 65, 144
Latour, M., Fontaine, G., Brassard, P., et al. 2011, \textit{ApJ}, 733, 100
Massey, P., & Grohwall, C. 1990, \textit{ApJ}, 358, 344
Moos, H. W., Cash, W. C., Cowie, L. L., et al. 2000, \textit{ApJL}, 538, L1
Napiwotzki, R. 1993, \textit{AcA}, 43, 343
Napiwotzki, R. 1999, \textit{AcA}, 49, 287
O’Touo, S. J., & Heber, U. 2006, \textit{A&A}, 452, 579
Ramspeck, M., Haas, S., Napiwotzki, R., et al. 2003, in ASP Conf. Ser. 288, \textit{Stellar Atmosphere Modeling}, ed. I. Hubeny, D. Mihalas, & K. Werner (San Francisco, CA: ASP), 161
Randall, S. K., Green, E. M., Van Grootel, V., et al. 2007, \textit{A&A}, 476, 1317
Rauch, T., Ziegler, M., Werner, K., et al. 2007, \textit{A&A}, 470, 317
Saffer, R. A., Bergeron, P., Koester, D., & Liebert, J. 1994, \textit{ApJ}, 432, 351
Sahnow, D. J., Moos, H. W., Ake, T. B., et al. 2000, \textit{ApJL}, 358, L7
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, \textit{ApJ}, 500, 525
Schoenberner, D. 1983, \textit{ApJ}, 272, 708
Seaton, M. J. 1979, \textit{MNRAS}, 187, 73P
Sonneborn, G., Andret, M., Oliveira, C., et al. 2002, \textit{ApJS}, 140, 51
Stroeer, A., Heber, U., Lisker, T., et al. 2007, \textit{A&A}, 462, 269
van Leeuwen, F. 2007, \textit{A&A}, 474, 653
Vennes, S., Chayer, P., & Dupuis, J. 2005, \textit{ApJL}, 622, L121
Wassermann, D., Werner, K., Rauch, T., & Kruk, J. W. 2010, \textit{A&A}, 524, A9
Werner, K. 1996, \textit{ApJL}, 457, L39
Werner, K., & Dreizler, S. 1994, \textit{A&A}, 286, L31
Werner, K., Heber, U., & Fleming, T. 1994, \textit{A&A}, 284, 907
Werner, K., Rauch, T., & Kruk, J. W. 2005, \textit{A&A}, 433, 641
Werner, K., Rauch, T., Ringat, E., & Kruk, J. W. 2012, \textit{ApJL}, 753, L7