SPECTROSCOPIC ANALYSIS OF THE WHITE DWARF KUV 02196+2816: A NEW UNRESOLVED DA+DB DEGENERATE BINARY

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ABSTRACT

A spectroscopic analysis of the DBA (or DAB) white dwarf KUV 02196+2816 is presented. The observed hydrogen- and helium-line profiles are shown to be incompatible with model spectra calculated under the assumption of a homogeneous hydrogen and helium chemical composition. In contrast, an excellent fit to the optical spectrum of KUV 02196+2816 can be achieved if the object is interpreted as an unresolved double degenerate composed of a hydrogen-line DA star and a helium-line DB star. The atmospheric parameters obtained from the best fit are $T_{\text{eff}} = 27170$ K and $\log g = 8.09$ for the DA star, $T_{\text{eff}} = 36340$ K and $\log g = 8.09$ for the DB star, which implies that the total mass of the system ($M \sim 1.4 M_\odot$) is very close to the Chandrasekhar limit. Moreover, the effective temperature of the DB stars lies well within the so-called DB gap where very few bright DB stars are found. The implications of this discovery with respect to the DAB and DBA spectral classes and to the evolution of double-degenerate binaries are discussed.

Key words: binaries: spectroscopic – stars: individual (KUV 02196+2816) – white dwarfs

1. INTRODUCTION

The discovery of double-degenerate binary systems is crucial to our attempt at better constraining their origin and evolution. In particular, these binary systems are thought to be the progenitors of Type Ia supernovae if the total mass of the two components exceeds the Chandrasekhar limit and if their orbital period is small enough to allow them to merge within a Hubble time. However, only a small percentage of double-degenerate binaries lead to supernova explosions according to Nelemans et al. (2001) and Napiwotzki et al. (2001). In 2006, only 10 such binaries composed of two white dwarfs were known (van der Sluys et al. 2006). Since then, the ESO Supernovae Ia Progenitor Survey (SPY) radial velocity survey has observed more than 1000 white dwarfs and prewhite dwarfs (Napiwotzki et al. 2007). One of the conclusions of that survey is that double-degenerate binaries cannot explain the existence of every low-mass white dwarf ($0.45 M_\odot$ or less). Indeed, only 42% of low-mass He-core white dwarfs are found in close binary systems.

Double-degenerate binaries are difficult to detect from single-slit spectroscopy alone. This is particularly true for systems composed of two DA stars since the composite spectrum can be reproduced almost perfectly with a single-hydrogen-rich model atmosphere (Liebert et al. 1991). In order to detect such spectroscopically invisible DA+DA systems, Lajoie & Bergeron (2007) compared effective temperatures determined from optical and ultraviolet (IUE) spectra, and identified three candidate systems. Double-degenerate systems composed of white dwarfs with different spectral types are easier to detect, however, since the modeling of these objects under the assumption of a single star leads to spurious results. This is precisely how Bergeron & Liebert (2002) showed that the DAB PG 1115+166 was in fact a double-degenerate binary system composed of a DA and a DB star. Their analysis revealed that the optical spectrum could not be reproduced with a single-model atmosphere with a mixed hydrogen and helium composition, or even a stratified chemical composition. Instead, the authors showed that a combination of a DA and a DB model spectrum could perfectly match the observed line profiles and photometry. Additional objects are also discussed in Pereira et al. (2005), and references therein.

We are currently conducting a spectroscopic survey of all the white dwarfs discovered in the Kiso Ultraviolet (KUV) survey with the aim of redetermining the luminosity function using the spectroscopic method of Bergeron et al. (1992, see also Liebert et al. 2005). One of these white dwarfs, KUV 02196+2816 (WD 0219+282, $V = 17.30$, was spectroscopically identified as a DBA star by Darling & Wegner (1996). However, this object should have been classified as a DAB star since the hydrogen lines are actually stronger than the helium lines (see Section 2). DAB white dwarfs are particularly interesting since they may represent the key to our understanding of the evolution of DAO and hot DB stars, and of the existence of a strong deficiency of DB stars between 30000 and 45000 K (see Vennes et al. 2004, for a review).

We report in this paper the discovery that KUV 02196+2816 is actually a double-degenerate binary composed of a DA and a DB star. An analysis identical to that of PG 1115+166 by Bergeron & Liebert (2002) indeed reveals that the spectrum of KUV 02196+2816 cannot be reproduced by a single-star model, and that a composite DA and DB model spectrum provides a much better fit to the observations. We first present our spectroscopic observations in Section 2. The model atmosphere calculations described in Section 3 are then used in Section 4 to analyze in detail the optical spectrum of KUV 02196+2816 using homogeneous as well as composite model atmospheres. Our discussion follows in Section 5.
2. SPECTROSCOPIC OBSERVATIONS

Optical spectroscopy for KUV 02196+2816 has been obtained on 2007 December 6 using the Steward Observatory 2.3 m telescope equipped with the Boller & Chivens spectrograph and a Loral CCD detector. The 4′′ slit together with the 600 line mm\(^{-1}\) grating in first order provided a spectral coverage of 3200–5300 Å at an intermediate resolution of ∼0.45 Å.

Our optical spectrum for KUV 02196+2816 is displayed in Figure 1. The hydrogen Balmer lines are clearly stronger than the helium lines and the star should thus be classified as a DAB white dwarf. The spectrum of KUV 02196+2816 is also compared with GD 323, the prototype of the DAB class (Perreira et al. 2005), PG 1115+166 (Bergeron & Liebert 2002), and MCT 0453−2933 (Wesemael et al. 1994). PG 1115+166 has already been discussed above while MCT 0453−2933 has been analyzed by Wesemael et al. (1994) and was shown to be an unresolved composite system consisting of a DA white dwarf and a DB or a DBA companion. The spectra are normalized at 4400 Å and are shifted vertically by 0.5 for clarity.

3. MODEL ATMOSPHERES AND SYNTHETIC SPECTRA

The model atmospheres and synthetic spectra for DA stars are described at length in Liebert et al. (2005), and references therein. The models for DB and DBA stars used in this analysis rely on a modified version of our model atmosphere code for DA stars in which we have included all the helium opacity sources from the DB model atmosphere code described in Beauchamp et al. (1996), and in particular the improved Stark profiles of neutral helium of Beauchamp et al. (1997). The mixed hydrogen and helium models assume a homogeneous chemical composition. We refrain here from using stratified models since Bergeron & Liebert (2002) demonstrated that such models could not fit the optical spectrum of PG 1115+166 with respect to homogeneous models. Also, because the hydrogen and helium lines in the spectrum of KUV 02196+2816 are almost of equal strength, DBA models with unusually high helium abundances had to be calculated for this analysis. Our DBA model grid covers a range of \(T_{\text{eff}} = 14000(2000)\) K, \(\log g = 7.0(0.5)\), and \(N(\text{He})/N(\text{H}) = -1.0(0.5)\), where the numbers in parentheses indicate the step value. Pure helium models were calculated as well.

4. MODEL ATMOSPHERE ANALYSIS

Our fitting technique 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 of KUV 02196+2816 are first normalized to a continuum set to unity. The calculation of \(\chi^2\) is then carried out in terms of these normalized line profiles only. All atmospheric parameters—\(T_{\text{eff}}, \log g, \) and \(N(\text{He})/N(\text{H})\)—are considered free parameters. When fitting DA+DB model spectra, the total flux of the system is obtained from the sum of the monochromatic Eddington fluxes of the individual components, weighted by their respective radius. The stellar radii are obtained from evolutionary models similar to those described in Fontaine et al. (2001) but with \(\text{C/O cores, } q(\text{He}) = \log M_{\text{He}}/M_{\odot} = 10^{-2}\) and \(q(\text{He}) = 10^{-4}\), which are representative of hydrogen-atmosphere white dwarfs, and \(q(\text{He}) = 10^{-2}\), and \(q(\text{He}) = 10^{-10}\), which are representative of helium-atmosphere white dwarfs.1

1 see http://www.astro.umontreal.ca/~bergeron/CoolingModels/
Our grid of model atmospheres with mixed H/He compositions has already been applied successfully to fit DB and DBA stars (Beauchamp et al. 1996) or hotter DAO stars (Bergeron et al. 1994). Hence, the bad fit displayed at the top of Figure 2 does not reflect the inability of our models to fit this star. We also note that Eisenstein et al. (2006) have obtained good fits to DB stars found in the Sloan Digital Sky Survey (SDSS) with temperatures similar to that of KUV 02196+2816 ($T_{\text{eff}} = 35200$ K), although none of these hot DB stars had hydrogen abundances as high as that inferred here ($N(\text{H})/N(\text{He}) \sim 0.7$). Even if we ignore the bad quality of the fit depicted at the top of Figure 2, the atmospheric parameters we obtain for KUV 02196+2816 based on homogeneous models represent a problem from an astrophysical point of view. Indeed, the typical hydrogen abundances measured by Voss et al. (2007) in DBA stars from the SPY survey are of the order of $N(\text{H})/N(\text{He}) \sim 10^{-3} - 10^{-4}$ (see their Table 2)—or even $10^{-3}$ in some extreme cases—and most of them have effective temperatures well below 30000 K. Similarly, the helium abundances measured in typical DAO and DAB stars range from $N(\text{He})/N(\text{H}) \sim 10^{-4}$ to 0.1 (see Figure 7 of Vennes et al. 2004). It is thus difficult to reconcile the atmospheric composition determined here for KUV 02196+2816 using homogeneous models with other single-DAB/DAO or DBA white dwarfs.

In contrast with the homogeneous solution, our DA+DB solution shown at the bottom of Figure 2 provides an excellent fit to the Balmer and neutral helium lines simultaneously. Our DA+DB fit yields a \( \chi^2 \) value of 0.543, a value that is significantly lower than that obtained for the homogeneous solution, \( \chi^2 = 1.416 \). All observed features are reproduced in detail and this is clearly a much better solution for KUV 02196+2816. The effective temperature determined for the DA component is significantly lower than the value achieved under the assumption of a single object with a homogeneous composition. This is a direct consequence of the hydrogen lines being diluted by the continuum flux of the DB star (see below); the Balmer lines are weakened, and the effective temperature of the model needs to be increased to match the observed line profiles. The effective temperature of the DB component, \( T_{\text{eff}} = 36340 \) K, is higher than the value obtained with our homogeneous models, \( T_{\text{eff}} = 35200 \) K, yet the He \( \lambda 4686 \) feature only appears as a small depression in the blue wing of He \( \lambda 4713 \). In this case, the presence of the DA star dilutes all the helium lines present in the DB spectrum. But the main physical reason for this difference in strength is that the overall opacity of the mixed H/He model is lower than that of the pure helium model at the same effective temperature, resulting in lower atmospheric pressures, which in turn favors the ionization of helium in the mixed atmosphere. Hence, the He \( \lambda 4686 \) feature appears stronger in the mixed model than in the pure helium model, even though the former is \( \sim 1000 \) K cooler.

The surface gravities of both components of the system are almost identical, \( \log g = 8.095 \) for the DA and \( \log g = 8.095 \) for the DB. These values can be translated into masses and cooling ages using the evolutionary models described above. We obtain, respectively, for the DA and the DB stars 0.69 and 0.68 \( M_\odot \), and cooling ages of \( 1.76 \times 10^7 \) and \( 5.13 \times 10^6 \) years. Since both stars have the same radius, the contribution of each component to the total luminosity is only a function of the effective temperature. Since the DB star is significantly hotter than the DA component, the former will contribute more to the combined luminosity of the system. This is illustrated quantitatively in Figure 3 where the contribution of each component to the total flux is depicted. There is a significant contribution of the flux of the DB star in the optical regions of the energy distribution. In particular, the cores of the lower Balmer lines are filled in by the continuum flux of the DB star, resulting in the poor fits of the homogeneous solution displayed in Figure 2 and discussed above.

5. DISCUSSION

Our analysis has shown that the simultaneous presence of hydrogen and helium in the spectrum of KUV 02196+2816 is better explained in terms of an unresolved binary system composed of a DA white dwarf and a DB star. We note that in at least two instances, PG 1115+166 and MCT 0453–2933 (displayed in Figure 1 and discussed above), this binary interpretation has been confirmed through spectral velocity variations, hence similar observations of KUV 02196+2816 should also confirm its binary nature. Despite the evidence of our spectroscopic
analysis, we discuss in the following the difficulty with interpreting KUV 02196+2816 as a single star, even from an evolutionary point of view.

There are actually two scenarios that can produce mixed hydrogen and helium atmospheres in the temperature range considered here. The first scenario, discussed in the context of DBA stars, is the accretion of hydrogen from the interstellar medium onto a helium-dominated atmosphere. However, the stellar wind model proposed by Fontaine & Brassard (2005) might prevent the accretion of hydrogen for stars hotter than $T_{\text{eff}} \sim 20000$ K. Hence, the presence of hydrogen in KUV 02196+2816 cannot be explained by this scenario, and another explanation must be sought for the existence of KUV 02196+2816 if it is to be interpreted as a single star.

Another scenario has been proposed by Fontaine & Wesemael (1987), where residual amounts of hydrogen left in the envelope of hot DO stars would gradually diffuse to the surface as the white dwarf evolves along the cooling sequence. This buildup of hydrogen at the photosphere would gradually turn DO white dwarfs into DA stars. Prior to the SDSS, the absence of any helium-rich atmosphere white dwarfs below $T_{\text{eff}} \sim 45000$ K (and above 30000 K) would impose a limit of $M_\text{He} \geq 10^{-16} M_\odot$ to the total mass of hydrogen left after the post asymptotic giant branch (AGB) phase. Such minute amounts of hydrogen are actually sufficient to turn all hot, helium-rich atmosphere white dwarfs into DA stars by the time they reach $T_{\text{eff}} \sim 45000$ K, which defines the blue edge of the so-called DB gap, a range in effective temperature between $T_{\text{eff}} \sim 30000$ and 45000 K where no helium-atmosphere white dwarf (DO or DB stars) had ever been identified (Liebert et al. 1986).

More recently, however, the SDSS has revealed the existence of several hot DB stars in this gap (Eisenstein et al. 2006), although the fraction of helium-dominated atmospheres in this temperature range remains significantly lower than that found at higher or lower temperatures. We note that the SDSS white dwarfs are much fainter than those investigated by Liebert et al. (1986) in the Palomar–Green sample. The implication of this result is that a few white dwarfs must necessarily survive the DO-to-DA transition at high temperatures. This in turn implies that the amount of hydrogen left in the envelope of pre-white dwarfs during the post-AGB phase is even smaller than previously anticipated. We must conclude that the born-again post-AGB scenario proposed by Werner & Herwig (2006) in which a violent mixing event is induced by a late helium flash in the post-AGB phase is efficient enough to leave virtually no helium behind. The recent discovery by Dufour et al. (2007, 2008) of a new class of white dwarf stars with carbon-rich atmospheres between $\sim 18000$ and 24000 K even suggests that these flash events might be efficient enough to leave no helium behind! In this context, it is perhaps no longer surprising to find hot DB stars in the gap. These hot DB stars are most likely the immediate progenitors of the carbon-rich atmosphere white dwarfs discovered by Dufour et al.

The significant increase in the number of helium-atmosphere DB white dwarfs below $T_{\text{eff}} \sim 30000$ K—whether in the PG or SDSS samples—can only be explained in terms of the convective dilution of the superficial hydrogen atmosphere by the underlying helium convective envelope, provided that the hydrogen layer is sufficiently thin ($M_\text{H}/M_\text{tot} \sim 10^{-15}$; MacDonald & Vennes 1991). As discussed by Bergeron & Liebert (2002), if the DO-to-DA and DA-to-DB transition scenarios discussed above are correct, white dwarfs with mixed hydrogen and helium compositions must be sought either at the hot end of the DB gap (or deficit) near 45000 K where an extremely thin hydrogen atmosphere in diffusive equilibrium on top of the helium envelope would make the star appear as a DAO star, or near the cool end of the gap, where convective dilution of the thin hydrogen atmosphere occurs. Excellent candidates of such stars caught in the act of changing from one spectral type to another are PG 1305–017, a DAO star at $T_{\text{eff}} = 44000$ K whose spectrum is better reproduced with stratified atmospheres (Bergeron et al. 1994), and GD 323 (as shown in Figure 1), a DAB star at $T_{\text{eff}} = 28750$ K (Koester et al. 1994) whose spectrum exhibits spectroscopic variations that have been interpreted as surface abundance inhomogeneities resulting from the convective dilution of hydrogen into helium (Pereira et al. 2005).

Going back to KUV 02196+2816, its effective temperature near 35000 K obtained under the assumption of homogeneous single-star models does not fit well into this picture. First, the convective efficiency of the helium envelope at that temperature (the He ii convection zone in this case) is much too low to produce any dilution of the hydrogen superficial atmosphere. Second, since KUV 02196+2816 is a full 10000 K cooler than the blue edge of the DB gap near 45000 K, it has necessarily survived the DO-to-DA transition. This in turn implies that the total amount of hydrogen left in the envelope during the post-AGB phase must be extremely small, and certainly too small to account for the hydrogen abundance inferred from our homogeneous model atmosphere analysis.

Thus, the DA+DB solution proposed here for KUV 02196+2816 not only provides a much better fit to the optical spectrum than the single-star model, but it also represents the only viable solution from an evolutionary point of view. Interestingly enough, the effective temperature we infer for the DB component of the system, $T_{\text{eff}} = 36340$ K, puts it right in the middle of the DB gap. This makes the DB component of the KUV 02196+2816 system the brightest DB white dwarf ever identified in the gap. From the atmospheric parameters of the DA and DB stars, we estimate the absolute visual magnitude of the system at $M_V = 9.51$, which combined with the visual magnitude of $V = 17.30$ yields a distance of 360 pc.

Wachter et al. (2003) also found from the Two Micron All Sky Survey (2MASS) photometry that KUV 02196+2816 was a good binary candidate composed of a white dwarf and a low-mass main-sequence star. This binary nature was confirmed by Farihi et al. (2006) in their study of white dwarf–red dwarf systems resolved with Hubble Space Telescope. Farihi et al. indeed found that KUV 02196+2816 has a red dwarf companion and both stars are believed to be gravitationally bound. Since KUV 02196+2816 itself is a double-degenerate binary, the system is thus composed of three stars, two of which are unresolved. As mentioned above, high-resolution spectroscopic observations similar to that obtained by Napiwotzki et al. (2005) for the double-degenerate system MCT 0453–2933 could help confirm our binary interpretation. Finally, we note that since the total mass of the KUV 02196+2816 system ($M \sim 1.4 M_\odot$) is close to the Chandrasekhar limit, a precise measurement of its orbital period would establish whether KUV 02196+2816 represents a likely supernova candidate.

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REFERENCES

Beauchamp, A., Wesemael, F., & Bergeron, P. 1997, ApJS, 108, 559
Beauchamp, A., Wesemael, F., Bergeron, P., Liebert, J., & Saffer, R. A. 1996, in ASP Conf. Ser. 96, Hydrogen-Deficient Stars, ed. S. Jeffery & U. Heber (San Francisco, CA: ASP), 295
Bergeron, P., & Liebert, J. 2002, ApJ, 566, 1091
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 247
Bergeron, P., Wesemael, F., Beauchamp, A., Wood, M. A., Lamontagne, R., Fontaine, G., & Liebert, J. 1994, ApJ, 432, 305
Burleigh, M., Bannister, N., & Barstow, M. 2001, in ASP Conf. Ser. 226, 12th European Workshop on White Dwarf Stars, ed. J. L. Provencal, H. L. Shipman, J. MacDonald, & S. Goodchild (San Francisco, CA: ASP), 135
Darling, G. W., & Wegner, G. 1996, ApJ, 111, 685
Dufour, P., Fontaine, G., Liebert, J., Schmidt, G. D., & Behara, N. 2008, ApJ, 683, 978
Dufour, P., Liebert, J., Fontaine, G., & Behara, N. 2007, Nature, 450, 522
Eisenstein, D. J., et al. 2006, AJ, 132, 676
Farhi, J., Hoard, D. W., & Wachter, S. 2006, ApJ, 646, 840
Fontaine, G., & Brassard, P. 2005, in ASP Conf. Ser. 334, 14th European Workshop on White Dwarf Stars, ed. D. Koester & S. Moehler (San Francisco, CA: ASP), 49
Fontaine, G., Brassard, P., & Bergeron, P. 2001, PASP, 113, 409
Fontaine, G., & Wesemael, F. 1987, in IAU Colloquium 95, The Second Conference on Faint Blue Stars, ed. A. G. D. Philip, D. S. Hayes, & J. Liebert (Schenectady: L. Davis Press), 319
Green, R. F., Schmidt, M., & Liebert, J. 1986, ApJS, 61, 305
Koester, D., Liebert, J., & Saffer, R. A. 1994, ApJ, 422, 783
Lajoie, C.-P., & Bergeron, P. 2007, ApJ, 667, 1126
Lievart, J., Bergeron, P., & Holberg, J. B. 2005, ApJ, 156, 47
Liebert, J., Bergeron, P., & Saffer, R. A. 1991, in 7th European Workshop on White Dwarfs, NATO ASI Series, ed. G. Vauclair & E. M. Sion (Dordrecht: Kluwer), 409
Liebert, J., Wesemael, F., Hansen, C. J., Fontaine, G., Shipman, H. L., Sion, E. M., Winget, D. E., & Green, R. F. 1986, ApJ, 309, 241
MacDonald, J., & Vennes, S. 1991, ApJ, 371, 719
Maxted, P. F. L., Burleigh, M. R., Marsh, T. R., & Bannister, N. P. 2002, MNRAS, 334, 833
Napiwotzki, R., et al. 2001, Astron. Nachr., 322, 411
Napiwotzki, R., et al. 2005, in ASP Conf. Ser. 334, 14th European Workshop on White Dwarf Stars, ed. D. Koester & S. Moehler (San Francisco, CA: ASP), 375
Napiwotzki, R., et al. 2007, in ASP Conf. Ser. 372, 15th European Workshop on White Dwarf Stars, ed. R. Napiwotzki & M. R. Burleigh (San Francisco, CA: ASP), 387
Nelemans, G., Vugelson, L. R., Portegies Zwart, S. F., & Verbunt, F. 2001, ApJ, 365, 491
Pereira, C., Bergeron, P., & Wesemael, F. 2005, ApJ, 623, 1076
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1986, Numerical Recipes, (Cambridge: Cambridge Univ. Press)
van der Sluys, M. V., Verbunt, F., & Pols, O. R. 2006, A&A, 460, 209
Vennes, S., Dupuis, J., & Chayer, P. 2004, ApJ, 611, 1091
Voss, B., Koester, D., Napiwotzki, R., Christlieb, N., & Reimers, D. 2007, A&A, 470, 1079
Wachter, S., Hoard, W., Hansen, K. H., Wilcox, R., Taylor, H. M., & Finkelstein, S. L. 2003, ApJ, 586, 1556
Werner, K., & Herwig, F. 2006, PASP, 118, 183
Wesemael, F., et al. 1994, ApJ, 429, 369