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DETERMINATION OF THE ATMOSPHERIC PARAMETERS OF THE BINARY DA WHITE DWARF L870-2 (EG 11)[1]

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ABSTRACT

We present an analysis of the close detached binary DA white dwarf system L870-2, with the aim of determining atmospheric parameters for both components of the system. Medium-resolution spectrophotometry of the high Balmer lines, Strömgren photometry, and the observed luminosity excess are used, together with the observed mass ratio, to constrain the effective temperature and surface gravity of each star. We find $T_1 = 7470 \pm 500$ K, $\log g_1 = 7.80 \pm 0.10$, $T_2 = 6920 \pm 500$ K, $\log g_2 = 7.89 \pm 0.10$. The corresponding masses are $0.47 \pm 0.05\ M_\odot$ and $0.52 \pm 0.05\ M_\odot$ for an assumed helium core compositon.

Subject headings: stars: atmospheres — stars: binaries — stars: white dwarfs

I. INTRODUCTION

The recent discovery that the cool DA white dwarf L870-2 (EG 11, WD 0135−052) is a double-lined spectroscopic binary composed of a close detached pair of DA white dwarfs (Saffer, Liebert, and Olszewski 1980, hereafter SLO) has raised some challenging problems for stellar evolution theories of such binary systems (Iben and Webbink 1989). The major interest in that discovery is that Type I supernovae are believed to be the result of the merging of such close pairs of degenerate stars (see SLO and references therein). L870-2 thus represents the first evidence that close noninteracting binary white dwarfs *do* indeed exist. One first important step in the understanding of L870-2 is to establish the atmospheric parameters of each component. SLO have argued from previous determinations of the effective temperature and absolute magnitude of the system, and also from their own study of the composite Hα profile, that the two components should be similar. In this *Letter*, we provide an analysis of this fascinating system, which combines new medium-resolution optical data with existing photometry of the system. We show that the range of atmospheric parameters can indeed be effectively constrained from spectroscopy of high Balmer lines and Strömgren photometry alone, once the mass ratio is known. Preliminary results of this work were presented in Bergeron *et al.* (1989), but we go beyond this earlier work here by making full use and modeling the Hα line profile, in order to test the internal consistency of our analysis, and by exploring the influence of the assumed core composition.

II. CONSTRAINTS ON THE ATMOSPHERIC PARAMETERS

As pointed out by SLO, L870-2 has been widely used as a photometric standard. In particular, several spectra of L870-2 at a medium-resolution of 2.25 Å have been obtained with the Steward Observatory 2.3 m reflector and blue photon-counting Reticon in the course of our study of the atmospheric properties of cool DA white dwarfs (e.g., Lacombe *et al.* 1983; Bergeron, Wesemael, and Fontaine 1989). Our spectrum of L870-2 is shown in Bergeron *et al.* (1989), where it is compared to that of G74-7, a DAZ star at a similar temperature (Lacombe *et al.* 1983). The point is made there, and further emphasized here, that the spectrum of L870-2 is not unlike that of other (presumably single) DA stars in that temperature range. In fact, the composite line spectrum can be fitted quite straightforwardly by a single-component spectrum. Using a newly developed grid of model atmospheres appropriate to the study of cool DA white dwarfs (Bergeron, Wesemael, and Fontaine 1989), we obtain for L870-2 an effective temperature of 7240 ± 35 K, with a surface gravity of 7.85 ± 0.10. The result presented here is slightly different from the preliminary values given in Bergeron *et al.* (1989), namely $T_e = 7240$ K and $\log g = 7.80$. This change originates in an improved treatment of the broadening of the high Balmer lines. The resulting fit is displayed in Figure 1. Our effective temperature is in good agreement with those previously obtained under similar assumptions (see Bergeron *et al.* 1989 and references therein). Thus, a first constraint can already be imposed from this spectroscopic evidence, namely that *the summed spectra from both components must be fitted by a single spectrum at* $T_e = 7240$ K *and* $\log g = 7.85$.

A second constraint is obtained from the study of the orbital parameters of the binary system. SLO have estimated the radial velocity semiamplitude for each component as $K_1 = 77.6$ km s^{-1} and $K_2 = 69.6$ km s^{-1}; this corresponds to a mass ratio of $q = M_2/M_1 = 1.115$. Our second constraint is thus that *the surface gravities of both components be consistent with a mass ratio of* 1.115.

A third constraint comes from the Strömgren photometry. Because $(u - b)$ ceases to be gravity-sensitive at the low effective temperature of L870-2 (e.g., Fontaine *et al.* 1985), not much can be learned from this particular color index. The color index $(b - y)$, however, is sensitive to the effective temperature. Fontaine *et al.* (1985) have measured $(b - y) = 0.274 \pm 0.019$. The Strömgren photometry thus imposes that *the* $(b - y)$ *obtained from the summed spectra of both components be consistent with the measured value of* 0.274.

Finally, a fourth constraint is obtained from the measured luminosity excess. Greenstein (1985) has found from his determination of M_V and from an accurate trigonometric parallax that L870-2 has a luminosity excess of 1.1 mag from the mean $(G - R)$-M_V relation for DA white dwarfs. This result can be translated into total luminosity if, as we argue below, the two components have similar effective temperatures, and thus bolometric corrections. Accordingly, the binary system has a total

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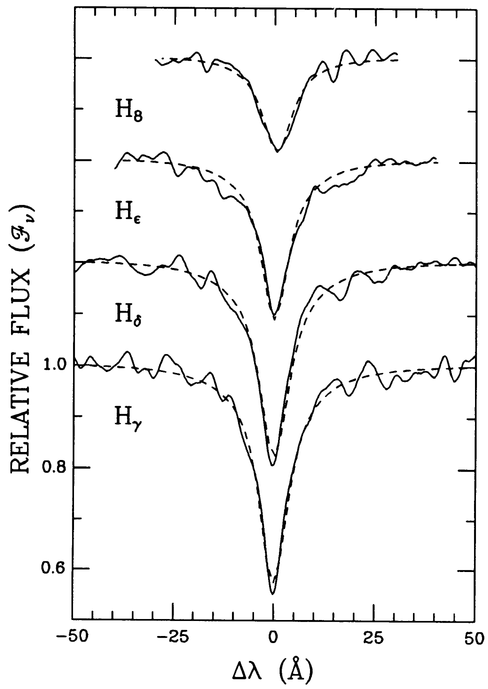

FIG. 1.—Our fit to the line spectrum of L870-2 at $T_e = 7240$ K and log $g = 7.85$, obtained under the assumption that a single DA star is being fitted. The continuum of each line has been normalized to unity, and the higher lines have been shifted vertically by a factor of 0.2 from each other.

luminosity ~2.75 times larger than that of a single star which would have the same color as L870-2 but at log $g = 8.0$, the gravity most appropriate to the mean relation defined by Greenstein. From our $(b - y)$-T_e calibration, we obtain for $(b - y) = 0.274$ an effective temperature of 7280 K, a value entirely consistent with our spectroscopic estimate of the effective temperature. We thus express the fourth constraint by requiring that *the sum of the individual luminosities for each component be equal to the observed total luminosity, namely* 2.75 *times that of a* 7280 K *star at log* $g = 8.0$.

In order to reconcile all these constraints, we use the following, rather lengthy, procedure. First, for a given set of surface gravities (g_1, g_2), consistent with the estimated mass ratio of 1.115 (second constraint), we add the surface fluxes (weighted by the respective radii assuming a given core composition) for a large set of effective temperature pairs (T_1, T_2). A model grid at log $g = 7.85$ (first constraint) is then used to fit each of these spectra in terms of that of a single star and to determine the temperature for each of these spectra. The locus of effective temperature-pairs which yield the required effective temperature of 7240 K is then plotted on a (T_1, T_2) diagram. An example of such a diagram is shown in Figure 2 where the solid line represents the desired locus of acceptable model combinations: on this line, the combined optical spectra are all rigorously equivalent and can be fitted by a single DA model at 7240 K, log $g = 7.85$. However, we should point out that these *best* fits, for a given set of (g_1, g_2), do not all represent necessarily *good* fits to the observed spectrum; indeed, the combined synthetic spectra occasionally do not reproduce adequately the gravity sensitive high Balmer lines. We then repeat the procedure but, this time, calculate the Strömgren color index $(b - y)$ and define in the (T_1, T_2) diagram the locus of constant $(b - y) = 0.274$, consistent with the third constraint (*dashed line*). Finally, we plot on the same diagram the locus of models with the appropriate overluminosity, according to the fourth constraint (*dash-dotted line*).

The morphology of the resulting fitting diagram depends strongly on the initial choice for the (g_1, g_2) set. The whole procedure is thus repeated for several such sets, which cover the range of $7.5 \leq \log g_1 \leq 8.5$ at steps of 0.1 in log g_1. The associated value of g_2 follows from the second constraint. All such fitting diagrams are then examined, and that providing the best internal consistency between the loci associated with the three constraints determines the optimal (g_1, g_2) set. With the assumption of a helium core composition, our results show that such consistency is best achieved for values of the surface gravity of the components of log $g_1 = 7.70$ and log $g_2 = 7.79$. With this set of surface gravities, however, the combined synthetic spectra do not reproduce adequately the strength of the gravity-sensitive high Balmer lines. In order to match these line profiles, the surface gravities must be increased to log $g_1 = 7.80$ and log $g_2 = 7.89$, which is our updated solution displayed on Figure 2. The uncertainties on the surface gravities of each component is roughly ± 0.10. With this last set of surface gravities, however, the observed luminosity excess of 1.1 mag cannot quite be matched. A luminosity excess of 0.97 mag, roughly 0.1 mag lower than Greenstein's (1985) estimated value, would allow us to satisfy simultaneously all three constraints. We note that Saffer and Liebert (1988) have shown that the estimated luminosity excess is strongly dependent on the assumed *color*-M_V diagram. For example, in a $[(V-I) + (G-R)]$-M_V diagram, the luminosity excess can be as large as 1.5 mag. Because of these uncertainties, we give greater weight to the evidence provided by the high Balmer lines, and adopt the pair of higher surface gravities in the rest of our discussion. It is also evident from Figure 2 that, in order to satisfy simultaneously the photometric and spectroscopic constraints, the effective temperatures of both components cannot differ significantly. A conservative estimate of the effective temperatures ranges from $T_1 = 6750$ K, $T_2 = 7585$ K, to

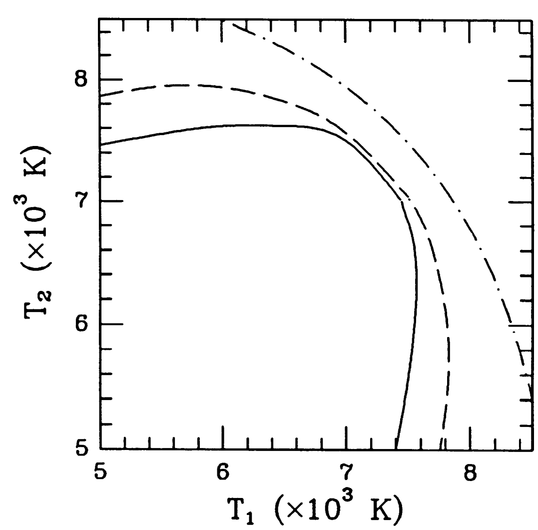

FIG. 2.—Fitting diagram for the temperature of each component, constrained by high Balmer line spectroscopy (*solid line*), Strömgren photometry (*dashed line*), and luminosity (*dash-dotted line*). The surface gravities displayed on this diagram (log $g_1 = 7.80$, log $g_2 = 7.89$) represent our adopted solution, which also satisfies the constraint imposed on the mass ratio of the components.

$T_1 = 7470$ K, $T_2 = 6830$ K, with all the intermediate cases equally acceptable.

The results presented in Figure 2 depend on the assumed core composition, as the Eddington fluxes from the individual components must be weighted by the respective stellar radii before being summed (constraint 1). At a given gravity (and effective temperature), the radius thus depends on the core composition. Furthermore, the optimal set of surface gravities obtained earlier can be converted to the more useful (from an evolutionary point of view) quantity of stellar mass only after having fixed the core composition. With the assumption of a helium core composition, the derived component masses are $M_1 = 0.47\ M_\odot$ and $M_2 = 0.52\ M_\odot$. In view of the fact that standard theories of binary white dwarf evolution suggest that such low mass white dwarfs probably have helium cores (Iben and Webbink 1989), the helium composition was preferred here, and the zero-temperature mass-radius relation of Hamada and Salpeter (1961) was adopted. How would these masses be affected if some other mass-radius relation were chosen? One could imagine, for example, that the choice of a carbon or carbon/oxygen core composition may not be entirely excluded by evolutionary considerations (Iben and Webbink 1989), especially for this system where the surface gravities do not appear exceedingly lower than average. Furthermore, departures from the zero-temperature relation should be considered as well.

To this end, we have used several evolutionary sequences calculated by Winget, Lamb, and Van Horn (1989), and Wood (1989). The core compositions used are pure carbon or a carbon/oxygen mixture, and a variety of envelope masses are considered as well. Not surprisingly we find, near $T_e \sim 7000$ K, negligibly small departures ($<3\%$ in radius) from the zero-temperature relation, even for the largest envelope masses available ($M_C = 0.6\ M_\odot$, $M_{He} = 10^{-2}\ M_\odot$, $M_H = 10^{-4}\ M_\odot$). Unfortunately, we are not aware of published cooling sequences with a helium core composition, which would allow us to evaluate the magnitude of finite-temperature effects for helium white dwarfs. The effects found in state of the art cooling calculations for C and C/O cores with realistic envelope masses suggest, however, that such finite-temperature effects would be small. Furthermore, had we adopted a different core composition for our analysis, the corresponding masses would have been only slightly affected: we find $M_1 = 0.47\ M_\odot$, $M_2 = 0.53\ M_\odot$, and $M_1 = 0.46\ M_\odot$, $M_2 = 0.51\ M_\odot$ for a carbon and carbon/oxygen composition, respectively. Thus, it appears that the masses determined here may not be overly sensitive to uncertainties in the core composition, envelope mass, or cooling physics, and that the largest uncertainty comes mainly from the determination of the individual surface gravities, which we estimate to be $\pm 0.05\ M_\odot$.

In their independent analysis, Iben and Webbink (1989) find masses of $M_1 = 0.54\ M_\odot$ and $M_2 = 0.605\ M_\odot$ on the basis of the cooling tracks of Iben and MacDonald (1986) for carbon cores, and attribute their higher masses to the use of a different mass-radius relationship. Our analysis shows, however, that the difference in radius between the 0.6 $M_\odot$ carbon sequence of Iben and MacDonald (1986) and those considered here is only of the order of 1% at low effective temperature and is unlikely to be the source of our different results.

III. ANALYSIS OF THE Hα PROFILES

Although clues had been uncovered earlier (e.g., Greenstein *et al.* 1977; Greenstein 1983), the binary nature of L870-2 has now been confirmed by SLO's measurements of radial velocities of the sharp Hα core. The normalized composite Hα spectrum of the L870-2 system, reproduced in Figure 3, shows that the cores from each component are resolved at quadrature. In principle, these Hα profiles could serve as another observational constraint to narrow further the temperature range of the system components. We have investigated this avenue with the following procedure. The different pairs of (T_1, T_2) selected from Figure 2 (*solid line*) are used to compute synthetic Hα line profiles. The profiles from each component are then shifted in wavelengths according to the spectroscopic orbital elements (see Table 2 of SLO), and added. In Figure 3, the blueward-shifted component has the largest radial velocity and is thus identified with the less massive component (or, equivalently, that with the smallest surface gravity) of the system (in our notation, component 1). Least-squares method and visual inspection are then used to find the best fit to the observed spectrum.

Perhaps not surprisingly, the Hα line cores predicted in LTE are flat-bottomed and quite unlike those observed in L870-2. A typical case is shown as a dotted line in Figure 3. It is clear that the Hα cores, formed high in the atmosphere, must be out of LTE. In order to check the consistency of the solution obtained in § II with the observed Hα cores, we have calculated a new grid of Hα line profiles in non–LTE. The code, which is

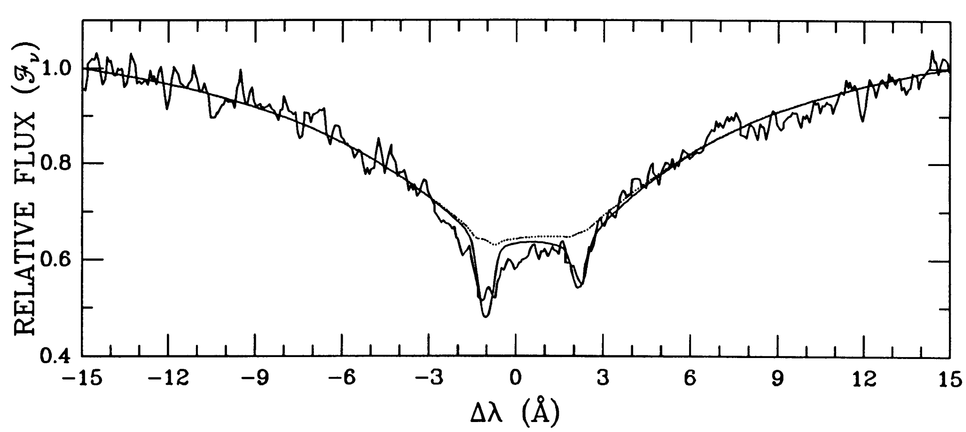

FIG. 3.—Comparison of the observed Hα profiles of the L870-2 system at quadrature with our best fit ($\log g_1 = 7.80$, $T_1 = 7470$ K; $\log g_2 = 7.89$, $T_2 = 6920$ K) using non–LTE line profiles (*solid line*). Also shown are the LTE line profiles (*dotted line*) obtained at the same effective temperatures and surface gravities.

similar to that described by Pilachowski and Milkey (1984), uses an eight-level model hydrogen atom plus continuum. Our fit to the observed spectrum is presented in Figure 3 (*solid line*). The improvement over the LTE result is significant.

Because these sharp non–LTE cores vary only slowly with T_e, the uncertainty associated with the estimated effective temperatures of the individual components is not significantly reduced by this procedure. In fact, least-squares fit to the observed spectrum shows that the value of the χ^2 is almost constant as T_1 goes from 6500 K to 7560 K (or correspondingly when T_2 goes from 7600 K to 6300 K). Even through a close visual inspection, the different solutions appear equally acceptable. That range of effective temperatures is even larger than previously determined in § II. Clearly, the fit presented in Figure 3 ($T_1 = 7470$ K, $T_2 = 6920$ K), which we adopt as our final solution, is satisfactory but is not unique. The Hα profiles are thus not sufficiently temperature-sensitive to allow us to determine precisely individual effective temperatures. This exercise has nevertheless demonstrated that the difference in effective temperatures of both components could be relatively large ($\Delta T \sim 600$ K) and still not affect significantly the relative depths of the non–LTE Hα line cores, in contrast to the suggestion of SLO.

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