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DISCOVERY OF A MAGNETIC/NONMAGNETIC DOUBLE-DEGENERATE BINARY SYSTEM

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ABSTRACT

We report the discovery of an unresolved binary system consisting of two degenerate stars: one a polarized object with an inferred magnetic field among the largest yet found on a white dwarf; the other a normal DA with no detectable field. We have deconvolved the composite 1250 Å–2.2 μm energy distribution into individual spectra and find that, with the exception of the graphic difference in magnetic field strength, the two stars are remarkably similar. For the normal DA, $T_{\rm eff} \approx 14{,}500$ K, log $g \approx 8.5$, and $M = 0.91 \pm 0.07\ M_\odot$, while the magnetic component has $T_{\rm eff} \approx 16{,}000$ K, log $g \approx 8.5$, and $0.76 \le M/M_\odot < 1.00$. The parameters of the latter are less accurately determined since it appears to have an atmosphere dominated by an element other than hydrogen.

At a distance of about 40 pc, the projected separation of the stellar components could be as large as 20 AU. The binary might therefore be a wide pair in which two stars of similar initial mass evolved into two very different end states. On the other hand, it could be an unusual product of close binary evolution, in which case this would be the first such example whose combined mass appears to exceed the Chandrasekhar limit. Potential implications and future observations to clarify the evolutionary and magnetic status of the system are suggested.

Subject headings: binaries: close — stars: individual (LB 11146) — stars: magnetic fields — ultraviolet: stars — white dwarfs

1. INTRODUCTION

Only a small fraction—about 2%—of field white dwarfs show detectable magnetism; the fields range in strength from $\sim 10^6$ G (1 MG) to nearly 10^9 G (Schmidt 1989). At their highest values, white dwarfs may overlap with the neutron stars (old pulsars), but most, if not all, neutron stars have fields at least this strong. The origin of magnetism in these objects remains an unsolved problem; thus it is not known why the relative fractions having detectable fields appear to differ so decisively between the two classes of remnant object. One potential clue is the evidence that at least some magnetic white dwarfs have high masses compared to the norm (Greenstein & Oke 1982; Sion et al. 1988; Liebert 1988).

There is also a contrast in the frequency and strength of magnetism between white dwarfs in the field (single stars) and in interacting binaries. The AM Her and DQ Her classes of cataclysmic variable (CV), which have magnetic degenerate primary stars, appear to form a much higher percentage of all CVs than the 2% cited for field stars. Admittedly, selection effects such as X-ray emission may skew the statistics in favor of the discovery of magnetic systems. Yet, the AM Her and DQ Her primaries also seem to be restricted to fields no higher than ~ 50 MG.

Until recently, there were no known binary systems involving a magnetic white dwarf which were detached, or noninteracting. One possible exception is V471 Tauri. The identification of X-ray and optical modulations with rotation rather than pulsations (Clemens et al. 1992) indicates that the white dwarf may have a composition which varies around the surface; this in turn suggests a model in which the white dwarf has a weak magnetic field.

Finally, Bergeron, Ruiz, & Leggett (1993) found triplet absorption features of Hα in the spectrum of G62-46, indicating a magnetic DA star. They were unable to reconcile the strengths of the hydrogen lines with the spectral energy distributions of single magnetic DA models; however, agreement could be reached by assuming that a second, lineless component—a DC white dwarf—is present in the system. It is not known whether the purported DC is also magnetic. It should be noted for completeness that three other DA+DC double-degenerates had previously been found on the basis of a strong discrepancy between color and line profiles (Greenstein & Liebert 1990; Bergeron, Greenstein, & Liebert (1990), but there is no evidence that any of these components are magnetic.

In this paper, we report an even more complex spectrum which leads us to the similar conclusion that two white dwarf stars are present. In this case, however, one component has a magnetic field which is among the largest yet measured on a white dwarf, while the other shows no detectable field at all.

LB 11146 (PG 0945+245) was one of the more than 130 DA white dwarfs selected for observation for the purpose of determining the atmospheric parameters and refining the mass distribution of these white dwarfs (Bergeron, Saffer, & Liebert 1992, hereafter BSL). As discussed in § 3, it was the *only* star which could not be fitted with normal hydrogen atmosphere models. The detailed set of observations obtained to solve this mystery is introduced in § 2. In § 4, linear and circular spectropolarimetry are presented and clues to the field strength and atmospheric composition of the magnetic component are discussed. In § 5, we consider the binary system itself and present ideas on how this unusual system was produced. Finally, § 6 offers a list of important future observations.

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2. OBSERVATIONS

2.1. *Multichannel Spectrophotometry*

Some years ago, as part of our original project to determine the luminosity function of DA white dwarfs in the Palomar Green Survey (Fleming, Liebert, & Green 1986), the spectral energy distribution of LB 11146 was measured using the Palomar 5 m telescope and multichannel spectrophotometer (MCSP; Oke 1974). These data, obtained on 1981 May 5, provide the best photometry over the wavelength region $\lambda\lambda$3225–10,000. The resolution was 80 Å shortward of 5800 Å and 160 Å longward of this value. While the Balmer features appear, in retrospect, somewhat unusual, the principal abnormality is an apparent depression centered near 5500 Å.

2.2. *Spectrophotometry of the Higher Balmer Series*

The optical spectrum of the Balmer series except Hα was obtained on two occasions using identical telescope/instrument configurations as described by BSL. In Figure 1 the combined spectrum of LB 11146 from 1989 December 5 and 1990 March 5 is compared with that of GD 394, a "normal" DA star with rather similar line strengths $T_{\rm eff}$ = 39,450 K, log g = 7.83; BSL). There exist subtle differences in the Balmer line profiles between the two stars, though the line cores of LB 11146 appear normal. Our unsuccessful attempt to fit the profiles of LB 11146 with single DA models will be discussed in § 3.1. The two individual observations of the object appear indistinguishable from each other; a third spectrum obtained by S. O. Kepler and M. A. Wood with a similar setting is entirely consistent with the previous observations. This result suggests that spectroscopic variations shortward of ~5000 Å, if any, are small.

2.3. *Ultraviolet and Infrared Data*

Three ultraviolet spectra were obtained with the *International Ultraviolet Explorer* (*IUE*) on 1992 November 6. The short-wavelength camera data ($\lambda\lambda$1200–2000) are characterized by a rapidly declining energy distribution to shorter wavelengths, a broad depression near 1600 Å and perhaps broad, blended absorption shortward of that. Any normal Lyα feature may be blended with features due to quasi-molecular hydrogen opacity. Data covering the lowest several hundred angstroms of the long-wavelength camera (LWP) are of very poor quality.

S. K. Leggett and J. Allyn Smith were kind enough to measure the star at the infrared *JHK* bands on two nights in 1991 March at the NASA Infrared Telescope Facility. The mean values were $J = 14.67 \pm 0.02$, $(J-H) = -0.01 \pm 0.05$, $(H-K) = -0.07 \pm 0.02$. The ultraviolet, multichannel, optical, and infrared data are analyzed in § 3.3.

2.4. *Spectropolarimetry*

Conclusive evidence of a magnetic component in LB 11146 was obtained through circular and linear spectropolarimetry on 1992 October 10–11 (circular) and 1993 February 26 and April 28 (linear) using the 2.3 m telescope of Steward Observatory and CCD spectropolarimeter described by Schmidt, Stockman, & Smith (1992b). These data also yielded the optical spectrum longward of ~5000 Å. The instrumental parameters, sequence of observations, and interpretation of the polarimetry are discussed in § 4.

3. SPECTRAL ANALYSIS

3.1. *Failure of DA Models*

The failure of BSL to obtain simultaneous fits to the hydrogen lines of LB 11146 using single DA star models is reproduced in Figure 2. The quality of the "best fit," with $T_{\rm eff}$ = 35,400 K and log g = 8.24, is obviously much poorer than that for any other star analyzed in the course of that study. The cores of the lines are modestly too shallow and the wings significantly broader than the predicted profiles. Subtle structure also appears to distort certain of the line wings.

The possibility that rotation could be responsible for the

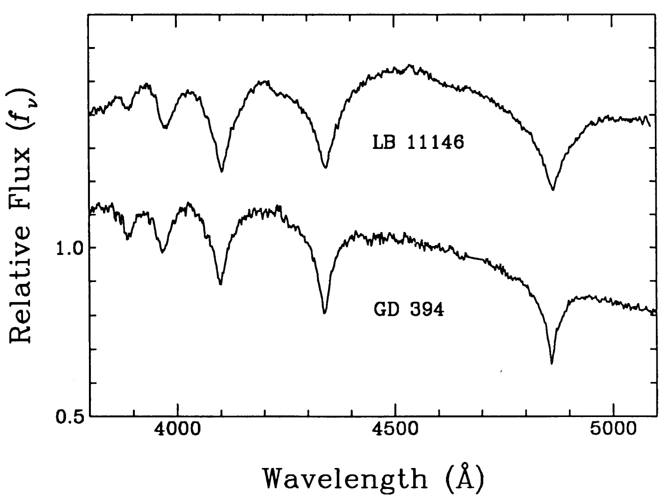

FIG. 1.—Spectra of LB 11146 and GD 394—a normal DA star with similar line strengths. The fluxes of both stars have been normalized to unity at 4600 Å, and the spectrum of LB 11146 has been displaced upward by an amount of 0.5 for clarity.

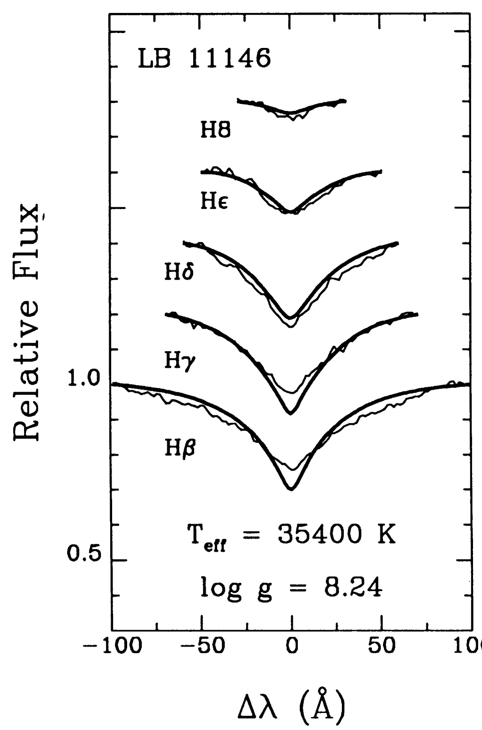

FIG. 2.—The unsatisfactory "best fit" of the high Balmer line profiles of LB 11146 to a single hydrogen atmosphere model. Compare, for example, with the much more precise fits illustrated in Fig. 4 of BSL.

lack of fit was considered. Some experiments were, in fact, performed in which model profiles were convolved with broadening by a uniformly rotating star at a prescribed value of $v \sin i$. Since rotational broadening does not alter substantially the equivalent widths of the lines, we could start with the parameters cited above as our first approximations to the temperature and surface gravity. However, no value of $v \sin i$ could be found which matched the observed profiles. The sharpness of the features near the line centers effectively precludes this proposed solution.

The sharpness of the line cores also argues against magnetic broadening ($\sim 10^{5-6}$ G) as the cause of the unusual profiles. The Balmer series of such a DA star is shown in Schmidt et al. (1992a). More conclusive evidence against significant magnetic distortion of the lines is presented in § 4.

3.2. *Evidence for a Composite Spectrum.*

Since no satisfactory fit could be achieved under the assumption that LB 11146 was a single DA star, we also considered briefly the possibility that the spectrum was composed of two DA white dwarfs of dissimilar temperatures and luminosities. In fact, Liebert, Bergeron, & Saffer (1991) had already performed the experiment of co-adding all possible combinations of hydrogen atmosphere models with surface gravities of $\log g = 7$, 8, and 9 and effective temperatures of 15,000 through 45,000 K in intervals of 10,000 K. It was clear from this work that there is always an intermediate temperature and gravity value between the extremes of the two input models which provides a satisfactory fit. Hence, binary DA white dwarfs are virtually undetectable from line fits alone, and this solution could not explain the apparent peculiarities of the Balmer profiles of LB 11146.

In the Introduction, we cited discoveries of white dwarfs having composite spectra with components of dissimilar spectral type, DA and DC. In all cases, this solution was required because the hydrogen lines were abnormally weak for a white dwarf of the observed colors. In each instance, the discrepancy could be resolved by assuming that a second, featureless component contributes a significant amount of radiation. In the case of G62-46, the apparent solution consists of a magnetic DA and a DC component.

A color discrepancy was not immediately apparent in LB 11146 because the spectrum itself appeared to be peculiar. We nonetheless explored the possibility that the spectrum consists of a normal DA white dwarf and a second component of unknown but dissimilar type. Of course, in this case, one must specify not only $T_{\rm eff}$ and $\log g$, but also a third parameter representing the light fraction (or relative surface area) of the DA star.

We began with the assumption that the hydrogen features originated from the DA star only. Subtraction of the appropriate DA model from the observed composite would thus yield the spectrum of the second component. Initially, the optimal atmospheric parameters for the DA model and the relative radii of the two components were estimated by trial and error until the hydrogen lines were completely eliminated. A more formal approach using the entire energy distribution is presented in the next section. The best fit, resulting in nearly exact cancellation of the Balmer series, was achieved using atmospheric parameters for the DA star of $T_{\rm eff} = 14{,}500$ K and $\log g = 8.5$, as shown in Figure 3. The fraction of the total flux at 5050 Å which arises from the DA component—which we

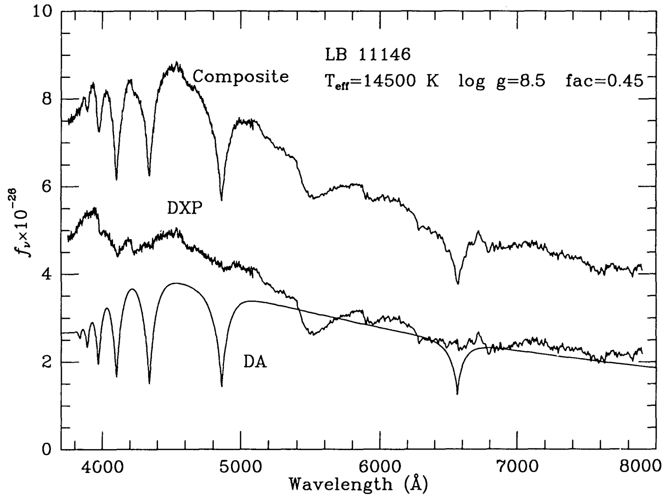

FIG. 3.—Result of subtracting a DA hydrogen atmosphere model (*bottom curve*) from the co-added blue and red Steward 2.3 m spectra of LB 11146 (*top curve*). Complete cancellation of the normal Balmer series in the resultant spectrum (*middle*) occurs for the temperature and gravity indicated. The legend fac = 0.45 implies that the DA model contributes 45% of the light of the system at 5050 Å. The presence of broad, unidentified absorption features in the difference spectrum suggests the presence of a magnetic, or DXP, binary component.

call LB 11146a—is the parameter fac. In the solution presented in Figure 3, fac has a value of 0.45.

From the resultant spectrum, the nature of the non-DA component, which we call LB 11146b, was not difficult to deduce. White dwarfs showing weak, broad features at unusual wavelengths, such as those at λ5500 or λ5900 in Figure 3, must either have an unprecedented chemical composition or be strongly magnetic. In the presence of a weak-to-moderate magnetic field, simple Zeeman components of the dominant species—hydrogen or helium—are recognizable in the form of triplet patterns. Features of the type extracted in Figure 3 suggest that, if magnetism is the correct explanation, the field strength must exceed 100 MG and therefore the continuum light will be strongly circularly and/or linearly polarized. The success of this prediction is documented in § 4.

3.3. *Modeling the Overall Energy Distribution*

The trial and error approach to fitting just the Balmer series allowed a somewhat large range of possible atmospheric parameters. Further constraints could be obtained by using the complete set of observations described in § 2 and displayed in Figure 4. The top data set portrays the observed spectrum in all ultraviolet, optical, and infrared regimes. On a wavenumber scale, the *IUE* range encompasses most of the abscissa, with the gap between 4.5 and 5.0 μm^{-1} being due to the exclusion of the noisy portion of the *IUE* long-wavelength spectrum. Steward 2.3 m spectra are plotted by the continuous line showing Balmer lines, pluses denote multichannel results, and filled circles are the *JHK* infrared flux points.

The optimal atmospheric parameters were determined by a least-squares fitting technique in which we required that the DA model completely account for the hydrogen features in the composite energy distribution, leaving a featureless continuum in those regions (in this case we assumed that the continuum could be approximated by a straight line). Specifically, we wanted to remove all the Balmer lines (Hα to H8) and the feature at 1400 Å ($\sim 7\ \mu m^{-1}$) which we identified later as being

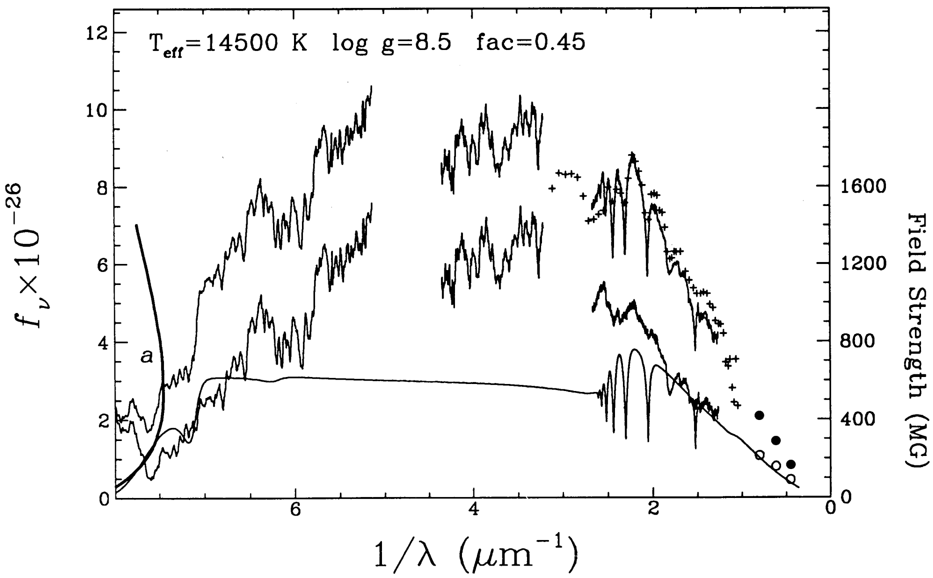

FIG. 4.—Overall energy distribution of LB 11146 from the ultraviolet to the infrared. Ultraviolet and optical data (Fig. 3) are represented by the continuous upper curves, multichannel data are indicated by plus signs, and infrared *JHK* fluxes are plotted as filled circles. The noisy region between 4.5 and 5.0 μm^{-1} is omitted —see § 3.3. The hydrogen atmosphere (DA) model of Fig. 3, extended in spectral coverage, is shown as the bottom, continuous curve. The difference (*middle curve* and *open circles*) portrays the spectrum of the magnetic component, LB 11146b. The feature a can be attributed to the σ^+ component of Lyα in a magnetic field of either ~300 MG or ~1000 MG, whose position is plotted as a function of field strength (right-hand axis) in the solid curve at the left end of the figure.

the satellite absorption of the H—H$^+$ quasi molecule. For the purpose of this analysis, the theoretical profiles of the Lyα satellites of Allard & Koester (1992) were included in our model calculations. We excluded from the analysis the multichannel observations since most of the relevant information was already contained in the optical data.

We found that a simultaneous cancellation of the hydrogen features could be achieved with parameters in the range $T_{\rm eff}$ = 13,500–15,000 K, log g = 8.4–8.6, and fac = 0.45–0.50, depending on the weight given to each line. A residual feature near Hδ was always present in the subtracted spectrum and could never be eliminated completely; we conclude that this feature is present in the spectrum LB 11146b. Models with the same effective temperatures, but log $g < 8.4$, result in a difference spectrum in which the higher members of the Balmer series reverse into emission, even though good cancellation of the lower members is achieved. This occurs due to the fact that the Balmer decrement is flatter at lower surface gravities. Of course, fac can be reduced to achieve proper cancellation of the higher Balmer lines, but then lower members of the series persist in absorption. These conclusions are independent of the temperature of the star over the range 13,000–16,000 K.

The overall energy distribution imposes further constraints on the parameters of the DA component. If $T_{\rm eff}$ were as high as 16,000 K, the DA model alone would have more UV flux than the observed composite spectrum. Similarly, if $T_{\rm eff}$ were as low as 13,000 K, the DA star would not contribute significantly at the shortest wavelengths and could not be reconciled with a value of fac acceptable to the optical fit. We note that among the acceptable solutions given above, only those around $T_{\rm eff}$ = 14,500 K (with the corresponding values of log g and fac) subtract out the 1400 Å feature completely. This is the solution presented in Figure 4. We conclude that the DA component has $T_{\rm eff} = 14{,}500 \pm 1000$ K, and log $g = 8.5 \pm 0.1$.

Subtraction of the DA model from the complete energy distribution results in a spectrum which is only somewhat brighter at optical and IR wavelengths, but dominates in the near-UV (see Fig. 4). Thus, the DXP component is inferred to be slightly hotter—perhaps 16,000 K. We discuss further the range of possible parameters of that component in § 5.1.

4. POLARIZATION AND MAGNETIC FIELD STRENGTH

Because LB 11146 was already slated as a candidate for the weak-field magnetic DA survey (see Schmidt et al. 1992b), our initial spectropolarimetric observations of the object utilized that standard instrumental setup: the rather restricted wavelength range $\lambda\lambda$4750–6650 and a resolution of ~7 Å. Evident in each of the three 10 minute data sets were the normal (unpolarized) features of Hα and Hβ from the DA component, as well as the red-shaded depression centered near λ5500. The magnitude of circular polarization present throughout the spectrum, $V \approx 1.2\%$, attests to a strong field ($\gtrsim$100 MG) on the DXP component of the binary. Two broader coverage, higher S/N observations were made the following night, using a lower dispersion grating to span $\lambda\lambda$4175–7900 with ~14 Å resolution, and linear polarization spectra covering a similar spectral range were obtained 4 and 6 months later.

Since no sign of magnetism is evident in the lines of the DA star, we have assumed that its continuum is unpolarized, and we present the co-added linear and circular polarization of the DXP component LB 11146b in Figure 5 after correcting for dilution by the model DA spectrum derived in § 3.3. Because of the generally weak values of linear polarization measured, we have made a first-order correction for the statistical bias by plotting values of $(P_{\rm obs}^2 - \sigma_P^2)^{1/2}$, where $P_{\rm obs} = (Q^2 + U^2)^{1/2}$, and display position angles only where they are well measured. Circular polarization is shown with the convention that $V > 0$ corresponds to counterclockwise rotation of the electric vector as viewed by the observer.

Strong circular polarization (V = 1%–2%) is present over the entire spectral range, but aside from a modest depression near the prominent λ5500 absorption feature, structure in the circular polarization spectrum is not obviously related to features in the spectral continuum. On the other hand, linear

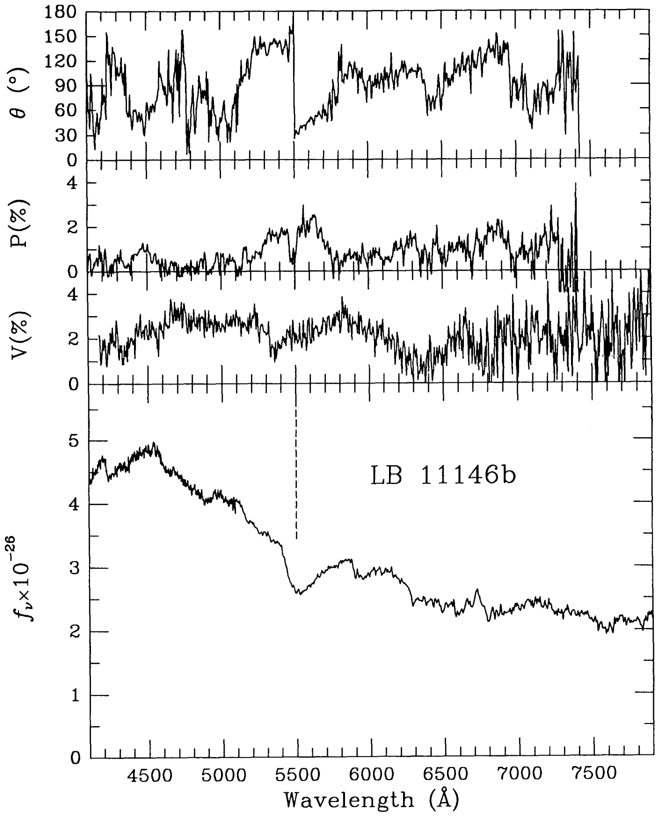

FIG. 5.—Linear (*P*) and circular (*V*) spectropolarimetry of LB 11146, corrected for dilution by the DA component and compared with the flux spectrum of the magnetic star. Note the presence of strong circular polarization throughout the spectrum as well as the double-peaked linear polarization profile and 90° position angle swing at the location of the broad 5500 Å absorption feature.

polarization is confined primarily to the λ5500 feature. Remarkably, this apparently single absorption line appears as a double-peaked linear polarization feature with a rotation of 90° in position angle occurring precisely in the middle of the feature. Equivalently, the feature can be regarded as a sine wave around zero in one of the linear Stokes parameters.

4.1. *Field Strength on DXP Component*

A crude estimate of the magnetic field strength on LB 11146b derives from arguments based on the relative amounts of linear and circular continuum polarization produced by magnetized stellar photospheres (see Schmidt, Latter, & Foltz 1990 for GD 229). Namely, for an object to display both significant circular *and* linear polarization, the atmosphere must be sufficiently dichroic that propagation eigenmodes distort from their low-field circular character into ellipses. With values of $P \approx 1\%$ and $V \approx 2\%$, the field on LB 11146b would therefore likely be stronger than that on G195-19 ($P < 0.13\%$; $V \approx 0.8\%$; $B \approx 100$ MG) but weaker than PG1031+234 ($P \approx 4\%$; $V \approx 8\%$; $B \lesssim 1000$ MG).

More convincing would be direct identification of Zeeman transitions in the absorption spectrum. Since hydrogen is the only chemical species whose behavior is understood in fields as large as those suggested above, we turn first to the UV for evidence of Lyα, which is a simple Zeeman triplet at all field strengths and will persist in even trace abundances. In the subtracted spectrum of Figure 4, a distinct feature, labeled "a" and centered at 7.6 μm^{-1} (1320 Å), can be readily ascribed to Lyα σ^+ (1*s*0 to 2*p* − 1; shown as the heavy curve) near its long-wavelength turnaround. As portrayed by PG 1031+234 (Schmidt et al. 1986), this feature is a clear diagnostic of field strength, since both the σ^- and π transitions are shifted by the quadratic Zeeman effect to wavelengths below the *IUE* sensitivity limit. Because the observed absorption in Figure 4 lies slightly blueward of the turnaround wavelength of 1341 Å, this assignment suggests a surface field strength which is either in the range ∼200–300 MG or ∼800–1200 MG.

With all other UV features being either extremely diffuse or of debatable significance, we now examine the optical spectrum for consistency with our Lyα interpretation, recognizing the possibility that another atomic species may be present, or even dominate, in this spectral region. For this purpose, we have replotted the spectrum of LB 11146b in Figure 6, labeling apparent features "b" through "j," and compare it to the predicted locations of principal hydrogen transitions for the range 0–1200 MG. Also depicted for comparison is another magnetic white dwarf whose spectrum requires explanation, GD 229 (Schmidt et al. 1990).

The most prominent features in the optical spectrum of hydrogen for very strong fields are: the 2*p*0–3*p*0 transition of Hα, which reaches a local wavelength minimum of 5830 Å at a field of 232 MG (not turning back toward shorter wavelengths until 1200 MG); the long-wave turnaround of Hα 2*p* − 1 to 3*d* − 2, which occurs at a 7450 Å for a field of 120 MG; the stationary regime of Hα 2*p*0 to 3*d* − 1 (8532 Å for $B = 616$ MG); and a wavelength minimum of Paβ 3*d*0 to 5*f* − 1 at 8360 Å for $B = 410$ MG. The variation in strength of these features with magnetic field over the range ∼100–1000 MG is beautifully portrayed in the rotationally modulated spectrum of PG 1031+234 (Latter, Schmidt, & Green 1987). Both of the latter two transitions are beyond the spectral coverage of our data and cannot be currently tested. The lack of a strong blue-shaded absorption feature near λ7400 in Figure 6 argues against the "low-field" interpretation of Lyα, but once the field strength exceeds ∼250 MG, this transition slides smoothly to shorter wavelengths and loses its integrity. Indeed, if feature *i* is due to the λ5830 turnaround ($B \gtrsim 300$ MG), the structure near feature j could be attributed to the remnants of the 2*p* − 1 to 3*d* − 2 transition. Several components of Hβ reach near-stationary points in the region λλ3800–4600 for fields $B \gtrsim 350$ MG and are then likely assignments for features b through e. Unfortunately, it is difficult to make positive identifications of these weaker components, since the detailed structure of both groups is sensitive to how accurately the undisplaced Balmer lines of the DA component can be modeled and subtracted from our composite spectrum.

Despite the likelihood that some UV and optical features can be attributed to hydrogen in fields of ≳300 MG, the principle feature in the spectrum of LB 11146b—the λ5800 absorption labeled h in Figure 6— is not explicable by hydrogen and thus requires a second atmospheric constituent. The most likely species at a temperature of ∼15,000 K is neutral helium, whose Zeeman spectrum has not yet been computed beyond a field strength of 20 MG (Kemic 1974). Helium was also proposed as the explanation of the mysterious spectrum of GD 229 (Schmidt et al. 1990), whose deep, red-shaded absorption features closely resemble feature h. Indeed, if the atmosphere of LB 11146b is truly mixed in composition, and a field strength can be confirmed, the star would offer an empirical bridge toward solving the long-standing puzzle of GD 229.

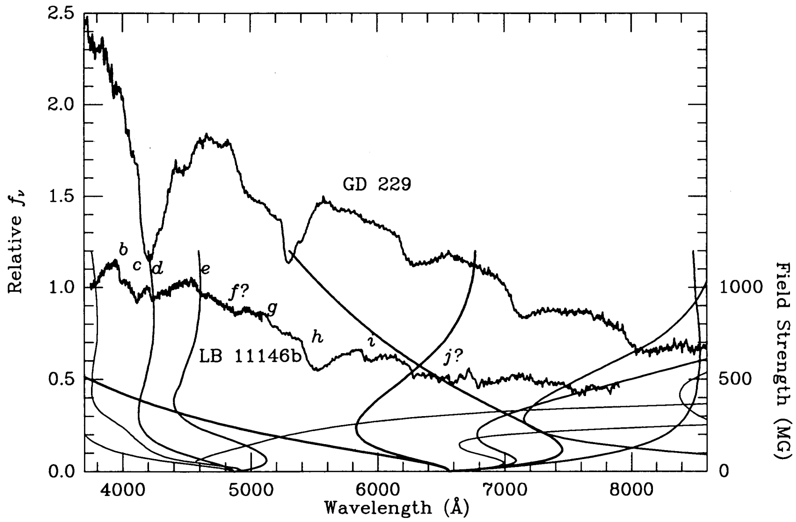

FIG. 6.—Spectrum of LB 11146b compared with calculations for hydrogen transitions in fields B = 0–1200 MG and with the highly polarized magnetic white dwarf GD 229. Features of the former are labeled with letters and discussed in § 4.1. Predicted relative strengths of the Balmer transitions are indicated by line thickness. While certain of the features of LB 11146b may be due to hydrogen, the strongest lines in both stars likely are due to helium or other ions for which Zeeman calculations in very strong fields are not yet available.

Without a firm field strength determination and candidate identification for feature h, it is not possible to be conclusive regarding its peculiar linear polarization profile (Fig. 5). The remarkable 90° rotation in position angle through the middle of the feature is suggestive of some fundamental physical origin. Several years ago, Angel (1979) proposed that a ~90° position angle rotation through the spectrum of Grw +70°8247 is a result of crossing the cyclotron fundamental—in the case of LB 11146b, the swing at λ5500 would imply a field strength of $B = 200$ MG. However, the rotation in Grw +70°8247 is a phenomenon of the continuum, not an individual absorption feature. Moreover, it is generally believed that cyclotron opacity cannot produce discrete lines such as feature h when averaged over the field spread present on a realistic stellar disk (e.g., Martin & Wickramasinghe 1979). Alternatives for the 90° swing in LB 11146b include a π-transition produced in an offset or nondipolar field, in which different portions of the line are produced by regions of the stellar photosphere with orthogonal field directions, or an opacity effect wherein the two halves of the feature "choose" orthogonal eigenmodes of propagation. Whatever the origin, this feature will likely be of considerable assistance in eventually understanding the field strength and distribution over the magnetic component of the binary.

4.2. *Time Variability*

The possibility of time variations in the spectrum and/or polarization of LB 11146 is of significance for the magnetic field pattern on the DXP star as well as for the nature and evolution of the binary system itself. As mentioned in § 2.2, no significant differences are evident among the flux spectra obtained during a single night, between nights, or between observing runs. Moreover, on each of the two consecutive nights of circular polarimetry, the spectrum-summed value is $V = +1.2\% \pm 0.1\%$, with the error bar representing the uncertainty of the lower quality (higher resolution) observations. The two epochs of linear polarimetry separated by 2 months similarly reveal no convincing evidence of rotation of the magnetic component.

4.3. *Field Strength on the DA Component*

Our highest resolution profiles of the Balmer series of LB 11146a (e.g., Fig. 2) lack any evidence of Zeeman structure at the level of ~2 Å, which for Hβ limits the mean "surface" field on the DA component to $B_s \lesssim 200$ kG. However, the circular spectropolarimetry can potentially provide a more stringent test. Assuming that the DXP component should generally lack relatively sharp structure at the rest positions of the Balmer lines, we subtracted a coarsely smoothed polarization spectrum from the original data and inspected the result for low-field circular dichroism across the profiles of Hα, Hβ, and Hγ. Comparison with predictions for various assumed field strengths (as in Schmidt et al. 1992a) leads to a formal mean longitudinal, or "effective" field of $B_e = -10 \pm 10$ kG, or an upper limit of a few tens of kilogauss. Evidently, the magnetic field on LB 11146a is *at least* several thousand times weaker than on its companion.

5. THE BINARY SYSTEM

5.1. *The Stellar Parameters*

In § 3.3, the cleanest subtraction of the DA component was obtained with a model having $T_{eff} = 14{,}500 \pm 1000$ K and $\log g = 8.5 \pm 0.1$. This would imply $M_V = 12.16 \pm 0.21$. Using the mass-radius of Wood (1990) with pure carbon composition, the implied mass is $0.91 \pm 0.07\ M_\odot$.

The magnetic component is more luminous and also apparently somewhat hotter. Energy distributions calculated from pure hydrogen models fail to match that of LB 11146b; the atmospheric composition appears to be dominated by an element other than hydrogen. Presumably, helium is the most likely candidate. Perhaps the best estimate of the effective temperature can be obtained by comparing the energy distribution with those of helium-rich white dwarf models, albeit with blanketing predicted in the absence of magnetic effects. In Figure 7 we show models whose energy distributions— while failing to accurately fit the observed distribution—at least bracket it in terms of overall shape. That is, the 18,000 K model clearly produces more flux on average at the shorter wave-

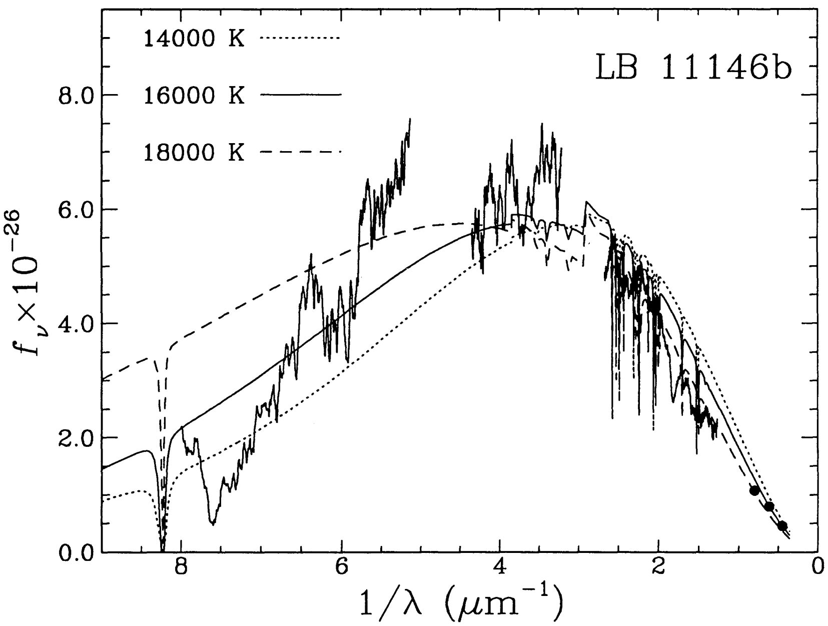

FIG. 7.—Overall energy distribution inferred for the DXP component compared with the predictions of helium atmosphere models at $T_{\rm eff}$ = 14,000, 16,000, and 18,000 K for N(H)/N(He) = 10^{-4} and log g = 8. The two temperature extremes would appear to roughly bracket the true value if our assumption about composition is not too unrealistic.

lengths, and less at longer wavelengths, while the opposite statements can be made for the 14,000 K model. We infer that the likely temperature of the DXP component is $T_{\rm eff}$ = 16,000 ± 2000 K.

Using the derived M_V for the DA component and the value of fac determined above, we obtain an absolute magnitude for the DXP component of M_V = 11.94. To match the latter value for a helium atmosphere at a temperature of $T_{\rm eff}$ = 16,000 K, the surface gravity of the DXP component is log g = 8.49, or a mass of 0.90 $M_\odot$. However, the last two parameters depend on the assumed $T_{\rm eff}$, which we admittedly know poorly. At $T_{\rm eff}$ = 14,000 K, the values are 8.27 and 0.76 $M_\odot$, while at 18,000 K, they are 8.64 and 1.00 $M_\odot$. These and other parameters describing the binary are summarized in Table 1.

One caveat concerning the parameters in Table 1 must be acknowledged: The procedure followed here for estimating the surface gravity and inferred mass of the DA component relies on the assumption that the unknown spectrum of the magnetic star is smooth across the Balmer line cores and λ1400 region. Because of the complexity of the inferred spectrum of the DXP component, this procedure is necessarily less certain than that of fitting the composite spectra of DA + DC binaries (Bergeron et al. 1990). Real structure in the spectrum of LB 11146b which contaminates these features might cause additional systematic errors, primarily in surface gravity and mass of both components.

What can we really conclude from these results? First, the DXP component is more luminous and probably hotter than the DA component. With estimated masses near 0.9 $M_\odot$, both white dwarfs appear to exceed the mean mass for field DA white dwarfs of 0.56 $M_\odot$ (BSL). It is not clear that the nonmagnetic DA is older, since the temperatures are similar and the cooling time depends on mass as well as interior composition. A much safer statement is that these two very different white dwarfs have very similar cooling ages.

We can use the parameters estimated for the DA component to estimate the distance to the binary system. The apparent V magnitude from the MCSP data (§ 2.1) is about 14.4. Assuming that fac is the same value of 0.45 over the V band, the DA component has V = 15.25. The M_V value derived above leads to a distance of 40 ± 5 pc. Because the binary appears spatially unresolved on the 2.3 m acquisition TV under conditions of excellent seeing (< 1″), the physical pair could have a separation on the plane of the sky as large as ∼20 AU.

5.2. *Evolution of the Binary*

Since there is an overwhelming likelihood that this unresolved spectrosopic binary constitutes a physical pair, the implications are that they formed at the same time and have the same total ages. The total age is the sum of the nuclear evolution time and the cooling time. The upper limit to the physical separation allows either that each has evolved essentially as a single object or that the system we observe is an unusual product of close-binary evolution.

The first possibility might at first glance appear unlikely: Since the nuclear lifetimes of both components must have been

TABLE 1
STELLAR PARAMETERS OF LB 11146

Component	$T_{\rm eff}$ (K)	log g	M_V	M ($M_\odot$)	Magnetic Field	Separation	Distance
LB 11146a.........	14,500 ± 1000	8.4 ± 0.1	12.16 ± 0.21	0.91 ± 0.07	B_e < 30 kG (3 σ) B_s < 200 kG (3 σ)	< 20 AU on sky	40 ± 5 pc
LB 11146b.........	16,000 ± 2000	8.5 ± 0.2	11.94 ± 0.21	$0.90^{+0.10}_{-0.14}$	$B \gtrsim$ 300 MG		

similar, they are required to have had very similar initial masses. Yet one component exhibits one of the strongest magnetic fields yet found on a white dwarf, while the field on the other is at least 10^4 times weaker. However, there may be a straightforward explanation. Angel, Borra, & Landstreet (1981) have porposed that the magnetic main-sequence stars— Ap, Bp and other peculiar subclasses— are the progenitors of magnetic white dwarfs. Their "fossil" fields must survive all phases of nuclear evolution. The peculiar A and B stars often have companions of similar mass with no detectable magnetic field or abundance peculiarities (Abt & Cardona 1984). Thus, if the Angel et al. hypothesis is correct, it would not be surprising to find a normal and a strongly magnetic white dwarf coexisting in a wide binary system. Although this explanation begs the question as to how a strongly magnetic/nonmagnetic main-sequence pair of similar mass forms in the first place, the well-known angular momentum difference between the peculiar and normal A and B stars is one possibility.

Evidence that at least some magnetic white dwarfs are quite massive (Greenstein & Oke 1982; Sion et al. 1988; Liebert 1988; Schmidt et al. 1992a) supports the notion that magnetic degenerates evolve from some B and A main-sequence stars, since the typical white dwarf arises from a progenitor with only 1–2 $M_\odot$. The conclusion that LB 11146b has a mass approaching 1 $M_\odot$ adds further evidence in favor of this scenario.

The assumption that close binary evolution was involved— should that be confirmed by further observation— might offer more fascinating possibilities to explain the very different field strengths. Unfortunately, we cannot be certain if the magnetic component became a white dwarf last or first, nor which of the two is the more massive, and thus whether the system passed through one or two phases of common-envelope evolution. Nevertheless, the masses of the two components imply that each core was allowed to progress beyond the helium-burning phase before the remaining envelope could be stripped by unstable or stable mass transfer. This requires that the initial separation should have been of the order of an AU or more.

LB 11146 is, in fact, the first double-degenerate system yet discovered whose combined mass appears to exceed the Chandrasekhar limit. If the orbital period is of order hours, evolution to Roche lobe overflow may occur on an interesting timescale (billions of years, or less). The individual white dwarfs likely have interiors composed of carbon and oxygen (or oxygen, neon, and magnesium), so that mass transfer on a dynamical timescale would be expected (Webbink 1984; Iben & Tutukov 1984). This opens up the possibility that this system could be a progenitor of a Type I supernova (Webbink 1979; Tutukov & Yungelson 1979), if indeed a dynamical merger of two massive white dwarfs can produce such an event (cf. Benz, Cameron, & Bowers 1989; Mochkovitch & Livio 1989).

6. FUTURE WORK

Of key importance to the questions of magnetism and evolutionary status of LB 11146 are the binary separation and rotation rates of the stellar components. Our observation of a change in polarization position angle between two observations separated by 40 minutes suggests a spin period for the magnetic star which is on the order of hours, comfortably in the midst of the periods determined for single magnetic white dwarfs which display rotation (Schmidt & Norsworthy 1991). A follow-up program of spectropolarimetry to secure this conclusion is in progress.

The current limit of $\lesssim 20$ AU binary separation (for $D = 40$ pc), set by the apparently point-source TV acquisition image, could be reduced to a few AU through high–angular resolution imaging, using either ground-based active-optics techniques or *HST*. Due to the equal brightnesses and temperatures of the two stars, the system is particularly susceptible to deconvolution in either the optical or infrared. Direct measurement of the orbital period is available through spectroscopy of the Balmer line cores of the DA star. A comprehensive program with a velocity precision of ~ 10 km s^{-1} would be sensitive to binary separations $a \lesssim 4 \sin^2 i$ AU or periods $P \lesssim 6 \sin^3 i$ yr. complementing the range accessible to imaging (barring an unfortunate viewing perspective).

The identification of a UV absorption line with Lyα σ^+ and our assignment of magnetized hydrogen transitions to certain of the optical features of the DXP component can be tested by a search for the expected strong absorption near 8532 Å due to the virtually stationary behavior of Hα $2p0$ to $3d-1$ in fields $\gtrsim 350$ MG (Fig. 6). If this bears out, detailed spectral modeling (through the rotation cycle) would likely yield details about the magnetic field strength and surface morphology. The fact that other spectral features, including the strong $\lambda 5500$ line, cannot be identified with hydrogen appears to make LB 11146b the first strong-field mixed-composition white dwarf known. As such, it offers impetus for continued quantum mechanical calculations of species such as neutral helium in very strong magnetic fields and at the same time provides a unique laboratory in which the known behavior of hydrogen could be used to verify those calculations.

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