A MULTIWAVELENGTH STUDY OF THE HIGH-FIELD MAGNETIC WHITE DWARF EUVE J0317–85.5 (=RE J0317–853)

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ABSTRACT

We present optical and ultraviolet photometry and spectroscopy and optical circular spectropolarimetry of the ultramassive, rapidly rotating, high-field magnetic white dwarf EUVE J0317–85.5. From the combined data sets, we establish an ephemeris for the photometric, spectroscopic, and polarimetric variations with a spin period of 725.7277 s, the fastest yet measured for an isolated white dwarf. We build a series of far-ultraviolet (FUV) and optical flux spectra as well as optical polarization spectra that describe the atmospheric properties as a function of rotation phase. Twelve components of the Lyman line series are identified in the FUV: seven of them are forbidden lines enforced by the electric field that permeates the strongly magnetized photosphere. Attempts at modeling the FUV and optical data with two classes of models indicate an unusual field structure on the star. Both offset-dipole and multipolar expansion models fail to adequately reproduce the spectroscopic and polarimetric properties simultaneously, and we postulate that the surface of EUVE J0317–85.5 may be punctuated by a high-field magnetic spot.

Subject headings: stars: individual (EUVE J0317–85.5) — stars: magnetic fields — ultraviolet: stars — white dwarfs

On-line material: color figure

1. INTRODUCTION

Many questions concerning the nature and origin of magnetic white dwarfs remain unanswered. Underlying these questions is the issue of magnetic field evolution across the H-R diagram. For example, if one accepts magnetic flux conservation throughout evolution ($Br^2 = \text{constant}$), then one must conclude that the magnetic Ap/Bp stars with $B \approx 10^3\text{--}10^4$ G evolve into high-field magnetic white dwarfs ($B > 10^7$ G) and that the progenitors of lower field white dwarfs ($B < 10^7$ G) are yet to be identified. A probable link between Ap/Bp stars and high-field white dwarfs also implies that their field structures should be similar. With increasingly complex patterns being used in the modeling of Ap stars (e.g., Landstreet & Mathys 2000), the field structures on the latter come into question. On the other hand, complex magnetic fields are more evident in rotating laboratories, and relatively few magnetic white dwarfs have been adequately studied over their rotation periods. The broad-band polarization and total flux spectrum of the DAP⁵ star PG 1015+014 ($B_p \sim 120$ MG) are modulated on its 99 minute period, but its field strength distribution appears to be more uniform than low-order multipoles can provide, and a satisfactory field pattern has not yet emerged (Wickramasinghe & Cropper 1988). The DAH WD 1953–011 ($B \sim 100\text{--}500$ kG; $P = \text{few days}$) and DAP PG 1031+234 ($B \sim 500$ MG; $P = 3.4$ hr) both exhibit magnetic spots with localized fields enhanced by at least a factor of 2 (Maxted et al. 2000; Schmidt et al. 1986, Latter, Schmidt, &

Green 1987). Even these well-observed stars are lacking full phase-resolved spectropolarimetry, so the models are not well constrained. Finally, there is the question of how often deviations from simple field patterns can be linked to chemical inhomogeneities on the surface of the star. One example, the DBAP star Feige 7 ($B_p = 35$ MG; $P = 3.26$ hr), shows spectral variations that have been attributed to an inclined, offset-dipolar field pattern plus abundance variations over the surface likely caused by magnetic effects on convective mixing (Achilleos et al. 1992).

One intriguing object is the high-field hydrogen-rich magnetic white dwarf RE J0317–853/EUVE J0317–85.5, which was identified in the *ROSAT* Wide Field Camera (WFC) and *Extreme Ultraviolet Explorer* (EUVE) Survey. Barstow et al. (1995) identified the extreme ultraviolet (EUV) source RE J0317–853 with a variable degenerate star—later named CL Octans (CL Oct)—and observed the effects on the spectrum of a strong magnetic field modulated on the remarkably short spin period of 12 minutes. The newly identified white dwarf forms a degenerate pair with the previously cataloged object LB 9802. Although the surface gravity of EUVE J0317–85.5 could not be measured directly, its estimated temperature ($T \geq 30,000$ K) and the atmospheric parameters of its companion ($T \sim 16,000$ K, $\log g \sim 8.5$) implied a very high surface gravity ($\log g \geq 9.3$). Barstow et al. noted that, contrary to the observations, the cooler star should have been the more massive. Ferrario et al. (1997) discussed some interesting aspects of the evolution; in particular, they proposed to resolve the age paradox with the suggestion that EUVE J0317–85.5 itself is a double-degenerate merger.

The field structure of EUVE J0317–85.5 is also very interesting. On the basis of *IUE* and optical spectroscopy, Barstow et al. (1995) estimated a polar field strength $B_d = 340$ MG offset by -0.2 of the stellar radius (toward the south magnetic pole). Ferrario et al. (1997) deconvolved very coarsely sampled optical circular polarization spectra and analyzed the results for the two opposing magnetic

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⁵ We follow a convention established by Sion et al. (1983) and use the suffix “P” to designate those magnetic white dwarfs with measured polarization, and the suffix “H” for all others.

hemispheres, preferring as a result $B_d = 450$ MG offset by $-0.35R_{\text{wd}}$. Ferrario et al. then established that magnetic dichroism in the photosphere of the rotating white dwarf is responsible for the photometric variation. They also identified a number of components of the Balmer lines, such as $H\beta$ 2s0–4f0 and $H\alpha$ 2s0–3p0, which have also been observed in the high-field white dwarf Grw +70°8247 (Greenstein, Henry, & O’Connell 1985; Wunner et al. 1985; Wickramasinghe & Ferrario 1988). Note that the line $H\beta$ 2s0–4f0 is forbidden at zero field where electric dipole selection rules apply but is allowed in the presence of a strong magnetic field where selection rules based on the parity and the magnetic quantum number apply. We shall refer to such lines as “permitted” under the circumstances (see a review by Garstang 1977).

From phase-resolved *Hubble Space Telescope* (HST) Faint Object Spectrograph (FOS) spectra of EUVE J0317–85.5, Burleigh, Jordan, & Schweitzer (1999) favor a multipolar expansion for the field pattern that results in values ranging from 180 to 800 MG over the surface. In addition, they detected the 1s0–2s0 $\text{Ly}\alpha$ component that violates the parity/magnetic moment rules. This “forbidden” line is enforced by the presence of a strong electric field in the atmosphere of the star: it has also been observed in the spectrum of the accreting magnetic white dwarf AR UMa (Gänsicke et al. 2001).

The optical and ultraviolet spectrum of EUVE J0317–85.5 is extremely rich and new observations covering the entire Lyman line series should help determine details of the magnetic field structure. As the first step toward these aims, we obtained new optical spectropolarimetry and photometry, as well as *Far Ultraviolet Spectroscopic Explorer* (FUSE) and EUVE spectrophotometry augmented with HST FOS archival data. We present our new observations in § 2 and new studies of the spectral energy distribution (SED) and rotation period in § 3.1 and § 3.2, respectively. On the basis of these results, we present an analysis of phase-resolved far-ultraviolet (FUV) spectroscopy (§ 3.3) and EUV/optical photometry (§ 3.4). We compare the observations against models based on previously deduced field structures in § 4, and we conclude in § 5.

2. OBSERVATIONS

The present study combines photometric, polarimetric, and spectroscopic data covering the complete spectral energy distribution of the magnetic white dwarf EUVE J0317–85.5 using ground-based and space-borne observatories. Table 1 summarizes our observations as well as data obtained from the Multimission Archive at Space Telescope.⁶

EUVE J0317–85.5 (DAP) and LB 9802 (DA3) form a visual double degenerate with the DA3 star 7''2 away at a position angle P.A. = 146°. LB 9802 is an optical/UV source comparable to EUVE J0317–85.5 but is not an EUV source.

2.1. Optical Spectrophotometry and Circular Spectropolarimetry

Spectropolarimetric data were acquired at the 74 inch telescope at Mount Stromlo Observatory (MSO) using the

TABLE 1
LOG OF OBSERVATIONS

Instrument	Range (Å)	UT Date	Exposures (s)
EUVE.....	70–670	1996 Jun 3	47,000
		1996 Aug 22	139,000
		1996 Sep 19	8000
		1996 Sep 24	61,000
		2000 Sep 18	102,000
		2000 Sep 22	48,000
		2000 Sep 25	55,000
HST FOS.....	1140–1604	1996 Nov 26	142 × ~30
FUSE.....	905–1181	2000 Sep 17	18,000
MSO 74 in.....	4220–7300	2000 Oct 27	24 × 120
		2000 Oct 28	29 × 120
		2000 Nov 3	39 × 120
		2000 Dec 23	19 × 120
		2000 Dec 25	20 × 120
		2000 Dec 27	18 × 120
		2000 Dec 28	10 × 120
		2001 Jan 18	18 × 120
		2001 Jan 19	20 × 120
		2001 Jan 20	12 × 120
		2001 Feb 16	10 × 120
		2001 Feb 25	10 × 120
Perth 24 in Imager....	R band	2001 Dec 19–23	92 × 30
MSO 74 in Imager....	B band	2002 Sep 22	91 × 20

Steward Observatory CCD spectropolarimeter (SPOL). The instrument setup is described in Schmidt, Stockman, & Smith (1992) and modifications brought at MSO are described in Schmidt et al. (2001). Circular polarization spectra of the white dwarf were obtained over the region to include $H\alpha$, $H\beta$, and $H\gamma$ at a resolution of ~ 10 Å. In all, 229 observations were obtained over a period of 4 months in multiple-exposure wave plate sequences. An integration time of 120 s per observation coupled with overhead for CCD preparation and readout resulted in an effective phase resolution of 190 s, or $\Delta\phi = 0.26$. An east-west orientation for the 2''4 wide slit was sufficient to eliminate flux contamination from LB 9802. Reductions were carried out using custom IRAF scripts with absolute flux calibrations enabled by observations of standard stars taken the same night.

2.2. Optical CCD Photometry

The DAP EUVE J0317–85.5 was observed using the 61 cm Perth/Lowell, Boller, & Chivens Cassegrain reflector (f/13.5) at Perth Observatory on 2001 December 19 and December 21–23. We obtained a series of 92 images in the R band with exposure times of 30/60 s using an Apogee AP7 camera and a 512×512 thinned and back-illuminated CCD. The images are $5' \times 5'$ and have a resolution of $0''.58$ pixel^{−1}.

More photometric data of EUVE J0317–85.5 were obtained at Mount Stromlo Observatory using the 74 inch telescope with the Monash Imager on 2002 September 22. We used a $2 \text{ k} \times 4 \text{ k}$ CCD camera binned 6×6 , and the B filter with exposure times of 10 or 20 s. The images are $3' \times 6'$ and have a resolution of $0''.546$ binned pixel^{−1}.

All images were overscan subtracted, bias subtracted, and flat-fielded. The images were reduced using QPHOT in the APPHOT package in IRAF. The comparison star for the B images was the companion, nonmagnetic white dwarf LB

⁶ Go to <http://archive.stsci.edu/>.

9802, and for the R images, we have used two isolated stars in the field. The reference magnitudes were subtracted from the measurement of EUVE J0317–85.5 to minimize any external effects causing variations between exposures. The overall average of the differential magnitudes is used as the photometric zero point for the light curve.

2.3. Ultraviolet Spectrophotometry: *FUSE*, *HST FOS*, *EUVE*

Both objects are FUV sources, and their relatively small separation ($7''.2$) required the adoption of a unique observation procedure for our *FUSE* observations. We had originally proposed to orient the slit perpendicular to the line of separation and to acquire EUVE J0317–85.5 in the medium aperture (MDRS: $4'' \times 20''$) while excluding LB 9802 from it. However, concerns about a misalignment of the LiF2, SiC1, and SiC2 spectroscopic channels relative to the LiF1 channel imposed a different strategy. We determined that the DA3 LB 9802 should be visible only in the LiF1 spectroscopic channel, which is guided using the FES camera, and therefore, we requested an observation of this star using the MDRS aperture, followed by exposures of the pair EUVE J0317–85.5/LB 9802 centered on EUVE J0317–85.5 and using the large aperture (LWRS: $30'' \times 30''$). It was then possible to subtract a spectrum of LB 9802 from the spectrum of EUVE J0317–85.5. The *FUSE* observations were analyzed with the most current version of the data analysis pipeline available (*calfuse 2.1*). The observations were obtained in TTAG mode, which enabled us to resolve the spectrum as a function of rotation phase. The 13 individual *FUSE* exposures in the LWRS aperture were combined using the *FUSE* analysis task TTAG_COMBINE. We developed a method to select each of 10 rotation phase bins using a time exposure mask based on our polarimetric ephemeris (see § 3.2) and added to the *calfuse* screening file. Each run of *calfuse* produced spectra in the LiF and SiC channels for each phase bin. This technique has now been added to the *FUSE* guest observer handbook. Spectra of the observation of LB 9802 in the MDRS aperture were extracted separately. A review of the *FUSE* instrument and in-orbit performance can be found in Moos et al. (2000) and Sahnou et al. (2000a, 2000b).

Burleigh et al. (1999) observed RE J0317–853/EUVE J0317–85.5 with *HST FOS* on 1996 November. They obtained 142 exposures of 30 s each. The relatively short exposure time ($t_{\text{exp}} < P_{\text{rot}}/20$) allows us to regroup the exposures in 10 separate phase bins (see § 3.3).

Table 1 lists observations obtained with the *EUVE* spectrometers and the deep-survey detector (DS) between 1996 June and 2000 September. The early DS/spectrometer observations (1996 June–September) used the spiral dithering mode to reduce fixed-pattern noise in the spectrum. We reduced the data using procedures in the EUV package within the IRAF environment and produced light curves for the DS data using timing routines found in the PROS XRAY.XTIMING package in IRAF. Finally, we corrected the light curves for dead time and telemetry loss. We combined the short-wavelength (SW; 70–190 Å), medium-wavelength (MW; 140–380 Å), and long-wavelength (LW; 280–760 Å) *EUVE* spectra expressed in flux units and binned the spectrum by 5 Å to improve the signal-to-noise ratio. The cooler DA3 LB 9802 does not contribute to the EUV flux.

FIG. 1.—Complete phase-averaged optical-UV spectral energy distribution (SED) of the DA2P EUVE J0317–85.5. Only FOS data are shown where they overlap with *IUE* at $\lambda \leq 1605$ Å and, similarly, only *FUSE* data are shown where they overlap with FOS at $\lambda \leq 1175$ Å. The EUV ($\lambda \leq 911$ Å) flux is deattenuated for an ISM column density $n_{\text{H}1} = 10^{18} \text{ cm}^{-2}$. The SED corresponds to an effective temperature of 33,800 K. [See the electronic edition of the *Journal* for a color version of this figure.]

3. SPECTRAL PROPERTIES AND ROTATION PERIOD

3.1. Spectral Energy Distribution and Temperature of EUVE J0317–85.5

Figure 1 shows a compilation of the spectroscopic measurements described above. Table 2 lists line identifications in the local interstellar medium (ISM). A few absorption lines from H I, C II, N I, N II, and O I are present, enabling an ISM abundance study toward this particular line-of-sight. A curve-of-growth analysis of the ISM Lyman lines results in $n_{\text{H}} = (0.5\text{--}1.6) \times 10^{18} \text{ cm}^{-2}$ for a velocity dispersion of $b = 9\text{--}14 \text{ km s}^{-1}$. The *EUVE* flux corrected for ISM attenuation using the cross sections of Rumph, Bowyer, & Vennes (1994) reveals a white dwarf cooler than

TABLE 2
ISM LINE IDENTIFICATIONS

Line	λ_{obs} (Å)	EW (Å)
H I Ly α 1s–2p	1215.69	0.64
H I Ly δ 1s–5p	949.73	0.20
H I Ly ϵ 1s–6p	937.80	0.20
H I 1s–7p	930.77	0.20
H I 1s–8p	926.25	0.17
H I 1s–9p	923.13	0.17
H I 1s–10p/20p	914–921	...
C II λ 1036.337	1036.30	0.087
N I λ 1134.33	1134.38	Emission blend
N I λ 1134.98	1134.94	Emission blend
N II λ 1083.99	1084.01	0.066
O I λ 1039.230	1039.18	0.017

originally estimated at $T_{\text{eff}} = 33,800$ K. The corresponding $\log g = 9.4$ (see Ferrario et al. 1997) corresponds to $M = 1.32 M_{\odot}$ close to the Chandrasekhar mass, and the revised spectral type for EUVE J0317–85.5 is DA2P.

3.2. Polarimetric Light-Curve and Phase-resolved Spectropolarimetry

Our next objective is to measure the spectroscopic and polarimetric properties of EUVE J0317–85.5 as a function of the rotation phase. The optical circular polarization spectra form our most extensive data set, covering over 4 months without cycle count ambiguity. The wavelength-averaged (4300–5700 Å) circular polarization is used to establish an ephemeris for the rotation phase. We define $\phi = 0$ at maximum polarization, which occurs at

$$T(\text{HJD}) = 2,451,845.16014(6) + 0.00839962(1)E, \quad (1)$$

where E is an integer and the numbers in parentheses denote the uncertainty in the last digit shown. The ephemeris is adequate for establishing phase to an accuracy of ± 0.1 for intervals of up to 2 yr from T_0 .

Figure 2 shows phased wavelength-averaged circular polarization $v = V/I$. The present data, which fully resolve the polarimetric variations as a function of rotation phase, confirm the reconstruction of Ferrario et al. (1997), which was based on a series of spectropolarimetric measurements obtained at the Anglo-Australian Telescope (AAT). Without prior knowledge of the rotation period, Ferrario et al. obtained 10 minutes exposures that covered $\sim 83\%$ of the rotation period. Assuming the presence of two distinct hemispheres, they were able to reconstruct the true polarimetric variations and correctly estimated that the wavelength average polarization should vary from $V/I = 0\%$ to 10% between phases $\phi = 0$ and 0.5 . Jordan & Burleigh (1999) also obtained a series of spectropolarimetric measurements at the AAT using a setup similar to Ferrario et al. (1997) but shorter exposure times. The spectra depicted in Jordan & Burleigh (1999) show features similar

to the data presented in Figure 2, but their observations were obtained in the course of a single night.

3.3. Phase-Resolved FUV Spectroscopy

Ten series of time filters were created, corresponding to phase intervals 0.05–0.15, 0.15–0.25, ..., 0.85–0.95, and 0.95–0.05. The $1s0$ – $2s0$ spectral line was used to phase the *HST* FOS spectra with the *FUSE* spectra in 10 separate phase bins. The spectroscopic match enforces a phase correspondence between maximum FUV $\lambda 1500$ flux and minimum optical flux discussed in Vennes et al. (2001).

Figure 3 shows FUV spectra at polarimetric phase 0.0 and 0.5 compared to Zeeman-shifted line positions. Table 3 summarizes the photospheric spectral line identifications. We considered all transitions between all levels tabulated in Rösner et al. (1984) and, in particular, transitions between levels coupled following selection rules in the presence of a magnetic field (Forster et al. 1984). Zero-field states labelled with their usual quantum numbers nlm are described in the presence of a magnetic field by high-field states labelled by the numbers $NM\mu$, where M is the magnetic quantum number and μ defines the z parity of the states [$\pi = (-1)^\mu$]. Applicable selection rules in the presence of a strong but finite field are $\Delta M = \pm 1$ if the z parity remains unchanged, i.e., $\Delta\mu$ is even, and $\Delta M = 0$ if the z parity changes, i.e., $\Delta\mu$ is odd (Garstang 1977).

A number of transitions that violate the above parity/magnetic moment selection rules are also observed due to the presence of a strong electric field (motional Stark effect): the transition $1s0$ – $2s0$ identified by Burleigh et al. (1999) in their *HST* FOS spectra is now joined by transitions ranging from $1s0$ – $3s0$ to possibly $1s0$ – $4d$ – 2 . The transitions vary greatly in strength, but most are comparable to permitted transitions. These lines will be referred to as “forbidden.” The present phase-resolved spectroscopy insures a greater accuracy in the line identifications, and these new identifications supersede those presented in Vennes et al. (2001). In particular, the $\lambda 1145$ feature now appears to belong to $\text{Ly}\beta$

Fig. 2.—Wavelength-averaged circular polarization (left) as a function of rotation phase and corresponding optical circular polarization spectra (right). Maximum optical circular polarization defines phase zero. Note that extreme variations between $\phi = 0$ and 0.5 are well in evidence in the spectroscopy.

FIG. 3.—Phase-resolved *HST* FOS/*FUSE* spectroscopy at $\phi = 0$ (left) and $\phi = 0.5$ (right). The FOS and *FUSE* data are merged at $\lambda = 1175$ Å. The spectra at both phases are compared to predicted line positions for permitted (solid lines) and forbidden lines (dashed lines), showing that $\phi = 0$ is characterized by a field strength of $B = 185$ MG, while $\phi = 0.5$ is characterized by a field strength of $B = 425$ MG.

1s0–3d–1 and not to 1s0–2p0 in the high-field hemisphere as postulated by Vennes et al. (2001).

3.4. EUV and Optical Photometric Light Curve

Figure 4 shows broadband *B* and *R* light curves as well as the corresponding optical flux spectra. Minimum optical flux corresponds to maximum optical circular polarization, possibly because of the blanketing effect of Balmer lines in the lower field hemisphere. Figure 5 shows the EUV 100 Å light curve. The EUV light curve bears some resemblance with ellipsoidal variations in Roche lobe-filling stars, but the optical light curve is single peaked. A more likely explanation invokes variable continuum opacities in the EUV, but Lyman cross sections in high-magnetic field are currently unavailable. Note that the Lyman edge should be

displaced toward higher energy ($\lambda_0 \approx 800$ Å) in high-field white dwarfs following the calculations of Rösner et al. (1984).

4. MODELING OF THE OPTICAL AND ULTRAVIOLET SPECTRA

On the basis of earlier work, we considered two classes of models: model A is an offset-oblique dipole and model B is an oblique multipolar expansion. Basic details of similar calculations are given in Ferrario et al. (1997) and Burleigh et al. (1999). Model A represents the best attempt to reproduce the optical spectral variations and overall polarization using a single dipole offset along its axis and uses parameters derived by Ferrario et al. (1997): the inclination of the rotation axis measured from the observer $i = 60^\circ$, the angle between the rotation and magnetic axes $\beta = 40^\circ$, the dipolar field strength $B_d = 450$ MG, and the field offset along the dipole axis expressed as a fraction of the stellar radius $z = -0.35$. The present model introduces varying viewing angles, and therefore, model A is a generalization of the single-angle/single-phase model presented by Ferrario et al. (1997).

Model B represents a multipolar expansion that optimizes the fit to the phase-resolved *HST* data by Burleigh et al. (1999): $i = 56^\circ$, $\beta = 29^\circ$, and multipolar expansion described in Burleigh et al. (1999).⁷ Both sets of models use $T_{\text{eff}} = 33,000$ K, $\log g = 9.3$.

⁷ The expressions for B_r and B_θ are as in Burleigh et al. 1999. We use the following for B_ϕ :

$$B_\phi = -\frac{1}{\sin \theta} \sum_{l=1}^{\infty} \sum_{m=0}^l P_l^m(\cos \theta) m [g_l^m \sin(m\Phi) - h_l^m \cos(m\Phi)],$$

where we have used $g(1, 0) = -206.0$ MG, $g(2, 0) = -77.0$ MG, and $g(3, 0) = -39.0$ MG (Burleigh et al. 1999).

TABLE 3
PHOTOSPHERIC LINE IDENTIFICATIONS

Line	$n l m - n' l' m'$	$N M \mu - N' M' \mu'$	Low Field $\phi = 0.0$ (Å)	High Field $\phi = 0.5$ (Å)
H I Lyα	1s0–2p–1	000–0–10	1304.1	1341.5
H I Lyα	1s0–2p0	000–001	1195.1	1146.4:
H I Lyα	1s0–2s0	000–002 ^a	1164.2	...
H I Lyβ	1s0–3d–2	000–0–20 ^a	1110.1	1119.1
H I Lyα	1s0–2p+1	000–110	1063.1	...
H I Lyβ	1s0–3d–1	000–0–11 ^a	1045.3	1048.3:
H I Lyβ	1s0–3p–1	000–0–12	995.5	...
H I Lyβ	1s0–3d0	000–004 ^a	982.8	...
H I Lyβ	1s0–3p0	000–003	971.4	...
H I Lyγ	1s0–4d–2	000–0–22 ^a	957.8	...
H I Lyγ	1s0–4d–1	000–0–13 ^a	939.1	...
H I Lyβ	1s0–3s0	000–006 ^a	924.7	...

^a Enforced by the electric field.

FIG. 4.—Optical *B*- and *R*-band light curves (*left*) phased according to our convention. The *B*-band data suffered from slightly imprecise phasing (~ 0.05). The optical spectra (*right*) showing variable line absorptions are shifted up for clarity and labeled with the rotation phase.

The oscillator strengths of ultraviolet lines that violate parity/magnetic moment selection rules were not available at the time of publication and were empirically adjusted to match the observed features. Wavelengths are determined using energy levels from Rösner et al. (1984). The oscillator strengths of permitted ultraviolet and optical lines are from Kemic (1974), Forster et al. (1984), Wunner et al. (1985), Henry & O’Connell (1985), and Wunner, Geyer, & Ruder (1987) and follow our original compilation (Ferrario et al. 1997).

Figure 6 shows FUV spectroscopy resolved in 10 separate phases. The spectra show that a rapid transition between poles and an overlap of high-field and low-field features is only apparent at $\phi = 0.3$ and 0.7 . This is illustrated by the rapid shift of the $1s0-2p-1$ component of $\text{Ly}\alpha$ (σ^+) between ~ 1300 Å and nearly 1340 Å for low fields and high fields, respectively, and the displacement of the $1s0-2p1$ component ($\text{Ly}\alpha$ σ^+) from its low-field position of ~ 1050 Å to below the short-wave limit of the data at high fields.

FIG. 5.—*EUVE* Deep Survey (100 Å) light curve for the 2000 September period, phased using the spectropolarimetric ephemeris (see Fig. 3). Phase zero corresponds to maximum optical polarization. Note the double-peaked light curve.

FIG. 6.—*HST* FOS and *FUSE* spectroscopy phased using the spectropolarimetric ephemeris. The FOS and *FUSE* data are merged at $\lambda = 1175$ Å. The spectra are shifted up by 0.5 for clarity and labeled with the rotation phase.

FIG. 7.—*HST* FOS and *FUSE* spectroscopy at phases 0.0 and 0.5 compared to multipolar expansion and offset-dipole models.

Figure 7 shows an attempt at reproducing this feature using our two classes of models. The offset-dipole model (model A) reproduces well most members of the Lyman series at $\phi = 0.0$, including the line blend at $\lambda \leq 1000$ Å. However, the same model produces weak high-field spectral lines and retains most low-field lines at $\phi = 0.5$, contrary to the observations. Ferrario et al. (1997) were successful in reproducing phase-averaged optical spectropolarimetry using this model. However, the same model is unsatisfactory in the FUV: the transition from the high-field to the low-field regimes is not well delineated. On the other hand, the multipolar expansion (model B) reproduces well the line positions at both rotational phases and shows a marked transition from low-field to high-field hemispheres. The multipolar model still exhibits excessive amounts of line opacity at shorter wavelengths.

Because the circular polarization spectrum provides additional information on the *direction* of the magnetic field, the comparison shown in Figure 8 represents a critical test of both classes of model. Each model can adequately account for most of the polarization features associated with the optical lines, but each also fails on a few. The offset-dipole model correctly reproduces the overall polarity of the field across the spectrum at both rotational phases and accounts for a key feature first noted by Ferrario et al. (1997) and depicted in Figure 2. Namely, the strong variation in mean polarization from $V/I = 0\%$ at $\phi = 0.5$ to $V/I = 10\%$ at $\phi = 0.0$. By comparison, the multipolar expansion model predicts the wrong polarity at $\phi = 0.5$, largely a result of the expansion term that was required to reproduce the high-field components in the FUV spectra near this phase. The multipolar expansion also produces very small polarization at $\phi = 0.0$.

The optical flux spectrum for the two phase extremes is compared with the model predictions in Figure 9. Once again, we see that discrepancies appear largely at the difficult $\phi = 0.5$, where the highest field strengths are seen, but

FIG. 8.—MSO spectropolarimetry (V/I) at phases 0.0 and 0.5 compared to multipolar expansion and offset-dipole models.

the net longitudinal polarization is near zero due to polarity cancellation over the surface. The multipolar expansion does a somewhat better job of reproducing the less-featured character of the spectrum at this phase. Both representations do reasonably well predicting the zero-phase optical spectrum.

Therefore, it appears that optical spectropolarimetry combined with FUV spectroscopy provides a critical test of magnetic white dwarf models. The offset-dipole models do reproduce key features of optical spectropolarization data but fail to account for a rapid transition from high-field to

FIG. 9.—MSO spectroscopy (f_λ) at phases 0.0 and 0.5 compared to multipolar expansion and offset-dipole models.

TABLE 4
SUMMARY OF PERIOD MEASUREMENTS

Instrument	Wavelength (Å)	$P \pm \Delta P$ (s)	References
White-light photometry	5000	725.4 ± 0.9	1
Circular polarization.....	5000	725.0 ± 2.5	2
<i>EUVE</i> photometry.....	100	725.5 ± 0.8	2
<i>HST</i> FOS spectrophotometry.....	1500	725.7 ± 1.1	3
<i>EUVE</i> photometry.....	100	<u>725.7277</u> , 725.7317 , 725.7357	4
Circular polarization.....	5000	725.727 ± 0.001	4

REFERENCES.—(1) Barstow et al. 1995. (2) Ferrario et al. 1997. (3) Vennes et al. 2001. (4) This work.

low-field FUV line spectra. Quite the opposite, the multipolar expansion models reproduce relatively well the phase-resolved FUV spectroscopy but produce optical circular polarization spectra with the wrong V/I fraction and wrong sign of polarization. However, model predictions are dependent on uncertain bound-free opacities at high fields, which may affect our conclusions regarding field structures. Note that line opacities at $\lambda \leq 1000$ appear excessive in both classes of models, especially at high fields, possibly because of the use of incorrect oscillator strengths for the forbidden lines.

5. SUMMARY AND DISCUSSION

We have presented new optical and FUV observations of the rapidly spinning, high-field magnetic white dwarf EUVE J0317–85.5. From wavelength-averaged spectropolarimetry, we established a new rotational ephemeris for the star. The result, summarized in Table 4, matches one of the period aliases allowed by the EUV photometry ($P = 725.7277$ s, underlined in Table 4). To improve the accuracy of the rotational ephemeris, one could substitute in equation (1) the polarimetric period of 0.00839962(1) by the EUV period of 0.008399626(1). The calculated rotational velocity, $v_{\text{rot}} = 25 \text{ km s}^{-1}$, is not directly measurable in the optical or FUV spectra. Indeed, no radial velocity variations are discernible in the phase-resolved FUV spectroscopy: the dispersion in velocity measurements of the well-defined $1s0-3d-1$ and $1s0-3d-2$ transitions does not exceed 10 km s^{-1} .

We identified 12 components of the Zeeman-shifted Lyman line series, including seven forbidden components enforced by the presence of a strong electric field (motional Stark effect). Table 5 summarizes phase-resolved optical and ultraviolet properties. First, we established a clear link between the degree of polarization and the magnetic field strength and distribution. In particular, the highest degree

of polarization is achieved at the rotation phase that exposes the lowest field strength but most uniform field distribution. We also noted that the FUV emission is in antiphase, with optical emission which is interpreted as a line-blanketing effect. The EUV emission is double peaked, probably because of the field dependence of the ground-state hydrogen photoionization cross section.

Published models for EUVE J0317–85.5 fail to account simultaneously for the field dependence of the FUV spectrum and for the phase-resolved properties of the optical polarization spectrum. The offset-dipole model of Ferrario et al. (1997), while correctly predicting the optical polarization spectrum, does not generate the observed high-field FUV line spectrum. While more successful in the FUV, the multipolar expansion of Burleigh et al. (1999) predicts the wrong sign of polarization and degree of optical polarization. Does it suggest that EUVE J0317–85.5 is a spotted star similar to WD 1953–011 (Maxted et al. 2000)? A high-field ($B \geq 425 \text{ MG}$) magnetic spot with underlying lower field ($B \leq 185 \text{ MG}$) surface would generate some of the observed characteristics, including a rapid transition from low-field to high-field line spectra and, quite possibly, the correct field polarity.

The new data also offer new modeling challenges: one should now account for opacity variations (line blanketing) over the stellar surface and calculate the resulting effects on the local temperature structure and emergent spectrum. The current failure to include this causes incorrect weighting of different field-strength regions as a function of rotational phase. The predicted polarization intensity is uncertain at present because of both very poorly known continuum opacities and inaccurate line opacities. The latter is particularly true for the forbidden FUV lines that are enforced by the presence of a strong electric field. Effort should also be spent toward the very difficult goal of formulating effective inversion techniques, such as those developed by Donati et al. (1994) or Euchner et al. (2002), for deriving, e.g., the

TABLE 5
SUMMARY OF PHASE-RESOLVED PROPERTIES

Property	$\phi = 0.0$	$\phi = 0.5$
Mode surface B	Minimum $B \approx 185 \text{ MG}$	Maximum $B \approx 425 \text{ MG}$
Broadband photometry	Minimum B , R	Maximum B , R
Soft X-ray photometry (100 Å)	Secondary minimum	Primary minimum
FUV flux (1500 Å).....	Maximum	Minimum
Circular polarization.....	Maximum $v = V/I$	Minimum v

multipolar field coefficients from phase-resolved spectroscopy and spectropolarimetry so as to reduce the subjectivity of model generation and evaluation.

The companion of EUVE J0317–85.5, LB 9802, is non-magnetic ($B_e \lesssim 10$ kG; Kawka et al. 2003, in preparation). The existence of this pair raises questions concerning the origin and evolution of magnetic fields in stars. With a projected separation of only 200 AU, the two stars certainly share a common origin, a conclusion suggesting that EUVE J0317–85.5's strong magnetic field could have been acquired only after the progenitors of these stars were formed. The rapid rotation rate of EUVE J0317–85.5, its high mass and strong magnetic field, and the apparent age disparity with its companion all suggest a rather uncommon past, possibly involving the merger of a double-degenerate star.

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