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TWO ULTRAMASSIVE WHITE DWARFS FOUND AMONG CANDIDATES FOR MAGNETIC FIELDS

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ABSTRACT

The enhanced and broad Balmer lines evident in spectrophotometry of the white dwarfs PG 1658+441 and PG 0136+251 were previously interpreted in terms of comparatively weak surface magnetic fields, in the range 1–3 MG. New CCD spectrophotometry and circular spectropolarimetry confirm a magnetic field of mean surface strength $B_s = 2.3 \pm 0.2$ MG on the former star, but provide only marginal evidence for a much weaker longitudinal component of $B_e = -75 \pm 35$ kG (1 σ) on the latter object. Through detailed spectral modeling of the Balmer series profiles, it is now clear that the line enhancement in each star arises largely through the intensified damping on a very high gravity object: for PG 0136+251, $\log g = 9.00 \pm 0.10$, indicating a mass of 1.20 ± 0.04 $M_\odot$; for PG 1658+441, $\log g = 9.36 \pm 0.07$ and $M = 1.31 \pm 0.02$ $M_\odot$ (error bars represent formal fitting uncertainties). Indeed, PG 1658+441 is the highest mass single white dwarf reported thus far. Assuming normal stellar evolution, these values and the stars' high temperatures ($T_{\rm eff} = 39{,}190 \pm 360$ K and $30{,}510 \pm 200$ K, respectively) imply extreme youth, both on and off the main sequence. However, their locations, at high Galactic latitude and well away from any clusters of similarly young stars, are perhaps more consistent with origins in recent stellar mergers. A mass near the Chandrasekhar limit for PG 1658+441 adds evidence for a relationship between surface magnetism and mass among white dwarfs in the field.

Subject headings: stars: evolution — stars: fundamental parameters — stars: individual (PG 1658+441, PG 0136+251) — stars: magnetic fields — white dwarfs

1. INTRODUCTION

About two dozen white dwarfs are known to have magnetic fields exceeding 10^6 G, comprising a few percent of all objects surveyed with sufficient sensitivity to have confirmed fields in this range. The stars have been identified as magnetic either by the detection of continuum polarization or by Zeeman splitting of photospheric absorption features. The two stars currently listed as having the lowest measured surface field strengths (e.g., Schmidt 1989) are objects originally selected for having peculiar but not obviously split Balmer line profiles. These are PG 1658+441 and PG 0136+251, analyzed in Liebert et al. (1983; hereafter LSGSM). Spectra of each star taken with an image-tube scanner system appeared to show an Hγ profile with a broadened, flat-bottomed core and an enhanced equivalent width relative to other DA white dwarfs of similar color (see Fig. 2 of LSGSM). Only a single spectrum of high (2.5 Å FWHM) resolution was initially available for each star, however, and only one Balmer line fell within the spectral coverage. Based on the UV–optical energy distributions, the cooler of the two stars was PG 1658+441 near 30,000 K, and its stronger lines presented a more convincing case for peculiarity. The overall continuum of PG 0136+251 indicated an effective temperature in the range 40,000–50,000 K and the Hγ line appeared shallower and weaker, though still stronger than other DA stars of similar temperature. Follow-up spectropolarimetry was able to discern circular dichroism across the Balmer lines of the former object, which also revealed the characteristic triplet splitting of the Hα line core in the flux spectrum. Similar observations failed to detect circular polarization or obvious line splitting in the latter object. However, the quality of the data was not sufficient to rule out the possibility that the apparently peculiar Hγ profile in PG 0136+251 was also due to magnetic broadening, but in a weaker overall field. LSGSM estimated a mean field strength of 2.3 MG (MG = 10^6 G) on PG 1658+441 and suggested a value of $\sim$1.3 MG for PG 0136+251.

In this paper we present higher quality spectropolarimetry and spectrophotometry of PG 1658+441 and PG 0136+251 which lead to a different conclusion for the latter star. The spectropolarimetry is presented in § 2, while § 3 discusses the spectrophotometry and high-quality line profiles. Adopting straightforward approximations for the magnetic object, the lines are successfully fitted with synthetic spectra from stellar atmospheres models, allowing the $T_{\rm eff}$ and surface gravity of each star to be determined. The remarkable result is that the enhanced Balmer lines of both can be attributed to unusually large surface gravities and therefore high mass, $M > 1.20$ $M_\odot$. The implications are discussed in § 4.

2. SPECTROPOLARIMETRY

In the low-field limit, a magnetic field splits a singlet transition into a simple triplet, consisting of an unshifted π component and blue and redshifted σ components, the latter of which are oppositely circularly polarized in a longitudinal magnetic field. Stark broadening in a white dwarf atmosphere typically overwhelms splitting due to the Zeeman effect for fields below a few MG, obviating the detection of very weak magnetic fields by line broadening alone. However, the offset between σ components results in circular polarization in the line wings, amounting for the Balmer series to

$$V_\lambda(\%) = 1.1 B_e \left(\frac{\lambda}{4861}\right)^2 \frac{1}{I_\lambda} \frac{dI_\lambda}{d\lambda} \qquad (1)$$

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(e.g., Angel, McGraw, & Stockman 1973), where V is the normalized Stokes parameter of circular polarization, B_e is the disk-averaged longitudinal, or "effective," magnetic field in kG (kG = 10^3 G), I_λ is the spectral flux and, λ is in angstrom units. Circular polarization of a tenth of a percent in the wing of Hβ results from a strong-lined DA white dwarf with a field of 10 kG. With such measurements practical for the brighter stars with an efficient instrument and today's CCD detectors on a modest-sized telescope, circular spectropolarimetry can be an efficient technique to extend our knowledge of the field strength distribution of degenerate stars to values which are orders of magnitude weaker than currently known.

New circular spectropolarimetry was obtained for PG 1658+441 and PG 0136+251 using the CCD spectropolarimeter developed by G. D. S. and H. S. Stockman (STScI) attached to the 2.3 m telescope of Steward Observatory. Briefly, the instrument is a classical 1 inch (2.5 cm) beam spectrograph which incorporates a Wollaston prism polarizing beam splitter in the collimated beam to produce two dispersed images of the split in complementary senses of polarization. While the instrument is equally well-suited for linear polarimetry, for these observations a rotatable achromatic 1/4 waveplate was inserted prior to the collimator to convert incident circular polarization to linear and to modulate the sense of polarization between the two parallel spectra on the CCD. Transmissive optics for the collimator and camera and UV-sensitization of the TI 800 × 800 thinned CCD result in an efficient instrument (more than 25% of photons at Hα incident at the spectrograph slit are detected). A 1′ long slit provides ample real estate for sky subtraction on point sources, and polarimetric efficiency exceeds 95% over the range 4500–8000 Å. Spectral resolution/coverage is 7 Å/2000 Å and 13 Å/4000 Å with 1200 g mm^{-1}, and 600 g mm^{-1} first-order gratings, respectively, for a 2″ wide slit on the 2.3 m telescope. The dedicated CCD, dewar, Caltech/JPL-style CCD camera controller (Gunn et al. 1987), and 386-based data-taking computer permit the instrument to be easily transported to other telescopes. An internal Ethernet interface enables images to be shared with more capable data-analysis computers, including a Sun workstation at the 2.3 m telescope running custom IRAF scripts for near on-line polarization analysis.

The new data were acquired on 1991 February 14–15 in the 1200 g mm^{-1} configuration. PG 1658+441 was observed for a total of 24 minutes over the spectral range $\lambda\lambda$4700–6700, while the observation of PG 0136+251 required 53 minutes in a setting roughly centered on Hβ. The data are presented in the two panels of Figure 1 as combined plots of spectral flux and circular polarization (an absolute calibration has not been applied to spectral flux due to the presence of significant cirrus during the observations). The results are consistent with those of LSGSM, but at much higher signal-to-noise ratio: PG 1658+441 reveals the presence of a substantial magnetic field in a Zeeman triplet at Hα and (marginally) Hβ, and in clear polarization reversals across both lines, while neither splitting nor polarization features are obvious at Hβ or Hγ for PG 0136+251.

The statement for PG 0136+251 is best quantified by integrating the point-by-point measures from equation (1) across a line profile. Since a field measurement from any given point in the line depends not only on the local degree of polarization but also on the flux gradient, noise in the line profile can corrupt the results, particularly in the wings. Therefore, the observed profiles were fitted by least squares to suitable smooth functions (e.g., Lorentzians) and the flux gradient computed analytically. Point-by-point uncertainties in the derived magnetic field were computed from the dispersion in circular polarization outside the line combined with the effect of uncertainties in the profile-fitting parameters. In all cases, the former component dominated, that being due almost completely to statistics of the detected photons. The net results are listed in Table 1 for the two lines observed for each star, with the sign of B_e derived from equation (1) and the convention that positive circular polarization corresponds to counterclockwise rotation of the electric vector as viewed from the Earth. Also shown is the magnitude of the disk-averaged surface field, $|B_s|$, for the two stars, as measured from the triplet splitting (or lack thereof) in the line profiles.

The measurement for PG 0136+251 has a sensitivity nearly a factor of 4 better than that of LSGSM and provides strong

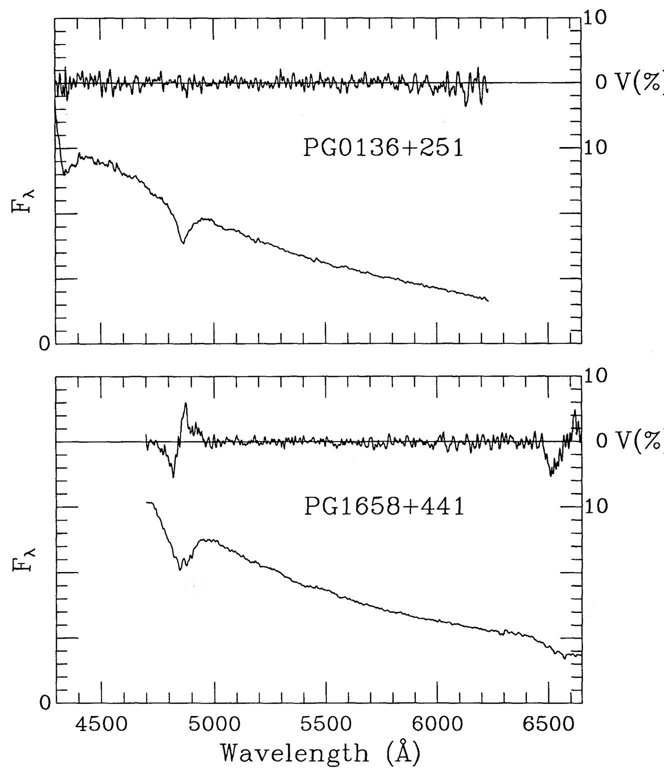

FIG. 1.—Total flux and circular polarization spectra of the white dwarf PG 0136+251 compared with the magnetic star PG 1658+441, both shown at a spectral resolution of 10 Å. Zeeman splitting and strongly modulated polarization are obvious for the latter object, which has a disk-averaged longitudinal field component of $B_e = +724 \pm 52$ kG. Marginal (2 σ) evidence exists for a field of $B_e \approx -75$ kG on PG 0136+251.

TABLE 1

MAGNETIC FIELD MEASUREMENTS

Star	Line	$\lambda\lambda$	$B_e \pm \sigma_B$ (kG)
PG 0136+251	Hγ	4312–4368	-70 ± 158
	Hβ	4771–4951	-75 ± 36
	Mean		-75 ± 35
			$|B_s| < 200$
PG 1658+441	Hβ	4770–4952	$+697 \pm 60$
	Hα	6472–6657	$+803 \pm 102$
	Mean		$+724 \pm 52$
			$|B_s| = 2300 \pm 200$

evidence against a surface field sufficiently strong to produce the qualitative line enhancement noted in the previous paper. Although there is an indication at the 2 σ level for a weak (~ 70 kG) longitudinal component, we will not claim significance for this result until the object is reobserved and our reduction and error analysis are vindicated to this level of accuracy on a larger sample of stars. We note, however, that the data on PG 0136+251 in Figure 1 are actually a combination of four separate observations, which individually yield $B_e = +9 \pm 78$, -122 ± 64, -149 ± 69, and -68 ± 75 kG. Thus the evidence in favor of a weak magnetic field is tantalizing. If it is verified, PG 0136+251 would become the weakest field magnetic white dwarf by more than an order of magnitude.

In contrast, the substantial surface field of PG 1658+441 is clearly evident in the S-shaped circular polarization signature in the bottom panel of Figure 1. The partially resolved splitting apparent in the line cores (see also Fig. 2) is sufficiently large that the weak-field approximation of equation (1) is breaking down; nevertheless, a sizable effective component of $B_e = 724 \pm 52$ kG results from a straightforward integration over Hβ and Hα. The ratio of effective-to-mean strength reflects the degree of structure in the field as well as the projection of any axial component onto our line of sight; the value of $B_e/B_s = 0.4$ is consistent with a ~ 3.0 MG polar-field dipole tipped 40°–60° from the line of sight (Achilleos & Wickramasinghe 1989). There is no indication that either the effective or mean measure for PG 1658+441 is significantly different from that measured in 1980 by LSGSM.

3. SPECTRA AND LINE PROFILE FITTING

3.1. *PG 0136+251*

Given the failure to detect substantial circular dichroism across the Hβ and Hγ lines of PG 0136+251 in data of such improved quality, other origins for the enhanced line strengths were explored. This was carried out through Balmer line spectroscopy from the limit to Hβ, using the facility CCD spectrograph on the 2.3 m telescope. In Figure 2 we compare the spectrum of PG 0136+251 at ~ 7 Å resolution with similar data on PG 1658+441, the massive white dwarf GD 50 (Bergeron et al. 1991), and GD 394—a comparison star of very similar effective temperature but with a surface gravity (log $g = 7.78$) much closer to the mean of the DA white dwarfs (log $g \approx 7.9$). In these data, the Zeeman-split triplet cores of Hβ and Hγ of PG 1658+441 are clearly evident. In contrast, the profiles and overall decrement of PG 0136+254 most closely resemble those of GD 50, with no distinct features in evidence shortward of the weak and peculiar Hϵ feature. Indeed, the cores of the lines—Hβ in particular—lack any indication of the flat-bottomed or troughlike shape which the poorer quality observations of LSGSM apparently had shown.

The Balmer profiles of PG 0136+251 were analyzed in a manner identical to that of Bergeron, Saffer, & Liebert (1992) for their sample of nearly 130 hot DA white dwarfs. In this treatment, the lines are simultaneously fitted with model atmosphere profiles in order to determine both $T_{\rm eff}$ and log g, with the higher Balmer lines being more sensitive to the latter. The

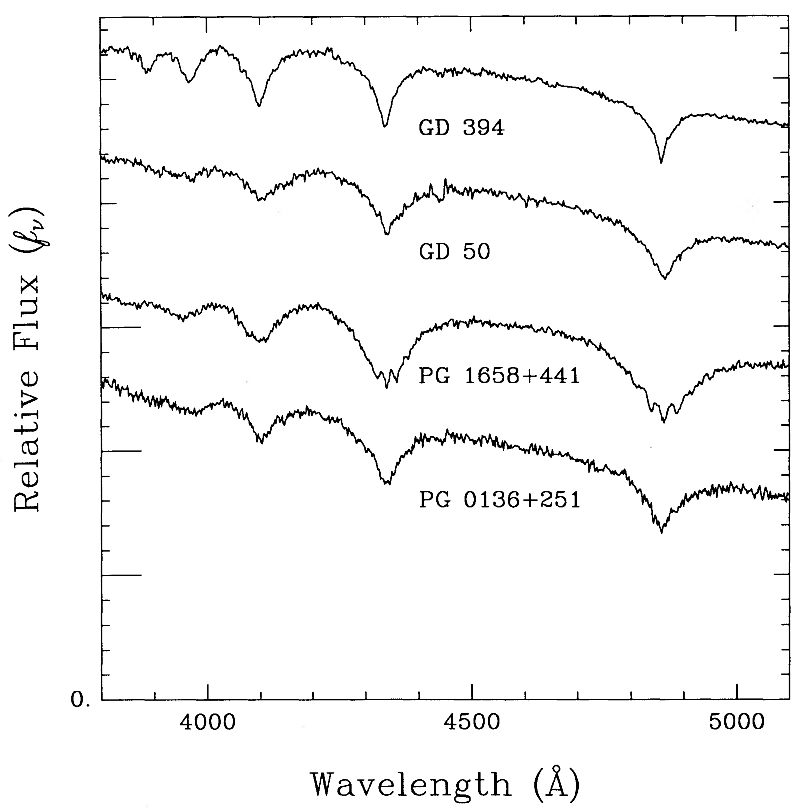

FIG. 2.—Comparison of the upper Balmer series of PG 0136+251 with the magnetic white dwarf PG 1658+441 ($B_s \approx 2.3$ MG), the massive GD 50 (1.27 $M_\odot$), and the more typical GD 394.

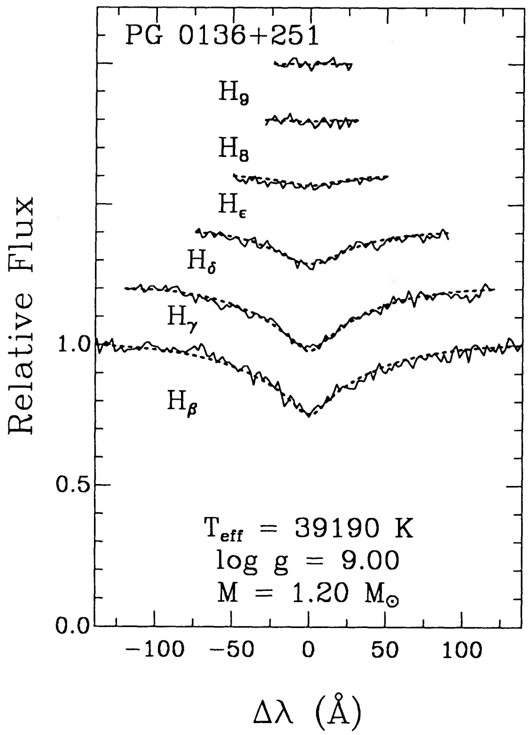

FIG. 3.—Comparison of measured and synthetic Balmer line profiles for PG 0136+251 using the stellar parameters indicated.

details of the reduction and analysis procedures are described in the above reference. The resulting excellent fit for PG 0136+251 is shown in Figure 3. The peculiar line profiles are entirely explicable by an unusually large surface gravity ($\log g = 9.00 \pm 0.10$), approximately 1 dex higher than the mean of the DA sample of Bergeron et al. (1992). There is, in fact, only one star in the sample with a higher surface gravity: GD 50 at $\log g = 9.22 \pm 0.08$[4] (Bergeron et al. 1991); the spectra of GD 50 and PG 0136+251 appear strikingly similar since their temperatures are also equal within a thousand degrees. At such a high surface gravity, finite-temperature effects are completely negligible, and masses can be estimated from zero-temperature mass-radius relations. Using the mass-radius relation of Hamada & Salpeter (1961) for carbon-core configurations, GD 50 is assigned a mass of $1.27 \pm 0.02\ M_{\odot}$, while PG 0136+251 receives a value of $1.20 \pm 0.04\ M_{\odot}$.

3.2. *PG 1658+441*

It is clear from visual inspection of Figure 2 that, away from the Zeeman-split cores, the Balmer profiles of PG 1658+441 are also much better approximated by the heavily damped wings of a high-gravity star like GD 50 than the more typical GD 394. This is particularly evident in the washed-out appearence of the high members of the series and almost complete absence of H8, where the magnetic splitting is less than two-thirds that at Hβ. The impression gains significance when one realizes that the color temperature of PG 1658+441 is some 10,000 K cooler than either GD 50 or PG 0136+251 (LSGSM); thus, other parameters being equal, its profiles should be sharper.

[4] The derived surface gravity of GD 50 presented here differs slightly from that of Bergeron et al. (1991), due to our use of an improved set of model spectra.

In general, a temperature/gravity analysis cannot be performed for a magnetic star with the same confidence that can be ascribed to a zero-field star. As is well known, at sufficiently high fields the *l*-degeneracy of the atom is removed, and a Balmer line breaks up from the symmetric Zeeman triplet into a more complex pattern which collectively shifts to the blue with the square of the field strength. At the same time, the Stark broadening function is reduced—profiles instead being dominated by the magnetic behavior of individual components and the spread in field strength over the star—and unusually sharp features can result (e.g., Liebert et al. 1977). For Hδ–Hβ, this develops in the regime ~2–10 MG, respectively.

However, at the low field strength of PG 1658+441, Stark broadening still dominates the line opacity, and a procedure similar to that outlined in Wickramasinghe & Martin (1979), in which the total opacity is calculated as the sum of individual Stark-broadened Zeeman components, should be accurate enough for the purpose of our analysis. The line displacements and strengths of the Zeeman components of Hβ–Hδ were taken from the tables of Kemic (1974). Hε was treated as a triplet of equal strength components which are split by the linear Zeeman effect and collectively displaced to the blue by the mean quadratic shift of the ensemble. The zero-field Stark-broadening formalism of Vidal, Cooper, & Smith (1970) was assumed to apply to each component, and the total opacity of a Zeeman-split line was normalized to that resulting from the zero-field strength solution. With this approximation, the specific intensity is calculated for various field strengths and angles between the emitted ray and normal to the surface of the star. The net emergent spectrum is then obtained from an integral over the surface of the star for a given distribution of the magnetic field. Inspection of model spectra for various polar field strengths and viewing angles led to the adoption of a centered 3.5 MG dipole tipped 60° to the line of sight. This is slightly stronger and at similar inclination to the conclusion of Achilleos & Wickramasinghe (1989), the difference being due largely to our new spectrum including Hδ and Hε, whose central wavelengths are strongly affected by the quadratic Zeeman effect. In fact, broadening due to magnetic field spread over the stellar surface is less than ±10 Å even at Hβ, so field geometry is of secondary importance to the determination of surface temperature and gravity.

The adopted profile fits are portrayed against the entire observed spectrum in Figure 4, and for individual lines in Figure 5. In general, Hε is predicted too weak, perhaps due to the necessity of using zero-field oscillator strengths for this line. In addition, the individual components of the triplet core of Hβ are predicted slightly too broad, and too deep, though the *relative* strengths and shifts are well reproduced. The discrepancy can probably be attributed to the partial lifting of the *l*-degeneracy in the line core by the magnetic field. A similar but smaller effect is also observed at Hγ. Since line broadening in a modest magnetic field is not yet a tractable problem, only the wings of Hβ (that portion above 50% line depth) were used in the fitting procedure. We note that, if the reduction in Stark broadening persists into the wings, our determinations of log *g*, and hence mass, will be *underestimates* of the true values.

With these considerations in mind, the adopted solution, $\log g = 9.36 \pm 0.07$ and $T_{\rm eff} = 30{,}510 \pm 200$ K, yields a satisfactory fit. The fact that the temperature derived by this technique falls well within the uncertainty of the continuum value of LSGSM bolsters confidence that the modeling procedure is accurate for a weakly magnetic star. From the Hamada-

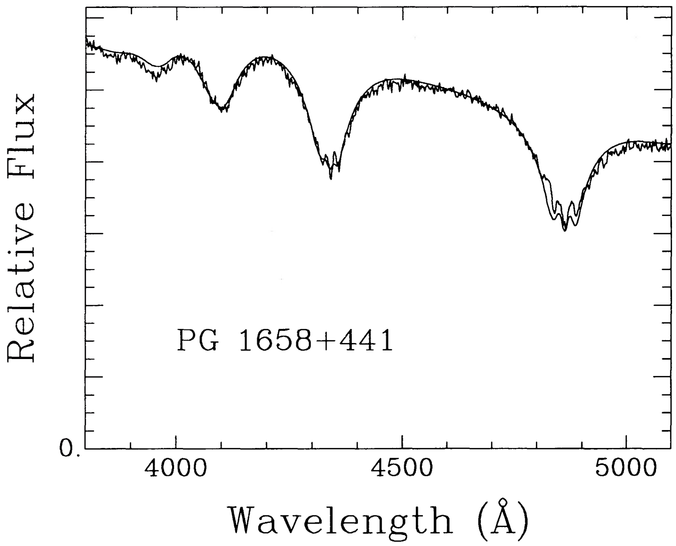

FIG. 4.—Observed and model spectra of PG 1658+441 illustrating the reproduction of the entire upper Balmer series by a model with $T_{\rm eff} = 30510$ K, log $g = 9.36$. Magnetic geometry is that of a centered dipole of polar strength 3.5 MG, viewed at angle of 60° to the line of sight. The bottom 50% of Hβ has been omitted from fitting procedure due to the reduction of the Stark effect by the magnetic field. An implied mass of $M = 1.31\ M_\odot$ marks PG 1658+441 as the most massive isolated white dwarf yet measured.

Salpeter mass-radius relation, we derive a mass of $M = 1.31 \pm 0.02\ M_\odot$. As for PG 0136+254, the error bar reflects the confidence interval of the formal fitting procedure; it may be somewhat underestimated on the high-mass side if the Stark broadening is overestimated. PG 1658+441 is the highest mass single white dwarf reported thus far. The atmospheric parameters and masses derived for both stars are sumarized in Table 2.

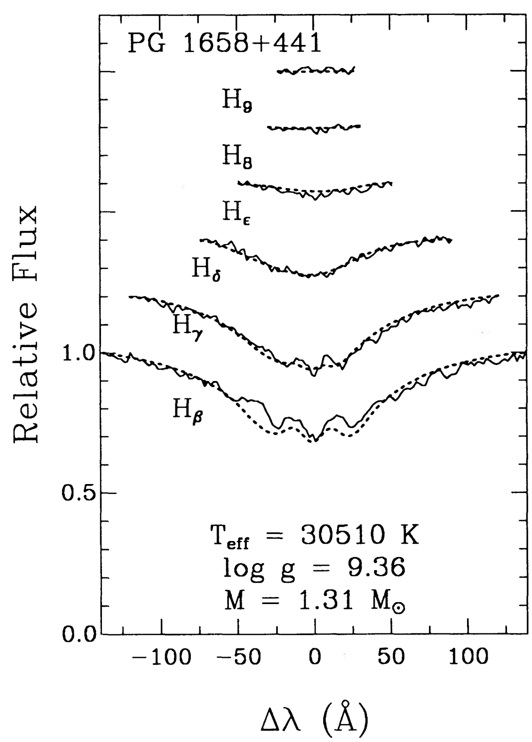

FIG. 5.—Detailed comparison of measured and synthetic Balmer line profiles for PG 1658+441 for the stellar parameters indicated. Magnetic geometry is as in Fig. 4.

4. DISCUSSION AND IMPLICATIONS

The massive white dwarf GD 50 was among the 130 DA stars selected by Bergeron et al. (1992) from the catalog of McCook & Sion (1987) on the basis of a published spectral classification of DA2 or DA3, indicative of expected effective temperatures in the approximate range 15,000–40,000 K. Both PG 0136+251 and PG 1658+441 were omitted from that survey, the former since it was classified DA1 (a subtype generally too hot for the line profiles to yield reliable surface gravities), the latter because of its magnetic nature. However, our derived effective temperature of $T_{\rm eff} = 39{,}190 \pm 360$ K places PG 0136+251 within the relevant range, and we have argued that the modeling procedure is probably accurate for stars with relatively weak magnetic fields. Clearly, the mass of each star is much higher than the average of $\sim 0.56\ M_\odot$ for the complete sample of DA stars analyzed by Bergeron et al. (1992).

Bergeron et al. (1991) discuss some implications of the unusually high mass found for GD 50, which generally apply also to the two additional stars and need only a brief summary here. A white dwarf mass of $\gtrsim 1.20\ M_\odot$ implies that the initial progenitor mass was comparable to or greater than that of the brightest main-sequence stars in the Pleiades cluster; this cluster possess a white dwarf with a mass near 1 $M_\odot$ (Wegner, Reid, & McMahan 1991; Bergeron et al. 1992). The further implication is that the nuclear lifetimes are short, of the order 10^8 yr or less.

The relative youth of these stars finds further support in Table 2, where we have listed the apparent visual magnitudes as taken from the Palomar multichannel spectrophotometry (MCSP) of LSGSM, the absolute magnitudes obtained from the derived parameters of § 3, and the implied parallaxes of the two stars considered here. The adopted V value for PG 1658+441 includes a correction of 0.4 mag for clouds based on the need to join the MCSP optical energy distribution at the atmospheric UV limit with the spectrophotometry of the *International Ultraviolet Observatory*. The small predicted distance of PG 1658+441 suggests that it has a small tangential velocity, since the star does not appear in any proper motion catalog or list of faint blue stars with small proper motion. While by no means complete, the Lowell "GD" lists (Giclas, Burnham, & Thomas 1980) and Luyten (1970, 1977) catalog of white dwarf candidates were generally efficient at identifying such objects, especially for very blue stars brighter than $V = 15$. The Lowell program attempted to identify stars with proper motions $\gtrsim 0\farcs10$ yr^{-1}, and some of the Luyten stars have motions only half this large. Both groups covered the region of the sky where this star lies. If we assume that PG 1658+441 has a proper motion of $0\farcs10$ yr^{-1} and lies at the predicted distance, its tangential velocity would be only 12 km s^{-1}. A small space motion would also indicate that the star is young.

TABLE 2

STELLAR PARAMETERS AND PREDICTED PARALLAXES

Star	$T_{\rm eff}$	log g	$M/M_\odot$	M_V	V	Predicted π
PG 0136+251......	39,190	9.00	1.20	11.37	16.01	$0\farcs012$
PG 1658+441......	30,510	9.36	1.31	12.56	14.62	$0\farcs039$

Given the high effective temperatures and corresponding short cooling times ($\sim 10^7$ yr for a star as hot as PG 0136+251), the implied (total) ages of these objects suggest that they might still be part of their parent clusters or associations of massive young stars. However, their positions at high Galactic latitude and away from any obvious region of recent star formation suggest an alternative possibility, namely that some or all could have formed as the result of the merger of two white dwarfs. Additional evidence that the field DA distribution includes a significant component due to close binary evolution is discussed by Liebert, Bergeron, & Saffer (1991) and Bergeron et al. (1992). On the other hand, how a stellar merger could preserve (or generate) a reasonably well-ordered magnetic field with no evidence for significant rotation (all epochs of spectroscopy and spectropolarimetry of PG 1658+441 yield common values of B_e and B_s) is not at all clear.

The white dwarf with the weakest confirmed magnetic field remains PG 1658+441. The fact that it also has a high mass lends support to the growing indication that magnetic stars are more massive than the norm (Greenstein & Oke 1982; Liebert 1988; Sion et al. 1988). As our spectra have shown, its surface value of ~ 2.3 MG is spectroscopically detectable at Hβ in good-quality spectra of moderate resolution. Thus, it is unlikely that a sizable fraction of white dwarfs have undiscovered surface fields in the vicinity of a few MG. Indeed, with only $\sim 5\%$ of white dwarfs having detectable fields, the question of where the bulk of the stars lies becomes interesting. Assuming a frozen-in field, values of 10–100 kG on a white dwarf correspond to fields of ~ 1–10 G in the parent core. Spectroscopically, strengths of tens of kG can be recognized only in cool DAs which exhibit sharp, non–LTE cores in the lower Balmer series (especially Hα). However, from the results presented here, it appears that this level of sensitivity for well-organized field patterns is also possible through accurate circular spectropolarimetry. The hot DA sample of Bergeron et al. (1992) is ideal for this purpose, since the objects are reasonably bright ($V < 15.5$) and the sample is sufficiently large to be statistically valuable. Such a survey is now underway and will be reported in future publications.

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