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THE DETECTION OF AN Hα ZEEMAN PATTERN IN THE COOL MAGNETIC WHITE DWARF G99-47

James Liebert
Department of Astronomy, University of California at Berkeley

J. R. P. Angel
Steward Observatory, University of Arizona

and

J. D. Landstreet
Department of Astronomy, University of Western Ontario
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ABSTRACT

An apparent Hα absorption feature has been detected in image tube scans of the cool magnetic white dwarf G99-47, previously classified as DC (featureless). The broad ~2.5 Å EW line is centered some 21 Å shortword from the normal Hα position. This line is interpreted as the π component of Hα-shifted by the quadratic Zeeman effect in a surface field of $\sim 15 \times 10^6$ gauss. This interpretation is supported by the detection of the characteristic circular polarization of the σ components at ± 350 Å in data obtained with the multichannel spectrophotometer. Both results are fitted well by a simple, centered dipole model with a mean longitudinal field of 5.6×10^6 gauss. However, the longitudinal field strength indicated from the continuum circular dichroism theory is about a factor of four smaller. The strength of the Hα absorption and absence of other detectable Balmer and Ca II lines are consistent with G99-47 being a very cool, metal-poor DA star.

Subject headings: magnetic fields — white dwarf stars — Zeeman effect

I. INTRODUCTION

Nearly all of the abundant white dwarfs with Balmer series in absorption (type DA) have no magnetic field detectable through Zeeman splitting or shifting of the lines (Angel and Landstreet 1970; Preston 1970; Trimble and Greenstein 1972; Elias and Greenstein 1974). Upper limits as low as a few kilogauss have been set for the few brightest DA's, while the absence of any quadratic Zeeman shift on the original classification plates sets a limit of $1\text{–}2 \times 10^5$ gauss on a larger number. Only one magnetic DA has been reported, GD 90, which displays clearly the Zeeman patterns characteristic of a field of 5×10^6 gauss (Angel *et al.* 1974). In this case the magnetic distortion of the Balmer lines (except Hα) is sufficiently large that identification as a DA from the blue spectrum is not immediately obvious, and somewhat larger fields could broaden the lines to the point that they are too weak to observe. This now seems to have been the case for G99-47 (GR 289) classified as type DC (featureless spectrum) by Greenstein *et al.* (1971) from blue spectra. This star was found to be magnetic through the discovery of continuous circular polarization of ~0.4 percent by Angel and Landstreet (1972).

G99-47 is the coolest of the eight known magnetic white dwarfs, with an effective blackbody temperature of about 5600 K, as found from Greenstein's multichannel spectrophotometry (Greenstein 1974). The star is in fact cool enough that it is near the temperature limit below which hydrogen lines could not have been seen in even a nonmagnetic hydrogen atmosphere. The available trigonometric parallax (Harrington *et al.* 1975) yields an absolute magnitude ($M_v = +14.57$) consistent with this view. Hence, the temperature as well as the magnetic field has made the detection of Balmer absorption features difficult.

The purpose of this *Letter* is to report new observations of the optical and polarization spectrum which show that the star apparently has Hα absorption indicative of a cool, hydrogen atmosphere.

II. THE OBSERVATIONS

Two new observations are presented here. First, spectrophotometry of G99-47 was obtained with the image tube scanner (ITS) system on the Lick Observatory 3 m reflector. Three short-duration scans, two covering the Hα region and one at shorter wavelengths, were made on the nights of 1974 January 30 and 1975 January 15, 16. The scans confirm that the star has a smooth, featureless spectrum from 3900 to 7000 Å except for the presence of a weak, absorption feature centered at 6542 ± 5 Å (1 σ), approximately 8 percent deep over some 30 Å in width. The equivalent width measured over the interval 6520–6570 Å is about 2.5 Å. Sources of error in this determination are discussed below.

In Figure 1 we compare the optical spectrum of G99-47 (from 4800 to 7000 Å) with that of G128-7

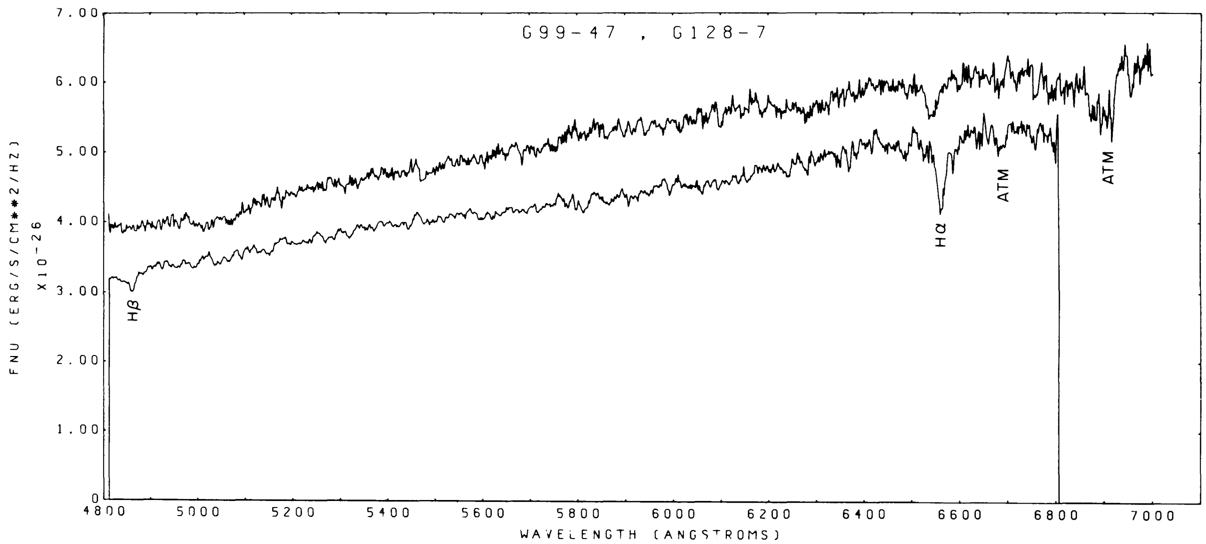

FIG. 1.—Optical intensity spectra of G99-47 (*upper tracing*) and the cool DA white dwarf G128-7 covering 4800–7000 Å. The fluxes of the latter have been scaled linearly for presentation. Both were obtained with the Lick ITS system; resolution was about 8 Å.

(GR 283), a nonmagnetic degenerate star having similar atmospheric parameters. This star has *UBV* colors and absolute magnitude ($M_v = +14.6$ from the trigonometric parallax) similar to those of G99-47 (Greenstein *et al.* 1971; Harrington *et al.* 1975). We note that Hα is easily the strongest hydrogen line in the star (EW ≈ 5 Å). The contrast in the positions and widths of the Hα line in G128-7 and the feature in G99-47 is evident. However, as discussed below, we believe that the available evidence strongly supports the interpretation of the feature in G99-47 as being due to Hα.

Our detection is not inconsistent with previous spectra and spectrophotometry of this star since (1) previous photographic spectra did not cover Hα, and (2) the feature would depress only one 80 Å channel in Greenstein's (1974) multichannel data by only ~3 percent. The ~8 percent Hα feature in G99-47 is several σ below the high frequency, photon-count-dominated noise level.

The other new datum is a low-resolution polarization spectrum obtained 1973 November 6.3 UT at the 5 m Hale telescope with the multichannel spectrophotometer (MCSP) and a Pockels cell polarizing modulator, as described by Angel and Landstreet (1974). Polarization is measured in 30 wavelengths regions simultaneously, the channel width being 160 Å from 3480 to 5720 Å and 360 Å from 5320 to 10360 Å. The results are plotted in Figure 2. Two ultraviolet points having very large errors were omitted from this figure, and the red points longward of 7800 Å were combined to decrease the errors. It will be seen that the general trend of wavelength dependence is in agreement with the previous broad-band results—that is, about +0.5 percent circular polarization in the blue, dropping somewhat in the red above 6000 Å. The apparent region of negative polarization beyond 8900 Å is not statistically very significant. However, there are two points in the

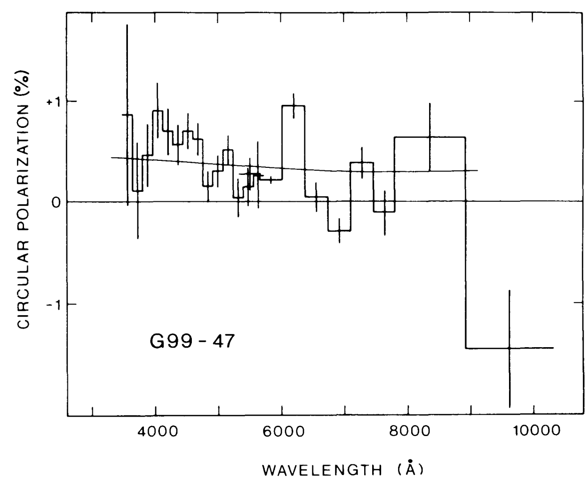

FIG. 2.—The wavelength dependence of circular polarization observed in G99-47, shown as a histogram. The observations were obtained with the multichannel spectrometer on the 5 m Hale telescope. The smooth curve through the data is the theoretical circular polarization spectrum calculated as described in the text.

spectrum that do deviate significantly from the average curve, namely the channels of high polarization from 6020 to 6380 Å ($V/I = 0.95 \pm 0.15\%$) and low polarization from 6740 to 7120 Å ($-0.28 \pm 0.15\%$).

III. DISCUSSION

Since the white dwarf is known to be magnetic from the continuous circular polarization, the obvious interpretation is that the λ6542 feature and the circular polarization structure around it are due to Hα. As we shall show below, this interpretation fits the data well.

In the presence of magnetic fields less than a few million gauss, Hα is simply split into a classical Lorentz triplet, the splitting of the two σ components being $\Delta\lambda_L(\text{Å}) = 21\ B_6$, where B_6 is the field in millions of gauss. The quadratic Zeeman effect becomes significant at higher fields, shifting both π and σ components to the blue by an amount $\sim\Delta\lambda_Q(\text{Å}) = 0.08 B_6^2$ (Kemic 1974*a*). We tentatively identify the observed absorption feature as the π component, which is shifted by the quadratic effect, and we find a mean surface field $\langle B \rangle \approx 1.6 \times 10^7$ gauss for the observed 21 Å displacement. In a uniform field of this strength we expect to see the σ components typically somewhat weaker than the π component (depending on orientation) at ± 340 Å. In any realistic situation in which the field is not highly uniform, the σ components will be too broad and weak to appear in the spectrophotometry (this is the case with Hα for GD 90), but they may still be detectable through their circular polarization. The observed opposite circular polarization on either side of Hα is what would be expected. The anomalous channels in the circular polarization spectrum are the polarized channels ± 360 Å from 6542 Å, in good agreement with the prediction from the quadratic shift. On the basis of these data alone, one would estimate a surface field in the range $8\text{–}25 \times 10^6$.

Next we ask if it is reasonable that none of the higher Balmer lines are detected. We adopt as our working hypothesis the idea that G99-47 would have the same line strength as our comparison star G128-7. DA white dwarfs of similar color may still have hydrogen lines systematically different in strength or shape, but it appears likely that the Balmer decrement steepens sharply for DA white dwarfs as the temperature goes lower—i.e., Hα is the last line to be seen at the cool end of the DA sequence (Liebert 1975). Theoretical calculations indicate that this effect may depend on the metal abundance (Hintzen and Strittmatter 1975), but there is evidence that metals are no more abundant in G99-47 than in G128-7 from the absence of absorption near the position of the Ca II H and K lines in G99-47. Kemic (1974*b*) notes that the positions of the H and K lines would not be drastically shifted in the presence of strong surface fields. Relatively unbroadened central π components should remain regardless of configuration up to 10^8 gauss. This is because the upper and lower state of the H and K transitions both have the same principal quantum number and hence a small Zeeman energy shift. Hence, we conclude that G99-47 is probably a metal-poor white dwarf like G128-7 which also lacks H and K lines.

Since the higher Balmer lines should be weak in G99-47 even with the field absent, it is understandable that the strong magnetic broadening will make these lines too shallow to detect. On the basis of the models below even the π component of Hβ (the best candidate for detection in the higher lines) will be broadened by some 80 Å due to the differential quadratic Zeeman shift across the face of the star.

We next would like to check if the simple centered dipole field model can reasonably reproduce the π component profile and the observed strength of circular polarization at the σ components, given the observed equivalent width of the π component. To do this, we have run a model calculation as follows:

1. The wavelength and strength of all the components in the Zeeman pattern for a given field strength were interpolated from the table of Kemic (1974*c*), which were obtained from accurate calculations of the linear and quadratic perturbations.

2. Broadening of the lines was taken into account by giving each subcomponent a Stark profile with a full width at half-maximum (FWHM) of 5 Å. In reality, the electric and quadratic Zeeman interactions are of comparable strength, and should be treated together; in addition, self-broadening is also significant. However, since the observed profiles are dominated by inhomogeneous magnetic field broadening, the exact form of line profile is unimportant. The radiative transfer of the polarized light was calculated according to the method of Unno (1956).

Model profiles in the three Stokes parameters, I, Q, and V were obtained by summing the calculated parameters for a grid of 75 equal-area elements over the visible disk of the star. Models of various polar field B_p and tilt α of the magnetic axis to the line of sight were explored; the ratio of the line to continuum opacity was treated as a free parameter and set to give the observed equivalent width of the π component. The value chosen for this ratio also seems reasonable since the program yields a 6 Å EW and 8 Å FWHM for Hα with no magnetic field (comparable to the parameters observed in G128-7). Two models which reproduce fairly well the observed 6542 Å feature are shown in Figure 3. These are (*a*) $\alpha = 30°$, $B_p = 2.0 \times 10^7$ gauss; and (*b*) $\alpha = 60°$, $B_p = 2.5 \times 10^7$ gauss. In both cases the mean field is directed away from the observer. The predicted linear and circular polarization Q/I and V/I which then follow for each model are also shown in the figure. The average circular polarization $\Sigma V/\Sigma I$, taken over the same bins as measured with the MCSP, are also given in the figure.

In case (*a*) these averaged polarization values for the 360 Å bins centered at 6200 and 6920 Å are +0.50 and −0.51 percent, respectively, in good agreement with the observed values of +0.6 and −0.6 from a mean continuum value of ∼+0.35 percent. In case (*b*), where the view is from closer to the plane of the magnetic equator, the values indicate less average circular polarization, +0.25 percent for 6200 Å and −0.3 percent for 6900 Å, in poorer agreement than case (*a*). However, in view of the crudeness of the data, it is difficult to place limits on α.

It would appear that the simple centered dipole model with the parameters of case (*a*) is adequate to explain all the observed characteristics of the Zeeman pattern in the optical and polarization spectra. The shift and width of the π component, the absence of detectable σ components in intensity but their location and strength in circular polarization, are all accounted for. No more elaborate treatment seems necessary at this stage.

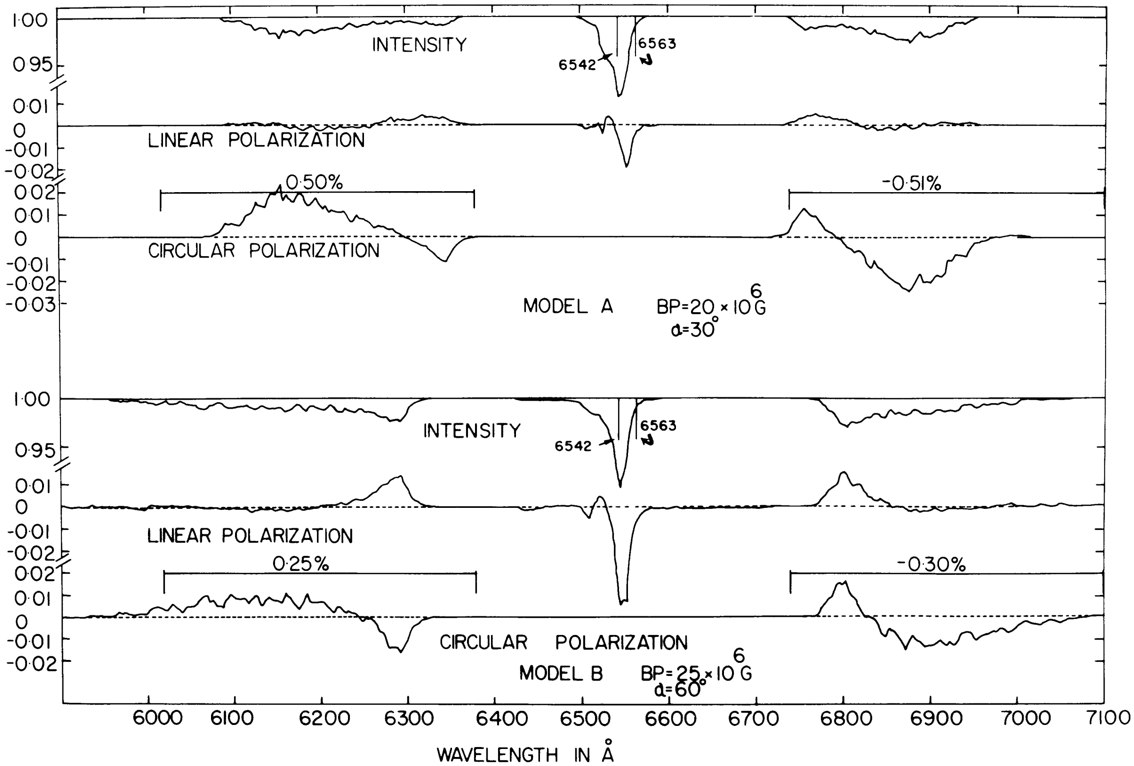

FIG. 3.—Predicted intensity, circular polarization, and linear polarization spectra near Hα for two best-fitting models discussed in § III. Parameters listed are the polar magnetic field strength B_p and the tilt angle α of the magnetic axis to the line of sight. In both cases the field is directed away from the observer.

The mean longitudinal field in the continuum for such a model is given generally by

$$\langle B_l \rangle = \int_{\text{disk}} B_z[1 + (3/2)\cos\theta]dxdy$$

$$= \tfrac{13}{40} B_p \cos\alpha \,,$$

where θ is the angle to the line of sight to the local normal on the disk, and B_z is the field component along the line of sight. For case (*a*), $\langle B_l \rangle = 5.6 \times 10^6$ gauss. One-sigma errors for this number appropriate to fitting $\Delta\lambda = \pm 5$ Å for the Hα line are estimated as -0.6, $+0.8 \times 10^6$ gauss. This is larger than the estimate of 1×10^6 gauss made previously on the basis of the continuum circular polarization data (Angel and Landstreet 1974). However, that estimate of $\langle B_l \rangle$ was made under the assumption of a pure helium atmosphere with He^- as the main source of the continuum opacity and dichroism. We have recalculated the expected continuum polarization spectrum for an atmosphere of pure H, in which H^- is expected to be the principal source of opacity and dichroism. Following the procedure discussed by Landstreet and Angel (1975), we find that the dichroism efficiency factor α_1 (eq. [8] therein) varies smoothly from 2.1 at 3500 Å to 1.6 at 9000 Å and that the expected continuum polarization gives a reasonable fit to the multichannel (MCSP) polarization spectrum for $\langle B_l \rangle = 1.2 \times 10^6$ G. The calculated spectrum is shown as a smooth curve in Figure 2; it is almost identical to the curve calculated with pure He and $\langle B_l \rangle = 1.0 \times 10^6$ gauss.

We thus find a disagreement of about a factor of 4 between the best estimates of longitudinal field strength based on observation of Hα and of the continuum polarization. The lowest acceptable value of $\langle B_l \rangle$ consistent with the dipole model interpretation of the Hα data is $\sim 3 \times 10^6$ gauss, still leaving a factor of 2.5 discrepancy. The apparent absence of continuum circular polarization in GD 90 may mean that a similar problem occurs with the other magnetic white dwarf having a hydrogen atmosphere (Angel *et al.* 1974). In view of the uncertainties in the magnetic circular dichroism theory and in the transfer effects for cool atmospheres, we believe that the new, larger result for $\langle B_l \rangle$ from the Zeeman effect is the more reliable field determination. We note also that the strong polarization features near the Balmer and Paschen limits predicted by Lamb and Sutherland (1974) would not be easily observable for this star since it is too cool for the bound-free opacities from excited levels to be important.

In conclusion, a wealth of information is potentially available and exploitable from further observations of this star's Hα intensity profile and linear and circular polarization profiles. From more refined observations a good picture of the surface field geometry should be obtainable. It is also interesting in a more general sense that one of the very coolest of the large sample of DA white Dwarfs is now one of only two known magnetic DA (or DAP) stars.

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J. R. P. Angel: Steward Observatory, University of Arizona, Tucson, AZ 85721

J. D. Landstreet: Department of Astronomy, University of Western Ontario, London, Ontario, Canada N6A 5B9

James Liebert: Department of Astronomy, University of California, Berkeley, CA 94720