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THE STRONG MAGNETIC FIELD IN G227−35

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ABSTRACT

Circular spectropolarimetry of the white dwarf G227−35 shows a prominent feature near 7450 Å, with a Stokes parameter jump $\Delta V = +0.05$. We identify this with the stationary point in the 2*p*-1–3*d*-2 transition of Hα, which has been calculated to be 7449.4 Å in a magnetic field of 117 MG. Other components of Hα also are seen. A crude model which can explain the observations is a centered dipole seen close to pole-on, with a polar field strength of about 130 MG.

Subject headings: polarization — stars: individual (G227−35) — stars: magnetic fields — white dwarfs

1. INTRODUCTION

Nine white dwarfs are now known or suspected of having surface magnetic fields in excess of 100 MG (Schmidt 1988). These fields can be identified through their strong continuum polarization, as was done for G227−35 by Angel, Hintzen, & Landstreet (1975), but they are more precisely identified by measuring the wavelengths of the magnetically shifted components of the hydrogen lines. Above about 10 MG the wavelength shifts are not well-described by the linear and quadratic Zeeman effects, and each of the 15 components of Hα, for example, has its own $\lambda(B)$ curve. Figure 1*c* shows these curves for some of the components of Hα and Hβ; calculations for the curves have been made by Henry & O'Connell (1985) and, more completely, by the Tübingen group (e.g., Wunner et al. 1985).

Note that some of the curves in Figure 1*c* have extrema, which we shall call "stationary points." At a stationary point the wavelength is roughly constant for a range of magnetic field strengths, and a feature might appear at that wavelength in a stellar spectrum if a reasonable fraction of the surface area contains fields in that range. A measurement of field strength in this way was first accomplished by Greenstein (1984) who identified the 1*s*0–2*p*-1 component of Lyα in Grw +70°8247; since then, other lines have also been identified in this star (Wunner et al. 1985; Angel, Liebert, & Stockman 1985; Wickramasinghe & Ferrario 1988). The result of these studies is that Grw +70°8247 has a magnetic field which can be approximated by a centered dipole with a polar strength of 320 MG.

The star PG 1031+234 has also been studied in this way. This star rotates, so that extra constraints are available. A centered dipole will not work, but a reasonable fit to the surface field can be made with two or three components (Schmidt et al. 1986; Latter, Schmidt, & Green 1987; Östreicher et al. 1992). The peak surface field is close to 1000 MG.

In this *Letter* we add G227−35 to this small list of stars whose magnetic field has been determined with stationary points. G227−35 is a white dwarf with $T = 7000$ K; $m_v = 16.0$. Angel et al. (1975) observed it in 1974 using low-resolution circular polarimetry. They found a polarization peak near 4500 Å with $V \sim -3.5\%$, a minimum of $\sim -1\%$ near 5500 Å, and a strong rise to the red. West (1989) gives data taken in 1986–1988 with similar resolution, but lower noise. His data agree with those of Angel et al. up to 8000 Å. Angel et al. suggested that the high circular polarization might result from dichroic opacity in a field of 30 MG or more, and if cyclotron absorption had a role then the field would be about 100 MG. By using circular spectropolarimetry, we find that the field may roughly be approximated as a centered dipole with a polar strength of about 130 MG.

2. OBSERVATIONS

Observations of a number of magnetic white dwarf stars were made on the nights of UT 1992 August 23, 24, 25, with the 5 m Hale telescope at Palomar Observatory. The polarimeter described by Goodrich (1991) was used in the Cassegrain double spectrograph (Oke & Gunn 1982), with a dichroic reflector at 5500 Å and gratings of 158 g mm^{-1} in the red and 300 g mm^{-1} in the blue. The slit width was 2″. Spectrum extractions from the CCDs were made using VISTA, and corrections for atmospheric oxygen and water absorption were made using tables provided by Charles Lawrence. The flux standards were variously BD +40°4032, Feige 15, and Hiltner 102.

Circular polarization was measured on the first two nights, and linear polarization on the third. The linear measurements used the procedure described by Goodrich (1991). Our circular polarimetry uses a rotatable quarter-wave plate, followed by a calcite prism which separates orthogonal linearly polarized components, which then are imaged on the CCD detectors. The measurement is made by taking two exposures, with the fast axis of the wave plate at 45° and then 135° to the beamsplitter planes. This gives the two circular components with enough redundancy that the different throughputs can be calibrated.

We observed G227−35 each night. The total exposures were 30, 50, and 48 minutes on nights 1, 2, and 3, respectively. Figure 1 shows the total flux F_λ and the normalized Stokes parameter V. The V plot agrees very well with those published by Angel et al. (1975) and by West (1989). We saw no significant difference in V between nights 1 and 2, and there are none over 5, 13, and 18 year intervals. Also, there are no significant differences in linear polarization between West's data and ours. This adds to the lack of evidence for rotation (West 1989). It is likely that any rotation period in G227−35 is substantially greater than 18 yr, unless the magnetic and rotation axes are nearly the same, and the field is rotationally symmetric.

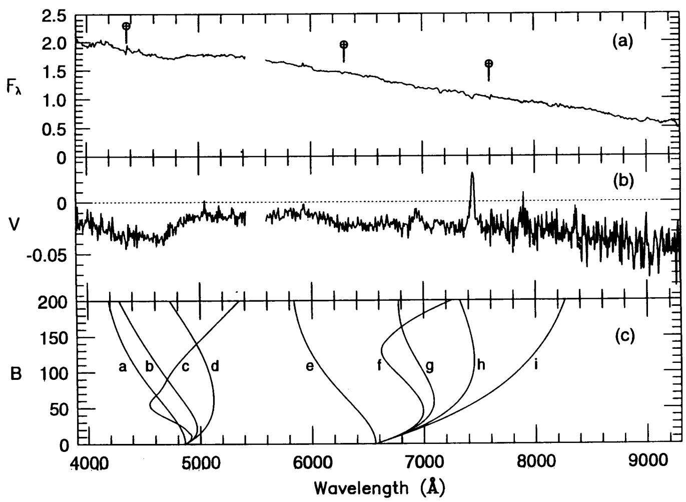

FIG. 1.—(*a*) F_λ vs. λ for G227−35, night 3. Some atmospheric and night sky features are marked. (*b*) Normalized stokes parameter *V* vs. λ. (*c*) Wavelength vs. magnetic field in MG for some of the components of Hα and Hβ, taken from tables in Wunner et al. (1985): (a) 2*s*0–4*f*0, (b) 2*p*0–4*d*-1, (c) 2*p*1–4*s*0, (d) 2*s*0–4*f*-1, (e) 2*s*0–3*p*0, (f) 2*p*1–3*s*0, (g) 2*s*0–3*p*-1, (h) 2*p*-1–3*d*-2, (*h*) 2*p*0–3*d*-1.

The prominent feature in *V* near 7450 Å is shown expanded in Figure 2 where the bins are 6.1 Å wide. An expanded view is shown in Figure 2, where the bins are 6.1 Å wide. A reference line has been drawn at $V = -0.024$, the mean between 6700 and 7700 Å, with 6875–7025 Å and 7350–7530 Å excluded. The red wing of the line is roughly a half-Gaussian with a measured peak close to 7450 Å and a width of about 12 Å, which is about half the instrumental broadening. Thus the red wing is consistent with an intrinsic sharp edge at 7450 ± 3 Å. This is in excellent agreement with the calculated stationary point of the 2*p*-1–3*d*-2 component of Hα, 7449.4 Å, which occurs at 117 MG (Wunner et al. 1985), and can be seen in Figure 1*c*. Further confirmation of the identification is seen in the extended blue wing, which is expected because the stationary point is a maximum in wavelength. The wing extends to about 7400 Å, which corresponds to fields from about 80 to 160 MG. This 2*p*-1–3*d*-2 transition has also been seen in Grw+70°8247; see Figure 3 of Angel et al. (1985), and the discussion by Wunner et al. (1985).

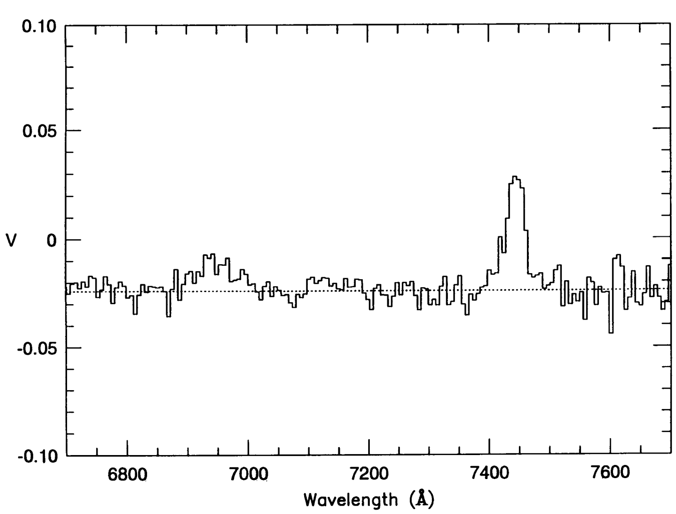

FIG. 2.—Expanded view of Fig. 1*b*

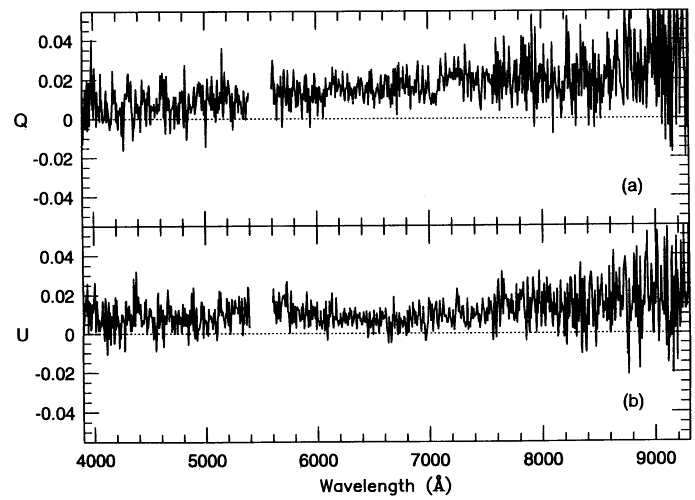

FIG. 3.—Normalized Stokes Parameters (*a*) *Q* and (*b*) *U* vs. λ

The total flux (Fig. 1*a*) shows a real if inconspicuous absorption feature at 7450 Å. It is clear that circular polarization gives a powerful advantage in the detection of this feature. The linear polarization is weak and noisy and to avoid a large bias we show *Q* and *U* separately in Figure 3. The parameter *Q* shows a barely significant jump at 7450 Å and *U* shows nothing; in any event any change in linear polarization is much smaller than that in circular polarization. We attribute this to a wide variation in the position angles of the transverse magnetic field over the visible hemisphere.

3. OTHER LINES

Figure 1*c* shows the components of Hα and Hβ which have stationary points between 20 and 200 MG, or are changing slowly. Curves c, d, f, and g show stationary points at about 4549, 5120, 6993, and 7088 Å in fields of strength 56, 61, 46, and 60 MG, respectively. The spectra (Figs. 1 and 2) contain no sharp features at any of these wavelengths, and so it is unlikely that the surface field becomes as weak as 60 MG. Similarly, the spectra do not show prominent features at 6643 or 6774 Å, the stationary wavelengths for curves f and g in magnetic fields of 140 and 200 MG, respectively. It thus is unlikely that any substantial region of the stellar surface contains fields as strong as 140 MG.

Even if the range of field strengths does not extend to the stationary points, shallow absorption lines should appear at wavelengths where the curves change slowly. A broad weak positive feature in *V* extending from about 6900 to 7000 Å can be seen in Figures 1*b* and 2; this corresponds to about 130–100 MG in the 2*s*0–3*p*-1 component. Its dipole strength is weaker than that for the 2*p*-1–3*d*-2 component (Wunner et al. 1985) and its strength in Figure 2 is correspondingly less. Note, however, that the dipole strengths can change rapidly near a stationary point, and detailed calculations are necessary to obtain accurate ratios. The 2*p*1–3*s*0 component has a yet smaller dipole strength but perhaps should show up at 6670–6750 Å. Indeed *V* shows a shallow positive bump near 6700 Å, but its significance is low. The noisy peak in *V* near 7900 Å corresponds to about 100–120 MG in the 2*p*0–3*d*-1 component. These σ_- components of Hα all show up with the same sign and roughly correct relative amplitudes and help confirm that the field strength is of order 100 MG over a substantial part of the visible hemisphere.

The Hβ σ_- component 2s0–4f-1 is slowly moving near 100 MG, and is probably responsible for the weak features seen in F_λ and V near 5050 Å. Curves a and e in Figure 1c are π components and should have an effect on linear polarization, but only a small effect on circular polarization. However, in Figure 3 the effects are very small, both for the π components and the σ_- component 2p-1–3d-2. This suggests that the dipole is tipped substantially from the plane of the sky, so that the orientations are mixed and the linear polarization reduced.

4. DISCUSSION

4.1. *A Dipole Model*

We seek a simple model for a magnetic field in the photosphere with $60 < B < 140$ MG, and with a substantial fraction of the surface having B on the order of 80–120 MG. Consider then a centered dipole with a polar field strength of 130 MG, viewed pole-on. The longitudinal component of magnetic field will go to zero and then reverse sign at a colatitude of 54°.7, where the field strength is 92 MG; 67% of the visible disk is inside this 92 MG circle. The 7450 Å feature in Figure 2, with $\Delta V > 0$, corresponds moderately well to this model. In addition, the equatorial region, containing field strengths between 92 and 65 MG, should be responsible for a weak feature with $\Delta V < 0$, between 7430 Å and 7340 Å. A region with $\Delta V < 0$ does exist on the blue side of the main line; the wavelength range is rather smaller than predicted but the signal-to-noise ratio is low. Furthermore, its reality depends on exactly how the baseline is drawn. A longer exposure might help to verify its existence.

This model also predicts a region with $\Delta V < 0$ on the red side of the 6900–7000 Å feature, caused by equatorial absorption of the 2s0–3p-1 component. This negative region should run roughly from 7020 to 7080 Å, a noisy negative region is seen, but it is of low significance.

In fact, the pole-on aspect is not necessary and only a detailed model calculation could find the best-fitting angle.

4.2. *Continuum Polarization*

West (1989) discusses three possible sources of opacity which can produce continuum polarization: photoionization of hydrogen atoms, cyclotron absorption, and magneto-bremsstrahlung. The latter two involve plasma processes whereas the first involves somewhat unknown atomic physics in intermediate fields (100–1000 MG). Schmidt et al. (1986) showed that a simple application of magneto-ionic theory gives the correct qualitative picture of the continuum polarization in PG 1031+234, and this procedure is substantiated, in part, by semi-empirical modeling of the star by Latter et al. (1987) and Östreicher et al. (1992). West made a similar analysis for Grw +70°8247. It appears then that the simple cold plasma picture can correctly, if qualitatively, predict the run of polarization in these stars, and we assume that it works for G227−35 also.

A surface field strength of 90–130 MG gives cyclotron frequencies (ω_c) corresponding to 1.2–0.8 μm. It thus is likely that differential absorption in the magneto-ionic modes is important. The modes are circular for $\omega/\omega_c \gg 1$ except for propagation directions in a narrow fan around 90°, and are linear for $\omega/\omega_c \ll 1$ except in a narrow cone around 0°. (See, e.g., the discussion by Schmidt et al. 1986.) In our wavelength range the modes will be close to circles except for small regions where the field is close to transverse.

The magnitude of the continuum circular polarization, 1%–4%, is consistent with typical values for strong-field white dwarfs (Schmidt 1988). Both circular and linear polarization increase to the red, as expected as the cyclotron frequency is approached. The linear polarization should be weakened by the suggested near pole-on aspect, which gives a full assortment of position angles for the projected magnetic field.

We see in Figure 1b that the sign of V in the continuum is opposite to that of ΔV for a σ_- absorption line. This is readily explained with our assumption of magneto-ionic theory in a cold plasma. Consider first the continuum polarization. In a quasi-longitudinal field the extraordinary mode is more closely coupled to the rotation of the electrons than is the ordinary mode, and has the higher absorption coefficient. The ordinary mode therefore comes from a deeper and hotter region, and gives its polarization to the emergent radiation. It rotates against the electrons, and since we receive left-hand radiation ($V < 0$), the longitudinal component of magnetic field is predominantly pointing into the star.

In a longitudinal field the σ_- photons are polarized against the rotation of the electrons, i.e., they have the same polarization as the ordinary magneto-ionic mode. The extra opacity of the Hα σ_- transitions lifts the $\tau = 1$ surface of the ordinary mode, decreasing its strength relative to the extraordinary mode, and the net polarization is reduced. Indeed, in Figure 1b V goes positive in the line; this means that the line opacity is so great that the $\tau = 1$ surface for the ordinary mode is lifted above that for the extraordinary mode.

This is only a primitive picture, of course, since the field has a varying orientation over the star, and a detailed calculation would have to involve an integration over the visible hemisphere. Östreicher et al. (1992) give a discussion similar to this for the π components seen in PG 1031+234 and Grw +70°8247.

5. CONCLUSIONS

1. We identify the strong 7450 Å feature in V with the stationary point in the 2p-1–3d-2 component of Hα, in a magnetic field of strength 117 MG. Four of the five σ_- components of Hα can be seen in V.

2. Circular polarization provides a powerful advantage over the total flux in the identification of this line.

3. The magnetic field on G227−35 can be crudely modeled as a centered dipole with a polar field of about 130 MG. This could provide a starting model for detailed calculations.

4. We confirm the general run of continuum polarization as determined by Angel et al. in 1974 and by West in 1986–1988. It is likely that the rotational period of G227−35 is substantially longer than 18 yr, unless the magnetic field is symmetric, and the rotation and magnetic axes are nearly coincident.

5. A simple application of magneto-ionic theory is consistent with the observation that, for a σ_- line, the sign of ΔV is opposite to the sign of V in the neighboring continuum.

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