THE ASTROPHYSICAL JOURNAL, 289:L25–L29, 1985 February 15

FURTHER IDENTIFICATIONS OF HYDROGEN IN Grw +70°8247

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Received 1984 September 14; accepted 1984 November 14

ABSTRACT

Numerous spectra of the magnetic white dwarf Grw +70°8247 were obtained with the double CCD spectrograph at Palomar with signal-to-noise ratio above 100. Five weak absorptions in the blue and four in the red are produced by hydrogen in a strong magnetic field. We compute new, precise, multiparameter, variational energy levels yielding intensity and wavelength, from 100 to 600 MG. We search for those Zeeman components with wavelengths nearly constant with field. Two such, which are relatively sharp and strong π transitions, explain the Minkowski band, 4137 Å (known since 1938), as the $2s0$–$4f0$ and the 5855 Å band as the $2s0$–$3p0$. Both have minimum wavelengths at $B \approx 300$ MG. Their absorptions resemble band heads degraded to the red, as observed. The mixed nature of the $4f0$ level results in an intensity ratio $(2s0–4f0)/(2s0–3p0) = 0.58$ at 280 MG, high for a line *forbidden* at zero field. Profiles computed for a pole-on dipole, near $\log B_p = 8.5$, fit the two observed lines. Other hydrogen transitions (including the core of Lyα) are consistent with that field strength. Six models with a variety of B_p and inclination are illustrated to show the quality of fit to the observations.

Subject headings: stars: individual — stars: magnetic — stars: white dwarfs — Zeeman effect

I. INTRODUCTION

Minkowski (1938) discovered unidentifiable, shallow, broad absorption features in the white dwarf Grw +70°8247 (G260−15, EG 129, 1900+70), type DXP5; with at least six found later, these have remained puzzling. The star was the first in which linear and circular polarization was detected, establishing a strong magnetic field (Kemp *et al.* 1970). Greenstein (1984) observed an absorption core at 1347 Å with the *IUE*, identifying it as $1s0$–$2p-1$ of hydrogen Lyα at fields $200 \le B \le 400$ megagauss (MG). Henry and O'Connell (1984*a*) computed hydrogen energy levels which gave this σ_- transition a maximum wavelength of 1342.6 Å at $B \approx 500$ MG. Rösner *et al.* (1984) and Forster *et al.* (1984) give intensities and wavelengths, with 1343 Å as the maximum wavelength. The 4 Å shift of the observed sharp core is probably observational error. Angel, Liebert, and Stockman (1985) note problems in understanding Lyα as the core alone. The core seen with *IUE* lies within an optically thick, Zeeman-split Lyα. Pressure and quadratic Stark effect further broaden each of the already magnetically broadened and shifted Zeeman components. A low enough collisional rate at small optical depth, τ, in the continuum may then produce a sharp 1343 Å core on broad absorption having the same magnetic shift. One of us (J. L. G.) is preparing such models of Lyα.

Angel (1978, 1979) illustrated and reviewed the absorption features and polarization in degenerate stars, suggesting that bandlike features with "heads" could arise in hydrogen if $B \ge 200$ MG. The dependence of energy levels on B could be such that $\lambda(B)$ was nearly constant. Such constancy was conjectured from a few early computations by Praddaude (1972). Greenstein (1984) interpolated in early computations of Lyα by the Louisiana State University (LSU) group (Smith *et al.* 1972, etc.). But only few lines remain genuinely stationary, in Angel's sense; see also Forster *et al.* (1984) and Rösner *et al.* (1984). Figure 2 shows how complex a "quasi-stationary" transition is, with wavelengths based on recent growth of the LSU and Tübingen computational programs. The $\lambda(B)$ for Lyα and three Balmer lines are now known over a wide range. Generalizations prove difficult, and detailed quantum-mechanical computations are essential. At LSU we searched for those transitions producing lines where known absorptions existed, in the range $100 \le B \le 600$ MG. With about 50 transitions, chance coincidences in wavelength may occur. However, a useful constraint arises from the fact that we must not assume a star to have only a single B. The field must be allowed to have an appreciable range.

To delimit the problem we model hydrogen Zeeman components in a magnetic dipole. Their visibility, if $\lambda(B)$ rapidly varies, increases inversely with $d\lambda/dB$. When $d\lambda/dB$ changes sign, as in Figures 2 and 3, bandlike absorption occurs on an unresolved background of the many, rapidly shifting lines. The mean strength $df/d\nu$ of all bound-bound transitions in a strong field equals the opacity in the Balmer continuum. The blurring effect of a dipole field on relatively stationary lines is shown in Figures 4 and 5.

The low-field classification of transitions is useful. With $\Delta m = 0$, some π components may be quasi-stationary for a range of B; the $\Delta m = -1$, σ_- components, reach maximum wavelength and turn back; the $\Delta m = +1$, σ_+, move rapidly to the violet. At $B \geq 2000$ MG, Rösner *et al.* (1984) find all components shifting into the ultraviolet. We concentrate here on the detailed identification and representation of two of the best defined and observed lines as two π components of hydrogen. The 4135 Å Minkowski band is forbidden at zero field but is the strongest component of Hβ, $2s0$–$4f0$; the 5855 Å band (found by Wegner 1971) is the strongest component of Hα, $2s0$–$3p0$.

II. OBSERVATIONAL DATA AND ANALYSIS IN THE BLUE REGION

Means in five good Palomar photographic spectra of 1 Å and 4 Å resolution are shown by Greenstein and Matthews (1957), 3400–4700 Å. Five broad lines had peak wavelengths 3425, 3650, 3910, 4135, and 4475 Å. We took two excellent Palomar CCD spectra in 1982, 6 Å resolution. Each averages 10^4 counts per pixel, signal-to-noise ratio of 100. At the 1% level, the (OB − AB) calibration for that night introduced a long-period waviness in the ABs. We therefore display a "ratio spectrum," i.e., the flux in EG 129 divided by that in G225−68 (EG 258, 1632+57) as observed the same night. Each mean of two spectra was smoothed over 3 pixels, or 12 Å. EG 258 is a cool, weak-lined C_2 white dwarf, type DQ8, with $T \approx 6000$ K; EG 129 has $T \approx 12{,}000$ K. The ratio, EG 129/EG 258, rises by 4 from red to violet. Taking ratios has eliminated the "waves" in the original ABs. We see, with better signal-to-noise ratio, the same features as in the 1957 spectrum. The wavelengths of absorption peaks (in Å), with approximate limits for each absorption are 3670 [3631–3709]; 3885 [3833–3932]; 4137 [4091–4245]; 4310 [4280–4345]; and 4488 [4419–4560]. The 4310 Å feature is new; 3425 Å is outside the present region. The spectrum appears to be constant on time scales of both 15 minutes and 40 yr. Lick spectra by Liebert, which are illustrated in Angel (1978), also match, confirming the reality of the 4310 Å dip. Figure 1 illustrates the ratio spectrum of EG 129 from the blue CCD camera.

III. COMPUTATION OF THE RELEVANT ENERGY LEVELS

We use an accurate multiparameter variational approach described in our original work (Smith *et al.* 1972), now including the correction due to the finite proton mass. O'Connell (1979) displays in equation (7) the basic Hamiltonian used. We use 17 Slater orbitals for each l, and values of l up to 23. The computational accuracy assures convergence of the eigenvalues to five significant figures. We retain the labeling by the quantum numbers of the energy levels at zero magnetic field, nlm. Thus, $4f0$ is an odd-parity state with $m = 0$ and l components $1, 3, 5 \ldots$ which for $B = 0$ simply has $n = 4$, $l = 3$.

Figures 2 and 3 show the $\lambda(B)$ from our calculations for the two important π components of Hβ and Hα; plotted are results by Forster *et al.* (1984), which agree well. We calculate the transition probabilities, with techniques outlined in Smith *et al.* (1973). Those to $4f0$, the first ever published, are a significant part of our analysis. The $2s0$–$4f0$ transition of Hβ violates the $\Delta l = \pm 1$ selection rule and is *forbidden* at $B = 0$. The mixed nature of $4f0$ makes it predominantly $l = 1$ at high field. At 280 MG, $2s0$–$4f0$ and $2s0$–$3p0$ are at 4127.6 Å and 5852.3 Å and have oscillator strengths 0.144 and 0.709. The energies absorbed by these components of Hβ and Hα have ratio 0.58. Typical hydrogen white dwarfs with $B \approx 10$ MG have not yet shown 4137 Å; Grw +70°8247 may remain unique unless fields above 150 MG are found.

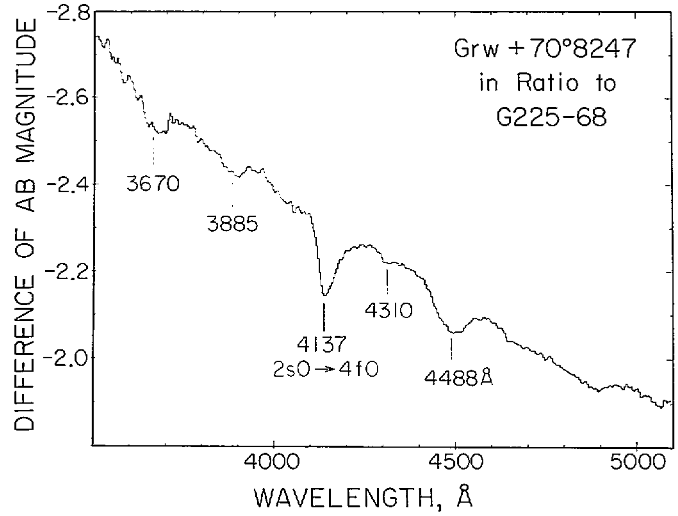

FIG. 1.—Broad, shallow lines of Grw +70°8247 are displayed; the vertical axis is the magnitude difference from a cooler, nearly DC, white dwarf (G225−68). The slope arises from the 6000 K temperature difference. Data are means of two spectra smoothed over three pixels (i.e., 12 Å).

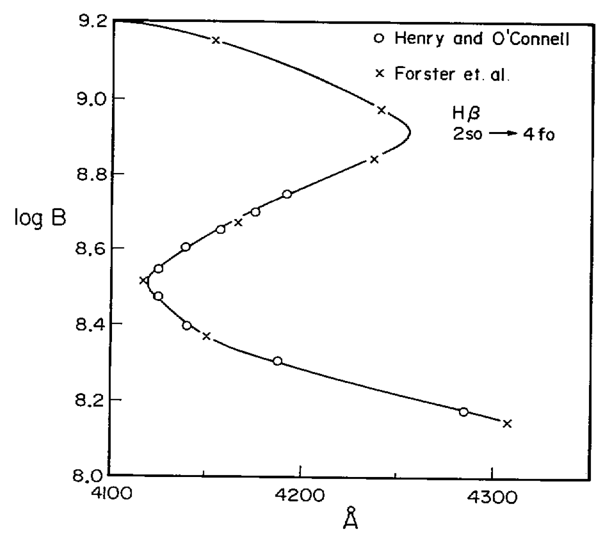

FIG. 2.—Theoretical wavelengths of the $2s0$–$4f0$ component of Hβ in a magnetic field (*circles*, our new results; *crosses*, Forster *et al.* 1984). A line, degraded to the red, can occur only at $\lambda \geq 4125$ Å, which is the minimum wavelength, attained near 320 MG. At $B = 280$ MG, this transition, forbidden at zero field, carries much of the strength of Hβ.

IV. SOME EFFECTS OF FIELD GEOMETRY ON 4137 Å

Greenstein and McCarthy (1985) studied an emission-line magnetic white dwarf GD 356 (Gr 329, 1639+73), type DC7EH, with field $11 \leq B \leq 25$ MG. A computer program manipulates wavelengths and intensities of all Zeeman compo-

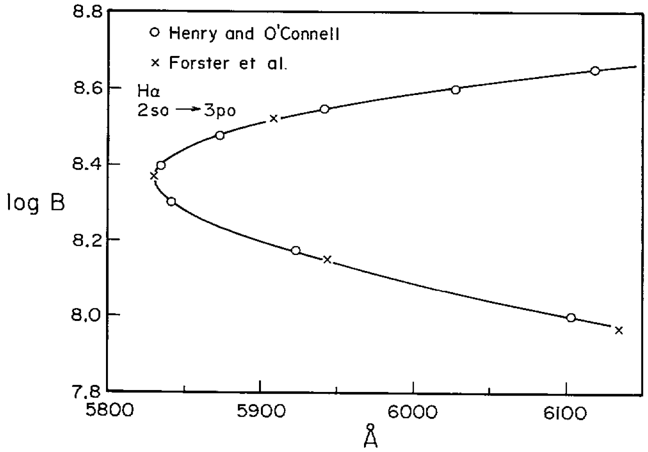

FIG. 3.—Theoretical wavelengths of the $2s0$–$3p0$ component of Hα (*circles*, our new results; *crosses*, Forster *et al.* 1984). The sharply defined minimum wavelength, 5825 Å, near 240 MG, will produce a line degraded to the red.

nents in a magnetic field. These need to be computed and tabulated for high fields from our new results. With geometry specified, each component's properly shifted contribution is evaluated over the visible hemisphere (for a thin shell) or in an extended volume. Since Figures 2 and 3 show that B cannot vary by a large factor, we exclude large radial variation. Our thin-shell dipole models are then specified by the density of hydrogen atoms in an homogeneous layer of fixed thickness and temperature; the polar field, B_p; its inclination to the line of sight α; and the limb darkening, e. We neglect polarization effects. We also explored a purely descriptive model with a mean B_0 and a Gaussian dispersion, σ. Figure 2 shows the computed wavelengths, reaching (at $\log B = 8.5$) 4125 Å, the shortest wavelength where $2s0$–$4f0$ could peak. It would shade toward long wavelengths, with a width dependent on the maximum field; $200 \leq B \leq 500$ MG seems possible. In a dipole, $0.5B_p \leq B \leq B_p$; Gaussian models produce similar profiles, with the effective $B_0 \approx 0.9\ B_p$. All lines are shallow and prove to be optically thin, because of magnetic broadening; on the average a dipole broadens the line about 100 Å. Even with 19 latitude zones the line, in each, is magnetically broadened by an internal $\Delta\lambda(B)$. To allow for the 12 Å smoothing (18 Å in the red) and for pressure broadening, we adopt a standard Gaussian line profile, with 25 Å full width at half-maximum.

The computational procedure to obtain results shown in Figures 4 and 5 is lengthy. We integrate over all magnetic latitudes to obtain the effective $\tau(\lambda)$. We use the Minnaert interpolation formula, in a Schuster-Schwarzschild atmosphere, as the relation between τ and line depth. Infinite τ is assumed to produce central absorption of 0.5. The calculated absorption is superposed on a continuum spline (shown dashed) which fits apparently line-free parts of the observed spectrum. The smooth curve is the final theoretical profile. We overplot the observed spectrum (the jagged line) for comparison. With parameters fixed for the correct line strength, we vary B_p, starting with the pole-on dipoles. In Figure 4 a predicted spectrum, $\log B_p = 8.42$, $\alpha = 0°$, 15,000 K and 10^{20} hydrogen atoms cm^{-2} fits the observed ratio spectrum well. Retaining column density, other models with similar B_p, α, e also fit, as does a Gaussian distribution with $\log B_0 \approx 8.45$. The asymmetry and the peak wavelength of the line varies rapidly with α, with increased α demanding increased B_p. Models with extreme (B, α) have wrong asymmetry, double or too strongly winged lines. The symmetry of $\lambda(B)$ in Figure 2 results in $\log B_p = 8.7$, $\alpha = 30°$ giving a correct peak wavelength, but, from the tilted field, extended wings. Determining the best field and geometry will require simultaneous interpretation of all lines profiles, and their polarization.

V. THE RED REGION AND THE 5855 Å FEATURE

The red CCD of the Palomar double spectrograph gives even better signal than the blue, from 5100 to 9800 Å. The flux-ratio spectrum (EG 129/EG 258), defined from the difference of the ABs shows at least four dominant absorptions. One, the relatively sharp 5855 Å, is like 4137 Å, degraded toward the red. Two quite diffuse features prove to involve three σ_- components of Hα, 7500 Å (which is double) and 8500 Å (which is surprisingly stationary). We limit ourselves here to 5855 Å. Inspection of Figure 3 shows a minimum wavelength of 5830 Å at $\log B = 8.37$. This shifts to 5900 Å by $\log B = 8.20$ or 8.52. Observations and computed profiles for three pole-on dipoles are in Figure 5. Tilting brings a larger near-equatorial area of low field into view; the winged profile for $\log B_p = 8.57$, $\alpha = 45°$ is nearly double. Large field, $\log B_p = 8.74$, $\alpha = 60°$, is unsatisfactory, with the high polar field contributing extended redshifted wings which would be lost in the noise. The interpretation of 5855 Å runs quite parallel to that of 4137 Å. Its isolated location is favorable for analysis of its polarization. Angel (1978, p. 502) displays wavelength-dependent polarization as more conspicuous than his absorption profile. Note the small central absorption and low noise in our new profiles. Observation of these shallow lines is made possible only by the excellent quality of Oke's double spectrograph.

VI. CRITIQUE AND CONCLUSIONS

When we require the magnetic field to be a pole-on dipole, these two π components suggest somewhat different fields, 280 and 320 MG. Computational effects may be partly responsible. We still lack a sufficiently fine grid of wavelengths and intensities within which to interpolate. The radiation transfer theory used is elementary, assumes fixed limb darkening, and neglects effects of polarization in radiative transfer. But in spite of our simplifications, the symmetry and placement of the $\lambda(B)$ curves insure that these two π components of Hα and Hβ are represented in a dipole field $8.42 \leq B_p \leq 8.52$ for the pole-on case. With twice those B_p, poorer fits exist at large α. We here prefer to assume the magnetic and rotation axes coaligned and in the line of sight, which avoids periodic spectral variation.

Other components of Hα and Hβ are shallower, less well defined by the observations, or have less sharply peaked $\lambda(B)$ curves. Henry and O'Connell (1984*b*) are extending their quantum-mechanical computation. Some observed lines are

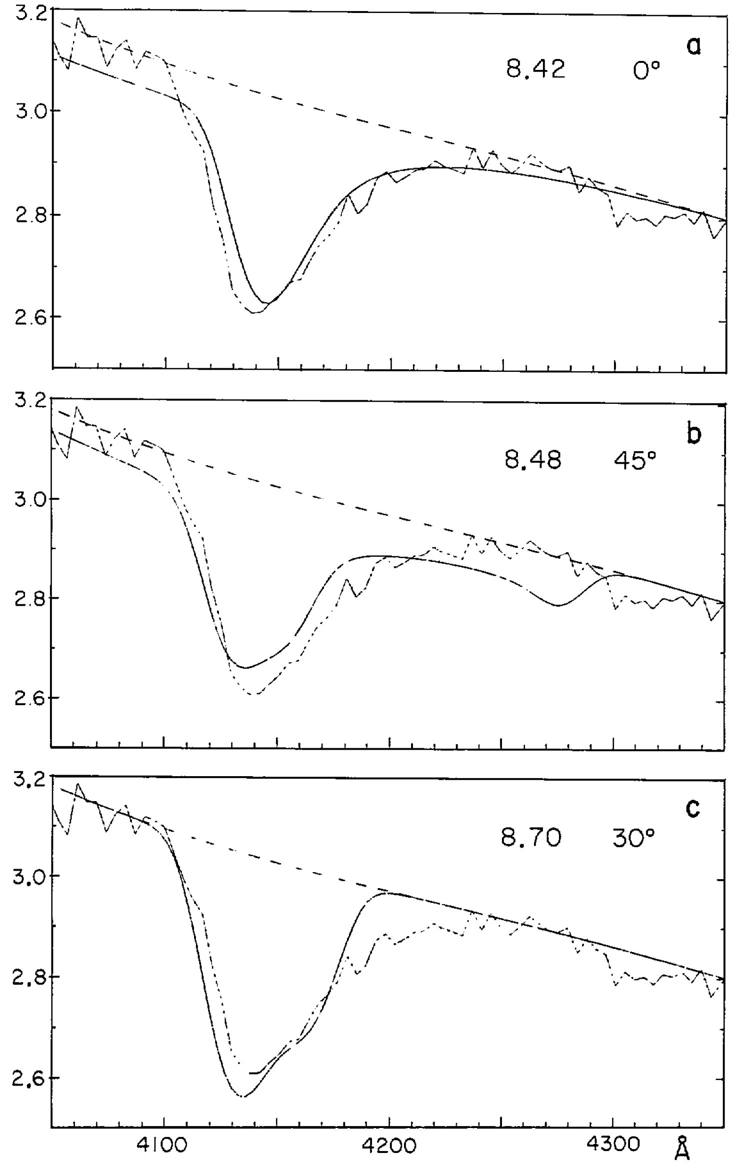

FIG. 4.—The predicted structure of the $2s0$–$4f0$ transition of Hβ has its blurred Zeeman absorption pattern (*solid curve*) superposed on a spline fitting the apparent continuum (*dashed curve*) of the ratio spectrum of Fig. 1. The data (*jagged curve*) are flux ratios, Grw +70°8247 divided by G225−68 (EG 258), with an arbitrary vertical scale correction. (*a*) The predicted profile in a pole-on, dipole magnetic field, with log B_p = 8.42, fits the observations well. (*b*) A larger field at tilt of 45° gives about the same peak wavelength, but shows an extended wing. (*c*) A very large tilted field gives a possible, if implausible, fit.

σ_- components near stationary points, supporting the present value, $B_p \approx 300$ MG. We conclude that not only are our two strong, relatively sharp absorption lines in Grw +70°8247 hydrogen in a magnetic dipole, but so are *all* observed features. (See also Angel, Liebert, and Stockman 1985). With a difficult, but theoretically plausible reinterpretation of Lyα, the long unidentified, mysterious lines come from the simplest element, hydrogen. But no two magnetic degenerates with very high field (if they exist) need look alike.

J. L. G. expresses his indebtedness to James K. McCarthy for continued development of the computational program, and to the National Science Foundation for support under grant AST 83-05504. The research of R. J. W. H. was partially supported by the National Aeronautics and Space Administration, Laboratory Astrophysics Program, under grant NASW-481, and that of R. F. O'C. by the Department of Energy, Division of Material Sciences, under grant DE-FG05-84ER45135.

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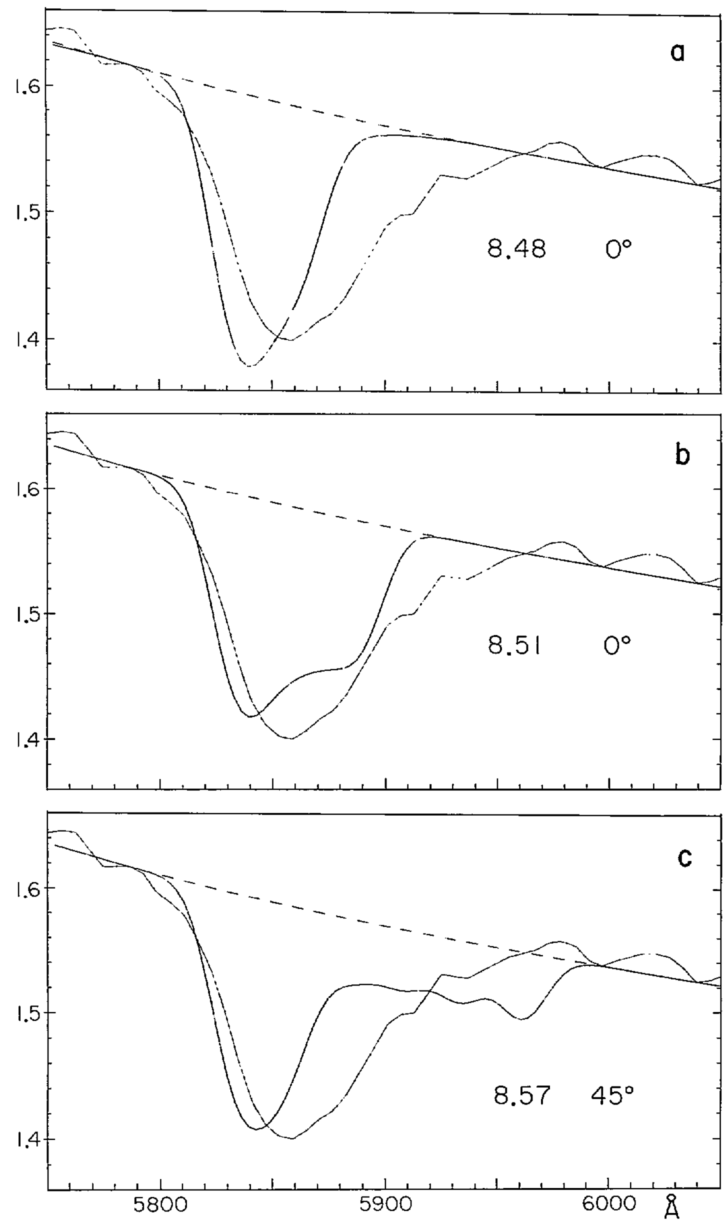

FIG. 5.—This transition is $2s0$–$3p0$ of Hα; symbols as in Fig. 4. (*a*) The ratio spectrum fits a pole-on dipole, log B_p = 8.48, moderately well. (*b*) The theoretical curve for the pole-on dipole, log B_p = 8.51, is a better fit. (*c*) For a tilted larger field, log B_p = 8.57, α = 45°, the increased area of low field visible near the equator contributes excessive wings.

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