THE ASTROPHYSICAL JOURNAL, 348:242–252, 1990 January 1

THE DISCOVERY OF MAGNETICALLY CONTROLLED CIRCUMSTELLAR MATTER IN THE HELIUM-WEAK STARS HD 5737 AND HD 79158

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Received 1989 February 8; accepted 1989 June 21

ABSTRACT

We report the discovery, using combined *IUE* spectroscopy and Zeeman polarimetric magnetic field measurements, of magnetically controlled circumstellar material in two helium-weak stars. HD 5737 = α Sculptoris is, except for its extreme helium deficiency, similar to the He weak sn star HD 21699. We report a unique period for the magnetic and C IV and Si IV variations of 21.65 days. The effective (longitudinal) field nulls coincide extremely well with C IV line strength maxima. The magnetic field and equatorial trapped plasma are highly oblique to the rotation axis (about 70°), and the line variations appear to be stable. We have discovered similar magnetospheric variations in HD 79158 = 36 Lyncis, for which no period had been previously available. The period is 3.84 days, yet it too displays magnetic-equatorial plasma. The magnetospheric axis is highly oblique to the rotation axis, around 80°.

Subject headings: stars: individual (HD 5737, HD 79158) — stars: magnetic — stars: peculiar A — ultraviolet: spectra

I. INTRODUCTION

The first detections of magnetically controlled mass loss from main-sequence stars were among the helium-strong B stars (Shore and Adelman 1981; Barker *et al.* 1982). Yet this class of magnetic stars is not an ideal population in which to study the physics of the upper main-sequence magnetospheres and winds. They span a narrow range in effective temperature, $17{,}000 \leq T_{\rm eff} \leq 25{,}000$ K (Walborn 1983), and a narrow range of magnetic field strengths ($B_{\rm eff,\,max} \approx 2$–3 kG (Bohlender *et al.* 1987). In contrast, the fact that the helium-weak B stars span a relatively wide range in each of these critical parameters makes them excellent candidates for the study of magnetospheric and wind phenometers in magnetic stars.

In two previous studies (Brown, Shore, and Sonneborn 1985; Shore, Brown, and Sonneborn 1987, hereafter SBS87), we reported the discoveries of the magnetically controlled stellar wind of HD 21699 and of similar ultraviolet resonance line variations in two other so-called sn stars (Abt 1979), HD 5737 and HD 79158, for which the rotation periods were then poorly determined. In this paper, we report further observations of the latter two stars which allow the determination of their rotation periods and a complete description of their UV spectral phenomenology. As will emerge from the following discussion, the configurations of the circumstellar plasma among the magnetic helium weak sn stars are more varied, and their dynamics more subtle, than we had anticipated.

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Following the first reports of C IV λ1550 and Si IV λ1400 variability in the helium-strong stars by Shore and Adelman (1981), Barker *et al.* (1982) showed that there is a correlation for these stars between magnetic field and C IV line strength variations. Specifically, stars with highly oblique magnetic fields, which showed large effective (longitudinal) magnetic field variations also showed large C IV amplitudes and always displayed strong absorption profiles. C IV is observed in emission in those stars with little or no magnetic variability.

At the time of these papers, a small data base hampered the precise discussion of both the magnetic and spectral variations. Subsequent *IUE* observations (see, e.g., Shore *et al.* 1984) now allow us to extend the descriptions of the behavior of stellar winds and magnetospheres through the entire class of main-sequence helium peculiar stars to the classical Ap stars. This is the purpose of the present study.

II. OBSERVATIONAL DETAILS

The ultraviolet spectra discussed in this study were obtained between 1983 and 1987 using the *International Ultraviolet Explorer* (*IUE*) *Satellite* in the short-wavelength primary camera (SWP) at high dispersion with the large aperture. These have been supplemented by small-aperture archival observations only for purposes of extending the temporal database in the C IV and Si IV variations. Since the absolute photometric calibration for the small-aperture *IUE* spectra are uncertain, we have used only *differential* measurements and have performed the statistical analyses using the large-aperture spectra only. Such a distinction is especially important because the archival spectra are quite mixed in quality. All spectra were reduced using standard software at the Regional Data Reduction Facility (RDAF) at Goddard Space Flight Center and augmented by special purpose programs for photometric analysis and spectral comparison. The journal of observations is provided in Tables 1 and 3.

Reduction of the *IUE* spectra was performed using the method previously employed for the sn stars (SBS87). We formed synthetic photometry using

$$a(\text{C IV}) = \tfrac{1}{2}(m_{1542} + m_{1562}) - m_{1548} , \qquad (1)$$

where all filters are rectangular profiles with 2 Å widths. Increasing absorption-line strength is indicated by increasing a(C IV). All spectra were smoothed with a boxcar filter to 3 points to improve S/N as in our previous studies. For Si IV, we have used

$$a(\text{Si IV}) = \tfrac{1}{2}(m_{1387} + m_{1397.5}) - m_{1394} \qquad (2)$$

with all filters being 2 Å wide. As in the earlier results, differenced spectra show that the Fe II and Fe III spectra which are responsible for most of the blending at C IV and Si IV are not variable to within the noise limit of the SWP spectra. Continuum variations at λ1542 and λ1562 show a scatter of $\sim$10% for both HD 5737 and HD 79158. Similar scatter was obtained for the λ1387 and λ1397.5 bandpasses.

The magnetic observations have been carried out using the University of Western Ontario Zeeman Photopolarimeter (see Shore, Brown, and Sonneborn 1987; Landstreet 1980). For HD 5737, we have exclusively used the 2.2 m at Mauna Kea Observatory, while for HD 79158 both the 1.2 m at University of Western Ontario and the 2.2 m at Mauna Kea have been used. Calibration was provided using β CrB and HD 37479, for which periods and effective magnetic field amplitudes have been well observed. The magnetic observations are listed in Tables 2 and 4.

Optical photometry of HD 5737 has been provided by P. North and G. Mathys (1988, private communication) using the Geneva photometer at ESO over a period of almost 5 yr. The observations will be published separately but are shown here for comparison purposes. Unpublished photometry was also provided by D. Tholen (1987, private communication). Photometry of HD 5737 has been published recently by Kurtz and Marang (1987).

HD 5737 and HD 79158 were included in the VLA radio observations reported of the Bp and Ap stars by Drake *et al.* (1987). HD 5737 was observed only at 6 cm, HD 79158 only at 2 cm. Neither star was detected. They report an upper limit of <0.27 mJy (6 cm) for HD 5737 and <0.62 mJy (2 cm) for HD 79158. The only other magnetic sn star, HD 21699, also yielded only an upper limit of <0.42 mJy (6 cm). By way of contrast, three magnetic helium-strong stars, HD 36485, 37017, and 37479, were detected at 6 cm. For HD 37479 there is only an upper limit at 2 cm, but variations in the 6 cm flux were observed. Phillips and Lestrade (1988) have recently resolved the radio emitting region of HD 37479 and HD 37017 with VLBI at 5 and 15 GHz. They report that the emission is compact, coming from a region of order 3 to $4R_*$ with a brightness temperature $T_b \geq 10^8$ K. They interpret the radio emission as gyrosynchrotron radiation from mildly relativistic electrons trapped in the magnetospheres of these helium-strong stars. Finally, HD 34452 and HD 215441—both non-sn helium-weak stars—have been detected by Drake *et al.*

III. DISCUSSION OF INDIVIDUAL STARS

a) *HD 5737 = α Sculptoris*

HD 5737 is classified as a B8 III star (Hoffleit 1982) with the footnote that it is helium-weak. Its outstanding spectroscopic anomaly, the apparently enhanced strength of C II λ4267, is due to a misclassification of the star caused by its extreme helium weakness (see SBS87 for discussion). The star is one of the slowest rotators among this class of Bp stars. Its magnetic field variations have been observed by Borra, Landstreet, and Thomson (1983) and SBS87.

In SBS87 we reported the discovery of phase dependent C IV and Si IV line profiles for HD 5737, but at the time were unable to determine a unique period with which to phase the magnetic field and UV spectra. HD 5737 has, at most, only a tiny range of photometric variability. Kurtz and Marang (1987) were unable to find a unique period on the basis of their rapid photometry, and P. North and G. Mathys (1988, private communication) have also reported similar discouraging results. This is in marked contrast to HD 21699, for which Percy (1985) and Skillman (1986) find a large amplitude ($\Delta U \approx 0.05$ mag) with a well-determined period. Since the magnetic amplitude of HD 5737 is also small, it is difficult to obtain an accurate period from even densely sampled magnetic data.

HD 5737 is similar in temperature and luminosity to HD 21699, and somewhat hotter than HD 79158. To date, these are the *only* three sn stars which appear to show the phenomenology of UV spectrum variations that are typical among the helium strong stars (Barker *et al.* 1982). HD 161480, another C II anomalous member of the class, has been observed twice during this program, and displays normal Fe II/III absorption in both spectra (SWP 32022, and 32053).

The new *IUE* spectra were obtained for this study using the SWP camera in high dispersion, with the large aperture; all spectra were exposed for 2 minutes. These have been supplemented by several archival spectra. The sequencing of exposures was optimized to search for periods between 10 and 30 days, the previously determined most probable period range. Magnetic observations Borra *et al.* had suggested a period of about 16 days, but with considerable uncertainty. We scheduled *IUE* in 14 half-shift allocations in sessions spread out over a period of about 20 days (see below).

The data for a(C IV) are given in Table 1. Figure 1 shows the run of spectra during 1987 October, with Figure 2 displaying the *unphased* a(C IV) data. Differenced spectra for the orders containing the C IV doublet show that only C IV is variable. For C IV, $\langle a(\text{C IV})\rangle = 0.200 \pm 0.253$. In contrast, $\langle a(\text{Si IV})\rangle = 0.233 \pm 0.076$ for the same set of spectra. In contrast, Si IV and C IV in the helium-strong stars typically show similar amplitudes of variability, suggestive of photospheric variations.

The most important quantity for the elucidation of the plasma distribution is the period of rotation of the star. Because all of the other variable magnetic chemically peculiar stars, with the exception of γ Equ, are periodic, we naturally suspected that the same was true for HD 5737. Estimated periods, however, spanned the range of 0.9 to more than 50 days, the most probable being in the range of 15–25 days. In order to optimize our shift allocation with *IUE*, we simulated the effects of incomplete sampling of periods in the probable range and determined an optimized observing sequence for half-shifts in an interval of 20 days. This was done to avoid the effects of aliasing on the 8 hr and 24 hr period associated with

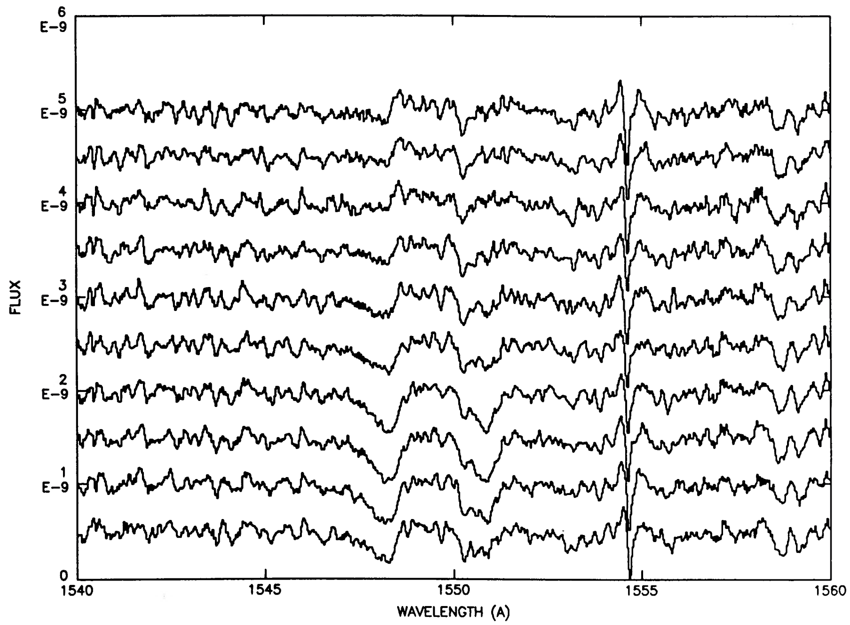

FIG. 1*a*

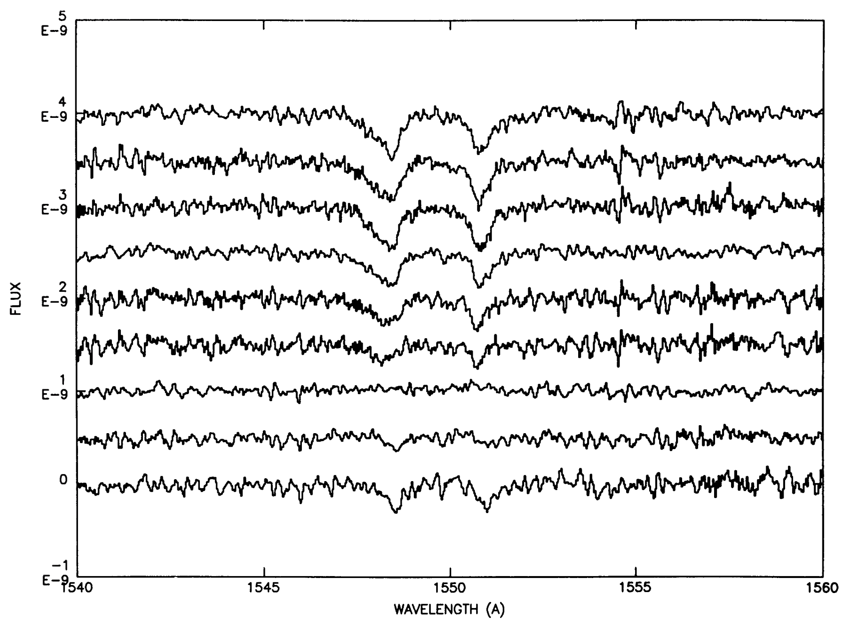

FIG. 1*b*

FIG. 1.—*IUE* high-dispersion SWP spectra of HD 5737 during 1987 October. From bottom to top: SWP 31198, 32012, 32023, 32032, 32055, 32065, 32075, 32093, 32106, and 32108. All spectra have been smoothed to three points and are displaced by a constant offset.

IUE scheduling. With the cooperation of the *IUE Observatory* staff, our observations were scheduled to closely match this optimized sequence.

We have used two different methods to determine the period from the C IV data, one due to Lafler and Kinman (1965) and the other a stochastic periodogram method due to Scargle (1982). A unique period of 21.655 days emerges from the Lafler-Kinman algorithm and from the periodogram analysis. The phased UV spectrum data are shown in Figure 3. The chosen initial epoch is arbitrary and early enough to be prior to the first *IUE* and magnetic observations, HJD 2,443,000.0. The data shown in Figure 3 consists of all available spectra, *including archival data.* Note that the variation is double-wave, unlike HD 21699 (BSS, SBS87). The scatter in the phased

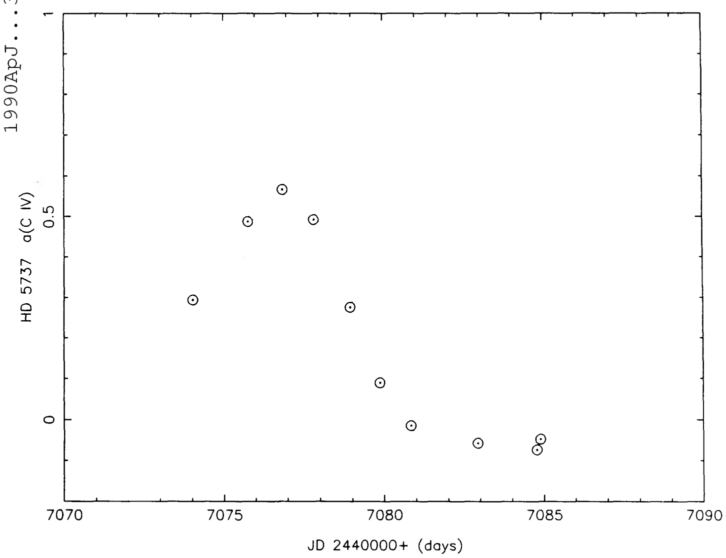

FIG. 2.—Unphased a(C IV) values for spectra in Fig. 1. The ordinate is JD 2,440,000+.

variations is quite small. The synthetic photometry is considerably more accurate than direct equivalent width measurements, although the two are well correlated, and immune to the errors of judgment that plague the latter.

For comparison, in Figure 4, we show the published Johnson U photometry (Kurtz and Marang 1987) phased on the 21.65 day period. There is some hint of variability, but the scatter is large enough to obscure any periodic variation. In Figure 5, we show the Geneva $B1$ and U photometry, phased on the 21.655 day period. Again, the scatter is too large to provide any chack on the proposed period. Similar results characterize the photometry by Tholan. Finally, we report that although Fine Error Sensor (FES) magnitudes were recorded at the start of each *IUE* observation, both HD 5737 and HD 79158 show such small photometric amplitudes that the FES failed to be a sufficiently accurate photometer to detect statistically significant variations and we will not report these data in detail. It suffices that no significant photometric variations were observed in either HD 5737 or HD 79158 during these observations at the level of 0.02 mag.

TABLE 1

HD 5737: C IV AND Si IV VARIATIONS

SWP	JD (2,440,000+)	a(C IV)	a(Si IV)
14946....................	4857.951	0.421	0.275
14947....................	4857.998	0.428	0.212
14984....................	4861.971	0.617	0.276
23936....................	5955.957	−0.080	0.118
23968....................	5959.058	−0.017	0.140
23969....................	5959.072	−0.046	0.138
23984....................	5960.903	0.089	0.200
24750....................	6060.983	0.386	0.233
24844....................	6071.597	0.513	0.313
27025....................	6363.825	0.348	0.226
27037....................	6375.818	0.711	0.354
27043....................	6376.728	0.641	0.299
27053....................	6377.876	0.494	0.250
27069....................	6379.847	0.153	0.195
27092....................	6381.882	0.361	0.216
31998....................	7074.008	0.292	0.206
32012....................	7075.751	0.486	0.281
32023....................	7076.847	0.565	0.357
32032....................	7077.812	0.491	0.334
32055....................	7078.935	0.274	0.260
32065....................	7079.865	0.088	0.243
32075....................	7080.826	−0.016	0.192
32093....................	7082.917	−0.059	0.169
32106....................	7084.760	−0.075	0.172
32108....................	7084.870	−0.049	0.117

We have phased all of our magnetic measurements, listed in Table 2, together with those of Borra *et al.* to produce a single magnetic curve. This is shown in Figure 6. A least-squares fit has been applied to the effective field measurements using

$$B_{\rm eff}(\Phi) = B_0 + B_1 \sin\left[\frac{2\pi}{P}(t - t_0) + \phi\right], \quad (3)$$

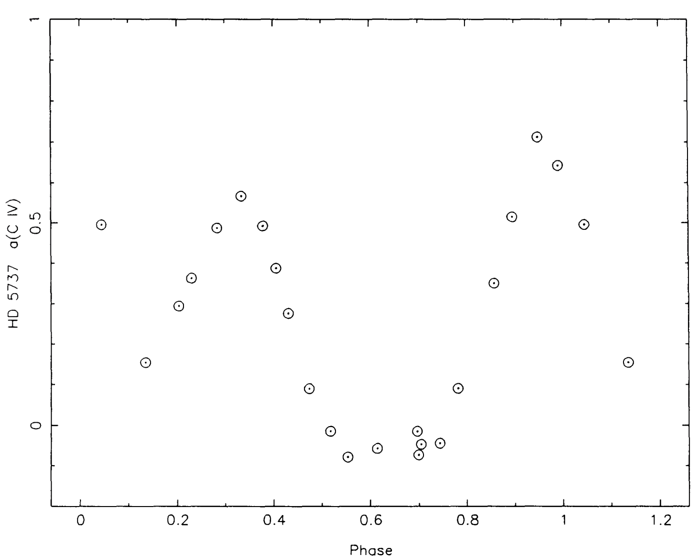

FIG. 3.—Phase-dependent variations of a(C IV) for HD 5737, phased with a period of 21.647 days and JD_0 = 2,443,000.0.

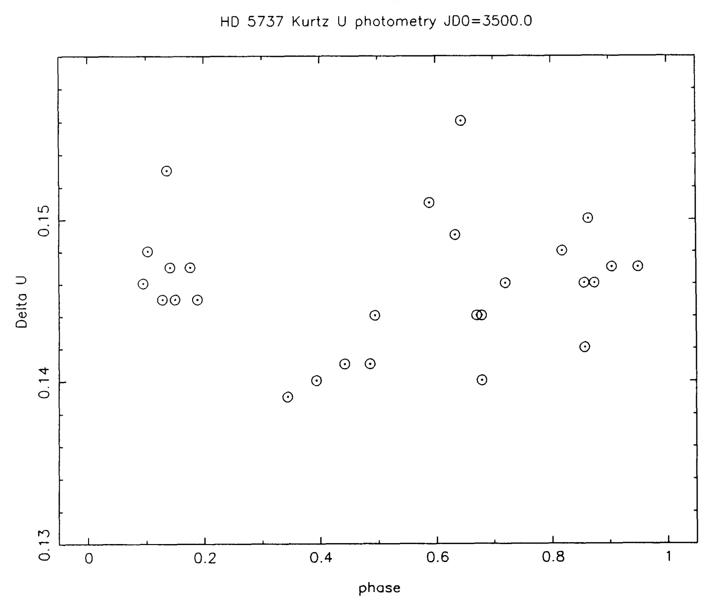

FIG. 4.—Johnson U photometry of HD 5737 from Kurtz and Marang (1987) phased as in Fig. 3.

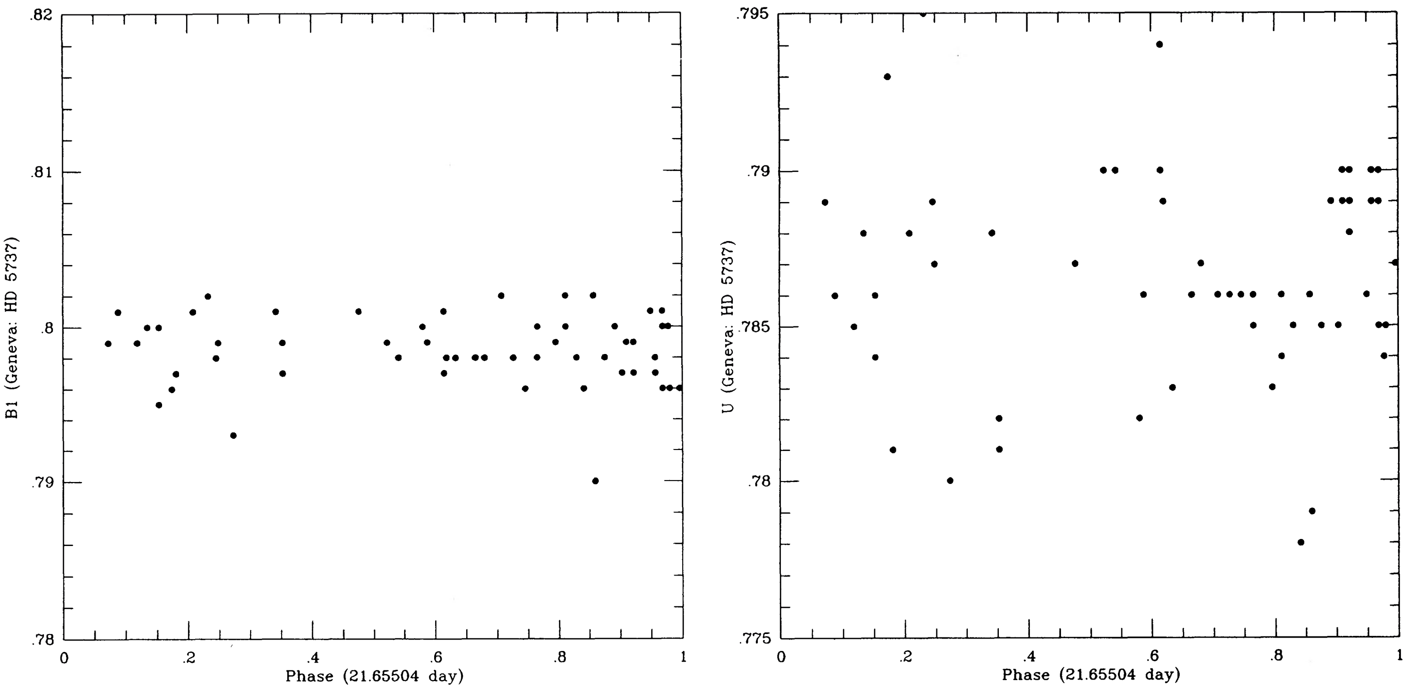

FIG. 5*a* FIG. 5*b*

FIG. 5.—Geneva *B*1 and *U* photometry for HD 5737 phased as in Fig. 3

where P is the period, t_0 is an initial epoch (first observation), and ϕ is the phase shift. The period derived from the magnetic observations, using least squares, is $P = 21^{\mathrm{d}}.654 \pm 0^{\mathrm{d}}.020$, in excellent agreement with the independent determination from the C IV variations. The best fit is $B_0 = 80$ G, $B_1 = 390$ G, $\phi = 0.52$ for an initial epoch $t_0 = 2443710.956$ with $\chi^2/\nu = 1.26$ for all available magnetic observations.

The photon-limited uncertainty associated with the magnetic measurements makes it difficult to say definitively that the field varies sinusoidally. The longitudinal magnetic field measurements are sensitive primarily to the dipole component. Unless the higher order multiples are rather larger than the dipole (which would probably lead to a highly nonsinusoidal B_{eff} variation which is not seen), we may use the argument by Preston (1974) to constrain the inclination, i, of the rotation axis to the line of sight and the obliquity, β, of the magnetic to rotational axes. Preston has shown that if one forms the ratio $r \equiv B_{\mathrm{eff,max}}/B_{\mathrm{eff,min}}$, then the obliquity and inclination are related by

$$r \equiv \frac{B_{\mathrm{eff,max}}}{B_{\mathrm{eff,min}}} = \frac{\cos(i-\beta)}{\cos(i+\beta)}\,.$$

The magnetic field variations for HD 5737 yield $r \approx -1$, so we see that either i of β must be near 90°. Due to the uncertainties in the rotational velocity for HD 5737, it is not possible to decide between these possibilities on the basis of only the magnetic data.

Photometric observations of He I λ4026 have been published by Pedersen (1979) for HD 5737. These data have also been subjected to period analysis. We obtain a period of 21.638 days for He I, which we combine with the magnetic and C IV data to give a weighted period of 21.647 ± 0.009 days. The He I λ4026 data is plotted on this period in Figure 7. Notice that the He I and C IV variations are roughly in antiphase. This is the only indicator we have of photospheric variations for HD 5737, other than the effective magnetic field variations. We postpone further discussion until the next section.

TABLE 2

HD 5737: MAGNETIC MEASUREMENTS

JD (2,440,000+)	B_{eff} (G)	σ (G)
6013.764	−250	130
6014.794	−330	110
6016.779	−20	190
6019.773	330	190
6047.835	440	110
7078.960	50	390
7079.911	210	80
7080.840	430	90
7081.053	260	100
7082.036	120	100
7082.825	460	80
7083.833	520	90
7167.805	400	90
7169.816	560	120
7170.774	390	80
7172.776	310	80

b) *HD 79158 = 36 Lyncis*

HD 79158 was included by SBS87 on the basis of the strong C IV line reported by Sadakane (1985) on two *IUE* spectra (SWP 4449, 4450). Early observations which we have previously reported confirmed that the C IV and Si IV lines are variable, with the latter having lower amplitude, but were of insufficient number to permit period determination.

The initial impression from the ultraviolet data reported in SBS87 and Shore, Brown, and Sonneborn (1988, hereafter SBS88) was that the period of HD 79158 should be about 2 days. Since the program MLHSS was optimized for HD 5737,

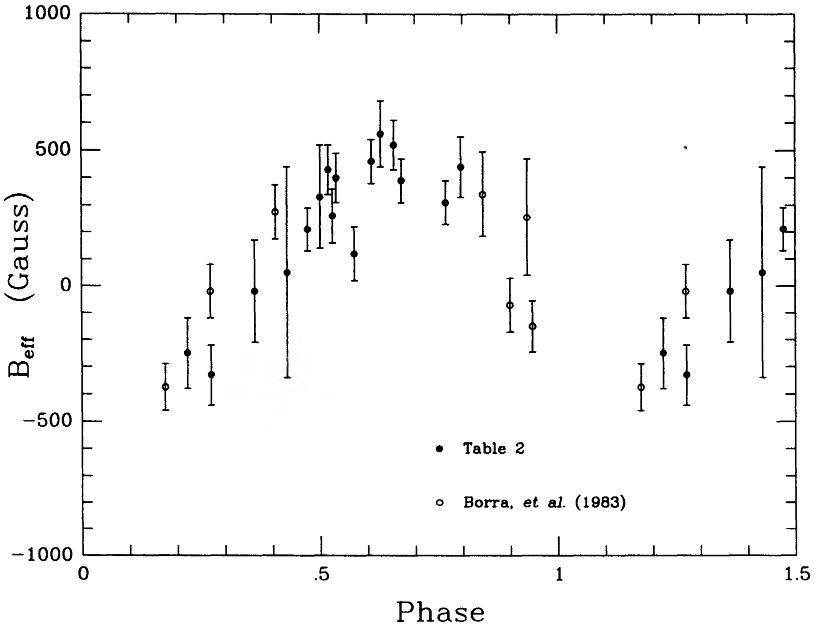

FIG. 6.—Effective (longitudinal) magnetic field variations for HD 5737 phased as in Fig. 3

we have undersampled the spectroscopic variations of HD 79158. Nonetheless, period determinations revealed a most probable period of $1^d.92 \pm 0^d.02$ from the *IUE* data reported in Table 3.

There is no published photometric study of this star, but BVR CCD and photometer observations made during 1987–1988 with the 0.45 cm reflector at the Joint Observatory for Cometary Research (Klinglesmith, Crain, and Shore 1988) give an upper limit to the photometric amplitude of $\Delta V < 0.05$ mag, with similar values for the other filters. While not a very restrictive upper limit, it agrees with the upper limit set by FES observations, also about 0.02 mag. This means that the photometric variability of HD 79158, like HD 5737, is smaller than that of HD 21699.

The magnetic observations for HD79158 are listed in Table 4, along with the 1 σ dispersions. The periodogram obtained using the Scargle algorithm is shown in Figure 8 and the phased magnetic data are shown in Figure 9. These data provide the key to the period determination. The magnetic field appears to be strong, about the same strength as for HD 21699, and reverses sign nearly symmetrically. The ratio of extrema in the unphased data suggests either that the star is rotating at nearly $i \approx 90°$ or that its magnetic and rotational axes are nearly orthogonal, as in HD 5737. These data include both observations from MKO and University of Western Ontario, *made with the same polarimeter*.

The C IV data yield ambiguous results for the period, because of large gaps and undersampling (see SBS87,

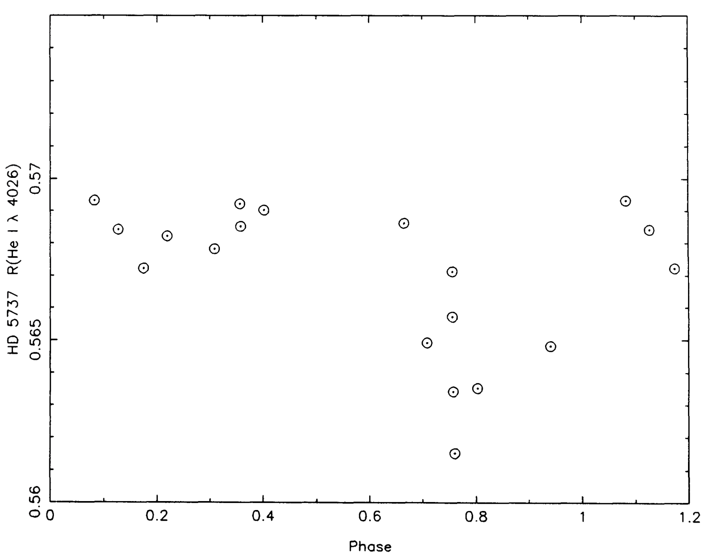

FIG. 7.—Helium line photometry [R(He I λ4026)] for HD 5737, from Pedersen (1979), phased as in Fig. 3.

TABLE 3

HD 79158: C IV AND Si IV VARIATIONS

SWP	JD (2,440,000+)	a(C IV)	a(Si IV)
4449..........	3934.474	0.813	0.530
4950..........	3934.549	0.893	0.550
27026..........	6373.878	0.244	0.393
27038..........	6375.871	0.138	0.303
27042..........	6376.672	0.441	0.274
27070..........	6379.923	0.177	0.244
27091..........	6381.820	0.146	0.256
31996..........	7073.912	0.254	0.239
32014..........	7075.339	0.240	0.344
32015..........	7075.865	0.181	0.244
32024..........	7076.899	0.931	0.400
32034..........	7077.899	0.185	0.244
32057..........	7078.829	0.767	0.493
32076..........	7080.872	0.743	0.306
32107..........	7084.870	0.239	0.252
32947..........	7211.564	0.346	0.285
32971..........	7215.501	0.336	0.279
32972..........	7215.562	0.273	0.265
32981..........	7216.504	0.485	0.565
32982..........	7216.533	0.476	0.160
32989..........	7218.479	0.696	0.345
32990..........	7218.548	0.933	0.298
32991..........	7218.573	0.927	0.429

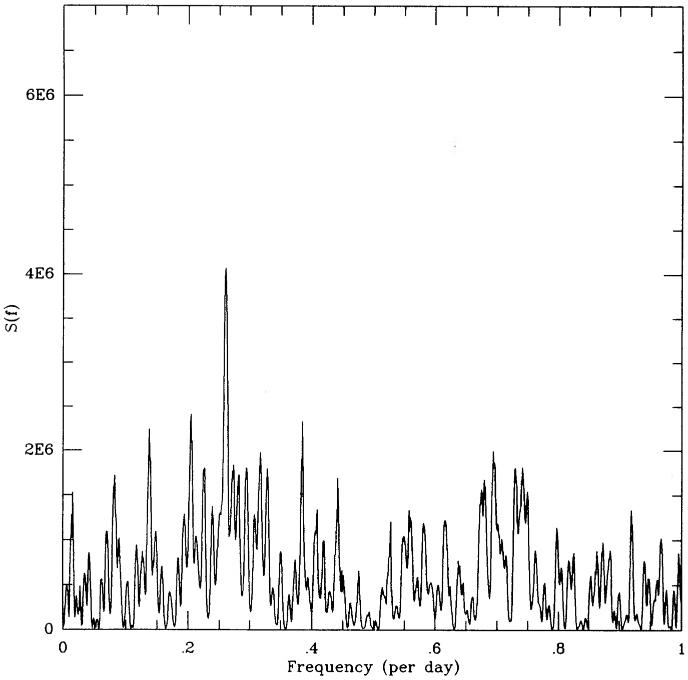

FIG. 8.—Periodogram of effective magnetic field variations for HD 79158, obtained using the Scargle (1982) method. All data from Table 4 has been included.

TABLE 4

HD 79158: MAGNETIC MEASUREMENTS

JD (2,440,000+)	$B_{\rm eff}$ (G)	σ (G)
6016.011	650	250
6016.990	−340	160
6019.983	540	180
6020.956	−710	180
6047.092	350	140
6047.974	−630	160
6102.970	320	130
6103.879	1000	140
7169.096	420	90
7170.131	700	120
7173.082	540	90
7209.817	−960	250
7210.805	−860	320
7225.595	−1470	240
7225.836	−440	390
7226.564	460	240
7226.851	760	240
7227.585	780	250
7227.830	390	270
7498.883	300	200
7502.788	600	230
7507.870	120	230

Appendix). The magnetic field data are much more useful for settling the period of this star. There is a fortuitous aspect to the manner in which these data were obtained which makes it especially well suited to period analysis. The UWO observations were planned to assure two measurements per night and were obtained within several months of the MKO data. The observatories are at longitudes which separate them by nearly 6 hr. Thus in the most recent data sets this effectively removes the diurnal alias. The Lafler-Kinman algorithm yields $3^{\rm d}.8340 \pm 0^{\rm d}.005$, and the periodogram method gives 3.8351 days. Fitting the magnetic data with a sinusoidal curve gives a best fit for $3^{\rm d}.8345 \pm 0^{\rm d}.001$. We adopt an approximate period of 3.834 days for the subsequent analysis. The magnetic data were analyzed using least squares. The resulting fit yields $B_1 = 900 \pm 30$ G, with no offset (B_0 consistent with zero), for a sinusoidally varying magnetic field with $\chi^2/\nu = 1.17$. The phase of positive crossover relative to JD 2,443,650.699 is $0^{\rm P}.50 \pm 0^{\rm P}.03$.

In Figure 10 we show the *a*(C IV) variations for HD 79158, which should be compared with the magnetic field data in Figure 9, phased on the 3.834 day period. The relative phasing of the magnetic and UV variations shows that the C IV line is strongest at magnetic nulls. In other words, HD 79158 also

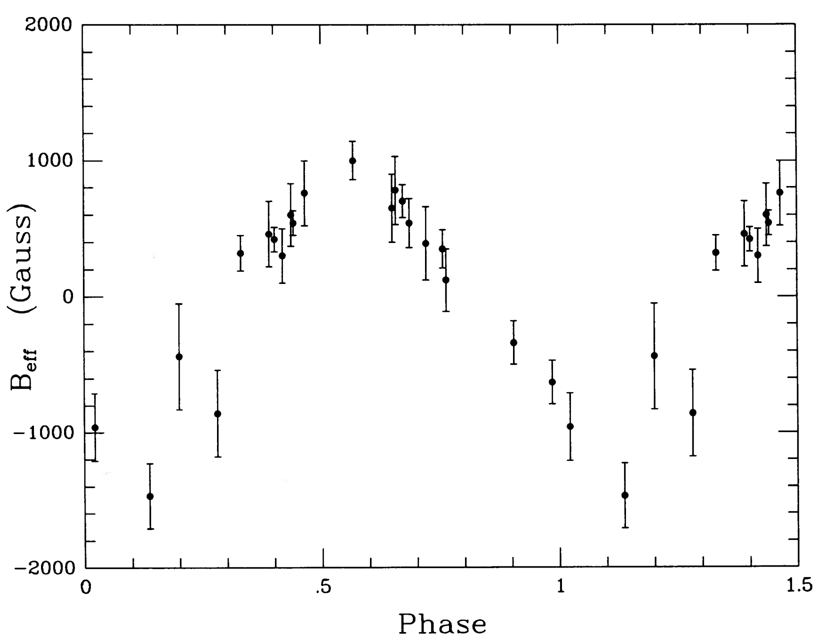

FIG. 9.—Phased variations of effective magnetic field for HD 79158. The ephemeris used a period of 3.834 days and $JD_0 = 2,443,000.0$.

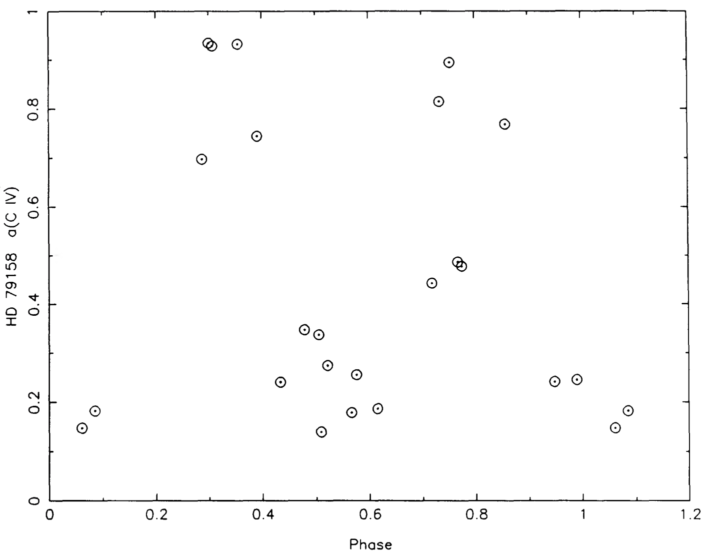

FIG. 10.—Phased a(C IV) observations for HD 79158, using the ephemeris of Fig. 9.

displays magnetically controlled circumstellar plasma. The Si IV lines vary in phase with C IV. The C IV maxima are separated by $0^{\mathrm{P}}43$. The peaks are narrow and well separated, with larger contrast between maxima and minima than for HD 5737. We shall return to this point in the analysis.

IV. MAGNETOSPHERES AND WINDS IN THE HELIUM PECULIAR STARS

In the discussion that follows, we shall adopt the definition magnetosphere provided by Hill, Dessler and Goertz (1983) as "surrounding regions [of celestial bodies] within which the motion of charged particles is influenced by the magnetic field of the central body." Alternatively, such a region is called the "plasmasphere" (Lyons and Williams 1984) or "inner magnetosphere" (Acuna, Behannon, and Connerney 1983).

a) Oblique Rotator Parameters

The comparison of the magnetic and UV line variations in HD 5737 and HD 79158 demonstrates that the C IV profile changes in these helium-weak stars are due to the rotation of a magnetosphere across the line of sight. Magnetic field nulls coincide with strongest C IV absorption, and the longitudinal field extrema coincide with C IV minima. Although there are some slightly negative a(C IV) measurements, these are consistent with nulls. The weakest C IV absorption corresponds to the strongest positive projected magnetic field.

We can place some limits on the oblique rotator properties of the magnetosphere of HD 5737. The rotational velocity of this star is poorly determined but appears to be no larger than 15 km s^{-1} (SBS87). We can use Shore (1987) to determine the probable obliquity of the magnetic field. The phase separation of the a(C IV) maxima is $\Delta\Phi \approx 0.4$, and the obliquity β is related to i by

$$\cos\left(\frac{\Delta\Phi}{2}\right) = \cot i \cot \beta \, . \quad (5)$$

Within the context of the oblique rotator model, the phase separation of maxima indicates that $i < 90°$. Assuming that HD 5737 is a main-sequence star, with $3 \leq R/R_{\odot} < 4$, the predicted equatorial rotation velocity is $v_{\mathrm{eq}} \approx 8 \pm 1$ km s^{-1}, much less than the available upper limit of $v \sin i$. Thus, currently available observations do not assist in constraining i. The phase separation of C IV maxima also constrains $\beta < 90°$. For instance, taking a range $30° \leq i \leq 60°$ gives $80° \geq \beta \geq 62°$. The magnetic field in HD 5737 is therefore likely to be highly oblique but clearly *not orthogonal.* It is interesting to note that the magnetic field variations can be related to the same quantities through the ratio r. With the available data, this constrains β to be large but also suffers from the indeterminacy of i.

The magnetosphere of HD 5737 appears to be nearly axisymmetric in the magnetic frame, and the variations of the line width suggest that it is corotating with the star to about $10R_{*}$; the maximum line width is consistent with a corotation velocity of order 200 km s^{1}. This value is consistent with the Alfvén radius expected for a corotating magnetosphere for a field strength of about 1 kG (Shore 1987). There is no shift in the wavelength of the line minimum indicating that the C IV is formed essentially contiguously with the stellar surface. That is, there are no phase-dependent gaps near the rest wavelength for C IV. The fact that the He I line variations are in antiphase with C IV also strengthens the conclusion that we are dealing with a magnetospheric phenomenon for C IV. The helium is concentrated at the magnetic poles, as one typically finds for the helium-weak stars, with the stronger of the polar spots presented at the weaker of the C IV minima. The ratio of the spot minima in the He I λ4026 photometry is suggestive of a relatively low inclination, somewhat in disagreement with the magnetic data, but consistent with the C IV variations. Most important is the fact that at the magnetic equator, there is low He abundance and an enormous increase in the abundance of the high-temperature species. Unfortunately, no such data exist for He I in HD 79158.

For HD 79158, the rotational velocity quoted by Hoffleit (1982) is 26 km s^{-1}. With a main-sequence radius $3 < R/R_{\odot} < 4$ and $\Delta\Phi = 0^{\mathrm{P}}43$, we obtain a range in the oblique rotator parameters of $27° < i < 36°$ and $76° < \beta < 83°$. This is consistent with the magnetic results, although the expected r is still smaller than observed. We expect $r \approx -0.7$, while the observed value is closer $r = -1$. However, the uncertainties in the oblique rotator parameters are sufficient that these do not appear in serious conflict.

The rotation period of 3.84 days makes HD 79158 very similar to HD 34452 and several of the intermediate helium-weak or extreme silicon stars, while it is still a longer rotation period than HD 21699. However, the similarity of the periods of HD 21699 and HD 79158, and the similar magnetic field strengths, suggest that the rotation period is not the critical factor in determining whether a star will possess a magnetosphere or a polar outflow.

b) Modeling the C IV *Profile Variations*

The C IV variations are those expected from a simple optically thick band at the magnetic equator. There is no evidence for secular variability for any of the sn stars over nearly a decade, since the archival spectra phase very well with the most recently obtained observations. In order to model the C IV variations, we assume a simplified oblique rotator model for the magnetosphere. Taking the C IV line strength to be S in the magnetic frame, the integrated line strength (absorption) against the stellar photosphere as a function of phase is given by

$$F_{\mathrm{C\,IV}}(\Phi) = \int S(\theta_m, \phi_m)\Lambda(\theta)\, d\Omega \, , \quad (6)$$

where θ_m and ϕ_m are the magnetic latitude and longitude (in the oblique frame, which are phase dependent), Ω is the solid angle of the stellar surface, and Λ is the normalized limb-darkening function. While we have not included the details of the line formation in these simple phenomenological models, the depth of the line is assumed to be a monotonic function of S along each line of sight. The line strength is usually expanded in spherical harmonics in keeping with the appropriate multipole expansion for the magnetic field. For the phenomenological models we have developed for the C IV observations in this paper, however, we take an even simpler approach. The expansion of S is assumed to be a simple function of $\cos\theta_m$ which is symmetric about the magnetic equator. The justification we offer is one of ignorance. Rather than introducing too many parameters into the fit, and not knowing precisely what processes structure the magnetospheres, we opt for simplicity of representation.

In Figure 11 we show several oblique rotator models for the C IV variation. We assume that the magnetosphere follows a latitude variation like

$$S_{\mathrm{C\,IV}} = S_0(1 + a_0 \cos^n \theta_m) , \tag{7}$$

where S_0 is the maximum strength of the C IV line, θ_m is the magnetic colatitude, and a_0 is a constant measuring the contrast of the equatorial band to the rest of the disk. In order to produce the sharp contrast between the band and disk, the distribution of C IV seems to require a magnetosphere more concentrated than $n = 2$; $n = 4$ is a better match to these data. The best fitting model for HD 5737 is obtained for $a_0 \approx 0.8$ for the observed i and β values. The line appears to be completely optically thick, difficult to understand if there were a large-scale mass outflow with a large velocity gradient but perhaps more easily achieved if the material is trapped in a corotating magnetosphere. Here the velocity gradients appear to be small,

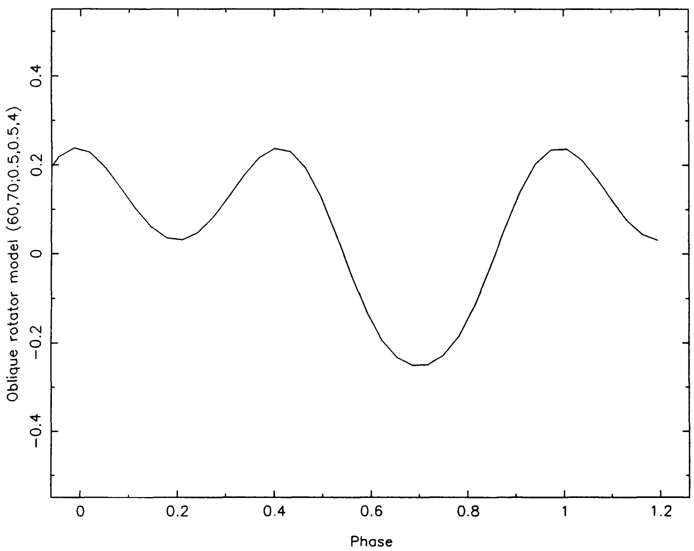

FIG. 11*a*

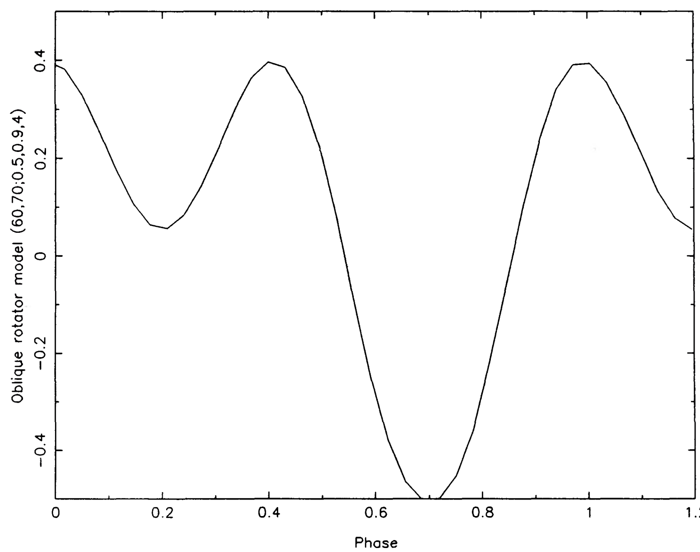

FIG. 11*b*

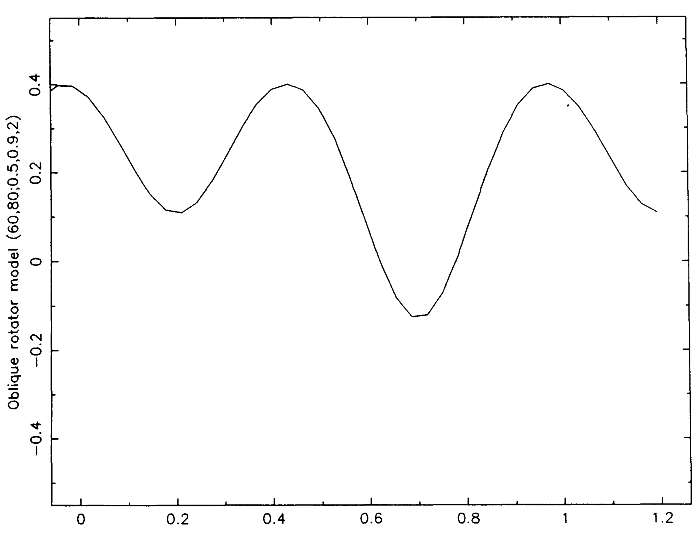

FIG. 11*c*

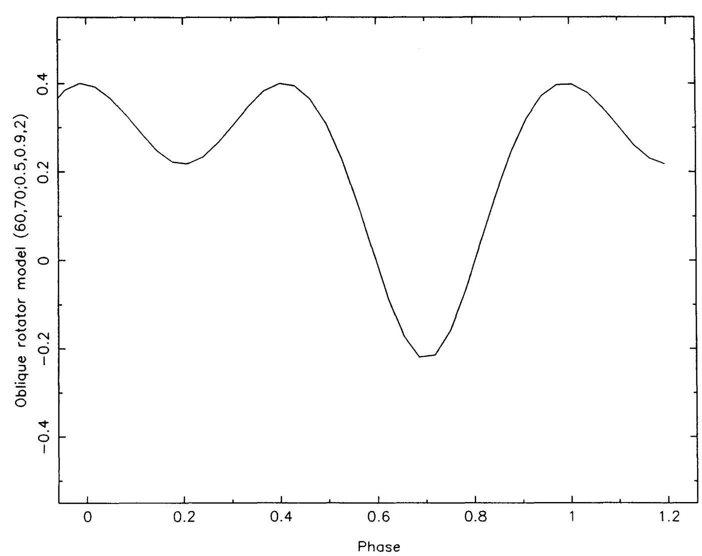

FIG. 11*d*

FIG. 11.—Oblique rotator models for a(C IV) variations in HD 5737. See text. Models are labeled by (i, β; u, a_0). Offset is in arbitrary magnitude units; phase is chosen to agree with a(C IV) measurements.

with the line width resulting from the corotation radius of about $10R_*$.

The Alfvén radius for a dipole field is given by:

$$R_{\rm A} = \left(\frac{B_* R_*^{\ 3}}{\Omega}\right)^{1/4} (4\pi\rho_{\rm A})^{-1/8} \qquad (8)$$

where $\rho_{\rm A}$ is the density at the Alfvén surface (Shore 1987). Taking the simple approximation of a centrifugal wind (Mestel 1968; Borra, Landstreet, and Mestel 1982), we have

$$\rho(r) \approx \rho_0 \exp\left(\frac{3\Omega^2 r^2}{2a_s^{\ 2}}\right), \qquad (9)$$

where a_s is the sound speed. Substituting this into the equation for the Alfvén radius, and assuming the approximate solution of a centrifugal wind, we obtain $R_{\rm A} \approx 8 \times 10^{11}$ cm for HD 79158, approximately $3R_*$, while for HD 5737, this comes out to about $30R_*$. The sound speed has been *assumed* to be of order 10 km s^{-1}, so the plasma is taken to have a kinetic temperature of about 10^4 K.

These are very rough figures, and given the high obliquities of these fields, they are quite likely only orders of magnitude representations of the true physical arrangement of the plasma. However, these parameters are similar to those derived for the helium-rich stars, and also about the same as the estimates obtained for HD 21699 on the basis of constraining the polar outflow to be corotating with the stellar photosphere (Shore 1987; SBS87). The opening angle of the polar region of open field lines (Shore 1987) is quite small, for HD 79158 about 35° and for HD 5737 about 10°. It is possible that the polar outflow, which one would expect to accompany the magnetosphere, is so small for HD 5737 that we simply do not see it. This explanation cannot, however, apply to HD 79158, whose properties are not significantly different from HD 21699, for which a polar outflow is observed.

A few points suggest that this picture is on the right track. For HD 5737, the magnetosphere is well modeled with an equatorial band which is extended in magnetic colatitude, so that $n = 2$ appears to reproduce the data, although $n = 4$ is a better match. For HD 79158, the equatorial band is more confined in latitudinal projection onto the photosphere and $n = 2$ clearly fails to reproduce the observed variations. The C IV line optical depths indicate densities of order 10^{15} cm^{-3} in HD 79158, assuming that $\tau \geq 1$ (SBS87). Finally, for HD 5737 the C IV strengths become slightly negative. While uncertain at best, this may indicate that the plasma is sufficiently distended that some emission contribution to the line profile, either from thermal plasma or from scattering, is observed. Also, the phase at which the magnetosphere should be in the plane of the sky—hence the phase at which we would expect to see emission in C IV—is the phase at which systematically (although small) negative values have been obtained for a(C IV). For HD 79158 there are no phases at which the C IV shows any hint of going into emission, supporting the idea that it is radially more concentrated toward the star.

Here we offer a conjecture that the magnetospheres of the magnetic helium-weak sn stars, being optically thick and relatively cool, may account for the radio quiescence of the stars. The inferred densities from VLA observations is about 10^6 cm^{-3}, while we obtain much higher values for the three stars displaying C IV variations. Why these stars are so different than the He weak stars with which they share the main sequence is, however, an open question.

c) *Comparison with the Helium-strong Stars*

The full range of phenomenology for magnetospheres is displayed by the helium-strong stars. HD 37017 shows only a single magnetic pole, and the C IV line displays only a single wave on the rotation period, with the strongest C IV occurring at the magnetic equator. HD 64740 shows double wave variations like HD 5737, with similar oblique rotator parameters, and HD 37479 shows a C IV curve which is almost the mirror image of the photometric variation. The details will be reported in a future paper (Shore and Brown 1989). It appears that those helium-strong stars, like HD 96446 and HD 133518, which show only C IV emission, are the slowest rotators. These stars can be modeled using the same oblique rotator picture that we have been discussing. Magnetospheric C IV resonance scattering produces relatively narrow emission lines which, because of inclination and obliquity effects, are constant and which do not cross the center of the stellar disk. Only HD 60344 shows strong, constant absorption. In this case the star may have a highly oblique (nearly perpendicular) magnetic field. There is no need, as in BBBL, to invoke a separate explanation for the slowly and rapidly rotating helium-strong stars. The difference in the line profiles is simply explained by an inclination plus obliquity effect. All of the helium-strong stars are probably intrinsically rapid rotators, with the differences in the observed rotational velocities being due to inclination of the rotation axis to the line of sight.

It is significant, however, that all of the magnetic helium peculiar variables which show C IV variability are dominated by the magnetosphere *with the sole exception of HD 21699.* HD 37776 is the only one of the magnetic variables to show essentially no large-amplitude variability. Instead, it appears that the magnetic field of this star being quadrupolar has had a deleterious effect on the stability of the trapped plasma. Even with moderately dense coverage of the magnetic cycle, there is no convincing evidence for the stability of the magnetospheric gas.

d) *Discussion*

HD 5737 shows no evidence for an IR excess, and the *IRAS* data at 12 μm are consistent with an effective temperature of 15,000 K. It is the only He-weak star in the *IRAS* Point Source Catalog, due probably to its proximity and relatively unconfused field. There is no evidence from the infrared for cool (10^4 K) plasma in the other helium-weak stars, nor is there any support for the suggestion that this is seen in the helium-strong stars. *IRAS* observations are in disagreement with the Groote and Hunger (1982) assertion that there is an IR excess at 2–3 μm for HD 37479.

No evidence has been reported in the literature for variability of the hydrogen lines in the sn stars, although there is surprisingly little optical spectroscopic coverage. This places limits on the density and temperature of the plasma using the variations observed in HD 37479 (Groote and Hunger 1982) as an exemplar. Note that the difference in the temperatures between the sn stars and their helium-strong counterparts makes it likely that the trapped plasma is at lower ionization and so should display the optical depth effects of the plasma even more critically. The lack of photometric variability also distinguishes these stars from the helium strong stars, and the optical spectra are not as variable. In the case of the helium weak stars, the lines other than C IV are also far less variable. Also, why does HD 21699 shows jet behavior and the other stras do not, even though we see both poles. The phasing of the magnetic field variations and the C IV is conclusive: the plasma in HD 5737, HD 79158, and in the helium strong stars is situated in magnetospheres above the magnetic equator.

Because there is no substantial outflow indicated, we do not know if the heating could be the same as that suggested in the polar flow of HD 21699 (SBS87). Rather, the C IV may simply be due to a normal non–LTE effect of high ionization in a low-density, trapped plasma. The star does not show any evidence for radio emission, as seen in the helium-strong star HD 37479, perhaps because of the weak field. It is also possible that the field in this star is too weak to prevent the outflow from occurring at the magnetic equator, but that it is strong enough to trap and funnel matter once the flow has reached some distance from the star. The plasma appears to be trapped in a field region, contiguous with the stellar surface (there is no evidence for a velocity gap in the profile, although it is very optically thick near line center which could obscure such an effect).

If the magnetic field of HD 21699 is different from the other sn stars, perhaps not being equatorially symmetric or being a quadrupole field, it may prevent the formation of a stable magnetosphere. In such a case, the polar outflow would dominate the C IV line formation. As observational support of this conjecture, it should be noted that one of the helium-strong stars, HD 37776, is known to have a strongly quadrupolar magnetic field (Thompson and Landstreet 1985) and does not show strong C IV variations (Shore 1990).

V. SUMMARY

To summarize, we have discovered that HD 5737 and HD 79158 display evidence for magnetospheric plasma, trapped at the magnetic equator, which is corotating with the stellar photosphere. The two stars have periods which are nearly an order of magnitude different from each other, although their magnetic field strengths and atmospheric parameters are similar. These are the only helium-weak stars to show such behavior, which has been well established for the He strong stars. The behavior of these stars is similar to HD 184927, which may also be a long-period system and is one of the coolest of the helium strong stars.

The helium-weak sn stars present a wide range of extremely interesting plasma phenomena. They are not strong radio sources, so there is no evidence for a large population of hot electrons, yet they display C IV lines as strong as those of the hottest helium strong stars. Their variations are stable on time scales of thousands of rotations, and there is no evidence for short term changes in the line profiles on anything other than the rotation period. The magnetic fields are strong and fixed by a stable photospheric field. Yet these stars show evidence for some process heating the plasma, or at any rate maintaining the ionization. Perhaps this is nothing more than what one would expect in ionization equilibrium, that because of the exponentially falling electron densities, the atoms trapped in the magnetosphere are overionized compared with that expected from $T_{\rm eff}$. In this case no additional heat source may be required. A detailed calculation appears in order for the ionization and thermal balance in a stellar magnetosphere.

We wish to thank T. Simon for trading *IUE* observing time on several dates during the 1987 October run, without which we would not have been able to obtain such effective phase coverage. C. Shrader is thanked for his heroic efforts in scheduling such an enormous number of half-shifts. Thanks are also extended to D. A. Klinglesmith III and K. Crain for their kind assistance with the photometric observations of HD 79158 during the winter season 1987–1988. Work at the Joint Observatory for Cometary Research is supported by NASA/Goddard Space Flight Center. We thank D. Tholan, G. Mathys, and P. North for providing photometry of HD 5737 prior to publication. We also thank P. K. Barker, T. Bastien, C. T. Bolton, C. Catala, D. Kurtz, T. LaRosa, and F. Praderie for interesting discussions. This work was supported by NASA and the French Ministry of Education.

REFERENCES

Abt, H. A. 1979, *Ap. J.*, **230**, 485.
Acuna, M. H., Behannon, K. W., and Connerney, J. E. P. 1983, in *Physics of the Jovian Magnetosphere*, ed. A. J. Dessler (Cambridge: Cambridge University Press), p. 2.
Barker, P. K., Brown, D. N., Bolton, C. T., and Landstreet, J. D. 1982, in *Advances in Ultraviolet Astronomy* (NASA CP-2238), p. 589 (BBBL).
Bohlender, D. A., Brown, D. N., Landstreet, J. D., and Thompson, I. 1987, *Ap. J.*, **323**, 325.
Borra, E. F., Landstreet, J. D., and Mestel, L. 1982, *Ann. Rev. Astr. Ap.*, **20**, 191.
Borra, E. F., Landstreet, J. D., and Thomson, I. 1983, *Ap. J. Suppl.*, **53**, 151.
Brown, D. N., Shore, S. N., and Sonneborn, G. 1985, *A.J.*, **90**, 1354.
Drake, S. A., Abbott, D. C., Bastien, T. S., Bieging, J. H., Churchwell, E., Dulk, G., and Linsky, J. L. 1987, *Ap. J.*, **322**, 902.
Groote, D., and Hunger, K. 1982, *Astr. Ap.*, **116**, 64.
Hill, T. W., Dessler, A. J., and Goertz, C. K. 1983, in *Physics of the Jovian Magnetosphere*, ed. A. J. Dessler (Cambridge: Cambridge University Press), p. 353.
Hoffleit, D. 1982, *Catalogue of Bright Stars* (4th ed.; New Haven: Yale University Press).
Klinglesmith, D. A., III, Crain, K., and Shore, S. N. 1988, unpublished.
Kurtz, D. W., and Marang, F. 1987, *M.N.R.A.S.*, **228**, 141.
Lafler, J., and Kinman, T. D. 1965, *Ap. J. Suppl.*, **11**, 216.
Landstreet, J. D. 1980, *A.J.*, **85**, 611.
Lyons, L. R., and Williams, D. J. 1984, *Quantitative Aspects of Magnetospheric Physics* (Dordrecht: Reidel).
Mestel, L. 1968, *M.N.R.A.S.*, **138**, 359.
Pedersen, H. 1979, *Astr. Ap. Suppl.*, **35**, 313.
Percy, J. 1985, *Pub. A.S.P.*, **97**, 856.
Phillips, R. B., and Lestrade, J.-F. 1988, *Nature*, **334**, 329.
Preston, G. W. 1974, *Ann. Rev. Astr. Ap.*, **12**, 257.
Sadakane, K. 1985, *Pub. A.S.P.*, **96**, 259.
Scargle, J. 1982, *Ap. J.*, **263**, 835.
Shore, S. N. 1987, *A.J.*, **94**, 731.
———. 1990, in preparation.
Shore, S. N., and Adelman, S. J. 1981, in *The Chemically Peculiar Stars of the Upper Main Sequence* (Liège: Institut d'Astrophysique), p. 429.
Shore, S. N., and Brown, D. N. 1989, preprint.
Shore, S. N., Brown, D. N., Barker, P. K., and Sonneborn, G. 1984, in *The Universe at Ultraviolet Wavelengths* (NASA CP-2349), p. 487 (SBBS).
Shore, S. N., Brown, D. N., and Sonneborn, G. 1987, *A.J.*, **94**, 737 (SBS87).
———. 1988, in *A Decade of UV Astronomy with the IUE Satellite*, ed. E. Rolfs (ESA SP-281, vol. **1**), p. 339 (SBS88).
Skillman, D. 1986, *J. AAVSO*, **15**, 22.
Thompson, I., and Landstreet, J. D. 1985, *Ap. J. (Letters)*, **289**, L9.
Walborn, N. R. 1983, *Ap. J.*, **268**, 195.

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