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MAGNETICALLY CONTROLLED CIRCUMSTELLAR MATTER IN THE HELIUM-STRONG STARS

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ABSTRACT

This paper reports the observation and interpretation of the ultraviolet spectrum variations of nine helium-strong stars: HD 36485, 37017, 37479, 37776, 58260, 60344, 64740, 96446, and 133518. A unified model is developed to account for the observed correlation among three stellar properties: the line profile characteristics of the C IV and Si IV resonance doublets, the variations in the strength of these lines, and the inferred magnetic field geometry. We propose that circumstellar plasma is trapped in the stellar magnetosphere near the magnetic equator or is channeled to form jetlike outflows from the magnetic polar regions. These results, together with those of our previous study of the helium-weak *sn* stars, show that both helium-weak and helium-strong stars can possess magnetospherically trapped plasma, notwithstanding their different photospheric properties. We also present new results for radii and temperatures of the helium-strong stars in Ori OB 1 and for HD 64740 from low-dispersion *IUE* spectra.

Subject headings: stars: circumstellar shells — stars: magnetic — stars: peculiar A — ultraviolet: spectra

I. INTRODUCTION

The helium-strong stars comprise a relatively small group of early B stars (B1V to B3V) which show unusually strong helium lines for their optical colors. Osmer and Peterson (1974) demonstrated that, in contrast to the hydrogen deficient stars and subdwarfs, they are unevolved objects, and suggested that they represent a high-temperature extension of the Ap/Bp stars. Subsequent observations have supported this interpretation.

Four of the helium-strong stars are members of the well-studied Orion OB 1 association: HD 36485, 37017, 37479, and 37776. Most are spectrum and photometric variables, showing both helium line and continuum variations (Walborn 1983; Hunger 1986). Although most are rapid rotators, with $v \sin i$ between 100 and 200 km s^{-1}, there is a subset with low observed rotational velocities. The rapid rotators are consistently variable in the optical, while the (apparently) slow rotators are typically constant.

Early theoretical work on the helium-strong stars addressed the origin of the helium abundance anomaly in the context of the diffusion model for the chemically peculiar stars, originally developed by Michaud (1980). Vauclair (1975) was the first to present the model of a stellar wind levitating atmospheric helium, which is supported in a cloud at small optical depth. Montmerle and Michaud (1976) showed that the diffusion is counteracted by electrical fields when the He/H ratio is of order unity. Peterson and Theys (1981) developed an alternative model in which radiative acceleration alone can support the helium at the magnetic equator through the effect of the magnetic field.

Shore (1978, 1987) showed that an additional effect of a magnetic field is to produce an anisotropic stellar wind. Nakajima (1985) argued that the hydrogen Balmer emission arises from a trapped, corotating magnetosphere above the magnetic equator and modeled the line profiles. A similar model has been adapted by Groote and Hunger (1982) for HD 37479; Landstreet and Borra (1978) and Borra and Landstreet (1979) have also employed magnetospherically trapped plasma to model the hydrogen line variations.

The phenomenology of these stars involves a complex interaction of radiative, magnetic, and centrifugal processes. Accordingly, large and diverse archives of data are required to characterize the magnetic, photometric, and spectroscopic behavior of these stars. Synoptic photometric observations of the He I λ4026 have been obtained for most stars in this class (Pedersen and Thomsen 1977; Pedersen 1979). Zeeman polarimetric observations by Landstreet and his collaborators have produced complete magnetic curves for most of the brighter members of the class, recently supplementing the standard Hβ magnetic measurements with He I λ5876 polarimetry for four of the stars (Bohlender *et al.* 1987; see also references therein).

The magnetic phenomenology of the stars is diverse. One, HD 37776, is the only confirmed case of a dominantly quadrupolar stellar magnetic field (Thompson and Landstreet 1985). Five stars show dominantly dipolar fields with a considerable range in strength. Repeated measurements of HD 60344 and HD 133518 have revealed no significant effective field at the level of a few hundred gauss, while HD 58260 and HD 96446 show constant fields of approximately 2 kG.

The helium-strong stars have been studied at centimeter wavelengths by Drake *et al.* (1987). Among the helium peculiar stars, HD 37017 and 37479 show the strongest radio emission, which is interpreted as nonthermal radiation from trapped magnetospheric electrons emitting gyrosynchrotron radiation. VLBI observations by Phillips and Lestrade (1988) have resolved the magnetosphere of HD 37479 and confirmed that the radio emission is nonthermal in origin, with brightness temperatures exceeding 10^9 K at 6 cm. Although the plasma heating and acceleration mechanisms are not currently understood, these observations suggest that the UV spectroscopic variations of all helium-strong stars may be the result of magnetospherically trapped circumstellar plasma.

The first report of ultraviolet line profile variations in the helium-strong stars was made nearly a decade ago (Shore and Adelman 1981, p. 429). This first *IUE* study concentrated on

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the C IV and Si IV resonance lines, demonstrating that the profiles in HD 37017, 37479, and 37776 varied on the rotation timescale. Subsequent work by Barker *et al.* (1982) delineated the phenomenology of the resonance line profiles in the helium-strong stars. They found that the profile morphologies could be divided into three general types: (1) variable, but always in absorption; (2) constant, strong absorption; (3) constant, asymmetric, redward-shaded emission. The variable profiles are associated with rapidly rotating stars, and the constant profiles are typically associated with slow rotators.

During the past seven years, a considerable archive of high-dispersion ultraviolet spectra has been accumulated. It is now possible to derive from these data a comprehensive model for the UV line profiles and their relation to the overall properties of the helium-strong stars. The purpose of this paper is to present the details of this behavior and to show how they can be understood in terms of a unified model, in which the UV resonance lines are formed in circumstellar material trapped above the magnetic equator and in jetlike outflows occurring above the magnetic poles, collimated by the magnetic field.

II. OBSERVATIONAL DETAILS

All observations presented in this study were obtained, between 1979 and 1984, with the *International Ultraviolet Explorer* satellite (*IUE*) at high dispersion, using the short-wavelength primary (SWP) camera. While some spectra were exposed through the small aperture, most were obtained using the large aperture for which the flux calibration is better determined. The journal of observations is contained in the tables, which present tabulated results for the ultraviolet line strengths.

The spectra were reduced using standard programs at the Regional Data Analysis Facility (RDAF) at Goddard Space Flight Center (GSFC). These were supplemented with special routines tailored to the analysis discussed in this paper and in our studies of the helium-weak stars (Shore, Brown, and Sonneborn 1987, 1988; Shore *et al.* 1990). Synthetic photometry of the C IV λλ1548, 1550 lines and of the Si IV λλ1394, 1403 lines was obtained by forming the indices *a*(C IV) and *a*(Si IV) described in Shore *et al.* (1987). The bandpasses are centered at 1542, 1548, and 1562 Å; each is 2 Å wide. The C IV λ1550 line is blended with iron peak lines which compromise the direct measurement of equivalent widths. The one alteration is that, as in Shore *et al.* (1990), we have adopted the revised convention that these indices are positive for *absorption.* For HD 37479, a similar index has been formed for the Al III doublet at λλ1856, 1863 using continuum points λλ1853.0 and 1856, with the line filter placed at 1854.5 Å; all bandpasses are rectangular profiles of 1 Å width. These measurements are included for completeness, since equivalent width measures have been previously published by Shore and Adelman (1981) for σ Ori E. Radial velocities have been measured by cross-correlation using the procedure CRSCOR (available at the GSFC RDAF).

While the quasi-photometric method is not a substitute for direct profile modeling, it provides a reproducible measure of the equivalent widths for the C IV and Si IV lines. Most important is the fact that it is insensitive to the placement of the continuum. The characteristics of the bandpasses from which *a*(C IV) and *a*(Si IV) are constructed were empirically determined to maximize their reproducibility in our study of the helium-weak *sn* stars. The individual bandpasses are made narrower than the widths of the lines to ensure that only the strongest portion of the line core is sampled. Their placement discriminates against the abundant Fe III lines which are strongly blended with the lines of interest, notably C IV λ1550.

Radial velocity measurements of our helium-strong stars have revealed no significant variability for any of these lines (see § III below). The resonance line profiles of all the stars in our sample are stable to far greater precision than the 390 km s^{-1} width of the bands from which *a*(C IV) is formed. We have, therefore, retained the previous definitions of *a*(C IV) and *a*(Si IV) in order to produce a consistent data set embracing these two varieties of the helium-peculiar stars.

Four of our helium-strong stars exhibit photometric or spectroscopic variations for which periods are known. One additional star, HD 96446, has a probable short photometric period (see below). We have used the magnetic field measurements of Landstreet and his collaborators (Borra and Landstreet 1977; Thompson and Landstreet 1985; Bohlender *et al.* 1987). Photometry is available for a few of these stars, notably HD 37479 (Hesser, Moreno, and Ugarte 1977). He I λ4026 line variations have been studied for these stars by Pedersen and Thomsen (1977) and Pedersen (1979). In a few cases discussed below, the data presented here are sufficient to allow checks of the published periods using the codes previously described in Shore *et al.* (1987).

III. OBSERVATIONAL RESULTS: ULTRAVIOLET LINE VARIATIONS

All the stars in this study have been extensively described in the literature; we refer the interested reader to Bohlender *et al.* (1987) for a summary of the relevant papers. Table 1 summarizes the observed physical properties of these stars relevant to our discussion.

a) HD 36485 = δ Orion C

Table 2 gives the values of the line strength indices determined from the available spectra. Although the stellar rotation

TABLE 1

SURVEY HELIUM-STRONG STARS: BASIC PROPERTIES

Star	Period (days)	$v \sin i$ (km s^{-1})	$B_{\rm eff}$ Extrema (G)
HD 36485........	...	32	−3400, constant
HD 37017........	0.901195	≤95[b]	−350 to −2170
HD 37479........	1.19081	170[a]	+2810 to −1490
HD 37776........	1.53869	95	+2540 to −2180
HD 58260........	...	≤30[c]	+2300, constant
HD 60344........	...	≤30	Below detection
HD 64740........	1.33026	160	+490 to −890
HD 96446........	...	≤30	−1650, constant
HD 133518.......	...	≤30	Below detection

NOTES.—Cols. (2) and (4): Bohlender *et al.* 1987; Col. (3): Walborn 1983.

[a] Bolton *et al.* 1986 give 162 km s^{-1}.

[b] Bohlender *et al.* 1987 quote Bolton (1987, private communication).

[c] Bohlender *et al.* 1987 give ≤18 km s^{-1} for this star.

TABLE 2

HD 36485: C IV AND Si IV MEASUREMENTS

SWP	JD	*a*(C IV)	*a*(Si IV)
19103.......	5362.604	−0.043	0.258
19120.......	5363.715	0.103	0.296
19137.......	5364.770	0.093	0.315
19150.......	5365.701	0.101	0.306
19339.......	5392.728	0.071	0.315

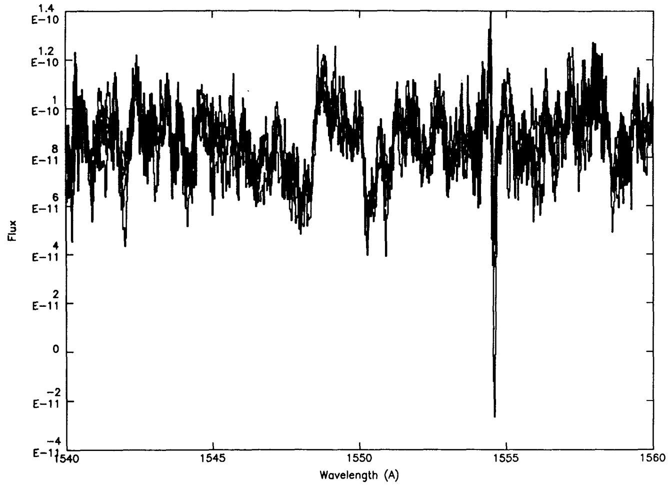

FIG. 1.—HD 36485. Overplot of five observed C IV profiles, each smoothed to three points.

period is unknown, Bohlender *et al.* (1987) report $v \sin i = 32$ km s^{-1} and argue that 7.4 days is an upper limit. The dispersion of a(C IV) suggests a modest amplitude of variation, while the a(Si IV) values are consistent with constant equivalent width. Figure 1 shows the range of observed C IV line profiles and contains all available spectra.

For HD 36485, as for the other three helium-strong stars in the Ori OB 1 association, we have been able to independently determine additional physical properties using *IUE* data. We have obtained low-dispersion, large-aperture short-wavelength primary (SWP) and long-wavelength primary (LWP) and redundant (LWR) spectra of this and the other helium-strong stars, described below. A recent study by Bohlender (1989) provides a temperature, determined from optical data, of 19,000 K. Low-dispersion *IUE* spectra newly obtained for this project, SWP 38185 and LWP 17356, have been measured between 1150 and 3400 Å to provide an integrated UV continuum flux $F_{\rm UV} = 1.09 \times 10^{-7}$ ergs cm^{-2} s^{-1}. Applying the reddening correction given by Warren and Hesser (1977, 1978) of $E(B-V) = 0.052$ gives $F_{\rm UV}^{\rm cor} = 1.61 \times 10^{-7}$ ergs cm^{-2} s^{-1}. Since the distance is known for this star (480 pc), we can determine the radius directly. We have used interpolated models from the Kurucz (1979) atmospheres grid to determine the UV flux, hence the radius. For HD 36485, this procedure gives 3.8 $R_\odot$, independent of any assumptions of period.

b) *HD 37017*

Table 3 gives the data for the variations in the C IV and Si IV line strength observed with *IUE*. Figure 2 shows the variations of a(C IV), a(Si IV), and effective magnetic field, plotted on the magnetic period of $0\overset{\mathrm{d}}{.}901195$ (Bohlender *et al.* 1987), but with an arbitrary initial epoch of 2,443,000.0.

The He I λ4026 photometry of Pedersen (1979) shows that the helium is strongest at the magnetic pole. The C IV and Si IV variations are clearly in phase with one another and in antiphase with the $B_{\rm eff}$. Both lines are strongest at the phase of magnetic equatorial traverse across the line of sight. The strength of C IV absorption, measured by a(C IV), is the weakest of the C IV spectrum variables in the sample; only the nonvariable HD 36485 shows weaker absorption. The profiles remain fairly symmetric throughout the cycle of variation.

TABLE 3

HD 37017: C IV AND Si IV MEASUREMENTS

SWP	JD	a(C IV)	a(Si IV)
7538.......	4241.747	0.235	0.546
7557.......	4243.390	0.134	0.451
7562.......	4243.663	0.300	0.546
7585.......	4245.276	0.217	0.489
7591.......	4245.578	0.442	0.650
7593.......	4245.674	0.317	0.607
7611.......	4247.505	0.282	0.529
7612.......	4247.551	0.267	0.530
7614.......	4247.656	0.170	0.447
7616.......	4247.758	0.136	0.396
15750.......	4953.659	0.289	0.513
15752.......	4953.713	0.240	0.551
15754.......	4953.759	0.274	0.558
15756.......	4953.804	0.308	0.540
15758.......	4953.849	0.415	0.557
15777.......	4955.717	0.452	0.690
15779.......	4955.765	0.460	0.641
15781.......	4955.812	0.316	0.581
15808.......	4958.599	0.209	0.501
15810.......	4958.654	0.139	0.471
15812.......	4958.705	0.147	0.412
15814.......	4958.751	0.171	0.409
15816.......	4958.798	0.141	0.479

Because HD 37017 is a known spectroscopic binary, we have searched carefully for radial velocity variations of and between C IV and Si IV. Each line was measured separately on each spectrum using cross-correlation relative to spectrum SWP 7538. We find no significant indication of differential radial velocity between these lines; for C IV, $\langle \Delta v_{\rm rad} \rangle = -1.6 \pm 19.4$ km s^{-1}, while for Si IV $\langle \Delta v_{\rm rad} \rangle = +8.1 \pm 7.7$ km s^{-1}. The mean difference between the radial velocities of the Si IV and C IV lines is $\langle v_{\rm rad,C\,IV} - v_{\rm rad,Si\,IV} \rangle = -6.2 \pm 12.4$ km s^{-1}.

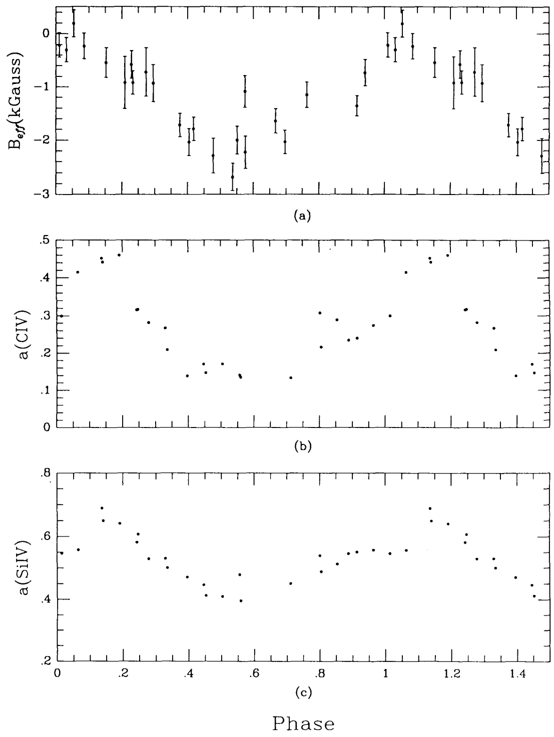

FIG. 2.—HD 37017. Variations of (*a*) $B_{\rm eff}$, (*b*) a(C IV), and (*c*) a(Si IV). Notice that C IV and Si IV minima coincide with the maximum of $B_{\rm eff}$.

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We have used the same UV flux procedure for HD 37017 as described for HD 36485 using archival spectra. The results are $F_{\rm UV} = 1.80 \times 10^{-7}$ ergs cm^{-2} s^{-1}. Using $E(B-V) = 0.062$ gives $F_{\rm UV}^{\rm cor} = 2.88 \times 10^{7}$ ergs cm^{-2} s^{-1}. Model atmosphere fitting gives $22500 < T_{\rm eff} < 25{,}000$ K, so that we obtain $3.4 < R < 4.2\ R_\odot$. Bohlender *et al.* (1987) quote a rotational velocity of ≤ 95 km s^{-1}.

c) *HD 37479 = σ Orion E*

The ultraviolet line data are provided in Table 4 for C IV, Si IV, and Al III. The latter resonance line, Al III λ1855, has previously been discussed for this star by Shore and Adelman (1981) and is included here for comparison. The variation of ultraviolet line indices and effective magnetic field are plotted in Figure 3, together with the photometric He I λ4026 index, *R*(He) (Pedersen 1979). The ephemeris is that based on the photometric period (Hesser *et al.* 1977):

$$\text{JD}(uvby\ \text{minimum}) = 2{,}442{,}778.81863 + 1^{\rm d}.19081E\ . \quad (1)$$

The variation of *R*(He) is roughly in antiphase with that of *a*(C IV): the strongest He I coincides with the weaker of the two C IV minima at the phase of strongest (positive) effective field. The C IV line profile remains substantially symmetric during the variation, and there is no significant radial velocity variability in any of the UV resonance lines.

HD 37479 is unique among the helium-strong stars for the close correspondence between the variations of its UV resonance line indices and its *uvby* light curves. C IV is strongest around the photometric minima, which have been shown to correspond to the magnetic equatorial crossings of the line of sight (Borra and Landstreet 1979; Groote and Hunger 1982). The scatter in the ultraviolet line indices shown in Figure 3 is small, indicating that the configuration of the trapped plasma is stable on a time scale of years.

TABLE 4

HD 37479: C IV, Si IV, AND Al III

SWP	JD	*a*(C IV)	*a*(Si IV)	*a*(Al III)
4840.......	3966.743	0.528	0.877	0.204
6116.......	4094.222	0.498	0.719	0.354
7529.......	4241.206	0.821	0.893	0.417
7532.......	4241.419	0.651	0.780	0.280
7534.......	4241.536	0.702	0.936	0.432
7536.......	4241.651	0.779	0.972	0.534
7537.......	4241.694	0.916	0.939	0.348
7553.......	4243.194	0.337	0.537	0.151
7555.......	4243.290	0.351	0.439	0.217
7556.......	4243.340	0.378	0.481	0.204
7558.......	4243.442	0.491	0.613	0.350
7560.......	4243.569	0.821	0.830	0.561
7583.......	4245.141	0.758	0.966	0.391
7587.......	4245.378	0.453	0.828	0.297
7589.......	4245.476	0.420	0.731	0.244
7607.......	4247.322	0.574	0.811	0.310
15751.......	4953.690	0.755	0.901	0.457
15753.......	4953.739	0.807	1.013	0.492
15755.......	4953.783	0.693	0.973	0.432
15757.......	4953.828	0.654	0.993	0.407
15759.......	4953.853	0.549	0.898	0.364
15774.......	4955.617	0.699	0.718	0.434
15778.......	4955.744	0.754	0.807	0.378
15780.......	4955.792	0.621	0.793	0.291
15782.......	4955.838	0.598	0.711	0.358
15785.......	4956.601	0.320	0.481	0.238
15786.......	4956.624	0.361	0.485	0.225
15787.......	4956.650	0.382	0.481	0.194
15811.......	4958.685	0.494	0.856	0.381
15813.......	4958.731	0.439	0.759	0.306
15815.......	4958.778	0.501	0.759	0.310
15817.......	4958.824	0.366	0.669	0.268

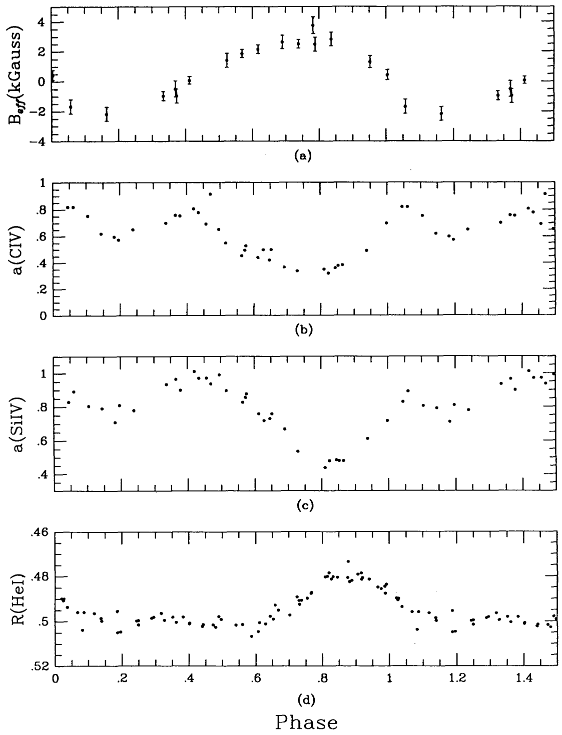

FIG. 3.—HD 37479. Variations of (*a*) $B_{\rm eff}$, (*b*) *a*(C IV), (*c*) *a*(Si IV), and (*d*) *R*(He I) λ4026 (Pedersen 1979) for HD 37479. See text for phasing.

HD 37479 is also the strongest Hα emitter among the helium-strong stars (Walborn 1983), the strongest nonthermal radio source, and the only star among the magnetic peculiar stars for which VLBI measurements of the extent of the trapped plasma are available (Phillips and Lestrade 1988).

The lower bound on the radius is given by the rotational velocity and period, so that $R \geq 3.8\ R_\odot$. Archival *IUE* spectra give $F_{\rm UV} = 1.809 \times 10^{-7}$ ergs cm^{-2} s^{-1}, and with $E(B-V) = 0.060$ we obtain $F_{\rm UV}^{\rm cor} = 2.93 \times 10^{-7}$ ergs cm^{-2} s^{-1}. For a temperature of 24,000 K, which is the best fitting interpolated model, we obtain $R = 4.2\ R_\odot$ (see discussion of HD 64740, below).

d) *HD 37776*

HD 37776 is known to possess a quadrupole magnetic field (Thompson and Landstreet 1985), the only such case verified for a chemically peculiar main-sequence star. It is a rapidly rotating star with a short period, 1.53869 days.

The variations of the ultraviolet line indices and of the effective magnetic field (Thompson and Landstreet 1985) are plotted in Figure 4; the values of *a*(C IV) and *a*(Si IV) appear in Table 5. The Si IV variations are poorly correlated with those of C IV, and their amplitude is somewhat smaller.

Many *IUE* spectra have been obtained for HD 37776, primarily because of its complicated magnetic and photometric behavior. They permit exceptional phase coverage of the C IV and Si IV variations. As first noted by Barker *et al.* (1982), the variation in the resonance line equivalent widths is not large. A periodogram analysis of the *a*(C IV) data independently yields

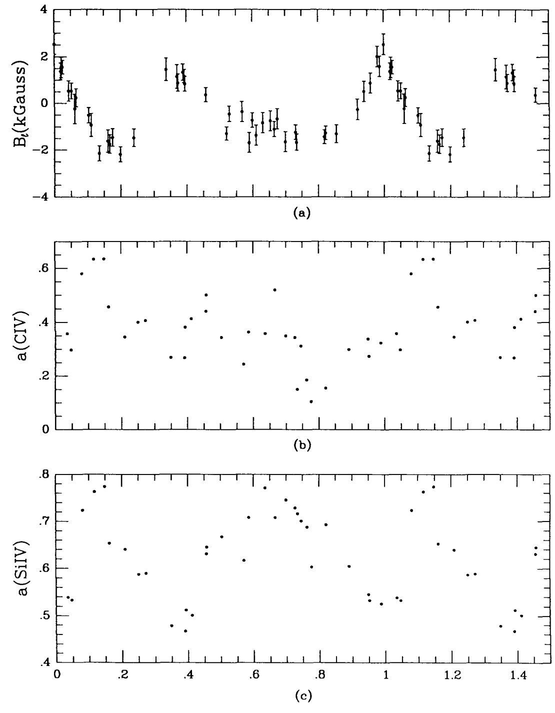

FIG. 4.—HD 37776. Variations of (*a*) $B_{\rm eff}$, (*b*) *a*(C IV), and (*c*) *a*(Si IV).

TABLE 5

HD 37776: C IV and Si IV MEASUREMENTS

SWP	JD	*a*(C IV)	*a*(Si IV)
7535.......	4241.601	0.635	0.774
7539.......	4241.793	0.407	0.590
7554.......	4243.233	0.346	0.640
7559.......	4243.514	0.268	0.467
7561.......	4243.613	0.441	0.631
7584.......	4245.225	0.344	0.667
7586.......	4245.328	0.244	0.617
7588.......	4245.428	0.358	0.771
7590.......	4245.524	0.350	0.746
7592.......	4245.625	0.186	0.688
7608.......	4247.360	0.300	0.605
7610.......	4247.455	0.274	0.533
7613.......	4247.601	0.298	0.533
7615.......	4247.708	0.634	0.763
7675.......	4255.855	0.413	0.501
7694.......	4257.878	0.344	0.729
19102.......	5362.565	0.519	0.708
19105.......	5362.669	0.151	0.717
19107.......	5362.736	0.106	0.604
19109.......	5362.803	0.156	0.693
19117.......	5362.615	0.269	0.478
19119.......	5363.683	0.382	0.512
19122.......	5363.782	0.501	0.645
19131.......	5364.538	0.339	0.546
19134.......	5364.671	0.358	0.539
19136.......	5364.740	0.580	0.724
19145.......	5365.517	0.364	0.708
19152.......	5365.763	0.312	0.701
19333.......	5392.561	0.457	0.653
19338.......	5392.698	0.401	0.588
19440.......	5404.555	0.324	0.526

TABLE 6

HD 58260: C IV AND Si IV MEASUREMENTS

SWP	JD	*a*(C IV)	*a*(Si IV)
14441.......	4796.182	−0.234	0.076
14458.......	4798.158	−0.215	0.073
14471.......	4800.149	−0.239	0.079
14490.......	4802.147	−0.263	0.046
14507.......	4804.167	−0.212	0.158
14658.......	4822.013	−0.279	0.027
15775.......	4955.643	−0.248	0.072

the magnetic period, but the details of the C IV line profile changes are complex and appear to be only weakly determined by the peculiar magnetic geometry. Thus, the details of the distribution and stability of the magnetospheric plasma of HD 37776 remain poorly determined by these data. Since the magnetic geometry of this star is unique in our sample, we are tempted to speculate that it also has an unusually complicated plasma environment.

Given the complexity of the observed variation, an attempt was made to set upper limits to the radial velocity variation of C IV in HD 37776. Spectra were cross-correlated against SWP 7535; we find no evidence for radial velocity variation at the level of 10 km s^{-1}. As for HD 37017, this limit is small compared with the rotational velocity of the star. For HD 37776 we have measured archival *IUE* spectra as in the previous cases of the Ori OB 1 stars to obtain $F_{\rm UV} = 1.25 \times 10^{-7}$ ergs cm^{-2} s^{-1}. The reddening for this star is somewhat higher than for the other Orion stars, $E(B-V) = 0.081$, yielding a corrected flux $F_{\rm UV}^{\rm cor} = 2.31 \times 10^{-7}$ ergs cm^{-2} s^{-1}. A best fitting atmosphere yields an effective temperature of 22,500 K, which gives $R = 3.7\ R_\odot$. This agrees very well with the value quoted by Thompson and Landstreet (1985) of 3.8 $R_\odot$.

e) HD 58260

The data are listed in Table 6, and the line profiles for C IV are shown in Figure 5. The C IV is consistently in emission, while the Si IV is only weakly seen in absorption. The dispersion in *a*(C IV) is the smallest observed for any helium-strong star, and is consistent with constancy. The C IV line profiles are *always seen in redward-shaded emission* with no hint of a blue-

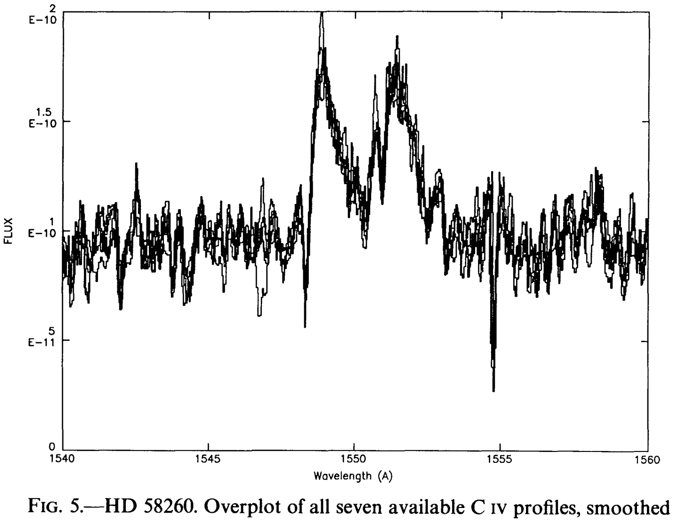

FIG. 5.—HD 58260. Overplot of all seven available C IV profiles, smoothed to three points.

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TABLE 7

HD 60344: C IV AND Si IV MEASUREMENTS

SWP	JD	a(C IV)	a(Si IV)
6811.......	4156.827	2.127	1.722
7676.......	4255.905	1.602	1.543

ward extension on the emission profile. There is, however, a hint of weak absorption on the blueward side, suggestive of interstellar absorption.

He I λ4026 photometry led Pedersen (1979) to suggest a possible period of $1^{\rm d}.657 \pm 0^{\rm d}.004$ for HD 58260, but this ephemeris is not sufficiently precise to provide an unambiguous phasing for our observations. We have too few spectra with which to support an independent period determination. The 10 magnetic observations of this star (Borra and Landstreet 1979; Bohlender *et al.* 1987) are consistent with a constant effective field of 2.3 kG; we assume this simplest interpretation in the following discussion.

Bohlender (1989) has recently performed a detailed optical analysis of HD 58260 (see next section). He obtains $T_{\rm eff}$ = 19,000 K. There are no low-dispersion spectra available from *IUE*, nor is the distance known for this star. We are, therefore, unable to compare this star directly with the Ori OB 1 helium-strong stars.

f) HD 60344

The ultraviolet line indices are given in Table 7 and the C IV profiles shown in Figure 6. The two *a*(C IV) values demonstrate that the C IV doublet in this star is the strongest observed in any helium-peculiar star. The differences in both C IV and Si IV between the two spectra are suggestive of variation. But because the spectra were taken through different apertures during the first two years of *IUE* operations, this apparent variation is suspect.

g) HD 64740

The data on the C IV and Si IV lines are provided in Table 8. The variations of the line indices and the effective magnetic field are shown in Figure 7, phased using the period of $1^{\rm d}.33026$ from Bohlender *et al.* (1987) and an arbitrary initial epoch JD 2,443,000.0. The field reverses sign, varying between +0.5 and −0.9 kG.

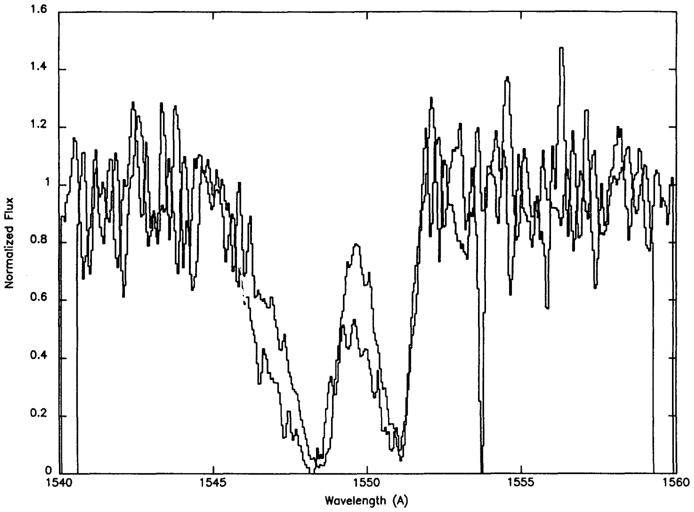

FIG. 6.–HD 60344. Overplot of both available C IV profiles, smoothed to three points.

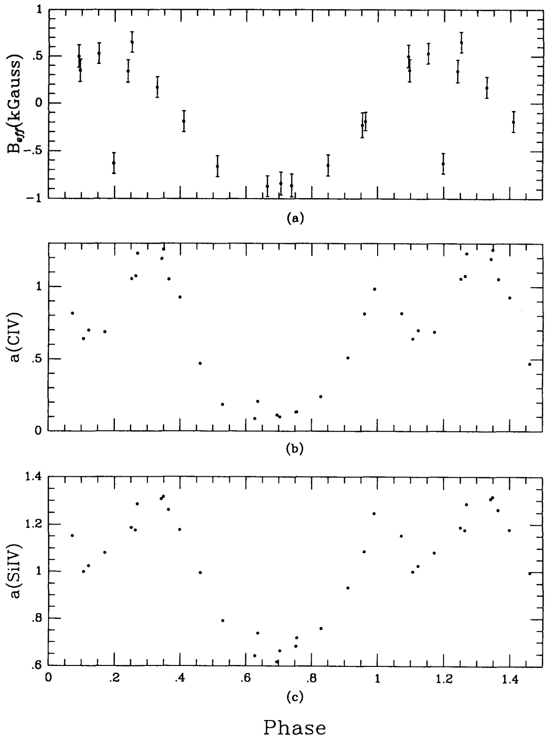

FIG. 7.—HD 64740. Variations of (*a*) $B_{\rm eff}$, (*b*) *a*(C IV), and (*c*) *a*(Si IV).

The *IUE* spectra for this star show that the C IV profile varies with two nearly equal maxima separated by $0^{\rm P}.4$. The weakest C IV absorption, consistent with *a*(C IV) = 0, occurs at *strongest* (negative) $B_{\rm eff}$. The strongest C IV occurs when the magnetic equator transits the line of sight. The character of the magnetic field and C IV variations is strikingly similar to that

TABLE 8

HD 64740: C IV AND Si IV MEASUREMENTS

SWP	JD	a(C IV)	a(Si IV)
5817.......	4071.000	0.642	1.000
14459.......	4798.185	0.133	0.719
14472.......	4800.176	1.056	1.187
14491.......	4802.174	0.133	0.683
14508.......	4804.192	1.231	1.286
14659.......	4822.051	0.113	0.617
14686.......	4824.243	1.194	1.308
15760.......	4853.898	0.208	0.738
15809.......	4958.628	1.052	1.262
19101.......	5362.528	0.986	1.246
19104.......	5362.638	0.816	1.153
19106.......	5362.704	0.700	1.025
19108.......	5362.769	0.688	1.081
19118.......	5363.645	0.240	0.758
19121.......	5363.752	0.511	0.932
19123.......	5362.817	0.813	1.086
19132.......	5364.576	0.186	0.792
19135.......	5364.707	0.088	0.642
19138.......	5364.808	0.100	0.664
19146.......	5365.553	1.076	1.176
19149.......	5365.666	1.258	1.317
19151.......	5365.733	0.929	1.177
19153.......	5365.815	0.471	0.996

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TABLE 9

HD 96446: C IV AND Si IV MEASUREMENTS

SWP	JD	a(C IV)	a(Si IV)
5765.......	4064.819	−0.106	0.261
14443.......	4796.239	−0.110	0.241
14460.......	4798.212	−0.161	0.264
14473.......	4800.199	−0.203	0.299
14492.......	4802.197	−0.161	0.235
14509.......	4804.218	−0.121	0.281
14660.......	4822.081	−0.204	0.278
15776.......	4955.676	−0.145	0.344

reported recently for the significantly cooler helium-weak star HD 5737 = α Scl (Shore *et al.* 1990), although the amplitude of the a(C IV) variation in this star is roughly 3 times greater, and the rotation period roughly 15 times shorter, than in its helium-weak counterpart.

In a recent optical study of HD 64740, Bohlender and Landstreet (1990) have derived an effective temperature of 25,000 K and log $g = 4.0$. They quote a derived radius of $R = 6.3 \pm 1.8$ $R_{\odot}$ and give $E(B-V) = 0.02$ and a distance of 350 pc. We have used recent archival *IUE* low-dispersion trailed spectra, SWP 32568 and LWP 12335, to independently determine the temperature and radius. The best fitting Kurucz (1979) model is 25,000 K. For comparison, we computed several helium-strong models, using recently calculated opacity distribution functions from Kurucz (1989, private communication). The most extreme model, $T_{\rm eff} = 25{,}000$ K, log $g = 4.0$, and He/H = 0.83, agrees with a normal model to within 1% over the entire *IUE* range of the ultraviolet. We obtained $F_{\rm UV}^{\rm cor} = 2.05 \times 10^{-4}$ ergs cm^{-2} s^{-1} which, when compared with the calculated UV flux from the model atmosphere, gives $R = 6.1$ $R_{\odot}$, in excellent agreement with Bohlender and Landstreet's (1990) result.

h) *HD 96446*

The C IV and Si IV line data are given in Table 9, and the C IV line profiles are plotted in Figure 8.

HD 96446 and HD 58260 are the only helium-strong stars which systematically display C IV emission. The C IV profile in HD 96446 is consistently truncated on the blueward side, with no absorption trough (as in a P Cyg line profile) and displays a redward-shaded emission. The Si IV profile is weak and in absorption. There is only weak evidence for variability of either line; no period can be determined from the present observations.

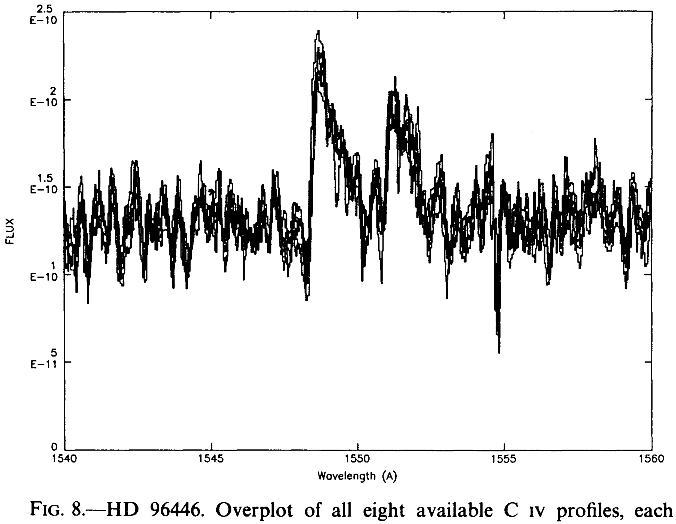

FIG. 8.—HD 96446. Overplot of all eight available C IV profiles, each smoothed to three points.

TABLE 10

HD 133518: C IV AND Si IV MEASUREMENTS

SWP	JD	a(C IV)	a(Si IV)
5816.......	4070.940	1.015	0.695
14662.......	4822.142	1.234	0.900
14684.......	4824.187	1.166	0.862

i) *HD 133518*

There are three archival SWP images of this star, all of which show extremely strong C IV absorption (a(C IV) > 1). The profiles are nearly symmetric, completely saturated, and strongly resemble those of HD 60344. The data are provided in Table 10, and line profiles are plotted for C IV in Figure 9.

IV. INTERPRETATION OF OBSERVATIONAL RESULTS: OBLIQUE ROTATOR MODELS

In this section, we use the theory developed by Shore (1987) to analyze the C IV variations of the helium-strong stars in our sample. The immediate motivation for our approach arises from the successful interpretation of similar C IV resonance line variations in three helium-weak stars (Brown *et al.* 1985; Shore *et al.* 1987, 1990). Two of these stars possess trapped magnetospheric plasma near the magnetic equatorial plane, while the third exhibits only a collimated outflow from one magnetic pole. Curiously, the rotation periods of the stars that possess trapped circumstellar plasma differ by one order of magnitude, while the amplitudes of their magnetic curves differ by a factor of 2.3.

As documented above, the relative phases of a(C IV) and $B_{\rm eff}$ variations in these stars are apparently consistent with the assumption that hot plasma is trapped above the magnetic equator and is rigidly corotating in the oblique magnetic frame. Our goal is to determine whether the models based on this assumption are consistent with other available observations of these stars. Such oblique rotator models are parameterized by the obliquity of the magnetic axis to the rotational

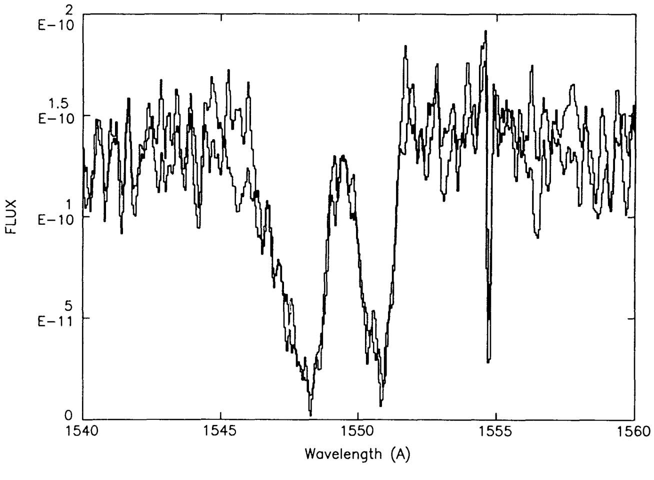

FIG. 9.—HD 133518. Overplot of the three available C IV profiles, each smoothed to three points. The continuum flux of the small aperture image, SWP 5816, has been matched to that of the large aperture images at λ1542.

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pole, β, and the inclination of the rotation axis to the line of sight, i. For a symmetric distribution, the separation in phase of the two maxima of the C IV, which are produced by the magnetic equator crossing the observer's line of sight, is given by

$$\Delta\Phi = 2\cos^{-1}(\cot i \cot \beta)\,, \tag{2}$$

(Shore 1987) so that the observation of two maxima requires that $i + \beta \geq 90°$. In most cases, the rotation period and stellar radius allow the determination of i so that the unknown factor, β, can be obtained from the C IV variations. Effective magnetic field measurements (Bohlender *et al.* 1987) usually provide an independent determination of β.

a) HD 36485

The appearance of the C IV lines in δ Ori C is consistent with that expected for a nearly aligned (oblique) rotator. The line profiles are similar to those observed at the weakest line phase of HD 37017: intermediate between those of HD 58260 or 96446 and those of the spectrum variables. The low observed $v \sin i$ suggests that the rotation and magnetic axes are roughly coincident and lie nearly in the line of sight. While more details of this configuration will be discussed below (see HD 58260 and HD 96446), we argue that the low rotational velocity and high field strength observed in δ Ori C are best understood in the context of the oblique rotator model. The parameter values implied are thus $i \approx 0°$ and $\beta \approx 0°$.

Bohlender (1989) has modeled the profiles of He I $\lambda\lambda$4121, 4168, and 4437 and of Si III $\lambda\lambda$ 4567, 4574 using a line synthesis program that incorporates the effects of a magnetic field and nonuniform abundances. He proposes that $i \approx 10°$ and $\beta \approx 0°$.

b) HD 37017

The magnetic measurements by Bohlender *et al.* (1987) give $23° \leq i \leq 37°$ and $42° \leq \beta \leq 59°$. We obtain $i \leq 27°$. The single waveform of the a(C IV) variation and the fact that the equator appears to cross the line of sight imply that $i + \beta \approx 90°$, consistent with the effective magnetic field results. The Si IV and C IV variations are strictly in phase, indicating that the high-temperature plasma is uniquely located near the magnetic equator. There is no evidence for higher harmonics in the variations.

c) HD 37479

The parameters listed by Bohlender *et al.* (1987) are $78° \leq i \leq 90°$ and β much larger than 0°, but otherwise indeterminate. Using our determination of the radius, $R = 4.1 \pm 0.1\ R_\odot$, along with the published rotational velocity and period yields $i = 70° \pm 5°$. Since the *IUE* results show that there are two C IV maxima, we determine β using equation (2) to be approximately 56°.

The maxima are coincident with the phases at which Groote and Hunger (1982) report deepest sharp line cores on the higher Balmer lines and Bolton *et al.* (1986) report Hα maxima. The optical helium line strength maximum occurs at the transit of the stronger magnetic pole, the weakest phase of C IV and Si IV.

The simplest explanation of these data is that scattering and absorption in the optically thick magnetospherically trapped plasma produces the observed line strength variations in the Balmer line cores and the visual photometric variations.

d) HD 37776

Given the quadrupolar field configuration of this star, it is not surprising that the relationships among its optical and ultraviolet spectra and its effective magnetic field are complex. We assume that, as in the cases of dipolar field geometry, the line-forming plasma is trapped in regions of horizontal field lines. It appears that C IV absorption is weakest at the phase of the broad negative magnetic field extremum, consistent with this assumption. No other characteristic of the C IV and $B_{\rm eff}$ variations suggests such a straightforward interpretation. In contrast to the cases of HD 64740 and HD 37479, the Si IV and C IV variations are poorly correlated.

The rotational velocity for this star and its radius, $R \approx 3.7\ R_\odot$, yields an inclination of $i \approx 47°$. However, β is indeterminate for this quadrupolar field.

e) HD 58260

HD 58260 possesses a constant effective field of 2300 G and $v \sin i = 18 \pm 2$ km s^{-1}. We therefore consider it an aligned rotator for which the magnetic field and the stellar rotational axis are projected nearly into the line of sight: $i \approx 0°$ and $\beta \approx 0°$. This geometry implies that the C IV–emitting plasma, located near the magnetic equator, always lies nearly in the plane of the sky.

Bohlender's (1989) synthesis of He I and Si III lines yields a best fit for $i \approx 40°$ with $\beta \approx 0°$, but all values in the range $10° \leq i \leq 50°$ yield approximately comparable fits (Bohlender 1990, private communication).

f) HD 60344

The four null magnetic measurements of this star strongly suggest that $B_{\rm eff} \leq 500$ G, while $v \sin i \leq 30$ km s^{-1}. The two available C IV line profiles, while possibly variable, are the strongest observed in any helium-strong star and show no hint of emission. We therefore take this star to be an example of a nearly orthogonal rotator: $i \approx 0°$ and $\beta \approx 90°$. The magnetic equator is always in the line of sight, thus always projected across the stellar disk, accounting for the extremely strong absorption.

g) HD 64740

Bohlender *et al.* (1987) give $i \geq 41°$ and $\beta \leq 76°$. The presumed stellar radius is $3.2 \leq R/R_\odot \leq 6.4$ and $v \sin i \approx 160 \pm 15$ km s^{-1} (Walborn 1983). We can now refine this analysis using the radius determined from UV spectra of 6.1 $R_\odot$. We find $i = 43°$. The separation of the C IV maxima is $\Delta\Phi \approx 0^{\rm p}.3$ so that $\beta = 61°$, which agrees well with the magnetic determination.

h) HD 96446

Like HD 58260, and unlike all other helium-strong stars in our sample, HD 96446 displays strong emission at C IV; like HD 58260, it exhibits a strong and approximately constant effective magnetic field. The available upper limit on $v \sin i$ is consistent with the poorly determined 23 ± 6 day period proposed by Pedersen and Thomsen (1977) for the low-amplitude 4026 Å photometric variations, but Matthews and Bohlender (1988) have recently detected *UBV* photometric variations which yield a period of roughly 0.85 days, leading them to propose that $i < 8°$ and $\beta > 60°$ (Bohlender 1990, private communication).

The discovery of a short period accords with our interpretation of all low rotational velocities among the helium-strong stars as inclination effects. The proposed large obliquity, however, requires some additional comment. The emission in HD 96446 is weaker in all spectra than observed for HD 58260. The absence of C IV absorption constrains the obliquity of the magnetic field to be small compared with 90°, but the precise value depends on the outer radius of the magnetosphere and on the latitudinal extent of the trapped plasma. From fits to C IV variations in HD 64740 (as with HD 5737, see Shore *et al.* 1990), the latitudinal extent of the C IV line forming region is about 20° to 30°; here we assume that the plasma is distributed as $\cos^n \theta$ in magnetic latitude, with $n = 4, 6$. Thus $\beta \leq 70°$, consistent with the results obtained from both the photometric variations and magnetic field. While the a(C IV) values may be consistent with variability, the currently available period is too imprecise to accurately phase these data.

i) HD 133518

Each of our three spectra for HD 133518 exhibits very strong absorption at both C IV and Si IV; we find no evidence for variation. Five magnetic observations at two epochs imply an upper limit of roughly 500 G for B_e. We propose that, like HD 60344 and in contrast with HD 58260 and HD 96446, HD 133518 is a *nearly orthogonal oblique rotator* for which the magnetospheric plasma is always seen projected against the stellar disk and the magnetic pole is never in the line of sight: $i \approx 0°$ and $\beta \approx 90°$.

V. UNIFIED OBLIQUE ROTATOR MODEL: DISCUSSION

The determination of oblique rotator parameters for the stars in our sample gives concrete expression to the following summary of the ultraviolet phenomenology. The stars with large equatorial velocities and short periods show strongly variable C IV and Si IV, while the stars which show low projected rotational velocities all show constant line profiles. Additionally, the stars with weak effective magnetic fields and low rotational velocity show the deepest absorption at Si IV and C IV, while those with no strong effective magnetic fields show constant *emission* at C IV and extraordinarily weak Si IV lines. This leads to the conclusion that *the slowly rotating helium-strong stars are likely seen rotation pole-on*. Indeed, the data can be explained on the parsimonious assumption that there are no anomalously slowly rotating magnetic stars among the upper–main-sequence helium-strong stars of this sample.

The magnetic fields of the spectrum variable helium-peculiar stars are typically highly oblique (Borra, Landstreet, and Thompson 1983; Bohlender *et al.* 1987). In the two cases of helium-strong stars for which null effective field measurements have been reported, the ultraviolet observations suggest highly oblique magnetic geometries viewed approximately pole-on. In two other cases, the presence of emission lines in the UV serves as a strong link between shell phenomenology and magnetic geometry. The stars which show strong, approximately constant magnetic fields, HD 58260 and HD 96446, are the *only* helium-peculiar stars seen to show emission at the C IV line. This is clearly true emission, coming above the stellar continuum.

No radial velocity variability of the C IV lines has been detected for any of the stars in this sample. Similarly, the Si IV lines appear to be constant. The He I optical lines also do not show large $v_{\rm rad}$ variations, especially the best studied star HD 37479 (Groote and Hunger 1982). The line shape variations are qualitatively consistent with those expected if the lines are formed in an extended region trapped at the magnetic equator, which slides over the line of sight as the star rotates.

At the effective temperatures typical of the helium-strong stars, C IV and Si IV should show strong photospheric components (Walborn 1983; Kamp 1982). It is difficult to remove such components from the observed profiles in order to address detailed questions regarding the structure of the proposed circumstellar plasma or to search for contributions from jetlike outflows.

This entanglement of photospheric and circumstellar contributions is most severe among the intermediate obliquity stars. These do not show emission at C IV and never display absorption at C IV and Si IV as strong as the orthogonal rotators. Therefore, the observed resonance line variations are more difficult to model unambiguously. Since we expect that both a polar outflow and magnetosphere are present, and that they are in antiphase with one another, it is likely that some combined effect should be seen. The absorption from a magnetosphere is continuous over the surface of the star, so that for two equally black regions (magnetosphere and jet) the total C IV absorption should be in the ratio of the solid angle subtended by the two. Thus, the magnetosphere should always dominate the profile by about one order of magnitude in equivalent width, all else being equal, and should obscure the presence of the jet. Hence, the currently available data are not inconsistent with the presence of multiple line-forming regions.

None of the stars in our sample exhibit compelling evidence for a polar jet of the sort discussed by Shore (1987) and seen in HD 21699 (Brown, Shore, and Sonneborn 1985; Shore, Brown, and Sonneborn 1987). But two stars (HD 58260 and HD 96446) represent orientations for which the polar cap is always approximately in the line of sight, whereby it is possible that the polar outflow could contribute to part of the observed C IV line. The profiles observed in these stars are peculiar in that they are cut off on the blueward side, although their widths are consistent with having rotation out to the Alfvén surface. That is, they have redward extensions which are consistent with rotational velocities about 10 times that of the stellar photosphere and observed at small inclination. Most of the additional width of the profile is likely due to partial redistribution of the scattered radiation. If a polar jet were present in these stars, however, it would be seen purely in absorption against the disk and would terminate the blueward edge of the profile.

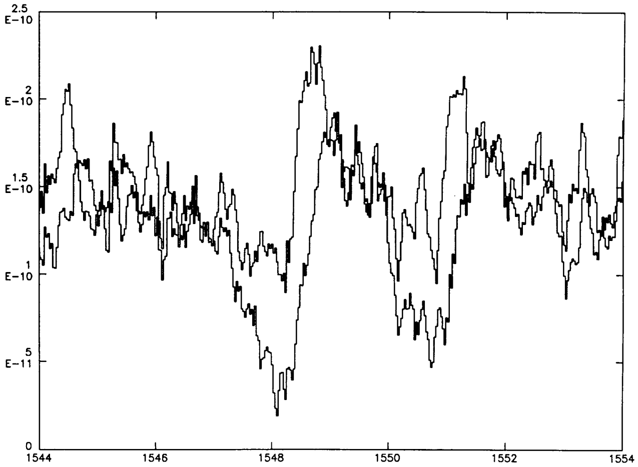

FIG. 10.—Proposed decomposition of the HD 96446 C IV profiles, using HD 21699 as the model for the jet profile (see text).

We have attempted a simulation of this effect by removing the only *observed* jet profile, that of HD 21699 (Brown *et al.* 1985) from the line profile of HD 96446. The strongest jet spectrum (SWP 21081) of HD 21699 was overplotted, without normalization, on the spectrum of HD 96446 (SWP 15776); the actual fluxes are almost identical. The differenced profile was smoothed by a five-point filter. The Fe III lines at λλ1557, 1558 are not the same, nor are the Fe II lines near λ1550, but overall the agreement between the two spectra is very good. The resultant emission-line profiles are nearly symmetric and in the expected ratio of oscillator strengths. We show the comparison between the two spectra in Figure 10. While this exercise is not definitive, it should serve as a "proof of concept." More detailed calculations are not currently available, although model calculations by Kunacz (1984) are consistent with this type of profile for a jetlike outflow. Such a flow produces no emission component and does not look like a normal stellar wind. The combined effect could produce the profile observed. For the high-obliquity/low-inclination objects, for which the magnetic equator is continually in view, the emission from the

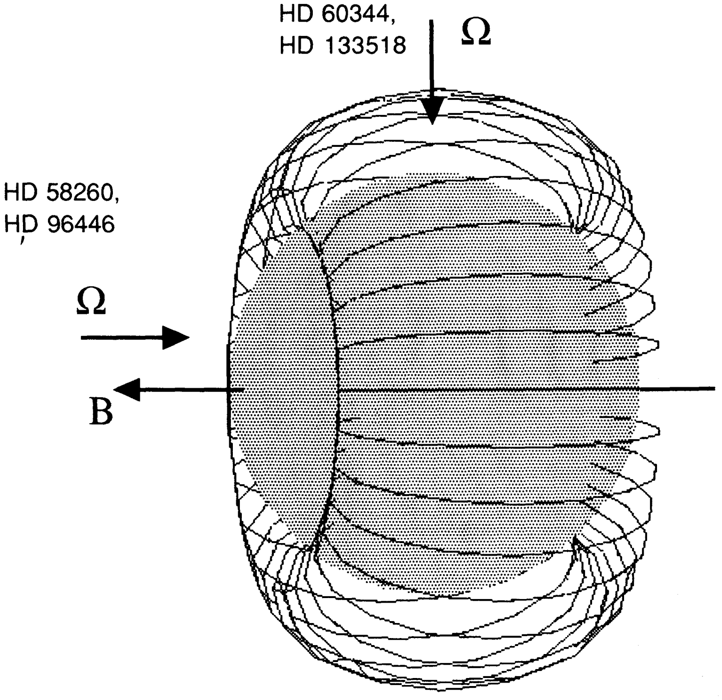

FIG. 11*a*

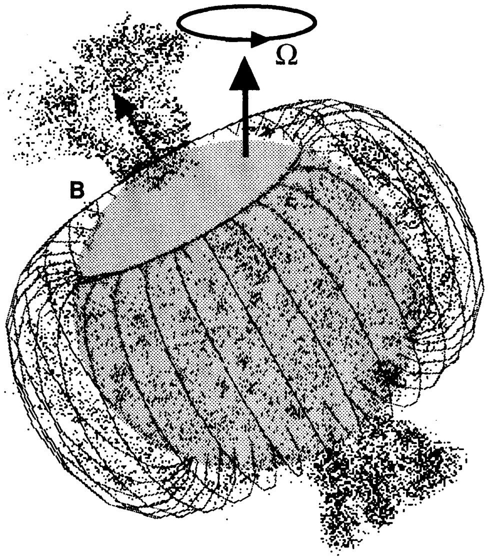

FIG. 11*b*

FIG. 11.—(*a*) Cartoon illustrating the geometry of the proposed model for the constant helium-strong stars. (*b*) Cartoon illustrating the geometry of the proposed model for an oblique rotator of intermediate obliquity.

TABLE 11

DERIVED OBLIQUE ROTATOR PARAMETERS

Star	i	β
HD 36485........	≈0°	nearly aligned
HD 37017........	≤25	≤65°
HD 37479........	72	56°
HD 37776........	≈52	unknown
HD 58260........	≈0	nearly aligned
HD 60344........	≈0	nearly orthogonal
HD 64740........	43	61°
HD 96446........	≈0	intermediate
HD 133518.......	≈0	nearly orthogonal

polar jet is so reduced that it does not contribute to the final profile. Unless seen in absorption against the disk, the effect would not be noticeable.

The currently available archive of high-resolution *IUE* spectra spans more than 1000 rotations for each of the stars of known period. The ultraviolet resonance lines show no detectable variation except that identified as rotational modulation. Thus, the magnetospheres appear to be stable. The best studied cases are HD 37017 and HD 37479, for which the scatter in the C IV line is small, about the same as that observed for HD 5737 (Shore *et al.* 1990). The profile variations over a span of 4 or 5 yr are consistent with the scatter (about 10%) expected in the *a*(C IV) index from the accuracy of the SWP camera.

It is worth emphasizing that a detailed model of the ultraviolet resonance lines in the helium-strong stars will require a fully self-consistent treatment of the radiative coupling between photosphere and trapped circumstellar plasma. Without such a treatment, we cannot expect our model to account for such fine details as the comparison between the line profiles of HD 36485 and HD 58260 or HD 96446.

Finally, on the basis of our unified picture for the helium-strong stars, we venture a prediction. We have specifically excluded one other well-observed helium-strong star, HD 184927, from our sample. This star is a well-known optical spectrum and photometric variable (see, e.g., Levato and Malaroda 1979). However, the proposed period of 9.54 days does not phase together the optical spectra, effective magnetic field, and UV line variations, and may well be severely aliased. For this reason, we cannot phase the relative variations on a consistent period in order to apply the model. Given the similarity in phenomenology of UV resonance line, optical spectroscopic, and optical photometric variability between HD 184927 and the rapid rotators in our sample, we strongly suspect that this star is a member of the rapidly rotating class, observed at small inclination and intermediate obliquity such that $i + \beta \leq 90°$. The magnetic variations are similar to those of HD 37017 in showing only one magnetic pole and presenting a transit of the magnetic equator. This is not to imply that there is anything in the model which specifically excludes intrinsically slow rotation for this or any helium-strong star, merely that the behavior of the group can be quite consistently understood without this assumption.

VI. SUMMARY

The primary result of this study is the demonstration that the variations of the UV resonance lines in the helium-strong stars can be understood on the basis of a single, essentially geometric, model. This model invokes the existence of a dense circumstellar trapped corotating plasma whose axis of symmetry is that of the magnetic field, which is in turn inclined to the rotation axis. In short, the UV variations of these stars are completely consistent with the oblique rotator model required to understand the longitudinal magnetic field variations.

Several important physical questions need now to be addressed. First, what is the mechanism by which the plasma is supplied to the magnetosphere? Is it the same as that hypothesized for the helium-weak stars (Shore *et al.* 1990) possessing centrifugal winds? What is the relation between the trapped plasma and the radio-emitting electrons?

In the context of this model, we are able to discern a striking consistency among the helium-strong stars in their resonance line properties. This stands in distinct contrast with the case of the helium-weak stars. The three helium-weak *sn* stars which have been found to exhibit rotationally modulated C IV appear to be more similar to each other than to the helium-strong stars. Yet two of these show C IV variations very similar to those reported here, while a third shows only a polar outflow (Shore *et al.* 1990). None of the helium-weak stars which are rapid rotators and/or possess strong magnetic fields show the same C IV and Si IV variability. The challenge with which we are now faced is the creation of a unified physical model for the helium-peculiar stars of the upper main sequence.

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