THE ASTROPHYSICAL JOURNAL, 277:241–249, 1984 February 1

ROTATIONAL MODULATION OF THE CHROMOSPHERIC ACTIVITY IN χ^1 ORIONIS (G0 V)

ANN MERCHANT BOESGAARD[1,2] AND THEODORE SIMON[1]
Institute for Astronomy, University of Hawaii
Received 1983 May 16; accepted 1983 July 26

ABSTRACT

The solar type star χ^1 Ori (G0 V) is thought to have an age of 6×10^8 yr (based on its Li abundance) and an apparent rotation period of $5\overset{d}{.}1$ (based on the modulation of its Ca II H and K flux). These characteristics make it well suited for a rotational modulation study of its strong ultraviolet emission lines. We have made *IUE* observations at four different phases during each of three separate rotation cycles over a time span of 325^d. Observations from 1981 March and October and 1982 February can be phased together and result in cyclical variations in the emission lines due to C IV (1549 Å) and He II (1640 Å). The amplitude of the flux variations in C IV exceeds a factor of 2. The sites of activity giving rise to this emission persist with lifetimes comparable to a year (or longer). On the other hand, the flux in the Mg II emission (2800 Å) is constant to within the photometric uncertainties of *IUE*, showing no convincing evidence for rotational variation. These observations are consistent with a uniform spatial distribution and brightness for the Mg II emission network and a more complicated distribution of the regions producing the ultraviolet transition region emission. Alternatively, if the area coverage of the chromospheric and transition region emission is nearly identical, then the contrast in surface brightness between stellar active regions and normal ("quiet") regions must increase by nearly an order of magnitude in the higher temperature lines. Interpretation of the observed fluxes and modulation in the context of other young solar type stars gives information on filling factors and contrasts for χ^1 Ori.

High-resolution observations of the Ca II K line *profile* of χ^1 Ori show subtle changes in the intensity and shape of the Ca II emission. The dominance of the blue versus the red peak emission in K2 appears to change, as might be expected from the Doppler effect as an active region crosses the line of sight.

Subject headings: Ca II emission — stars: chromospheres — stars: individual — stars: rotation
ultraviolet: spectra

I. INTRODUCTION

Several studies by Wilson and others (Wilson 1963; Wilson and Skumanich 1964; Wilson 1968; Wilson and Woolley 1970) have shown that the strength of the emission in the cores of the Ca II H and K absorption lines is inversely correlated with stellar age for main-sequence stars. Since the Ca II emission strength in the Sun is high in active regions, young main-sequence stars are thus said to have "active chromospheres" inasmuch as their Ca II emission is strong.

Some of the solar type stars that Wilson (1978) monitored for activity cycles in their H and K emission show "chaotic" flux variations on time scales of days and weeks, which he conjectured were a result of the rotation of the star. Vaughan (1980) has found that these variations preferentially occur in the younger solar type stars with stronger fluxes, and evidence has been presented by Vaughan *et al.* (1981) that these short-term variations do indeed result from stellar rotation as different active regions rotate into view.

In this study we have chosen to examine the variations due to rotation in the emission flux from ultraviolet chromospheric and transition region (TR) lines in the young G0 star, χ^1 Ori, to understand more about the structure of stellar chromospheres. In the work of both Wilson (1978) and Vaughan *et al.* (1981), only the total emission *flux* in the Ca II H and K lines was monitored; we have also obtained some high-resolution spectra of χ^1 Ori at the Ca II K line to investigate the variations in the line profile shape, which provide additional constraints on the geometry of stellar active regions.

Duncan (1981) has derived ages for solar type stars based on their Li abundance. Both empirical evidence and theoretical predictions indicate that Li abundance decreases with stellar age (e.g., Skumanich 1972; Duncan 1981; Herbig and Wolff 1966; Bodenheimer 1965) during pre-main-sequence and main-sequence evolution. One of the youngest G stars by this criterion is χ^1 Ori for which Duncan derives an age of 6×10^8 yr. Also according to Duncan (1981), χ^1 Ori has a normalized Ca II K line flux, $R_K = f_K/l_{bol} = 22 \times 10^{-6}$—a value among the highest in his sample of 109 F5–G5 dwarfs and indicative of its youth. For solar type stars, Kraft (1967) showed that rapid rotation indicates youth. Soderblom (1982) has found a value of $v \sin i = 9.4$ km s^{-1} for χ^1 Ori, a velocity that is among the very highest for stars with $M < 1.2\ M_\odot$ or $T < 6000$ K. There is evidence that χ^1 Ori like other young stars has a bright corona as indicated by its soft X-ray emission (Walter *et al.* 1980; Mewe, Schrijver, and Zwaan 1981). As in the Sun, the He I 10830 line may also be a measure of coronal emission (Zirin 1975, 1982). Whereas the average equivalent width for G dwarfs is 67 mÅ, χ^1 Ori, with a He I 10830 strength of 350 mÅ, is one of the strongest of the 30 G

[1] Guest Observers with the *International Ultraviolet Explorer* (*IUE*) satellite.

[2] Visiting Astronomer, Canada-France-Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientific of France, and the University of Hawaii.

dwarfs Zirin (1982) studied, only five of which have equivalent widths >150 mÅ. Gary and Linsky (1981) recently detected χ^1 Ori at 6 cm with the VLA; they suggest that this microwave emission comes from a hot 10^7 K corona. In addition to this bright corona, the strengths of the ultraviolet chromospheric ($T \sim 10^4$ K) and transition region ($T \sim 10^5$ K) emission lines of χ^1 Ori indicate that it is young from the correlation between UV line strength and Li-derived age established by Boesgaard and Simon (1982) and Simon and Boesgaard (1983). In summary, the G0 dwarf χ^1 Ori is a young star according to the three traditional indicators of youth: high axial rotation, high Ca II emission, and high Li abundance. The same conclusion is suggested by its intense X-ray, UV, and radio emission, all of which imply a very active outer atmosphere.

Because of its youth and plethora of strong emission lines, χ^1 Ori is an excellent candidate to study rotational modulation of its chromospheric activity to supplement the Ca II flux monitoring of Vaughan *et al.* (1982). Stimets and Giles (1980) have used Wilson's (1978) data on the Ca II emission flux to derive a rotation period of $5^d.10$ for χ^1 Ori. This period of rotation is short enough to cover complete cycles during an *IUE* or ground-based telescope observing run, and yet the star is rotating sufficiently slowly ($v \sin i = 9.4$ km s^{-1}) to resolve details in the Ca II K line profile. Furthermore, if we combine Soderblom's $v \sin i$ value with $\log R/R_\odot = +0.02$ and $P = 5^d.10$, we find $i = 65°$. Repeated observations over 5 day intervals, therefore, can reveal information about the rotational modulation and the "surface" geometry of the active regions since the star is nearly "face-on."

II. OBSERVATIONS

a) *Ultraviolet Emission Lines Observed with IUE*

With the *IUE* satellite we have observed χ^1 Ori during three different rotational cycles over a time span of about 4 days each during 1981 March, 1981 October, and 1982 February. Four phases were observed within each of the three cycles. Observations at high resolution (~0.2 Å) of the Mg II resonance lines with the LWR camera and at low resolution (~6 Å) with the SWP camera were made. The LWR exposure times were all 15 minutes, while those with the SWP camera were 45 minutes, except SWP 15198 and SWP 15205, which were 35 and 50 minutes, respectively.

The spectra were examined for radiation hits, camera defects, and effects of temperature changes on camera sensitivity (found to be small according to the temperature coefficients derived by Ake 1982). Using the net spectra provided on the Guest Observer tapes by the Goddard Space Flight Center and standard reduction software available at the Goddard Regional Data Analysis Facility, we measured integrated line fluxes for all of the prominent unsaturated lines in the short wavelength (1200–2000 Å) region. For the Mg II lines we used an interactive-ripple correction routine rather than Ake's (1982) parameterization of the echelle blaze. The interactive routine derives an optimum blaze function by matching the flux levels in successive spectral orders of the echelle that contain the Mg II *h* line at 2803 Å. We summarize the results of these measurements in Tables 1 and 2 for the individual spectra, along with an average observed flux, $\langle f \rangle$,

TABLE 1[a]

INTEGRATED LINE FLUXES AT THE EARTH, 1200–2000 Å (10^{-13} ergs cm^{-2} s^{-1})

SWP Image	Exp. Start[b] (m/d/y, UT—h:m)	Phase	N V 1240 Å	O I 1305 Å	C II 1335 Å	Si IV 1400 Å	C IV 1549 Å	He II 1640 Å	C I 1657 Å	Si II[c] 1815 Å
13554[d]	3/23/81, 19:36	0.749	0.9	2.7	3.4	5.2	7.9	3.8	3.0	...
13568	3/24/81, 22:04	0.965	0.7	1.4[e]	5.2	3.4	2.6	2.6	1.9[e]	5.5
13577	3/25/81, 21:36	0.158	0.4[e]	3.3	3.9	4.1	4.1	2.1	3.6	6.6
13595	3/27/81, 20:26	0.540	1.1[e]	5.4	5.1	...	5.5	3.8	4.9	8.3[e]
15198	10/7/81, 12:28	0.537	1.5[e]	...	3.1	4.2	6.3	2.5	≤4.7[f]	10.5
15205	10/8/81, 12:05	0.730	1.5	1.7[e]	4.5	4.3	6.9	3.7	2.6	...
15213	10/9/81, 12:09	0.927	0.7[e]	2.4	3.2	3.6[e]	5.5	1.8	4.6[f]	...
15224	10/10/81, 09:14	0.099	1.2	3.6	3.3	4.7	4.2	2.2	2.8	...
16310	2/11/82, 05:01	0.393	1.4	2.9	4.6	2.6	5.5	2.2	3.2	...
16316	2/12/82, 03:22	0.575	1.2	3.3	4.6	4.4	6.0	2.6[f]	6.1[f]	10.5
16326	2/13/82, 22:38	0.929	1.3[e]	2.8	5.1	5.0	4.1	2.4	4.8	...
16332[g]	2/14/82, 18:29	0.091	1.2	3.5	5.7	4.2	4.1	1.6	...	...
$\langle f_{\rm line} \rangle$[h]			1.1(−13)	3.0(−13)	4.3(−13)	4.5(−13)	5.2(−13)	2.6(−13)	3.8(−13)	8.3(−13)
σ (1 s.d.)[h]			±0.3(−13)	±1.1(−13)	±0.9(−13)	±1.4(−13)	±1.5(−13)	±0.7(−13)	±1.2(−13)	±2.6(−13)
$\langle f_{\rm line}/l_{\rm bol} \rangle$[i]			2.3(−7)	6.4(−7)	9.3(−7)	9.7(−7)	11.2(−7)	5.6(−7)	8.1(−7)	1.8(−6)
$\langle F_{\rm line} \rangle$[j]			1.4(4)	4.0(4)	5.7(4)	6.0(4)	7.0(4)	3.5(4)	5.0(4)	1.1(5)
Modulation index (see text) (percent)			86	99	51	84	78	79	85	74

[a] All observations were made in low dispersion through the large aperture.
[b] Exposure times were 45 minutes for all images except SWP 15198 and 15205, which were 35 minutes and 50 minutes, respectively.
[c] Continuum or line generally saturated or extrapolated above the highest level in the ITF calibration.
[d] Obtained by T. R. Ayres.
[e] Uncertain.
[f] Possible blend.
[g] Obtained by G. H. Herbig.
[h] Mean integrated line flux ±1 standard deviation (ergs cm^{-2} s^{-1}).
[i] Apparent bolometric luminosity $l_{\rm bol} = 4.7 \times 10^{-7}$ ergs cm^{-2} s^{-1}.
[j] Mean integrated surface flux.

TABLE 2[a]

INTEGRATED LINE FLUXES AT THE EARTH OF Mg II LINES (10^{-11} ergs cm^{-2} s^{-1})

LWR Image	Exp. Start (m/d/y, UT—h:m)	Phase	Mg II 2796 Å	Mg II 2803 Å	Sum 2800 Å
10194[b]	3/23/81, 19:19	0.746	1.67	1.15	2.82
10203	3/24/81, 21:44	0.962	1.54	1.24	2.78
10210	3/25/81, 21:08	0.154	1.55	1.24	2.79
10224	3/27/81, 21:37	0.550	1.60	1.28	2.88
10268[b]	4/2/81, 10:48	0.639	1.63	1.23	2.85
11716	10/7/81, 12:03	0.533	1.57	1.34	2.91
11726	10/8/81, 11:38	0.726	1.64	1.28	2.92
11731	10/9/81, 11:48	0.924	1.53	1.33	2.86
11741	10/10/81, 08:55	0.097	1.52	1.28	2.80
12551	2/11/82, 04:34	0.389	1.51	1.16	2.67
12562	2/12/82, 02:54	0.598	1.63	1.26	2.89
12573	2/13/82, 22:12	0.925	1.60	1.30	2.90
12587[c]	2/14/82, 05:16	0.179	1.56	1.18	2.74
$\langle f_{\mathrm{Mg\,II}} \rangle$			1.58(−11)	1.25(−11)	2.83(−11)
σ (1 s.d.)			±0.05(−11)	±0.06(−11)	±0.07(−11)
$\langle f_{\mathrm{Mg\,II}}/l_{\mathrm{bol}} \rangle$			3.40(−5)	2.69(−5)	6.09(−5)
$\langle F_{\mathrm{Mg\,II}} \rangle$			2.10(6)	1.66(6)	3.76(6)
Modulation index (see text)					7%

[a] All observations obtained at high dispersion through the large aperture, with 15 minute exposure times.
[b] Obtained by T. R. Ayres.
[c] Obtained by G. H. Herbig.

average normalized flux, $\langle f/l_{\mathrm{bol}} \rangle$, average surface flux, $\langle F \rangle$,[3] and also a modulation index analogous to the Ca II modulation index $\Delta S/S$ (Vaughan *et al.* 1981). For χ^1 Ori, the conversion from apparent flux to surface flux is $F = 1.33 \times 10^{17} f$ for an angular diameter of 1.1 milli-arcsec obtained from the Barnes-Evans relation (Linsky *et al.* 1979).

b) Ca II *Profiles*

Spectra of the Ca II K line profile were obtained with the liquid-nitrogen–cooled Reticon and the coudé spectrograph of the Canada-France-Hawaii 3.6 m telescope at Mauna Kea. The pixel-to-pixel separation is 0.034 Å, giving a resolution of about 0.07 Å. Spectra were obtained on 1982 January 5 and 6 and October 26 UT with signal-to-noise ratios in the continuum of 380, 160, and 285 respectively. The observed spectra were divided by flat field spectra exposures exposed to the same continuum signal-to-noise ratios to remove pixel-to-pixel variations. This procedure corrects virtually all the differences in the individual photodiode response and gain differences between the four readout amplifiers. By assuming that the average of all the points over the entire spectrum is the same for each of the four output channels, any remaining (small) departures from linearity can be removed.

[3] The surface flux F includes the factor of π and is more commonly denoted by $\mathscr{F}$.

TABLE 3

SURFACE FLUXES IN χ^1 ORIONIS AND THE SUN

	χ^1 ORI				SUN	
ION[a]	$F_{\max}$[b]	$F_{\min}$[b]	$F_{\max}/F_{\min}$	$\langle F \rangle$[b]	$\langle F \rangle$[b,c]	$F(\chi^1)/F(\odot)$
Mg II	3.9(6)	3.5(6)	1.1	3.8(6)	1.5(6)	2.4
Si II	1.4(5)	8.0(4)	1.8	1.1(5)	2.1(4)	5.2
C I	7.3(4)	3.0(4)	2.4	5.0(4)	1.3(4)	3.9
O I	6.0(4)	2.1(4)	2.9	4.0(4)	7.2(3)	5.6
C II	7.3(4)	4.2(4)	1.7	5.7(4)	1.0(4)	5.7
He II	5.0(4)	2.2(4)	2.3	3.4(4)	3.2(3)	11.
Si IV	6.8(4)	4.0(4)	1.7	6.0(4)	4.7(3)	13.
C IV	9.9(4)	4.4(4)	2.3	6.9(4)	9.4(3)	7.4
N V	2.0(4)	0.8(4)	2.5	1.4(4)	6.3(2)	22.

[a] Listed in approximate order of increasing temperature of formation.
[b] Units for surface flux, F, are ergs cm^{-2} s^{-1}; exponent for power of ten given in parentheses. For χ^1 Ori, $F_{\max}$ is the average of the two highest values, $F_{\min}$ the average of the two lowest.
[c] From Ayres, Marstad, and Linsky 1981.

III. RESULTS AND DISCUSSION

a) Mean Fluxes Relative to the Sun

Ayres, Marstad, and Linsky (1981) have published ultraviolet line fluxes for the Sun for sunspot maximum based on a rocket spectrum from 1979 June (Mount, Rottman, and Timothy 1980) degraded to the *IUE* 6 Å resolution and for a quiet Sun spectrum based on a private communication from Rottman. They state that the fluxes from a "moderately active phase" are typically twice those of a quiet phase in the sunspot cycle. In χ^1 Ori, the ratios of maximum flux to minimum flux due to *rotation* are presented in Table 3 and are typically factors of 2, ranging from 1.7 for C II and Si IV to 2.9 for O I, with the exception of Mg II, which shows virtually no variation (see § III*d* below) and $F_{max}/F_{min} = 1.1$.

The mean fluxes for each ion for χ^1 Ori from Table 2 can be compared with the solar mean[4] and are given in Table 3. For Mg II the flux from χ^1 Ori is ~2.4 times stronger than that from the Sun. For Si II, O I, and C II, other low chromosphere ions, the flux from χ^1 Ori is 5–6 times that from the Sun. The higher temperature/transition region (TR) ions C IV, He II, Si IV, and N V are even more strongly enhanced in χ^1 Ori: factors of 7–12, i.e., an order of magnitude greater. Such enhancements can arise from greater surface area coverage and/or greater contrast of the network and/or the plage regions; this is discussed in § III*f* below.

b) C IV *Modulation*

Variations in the line flux of several ions from the first rotation cycle in 1981 March were reported earlier (Boesgaard and Simon 1982), but subsequently we found that the two cycles observed later—1981 October and 1981 February—could be phased together with the earlier observations using the $5^d.10$ period derived by Stimets and Giles (1980) from Wilson's Ca H and K flux measurements of χ^1 Ori. (A slightly better fit to the C IV variations was obtained with $P = 5^d.097$, which has been used in this paper.) Stimets and Giles showed that the active regions giving rise to the Ca II emission of χ^1 Ori had lifetimes of $\geq 500^d$. Similar persistence was found over time scales of $\sim 100^d$ for a number of stars by Vaughan *et al.* (1981). Our observation-span is 325^d; although our observations are widely spaced, the apparent phasing of the UV observations is consistent with long lifetimes.

Figure 1 shows the variations we observed in the emission flux of the transition region doublet of C IV at 1549 Å phased with $P = 5^d.097$. We define 1981 March 21, 00:00 UT, to be phase 0.0. There is a slow rise in f_{line}/l_{bol} to 16×10^{-7} at phase 0.75 and a steep drop by more than a factor of 2 to 7×10^{-7} at phase 1.0. For the background levels characteristic of these spectra of χ^1 Ori, we estimate the reproducibility at low dispersion or the uncertainty in the integrated line flux to be ~10% at the 1 σ level (see also Bohlin *et al.* 1980 and Crivellari *et al.* 1983 for discussions of the broad-band photometric and emission line reproducibility of *IUE*), so the observed C IV variations are clearly real. The apparent asymmetry between the rise time and the decline would require a complex distribution to produce the non-sine wave, non-symmetric variation, for example, a dominant large plagelike region followed by a second emission spot a quarter of a cycle later all superposed on a general network of emission. An asymmetry of the kind exhibited here by the C IV emission is occasionally observed in the *continuum* light curves of heavily spotted stars like the RS CVn binaries and the dMe or BY Dra variables. Torres and Ferraz Mello (1973) have shown how this type of light curve can be reproduced with a model having two active regions, separated in longitude, on the surface of the star (cf. their Fig. 3 and calculations for AU Mic). The pronounced asymmetry does not appear in the 1982 February data, but the observations near maximum occurred at about 21 hours before and 22 hours after the time of the peak and the minimum was missed by ±9 hr. The recurrence of the peak at the same phase in three rotation cycles and the long rise time (which exceeds one-half a cycle) eliminates the possibility that the observed variations are due to bright flares, since the time scale for flares in solar type dwarfs is about 1 hr. The C IV line is presumably formed in the transition region at temperatures near 10^5 K; that it shows the same periodicity as the low-chromosphere lines of Ca II indicates that the active regions have a substantial vertical extent.

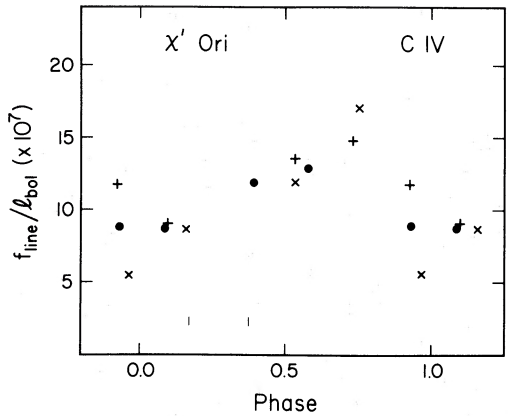

FIG. 1.—Observed variations in the emission flux of the C IV doublet at 1549 Å in χ^1 Ori. The X's denote observations in 1981 March 23–27, the plus symbols are from 1981 October 7–10, and the filled circles are from 1982 February 11–15. The period used is $5^d.097$, adjusted from the $5^d.10$ period of Stimets and Giles (1980) to fit our UV data, and phase zero is 00:00 UT on 1981 March 21. There is a slow increase in $f_{C\,IV}/l_{bol}$ to 16×10^{-7} at phase 0.75 and a steep drop to 7×10^{-7} at phase 1.0. The two tick marks at phase 0.169 and 0.374 denote observations of the Ca II K line profile (see Fig. 6).

c) He II *Modulation*

The normalized flux in He II 1640 Å is shown in Figure 2. Here the variation is not as pronounced as in C IV, but the same maximum is seen near phase 0.75. The He line may be formed by irradiation of the chromosphere by coronal X-rays as proposed, for example, by Zirin (1975) and Avrett, Vernazza and Linsky (1976) for the Sun. We note in this context that the two X-ray observations of χ^1 Ori (Mewe, Schrijver, and Zwaann 1981; Walter *et al.* 1980) differ by a factor of ~7, providing weak evidence for variations in the coronal soft X-ray emission.

[4] χ^1 Ori is a young star which shows little evidence of a solar type 11 yr cycle; Wilson's (1978) observations of the mean Ca II H and K flux from 1966 to 1977 show a possible secular decrease since 1967.4 of no more than 11% in the mean flux. Therefore, our mean fluxes can be presumed to be representative of mean fluxes over long time scales, i.e., decades.

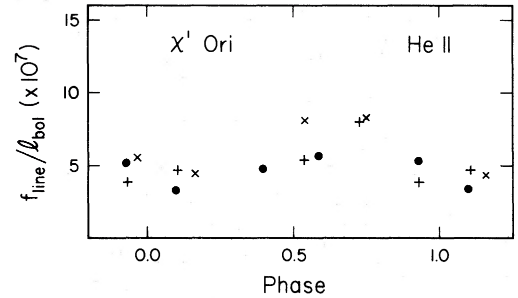

FIG. 2.—The emission flux in the He II line at 1640 Å throughout the 5^{d}1 rotation cycle of χ^1 Ori. The three observing periods are indicated as in Fig. 1. The variation is similar to that found for C IV with the maximum near phase 0.75 and the minimum near 0.0, but the amplitude of the variation is less.

d) Mg II *Doublet*

No variations were found in the emission strength of the Mg II *h* and *k* lines at 2800 Å, however, as seen in Figure 3. Nor did the Mg II profile shapes change according to our echelle spectra. The mean value of $f_{line}/l_{bol} = 6.09$ (± 0.16) $\times 10^{-5}$ for the doublet. That uncertainty of one standard deviation corresponds to a flux constancy of ± 2.6%. Another measure of the flux "error" is $(f_{max} - f_{min})/f_{mean} = 9$%, which is an upper limit for the modulation range since, for example, lapses in measurement technique must contribute in part to this variation. Some 37 flux measurements of Ca II have been made by Vaughan *et al.* (1982) during the (ground-based) observing season of χ^1 Ori near in time to our three *IUE* runs. (The 1981 October 8 observations were the only ones to be nearly simultaneous, however.) During the period from 1981 January to 1982 March, the Ca II flux, *S*, showed a modulation range, $(S_{max} - S_{min})/S_{mean} = 18$% (here, $S_{mean} = [S_{max} + S_{min}]/2$) (Vaughan *et al.* 1982), twice our upper limit for the Mg II lines. A relative variation of that size could have been detected in the Mg II emission if it were present.

We can suggest two possible explanations for the lack of detectable modulation in the Mg II emission features: (1) Mg II emission is uniformly distributed and covers a significant fraction of the stellar surface, or (2) there is a nonuniform distribution similar to that responsible for the C IV and the

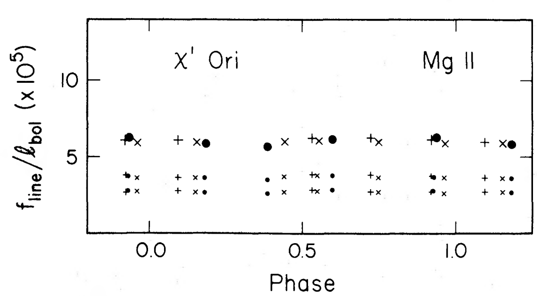

FIG. 3.—The emission flux in the Mg II *h* and *k* line at 2800 Å throughout the 5^{d}1 rotation cycle of χ^1 Ori. The three observing periods are indicated by different symbols as in Fig. 1. The large symbols correspond to the sum of the *h* and *k* lines while the smaller ones show the individual *h* (*lower*) and *k* (*upper*) lines. No variations are seen in the flux or in the shapes of the line profiles.

He II variations, but due to a lower contrast between bright and quiet regions for Mg II, no variation can be observed in the Mg II lines.

For the first explanation we imagine a very extensive chromospheric network of approximately uniform surface brightness, analogous to the solar network which covers ~ 40% of the solar disk and contributes ~ 60% of the integrated brightness of the quiet Sun (Skumanich, Smythe, and Frazier 1975; Reeves 1976). Since χ^1 Ori is ~ 3 times the quiet solar brightness in Mg II, an area coverage of solar type network of ≥ 100% is needed to account for the Mg II flux, and this would imply a lack of variation with rotation. Since the EUV network of the Sun is roughly the same size as and cospatial with the chromospheric network, but has a brighter network/cell contrast by a factor of 3 (Reeves 1976), we expect the EUV network of χ^1 Ori also to have comparable size and distribution as its chromospheric network. Therefore, in this scheme the C IV strength (7 times that of the Sun) and the large amplitude of its rotational modulation must be attributed to bright stellar plage areas in addition to solar type EUV network. However, the Mg II brightness is dominated by the network, not by the plages.

For the second explanation the regions of Mg II and C IV might have the same area filling factors (as is approximately the solar situation) and the modulation of the line flux would be due to a nonuniform distribution of active regions over the stellar surface. The magnitude of the modulation would result from the bright/quiet contrast. For the Sun the plage coverage can be as high as 20% near the maximum of activity (e.g., Sheeley 1967), and we could postulate that it could be 2–3 times that in a young active star. If there is an uneven distribution of plage over the χ^1 Ori disk (~ 10% on one hemisphere and < 40% on the opposite hemisphere to be compatible with the narrow peak in the C IV light curve), then the observed modulation (< 10% for Mg and a factor of 2.5 for C IV) can be explained by adjusting the relative contrast of the chromospheric and TR lines. In a very rough calculation, we find that the enhancement of emission in active regions over the surface brightness in quiet regions of the star must be a factor of 6–10 greater for C IV than for Mg II. (For the Sun this is ~ 3.) These numbers for Mg II: 10% plage coverage on one hemisphere, 40% on the other, contrast plage to quiet regions of ~ 1.7, result in a modulation near the limit of detectability with *IUE*. The C IV line strengths are enhanced over those of Mg II by a factor of 3 relative to that ratio in the Sun, and this extra factor, attributed to the greater contrast of plage/quiet, accounts for both the line strengths and modulations for C IV. One argument against such bright C IV plages, however, relates to the continuum observations. We carefully looked for variability in the 1600–1800 Å region and find no changes > 10%, although in solar plages, this part of the spectrum is enhanced by 80%–100% (a factor of 1.8–2.0) according to Brueckner *et al.* (1976). Scaling from the Sun, for the changes observed in the C IV intensity of χ^1 Ori in different rotation cycles of this star, we would have predicted continuum brightness changes of 8%–30%. Variability at the high end of this range would have been noted but was, in fact, not detected.

Both of the Mg II lines in χ^1 Ori are strong and optically thick; the ratio of *k*/*h* predicted by the *gf*-values is 2/1, while the observed ratio is 1.27 ± 0.08.

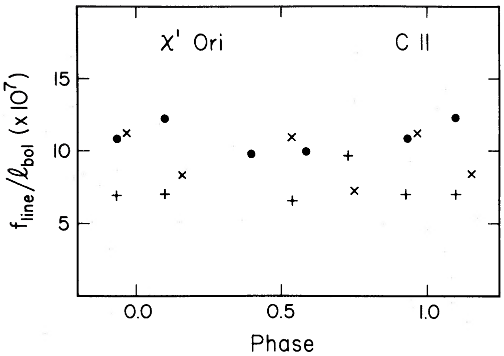

FIG. 4.—The emission flux of the C II multiplet at 1335 Å throughout the 5ᵈ1 rotation cycle of χ^1 Ori. The symbols are as in Fig. 1. No long-term cyclical variations are apparent but the general level of emission in 1982 February (*filled circles*) may be greater than in 1981 October (*pluses*).

e) *Other Ions*

No definite, *recurrent* variations were found in any of the other prominent chromospheric and TR features measured: N V (1240 Å), O I (1305 Å), C II (1335 Å), Si IV (1400 Å), or C I (1657 Å). Figure 4 shows the observed flux in the C II multiplet at 1335 Å as an example of a feature that varies, but not in a cyclic pattern. One interesting aspect of the C II data is that the mean flux for the 1982 February data is 50% larger than the mean for 1981 October. Inspection of Table 1 shows that variations 5–7 times larger than average measurement errors of ~15% are present for all moderately strong emission features including C IV, but excluding Mg II. Referring to Table 3, one can see the enhancement factors for the flux at maximum over that at minimum for these ions, with an average $F_{max}/F_{min} = 2.2$. Variations presumably due to rotation *are* present but not cyclic.

Figure 5 shows the line strengths for C I, O I, Si II, and Si IV, which have a cyclic variation only in the 1981 March rotation with the same pattern of variation as seen for C IV. The cyclic pattern is lost in combining the data over the longer time span through the rotation cycles 1981 October and 1982 February. The regions giving rise to those emission features seemingly do not have the longevity of the Ca II and C IV regions, or the other types of activity such as minor flares or giant prominences may mask the cyclic behavior on time scales like months. Another indicator of the complexity of the activity can be seen in the behavior of the C II line in the 1981 March observations: it became *stronger* on the second observation than it was on the first and third—just the opposite of the behavior of the other ions. Inspection of the spectra leaves no question that the C II feature is about twice as strong as the C IV feature on SWP 13568 (March 24, 22:04 UT) and the two are about equal on SWP 13577 (March 25, 21:36 UT). This curious countervariation for C II can probably not be explained as a C II (only) flare on March 24, 22:04, since it is not uniquely strong that day and C II shows the least variability as indicated in the last line of Table 1.

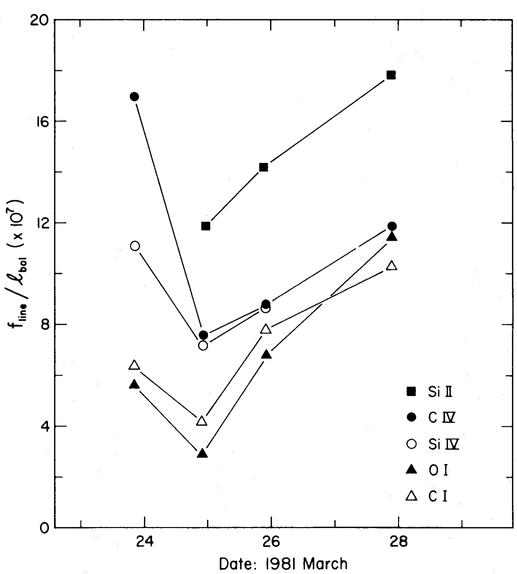

FIG. 5.—The emission flux observed in the 1981 March cycle for lines from individual ions. The C II flux (not plotted) shows anomalous behavior on the second day when it is especially strong ($f_{line}/l_{bol} = 11.1 \times 10^{-7}$), whereas the other three days it is about the same strength as C I.

A modulation index, defined as the average of the two highest values minus the average of the two lowest values divided by the mean (in percent) is presented in Table 1. This index also shows that variations beyond the measurement errors are present for all lines. As mentioned above, the modulation of 51% for C II (Fig. 4) is the smallest recorded. For each of the prominent lines, we have also examined the residuals of the brightness fluctuations from the average emission line flux listed near the bottom of Table 1. After normalizing the residuals to the corresponding standard deviation given in Table 1 for each spectral line, we applied a Kolmogorov-Smirnov test, the results of which indicate that the observed brightness variations cannot be distinguished from a Gaussian ("random") statistic. That these line strengths vary, but in a more random way in both amplitude and phase than the C IV feature, seems to indicate that there are multiple emission regions widely distributed over the entire surface with varying lifetimes rather than just two or three dominant and long-lived active longitudes.

f) *Flux, Area, and Contrast*

The age of χ^1 Ori is considerably less than that of the Sun according to Duncan's (1981) Li-age calibration: 6×10^8 versus 4.5×10^9 yr. It is not obvious that the solar network, solar active regions, and solar plages—solar activity in general—should be used as a standard for young stars. In concurrent work with Dr. G. Herbig, which will be reported in a subsequent publication, we have accumulated much data on the ultraviolet emission spectra of young solar type stars.[5] Although we see a general decline in stellar activity with age from 0.8 to 8 billion years, the main-sequence stars between ages $1–6 \times 10^8$ yr, show a uniform upper envelope in the surface flux as if the maximum flux for each ion has been reached through filling factors near unity and uniform contrast between active and quiet regions. With the assumption that all the relevant latitudes for activity are filled. We can define F_A, the surface flux from the active regions, to correspond to

[5] Preliminary results on part of the sample of stars have been reported by Boesgaard and Simon (1982) and Simon and Boesgaard (1983).

the upper bound defined by the observations for each ion in the youngest solar type stars. The "quiet" flux from a young star is a difficult notion since the *minimum* activity level surpasses that of the *active* Sun by a factor of 3 or more for all these ions except Mg II. We define the "quiet" flux, F_Q, for young stars from the lowest value for each ion as measured in χ^1 Ori since (*a*) it is young and (*b*) we have multiple observations of it and thus a greater chance of observing a minimum of activity.[6] This F_Q may contain contributions from both the bright network and the bright plage areas. The ratio F_A/F_Q gives the contrast, C, between active and quiet regions in young stars. These values, listed in Table 4, may in fact be lower bounds if there is a major contribution to F_Q from plage areas. We then calculate the fraction of the stellar surface, A, covered by active regions at the mean flux and the maximum flux in χ^1 Ori according to:

$$F = AF_A + (1 - A)F_Q = F_Q[AC + (1 - A)] .$$

The mean flux, $\langle F \rangle$, gives a mean areal coverage, $\langle A \rangle$, in percent, while $F_{\max}$ corresponds to the maximum area, $A_{\max}$, covered by activity; these values are also given in Table 4. For the low chromosphere of χ^1 Ori, typical contrasts are 2–5, typical area coverage is $\sim 20\%$ up to 50% or more at maximum activity. The exception again is Mg II which seems more solar-like in its characteristics. In the transition region for χ^1 Ori, typical contrasts are 4–7 where a 20% coverage increases to 35% during peaks of activity.

g) Ca II *Profile Changes*

The rotation period used for the C IV variations is that derived from changes in the emission intensity, S, for the Ca II lines by Stimets and Giles (1980). We have looked at the line profile shape of the Ca II K line and can discern changes in intensity and probably in shape. Figure 6, from CFHT Reticon spectra, shows the subtle changes that occurred on two successive nights; the interval between the two observations is 25 hr or 41% of the time for an active area to traverse the visible hemisphere. The phases, corresponding to the plot in Figure 1 for the C IV variation, are 0.169 (1981 January 5 UT) and 0.374 (1981 January 6 UT) and are indicated on Figure 1. The Ca II emission increases as does the C IV emission at the later phase as more emission, more area with activity, rotates into view. Furthermore, the blue-to-red ratio in the K2 peaks appears to reverse. The signal-to-noise ratios in the continuum for these two observations are 380 and 160, respectively. That and the good match in the rest of the spectral region lends credence to the reality of the change. Although the reality of the profile change is not established beyond a doubt, one interpretation of this change from blue to red in the dominant peak in that 25 hr interval is that a dominant active region first approaches the observer and then recedes as the area traverses the center of the line of sight. The change in the Ca II intensity could be due to a bright compact structure near the leading edge of the large active region responsible for C IV emission as it makes its appearance on the approaching limb of the star. One later observation on 1982 October 26 occurs at phase 0.876. It has the same flux intensity as the January 6 observations, as would be expected from the C IV plot in Figure 1 where phase 0.374 and 0.876 give virtually identical C IV emission. The October 26 spectrum shows little or no reversal half a phase later than the January 6 observation when the opposite side of the star is facing the observer.

If there are Mg II counterparts to the subtle changes seen in these high-resolution Ca II spectra, they could not be detected in Mg II given the resolution and signal-to-noise ratios of the *IUE* spectra.

IV. CONCLUSIONS

We have looked for variations in the measured line strengths of several chromospheric and transition region lines that could result from the rotation of the young, active solar type star, χ^1 Ori. The rotation period of $5\overset{d}{.}10$ found from variations in

[6] The exception to this is Si II for which we have few observations of χ^1 Ori, and we adopt the lower bound for the other young stars. The lower bound from the young stars for the other ions is in excellent agreement with the low χ^1 Ori value.

TABLE 4

FLUX, CONTRAST, AND AREA COVERAGE OF ACTIVE REGIONS IN χ^1 ORIONIS

Ion	Approx. Temp. for Emission	F_A[a]	F_Q[b]	C	$\langle F \rangle$[c]	$\langle A \rangle$ (%)	$F_{\max}$ (%)	$A_{\max}$ (%)
Mg II	≤1(4)	6.0(6)	3.5(6)	1.7	3.8(6)	11	3.9(6)[b]	16
Si II	<1(4)	1.7(5)	6.0(4):[d]	2.8:	1.1(5)	46:	1.4(5)[e]	74:
C I	<1(4)	1.2(5)	2.5(4)	4.8	5.0(4)	26	7.3(4)[e]	51
O I	<1(4)	1.0(5)	1.8(4)	5.5	4.0(4)	27	6.0(4)[e]	52
Typical low chromosphere		...	...	2–5	...	20	...	50
C II	2(4)	1.5(5)	4.0(4)	3.8	5.7(4)	16	7.3(4)[e]	30
He II	>2(4)	9(4)	2.0(4)	4.5	3.4(4)	20	5.0(4)[b]	43
Si IV	1(5)	1.5(5)	3.5(4)	4.3	6.0(4)	22	6.8(4)[e]	29
C IV	1(5)	2(5)	4.0(4)	5.0	7.0(4)	18	9.9(4)[b]	37
N V	2(5)	4.5(4)	6.0(3)	7.5	1.4(4)	22	2.0(4)[e]	35
Typical transition region		...	...	4–7	...	20	...	35

[a] From upper bound for young stars.
[b] From plots like Figs. 1–4.
[c] From Tables 1 and 2.
[d] From lower bound for young stars.
[e] From mean of two highest values.

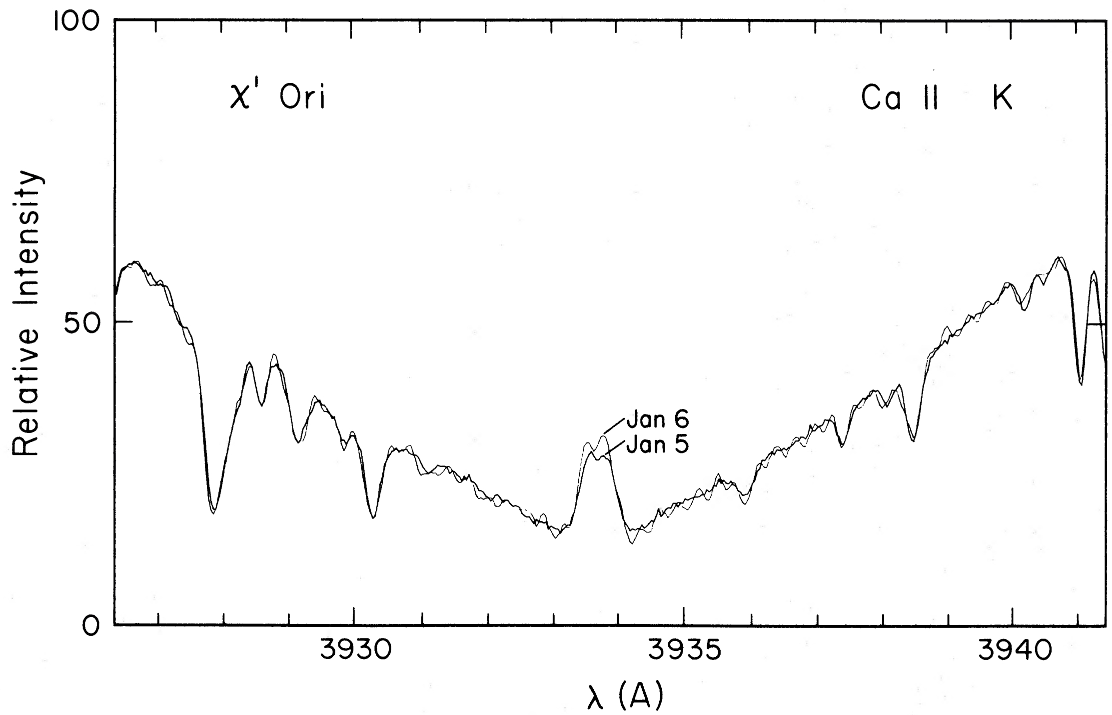

FIG. 6.—The region of the core of the Ca II K line on two successive nights (a 25 hr interval) during the rising part of the C IV emission cycle. This is a 15 Å region of the 67 Å observed with the CFHT Reticon. The signal-to-noise ratio in the continuum is 380 for the 1982 January 5 data (phase = 0.169) and 160 for the 1982 January 6 data (phase = 0.374). The K2 emission intensity increases (as does the C IV emission), and the ratio of the blue-to-red peak K2 intensity reverses. The shift in the peak emission corresponds to ~13 km s^{-1}, consistent with the velocity shift expected in the 25 hr interval.

the Ca II flux intensity (Stimets and Giles 1980) is consistent with the value of $v \sin i = 9.4$ km s^{-1} (Soderblom 1982). The following effects were found:

1. The mean flux level for all ions exceeds that of the Sun by a factor of 2.4 for Mg II to an order of magnitude for the TR ions. Variations in the flux were found for all ions except Mg II with values of $F_{max}/F_{min} = 2$–3.

2. The transition region emission of C IV at 1549 Å varies in strength by more than a factor of 2 with the same period as the Ca II emission flux. The asymmetric shape of the variation implies a complicated geometric distribution for the C IV emission, possibly a large dominant region followed a quarter of a phase later by a second emission area. To account for the great strength of the C IV emission we postulate a bright network with a superposed plage component.

3. The emission line of He II at 1640 Å, which may be formed by photoionization of chromospheric material by coronal X-rays, shows a similar pattern of variation as the C IV TR line, and the same period and persistence of the Ca II chromospheric lines.

4. Although there are extended gaps between our sets of the *IUE* observations, the same phasing seems to persist for over 325^d for C IV and He II. Stimets and Giles found the lifetime for the Ca II flux periodicity to exceed 500^d.

5. No variations of this persistence and periodicity were detectable in the emission from N V (1240 Å), O I (1305 Å), C II (1335 Å), Si IV (1400 Å), or C I (1657 Å). However, variation showing the same pattern as those of C IV were found for O I, C I, Si II, and Si IV in the 1981 March cycle. These emission regions presumably have shorter lifetimes than those of C IV and may come from a greater array of active longitudes.

6. For the Mg II lines, the mean ratio of the sum of the flux, f_{line}/l_{bol}, from the two lines is $6.09\ (\pm 0.16) \times 10^{-5}$. The difference in the extrema divided by the mean is 9%, whereas the comparable figure for Ca II is twice that, or 18%. The Mg II emission network is widespread and uniform in distribution and brightness over the disk, or if the bright areas are non-uniform in distribution, they are of low contrast compared to the quiet areas.

7. Comparison of χ^1 Ori with other stars in its age group (1–6×10^8 yr) yields insights beyond the comparison with the Sun. Contrasts of active to quiet regions for young stars were deduced and used to determine average and maximum areas covered by active regions during the rotation of χ^1 Ori. In this framework for the low chromosphere the average level of 20% coverage can reach ~50% at maximum. The transition region is covered on average 20% by active regions and up to 30%–40% at maximum. The differences in maximum coverage between high-temperature and low-temperature lines may not be significant in view of the uncertainties in the data and analysis.

8. Subtle changes in the Ca II K line profile can be seen when it is observed at high resolution. The K2 emission intensity changes consistently with the C IV phasing and the sense of asymmetry, or the blue-to-red emission, ratio, changes. Observations made on successive nights show a change in blue-peak dominance to red-peak dominance that can be due to Doppler shifts as a dominant active region traverses the disk center.

A composite picture of the activity in χ^1 Ori emerges. First Mg II shows the least enhancement relative to the Sun and virtually no modulation in the line flux due to rotation. This can be attributed to a nearly uniform distribution of bright solar-like network (filling factor near unity) or plagelike regions covering 10%–15% of the disk with a rather low contrast between active and quiet regions. The other ions all show stronger enhancements compared to the Sun with the "quiet" disk of χ^1 Ori showing 3+ times the flux level of the *active* Sun. The quieter phase of χ^1 Ori may have some plage areas as well as the active phase. The low chromosphere ions, C I, O I, and Si II, show enhancements which can be due to bright plages with contrasts of 3–5 covering about one-third of the disk on average. These ions show variations which we can account for by greater area covered, up to one-half or so occasionally. The bright areas giving rise to these emissions are not long-lived, but at least in the 1981 March cycle were apparently coincident with C IV emission regions. The most persistent regions are those giving rise to the transition region C IV emission since observations covering a time span of 325^d can be phased together for one light curve. The transition region ion He II shows this same persistence and pattern. Both C IV and He II can arise from the same regions of activity that cover 40% of the hemisphere at maximum flux. Other transition region species, C II and Si IV, show smaller modulation and a maximum area coverage more like 30%.

Feldman (1983) has recently suggested that most of the solar emission from plasma at temperatures between 4×10^4 K and 2×10^5 K originates in magnetically isolated structures, which he calls the Unresolved Fine Structure, rather than in TR material forming the interface between the solar chromosphere and corona. Could this proposal also account for the persistence of the rotational modulation in the C IV and He II in χ^1 Ori and the different modulation patterns exhibited by its chromosphere lines? This star clearly deserves further attention with *IUE* observations over an even longer baseline and with high-resolution Ca II K line monitoring. The $5^d.1$ period, the nearly face-on orientation, and the long lifetime of the active areas mean that more the subtleties of the geometry and lifetime of the active regions could be discerned on this young solar type star.

We are grateful to Dr. Thomas Ayres and Dr. George H. Herbig for obtaining some of the *IUE* spectra for us. We are pleased to acknowledge Dr. Sallie Baliunas, who communicated the results of the Ca II flux monitoring program on χ^1 Ori to us. We wish to thank Dr. A. Boggess and the staff of the *IUE* Observatory for their assistance in the acquisition and reduction of the ultraviolet spectra and are grateful to Keith Feggans and Ruth E. Bradley for their assistance at the Goddard RDAF. We are indebted to Dr. William Heacox and Mr. Russell Lavery for their important contributions in obtaining the CFHT spectra. This work was supported by NASA grant NAG 5-146 to the University of Hawaii.

REFERENCES

Ake, T. B. 1982, *NASA IUE Newsletter*, No. 19, 37.
Avrett, E. H., Vernazza, J. E., and Linsky, J. L. 1976, *Ap. J. (Letters)*, **207**, L199.
Ayres, T. R., Marstad, N. C., and Linsky, J. L. 1981, *Ap. J.*, **247**, 545.
Bodenheimer, P. 1965, *Ap. J.*, **142**, 451.
Boesgaard, A. M., and Simon, T. 1982, *Smithsonian Ap. Obs. Spec. Rept.* 392, Vol. **II**, p. 161.
Bohlin, R. C., Holm, A. V., Savage, B. D., Snijders, M. A. J., and Sparks, W. M. 1980, *Astr. Ap.*, **85**, 1.
Brueckner, G. E., Bartoe, J.-D. F., Kjeldseth Moe, O., and Van Hoosier, M. E. 1976, *Ap. J.*, **209**, 935.
Crivellari, L., Franco, M. L., Molaro, P., Vladilo, G., and Beckman, J. E. 1983, *Astr. Ap. Suppl.*, **52**, 135.
Duncan, D. K. 1981, *Ap. J.*, **248**, 651.
Feldman, U. 1983, *Ap. J.*, **275**, 367.
Gary, D. E., and Linsky, J. L. 1981, *Ap. J.*, **250**, 284.
Herbig, G. H., and Wolff, R. J. 1966, *Ann. d'Ap.*, **29**, 593.
Kraft, R. P. 1967, *Ap. J.*, **150**, 551.
Linsky, J. L., Worden, S. P., McClintock, W., and Robertson, R. M. 1979, *Ap. J. Suppl.*, **41**, 47.
Mewe, R., Schrijver, C. J., and Zwaan, C. 1981, *Space Sci. Rev.*, **30**, 191.
Mount, G. H., Rottman, G. J., and Timothy, J. G. 1980, *J. Geophys. Res.*, **85**, 4271.
Reeves, E. M. 1976, *Solar Phys.*, **46**, 53.
Sheeley, N. R., Jr. 1967, *Ap. J.*, **147**, 1106.
Simon, T., and Boesgaard, A. M. 1983, in *IAU Symposium 102, Solar and Stellar Magnetic Fields: Origins and Coronal Effects*, ed. J. O. Stenflo (Dordrecht: Reidel), in press.
Skumanich, A. 1972, *Ap. J.*, **171**, 565.
Skumanich, A., Smythe, C., and Frazier, E. N. 1975, *Ap. J.*, **200**, 747.
Soderblom, D. 1982, *Ap. J.*, **263**, 239.
Stimets, R. W., and Giles, R. H. 1980, *Ap. J. (Letters)*, **242**, L37.
Torres, C. A. O., and Ferraz Mello, S. 1973, *Astr. Ap.*, **27**, 231.
Vaughan, A. H. 1980, *Pub. A.S.P.*, **92**, 392.
Vaughan, A. H., Baliunas, S. L., Duncan, D., Noyes, R., Frazer, J., Lanning, H., Woodward, L., and Preston, G. W. 1982, private communication.
Vaughan, A. H., Baliunas, S. L., Middlekoop, F., Hartmann, L. W., Mihalas, D., Noyes, R. W., and Preston, G. W. 1981, *Ap. J.*, **250**, 276.
Walter, F. M., Linsky, J. L., Bowyer, S., and Garmine, G. 1980, *Ap. J. (Letters)*, **236**, L137.
Wilson, O. C. 1963, *Ap. J.*, **138**, 832.
———. 1968, *Ap. J.*, **153**, 221.
———. 1978, *Ap. J.*, **226**, 379.
Wilson, O. C., and Skumanich, A. 1964, *Ap. J.*, **140**, 1401.
Wilson, O. C., and Woolley, R. 1970, *M.N.R.A.S.*, **148**, 463.
Zirin, H. 1975, *Ap. J. (Letters)*, **199**, L63.
———. 1982, *Ap. J.*, **260**, 655.

A. M. BOESGAARD and T. SIMON: Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822