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ACTIVITY IN F STARS

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ABSTRACT

Observations of C IV λ1549 and of He I λ5876 are used to determine activity levels in late A and F stars. The onset of activity occurs near $B-V = 0.28$, which corresponds approximately to spectral type F0 and $T_{eff} = 7300$ K. Cooler than $T_{eff} = 6600$ K, the level of activity can be characterized by the same relationship between Rossby number and C IV flux that is valid for solar-type stars. There is no correlation between the level of activity and the abundances of lithium and beryllium in F stars hotter than $T_{eff} = 6600$ K. The cooler stars that are deficient in beryllium are somewhat more likely to be active than those with normal beryllium.

All but one of the stars in the temperature interval 6600 K $< T_{eff} <$ 7300 K are active. The levels of activity in these stars are independent of Rossby number. The ubiquity of activity in stars with very shallow convection zones is surprising and may indicate that some mechanism other than the dynamo (acoustic flux?) contributes to the nonradiative heating in early F stars.

Subject headings: stars: chromospheres — ultraviolet: spectra

I. INTRODUCTION

The origin of stellar activity in late-type stars is almost certainly to be found in the interaction of differential rotation and convection with magnetic fields. Convection zones are thought to appear at a spectral type near F0, and so one might expect the onset of activity to occur at about this same spectral type. If activity can indeed be detected in very early F-type stars, then we have the opportunity of studying nonradiative processes that take place under conditions very different from those that characterize solar-type stars. The F-type stars typically rotate much more rapidly and have much shallower convection zones than do G- and K-type stars.

Unfortunately there are very few useful diagnostics of activity in early F-type stars. Their coronal soft X-ray fluxes are fairly large, but only a relatively small number of F-type stars have been observed in the X-ray spectral region. Diagnostics such as the filling in of the core of Hα or emission in Ca II H and K are of limited utility because of rotational broadening, the small contrast between photospheric and chromospheric emission, or both. In the very earliest F-type stars, even ultraviolet emission lines in the regions accessible to *IUE*, which are good indicators of activity in cooler stars, may suffer from low contrast with respect to the photospheric spectrum.

One of the best currently available indicators of activity in early F-type stars is the strength of the helium triplet line He I λ5876 (D_3). In a recent survey, the D_3 line has been seen in stars at least as early as F0 (Wolff, Heasley, and Varsik 1985), and since the feature appears in absorption, there is no problem in detecting it against a strong photospheric background. In the Sun, the D_3 absorption is cospatial with plages (Landman 1981). In stars of spectral types late F, G, and K, the equivalent width of D_3 correlates well with such indicators of activity as X-ray emission and the flux in the Ca II H and K lines (Wolff, Heasley, and Varsik 1985; Danks and Lambert 1985). There remains some uncertainty about whether level populations of helium in the atmospheres of cool stars are controlled by (downward directed) soft X-ray emission from the corona, by collisional excitation in the chromosphere, or a combination of both (Zirin 1975; Wolff and Heasley 1984). Nonetheless, the simple presence of these lines in stars with photospheric temperatures less than 7000 K is an unmistakable indication of nonradiative heating.

In the present paper we report measurements of He I λ5876 and *IUE* measurements of chromospheric and transition region lines in a large sample of F-type stars. The data show that activity is detectable in nearly all early F-type stars and differs in several of its characteristics from that typically seen in cooler stars with slow rotation and fully developed convection zones.

II. OBSERVATIONS

The stars included in this survey are all on or near the main sequence and span the spectral range from F0 to F9. Many of the stars were chosen because beryllium and/or lithium abundances had previously been derived for them, and we were interested in exploring the question of whether or not deep convection (or considerable convective overshoot) is responsible for both the light element depletions and the strong mechanical heating of the chromosphere. Stars observed in the earlier D_3 survey by Wolff, Heasley, and Varsik (1985) have also been included here.

The ground-based data were obtained with the Reticon detector system mounted at the coudé spectrograph of the Canada-France-Hawaii 3.6 m telescope on Mauna Kea. The

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[2] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
[3] Guest Observer with the *International Ultraviolet Explorer* (*IUE*) satellite.

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TABLE 1

OBSERVATIONAL DATA[1]

Star Name	HD	Sp. Type	V	B−V	T_{eff}	M_{bol}	D_3 (mÅ)	$\frac{F(C\ IV)}{\sigma T_{eff}^4}$	v sin i (km s^{-1})	log Ro
HR 17	400	F8 IV	6.19	0.48	6400	3.55	<3		6	0.36
6 Cet	693	F7 V	4.89	0.49	6350	3.41	<4		4	0.48
ρ Psc	8723	F2 V	5.38	0.39	6720	3.16	48	$2.2 x 10^{-6}$	61	−0.12
α Tri	11443	F6 IV	3.41	0.49	6350	2.49	78	$5.42 x 10^{-6}$	93	−0.89
HR 784	16673	F6 V	5.78	0.52	6230	3.95	19	$4.0 x 10^{-7}$	6	0.16
θ Per	16895	F8 V	4.12	0.49	6350	3.75	13	$1.8 x 10^{-7}$	9	0.13
τ^1 Eri	17206	F6 V	4.47	0.48	6400	3.58	23	$1.2 x 10^{-6}$	27	−0.29
47 Ari	18404	F5 IV	5.80	0.41	6640		26	$(1.4 x 10^{-6})$	28	0.09
τ^6 Eri	23754	F3 III	4.23	0.42	6600	2.85		$4.1 x 10^{-7}$:	6	0.69
45 Tau	26462	F4 V	5.72	0.36	6890			$3.1 x 10^{-6}$	6	1.08
ζ Dor	33262	F7 V	4.72	0.52	6230	4.24	30	$2.2 x 10^{-6}$	0	
γ Lep	38393	F6 V	3.60	0.47	6440	3.46		$<6.6 x 10^{-8}$	11	0.14
ξ Gem	48737	F5 III	3.36	0.43	6560	2.28		$1.4 x 10^{-6}$	70	−0.43
α CMi	61421	F5 IV-V	0.38	0.42	6600	2.56		$3.9 x 10^{-7}$	6	0.69
χ Cnc	69897	F6 V	5.14	0.47	6440	3.70		$<7.6 x 10^{-8}$	<4	>0.58
10 UMa	76943	F5 V	3.97	0.44	6530	2.89		$9.7 x 10^{-7}$	26	−0.06
τ^1 Hya	81997	F6 V	4.60	0.46	6490	3.23		$1.0 x 10^{-6}$	28	−0.20
θ UMa	82328	F6 IV	3.17	0.46	6490	2.99	<2	$9.9 x 10^{-8}$	12	0.16
HR 3991	88215	F5 V	5.31	0.36	6890	2.59		$1.8 x 10^{-6}$	148	−0.31
40 Leo	89449	F6 IV	4.79	0.45	6510	3.07	13	$6.2 x 10^{-7}$	20	0.00
37 UMa	91480	F1 V	5.16	0.34	7000	3.05		$8.7 x 10^{-7}$	87	0.06
ι Leo	99028	F4 IV	3.94	0.41	6640	2.13	40	$2.0 x 10^{-6}$	19	0.26
62 UMa	101606	F4 V	5.73	0.43	6560	3.46	<2		14	0.27
β Vir	102870	F9 V	3.61	0.55	6100	3.36	10	$2.1 x 10^{-7}$	<4	>0.21
γ Vir N	110379	F0 V	3.65	0.36	6890	3.17	25	$(1.2 x 10^{-6})$	25	0.46
γ Vir S	110380	F0 V	3.68	0.36	6890	2.93	42	$(1.2 x 10^{-6})$	32	0.36
HR 4867	111456	F5 V	5.85	0.46	6490	3.99		$1.1 x 10^{-6}$	36	−0.31
HR 4934	113337	F6 V	6.00	0.41	6640	3.17	29	$(1.4 x 10^{-6})$	9	0.58
HR 5156	119288	F3 Vp	6.16	0.42	6600	3.14	5	$4.1 x 10^{-7}$	18	0.21
τ Boo	120136	F6 IV	4.50	0.48	6400	3.35	14	$<4.3 x 10^{-7}$	17	−0.09
14 Boo	124570	F6 IV	5.54	0.54	6140	3.08	<2		5	0.16
ι Vir	124850	F6 III	4.08	0.52	6230	2.92	13	$9.7 x 10^{-7}$	15	−0.23
18 Boo	125451	F5 IV	5.41	0.38	6780	3.11	40	$2.8 x 10^{-6}$	42	0.10
θ Boo	126660	F7 V	4.05	0.50	6310	3.46	35	$1.6 x 10^{-6}$	32	−0.47
σ Boo	128167	F2 V	4.46	0.36	6890	3.15	8	$<8.6 x 10^{-7}$	3	1.38
μVir	129502	F2 III	3.88	0.38	6780	2.86	25	$(1.3 x 10^{-6})$	46	0.06
HR 5529	130817	F2 V	6.16	0.36	6890	2.81	12	$<5 x 10^{-7}$	20	0.56
γ Ser	142860	F6 V	3.85	0.48	6400	3.52	<2	$<6.70 x 10^{-8}$	12	0.06
20 Oph	151769	F7 IV	4.65	0.47	6440	2.25	23	$1.0 x 10^{-6}$	15	0.01
19 Dra	153597	F6 V	4.89	0.48	6400		23		9	0.18
HR 6493	157950	F3 V	4.54	0.39	6720	2.33	27	$1.4 x 10^{-6}$	50	
HR 6541	159332	F6 V	5.64	0.48	6400	2.78	<4		12	0.06
ξ Ser	159876	F0 IV δ Sct	3.54	0.26	7400	1.62	<2		25	1.24
HR 6670	162917	F3-5 IV-V	5.77	0.42	6600	3.18	32	$1.2 x 10^{-6}$	25	0.07
99 Her	165908	F7 V	5.04	0.52	6230	4.28	<3		4	0.34
HR 6797	166285	F5 V	5.69	0.47	6440	2.99	8		10	0.19
χ Dra	170153	F7 V	3.57	0.49	6350		<8	$<5.6 x 10^{-8}$	4	0.48
HR 6985[2]	171802	F5 V	5.39	0.37	6425,6755		31	$(1.2 x 10^{-6})$	27	

TABLE 1—*Continued*

Star Name	HD	Sp. Type	V	B-V	T_{eff}	M_{bol}	D_3 (m Å)		v sin i (km s^{-1})	log Ro
110 Her	173667	F6 V	4.19	0.46	6490	2.79	13	1.0×10^{-6}	20	-0.06
θ Cyg	185395	F4 V	4.48	0.38	6780		20	1.2×10^{-6}	5	1.03
17 Cyg	187013	F7 V	4.99	0.47	6450		<4		9	0.23
HR 7925	197373	F6 IV	6.01	0.46	6490	3.30	24	1.4×10^{-6}	30	-0.23
ψ Cap	197692	F4 V	4.14	0.43	6560	3.04	11	2.5×10^{-6}	41	-0.20
HR 7955	198084	F8 IV-V	4.51	0.54	6140	3.25	<3	$<1.1\times10^{-7}$	6	0.08
μ^1 Cyg	206826	F6 V	4.73	0.48	6400		<2	3.3×10^{-7}	12	0.06
16 Cep	209369	F5 V	5.03	0.44	6530		40	3.1×10^{-6}	27	-0.07
ι Peg	210027	F5 V	3.76	0.44	6530	3.44	<2	2.5×10^{-7}:	9	0.40
ξ Peg	215648	F6 III-IV	4.19	0.50	6310	3.42	<4	1.2×10^{-7}	9	0.08
7 And	219080	F0 V	4.52	0.29	7260	2.24	24	2.1×10^{-6}	59	
ι Psc	222368	F7 V	4.13	0.51	6270	3.49	<4	$<3.2\times10^{-7}$	6	0.21

[1] C IV fluxes in parentheses were inferred from the equivalent width of D_3 and the correlation between D_3 absorption and C IV emission on the assumption that $D_3 > 25$ mÅ corresponds to $F_{C\,IV} \geq 1.5 \times 10^{-5}$ ergs cm^{-2}.

[2] Double-lined spectroscopic binary. The cooler component has D_3; the hotter one does not.

Reticon was cooled with liquid nitrogen. The dispersion of the observations was 0.031 Å pixel^{-1}, and the projected slit width was 1.43 pixels. Each star was observed only once with typical signal-to-noise ratios of at least 100 and usually in the range 400–700. Typical exposure times were 5 to 30 minutes. In order to correct the observations for pixel-to-pixel variations in sensitivity of the detector, the stellar observations were divided by the mean of four measurements of a flat field lamp exposed to a level appropriate to the stellar continuum level for each stellar observation. Any remaining nonlinearities were removed by a standard four-channel normalization routine.

Several water vapor lines, including one at λ5875.6, fall near D_3. These lines were detectable on only one of the nights on which we obtained observations, and we determined equivalent widths by measuring the strengths of the H_2O features in stars in which D_3 proved to be absent. Because the stellar lines in F-type stars usually show significant rotational broadening while atmospheric water vapor lines do not, it proved quite easy to distinguish stellar and terrestrial features. The equivalent widths of D_3 listed in Table 1 have all been corrected for contamination, if any, by H_2O.

The data from Mauna Kea were supplemented by additional measurements of D_3 made at the McMath solar telescope. The McMath spectra have a typical S/N of 100, but the resolution of the McMath observations is about a factor of 3 lower than the resolution obtained at the Canada-France-Hawaii telescope. The accuracy of the measurements of D_3 data obtained at the McMath is severely compromised by the strong water vapor lines superposed on the stellar spectrum. In order to correct for the contribution of H_2O absorption, we obtained measurements at varying air masses of stars with lines so rotationally broadened that stellar D_3, even if present, would be undetectable. Since the H_2O atmospheric lines are quite sharp, they were easily identifiable in these spectra. The total equivalent width of the contaminating H_2O lines was never less than 15 mÅ and so was in most cases comparable to the strength of D_3 itself. For this reason, the McMath data will not be used in the detailed analysis of activity levels. These data are more than adequate, however, for determining whether D_3 is present or absent and are crucial in establishing the high temperature cutoff of activity.

The stars observed with the McMath are listed in Table 2. Note that the equivalent widths of the four stars observed both with the McMath and CFHT (γ Vir N and S, μ Vir, and ξ Ser) are in reasonable agreement. The star μ Vir was observed 12 times at the McMath, and the equivalent widths ranged from 11 to 29 mÅ, with a mean of 19 mÅ. Whether D_3 is intrinsically variable or not we cannot say from data so strongly contaminated by variable water vapor. The most extreme values of the intensity of D_3 in μ Vir were measured on nights when the corrections for H_2O absorption were unusually large. If we attribute all of the variation of D_3 to measurement error, then we can obtain an upper limit to the uncertainty in the D_3 equivalent widths. From examining the multiple observations of μ Vir and several other stars, we estimate the standard deviation of a single observation obtained at the McMath to be ±6 mÅ. In no case is there any uncertainty about whether or not D_3 is present.

In addition to the equivalent widths of He I λ5876, Tables 1 and 2 also give several other properties of each star. The spectral types and $B-V$ colors are from the *Bright Star Catalog* (Hoffleit 1982). The rotational velocities are from Wolff, Heasley, and Varsik (1985) or from the *Bright Star Catalog*. The effective temperatures were estimated by averaging the two calibrations between $B-V$ and T_{eff} given by Böhm-Vitense (1981) for stars in this color range. This adopted calibration agrees to within ±50 K with those proposed by Buser and Kurucz (1978) and by VandenBerg and Bridges (1984). The bolometric corrections are from Buser and Kurucz (1978), and the absolute visual magnitudes were taken from the compilation of Philip, Miller, and Relyea (1976), who used the prescription given by Crawford (1975) to derive M_v from *ubvyβ* photometry. These temperatures are on average about 150 K higher than those given by the (β, T_{eff}) relationship of Hearnshaw (1974). The Hearnshaw calibration seems to give more normal (solar) Fe/H ratios for F-type stars (Boesgaard and Tripicco 1986*b*). A recent empirical calibration between T_{eff} and $B-V$ has been derived by Saxner and Hammerbäck

TABLE 2

OBSERVATIONAL DATA FOR STARS OBSERVED AT THE MCMATH TELESCOPE

Star Name	HD	Sp Type	$B-V$	T_{eff}	M_{bol}	D_3 (mÅ)	$v \sin i$ (km s^{-1})
ρ Gem	58946	F0 V	0.32	7120	2.63	38	68
12 Cnc	67483	F3 V	0.43	6560	2.34	40	40
13 LMi	83951	F3 V	0.36	6890	2.48	29	12
HR 3979	87822	F4 V	0.45	6510	3.08	<10	8
30 LMi	90277	F0 V	0.25	7500	0.89	<10	31
81 Leo	99285	F2 V	0.36	6890	2.07	20	30
HR 4555	103313	F0 V	0.20	7910	0.99	<10	75
γ Vir N	110379	F0 V	0.36	6890	3.17	25	25
γ Vir S	110380	F0 V	0.36	6890	2.93	28	32
39 Com	113848	F4 V	0.39	6720	2.86	14	30
73 Vir	117661	F0 IV–V	0.18	8030	1.54	<10	60
HR 5229	121164	A7 V	0.20	7910	1.68	<5	57
HR 5245	121682	F4 IV–V	0.37	6830	2.13	18	8
HR 5275	122797	F4 V	0.39	6720	2.96	13	50
22 Boo	126661	F0m	0.23	7690	1.16	<10	29
μ Vir	129502	F2 III	0.38	6780	2.86	⟨19⟩	46
ϵ Ser	141795	A2m	0.15	8200	2.06	<5	37
σ Ser	147449	F0 V	0.34	7000	2.58	23	80
HR 6193	150366	F0 V	0.20	7910	1.89	<5	34
53 Her	152598	F0–2 V	0.29	7260	...	37	59
ξ Ser	159876	F0 IV	0.26	7400	1.62	<5	25
HR 7327	181240	F0 III	0.27	7340	...	<10	67
28 Aql	181333	F0 III	0.26	7400	0.87	<10	59

(1985), who made use of integrated fluxes, including infrared colors, and angular diameters. This relationship includes a metallicity term. For solar metallicity the Saxner and Hammerbäck scale is about 150 K higher than ours for the hottest stars in the present sample. The two scales converge near 6400 K. These results suggest that the values of T_{eff} adopted here may be systematically in error by 150 K or more for the stars with the highest temperatures.

Low-resolution (6 Å) spectra were obtained with the short-wavelength (1200–2000 Å) camera of the *International Ultraviolet Explorer* satellite (Boggess *et al.* 1978) and reduced at the Regional Data Analysis Facility of the Goddard Space Flight Center. Standard *IUE* software and calibrations were used to obtain spectra in absolute flux units. Additional spectra were requested from the *IUE* archives and also reduced at the RDAF. The photometric accuracy of the *IUE* data is limited to $\sim 20\%$ by uncertainties in the intensity transfer function and fixed pattern noise of the Vidicon detector. We measured line fluxes from each *IUE* spectrum by integrating above a background extrapolated by eye under the emission line. Upper limits to the line fluxes were estimated from the strengths of weak noise features at the nominal wavelengths of the emission lines. For the early F-type stars, the continuum at the long-wavelength ($\lambda > 1700$ Å) end of the SWP camera rises steeply with increasing wavelength. Therefore, we were able to measure the fluxes of lines only at shorter wavelengths where they remain prominent in contrast against a weak stellar continuum.

The chromospheric and transition region emission line surface fluxes that we have measured are listed in Table 3. Table 3 also lists the ratio F/f required to convert observed to surface fluxes. We have used the Barnes-Evans (1976) relation between the color index $(V-R)$ and stellar angular diameter to derive this conversion factor. In Table 1 we list surface fluxes for the C IV line both from Table 3 and from sources in the literature (Walter *et al.* 1984; Simon, Herbig, and Boesgaard 1985).

III. ANALYSIS

a) Onset of Activity

Previous studies of He I $\lambda 5876$ in main-sequence stars with spectral types of late, F, G, and K (Danks and Lambert 1985; Wolff, Heasley, and Varsik 1985) have shown that the equivalent width of this line correlates well with such indicators of stellar activity as emission at Ca II H and K and in the X-ray region. Does this line continue to serve as a useful diagnostic in early F-type stars? Figure 1 shows the relationship between He I $\lambda 5876$ and the surface flux measured for C IV $\lambda 1549$. The correlation is good, particularly since the two sets of measurements were not made simultaneously. Both lines are known to vary in solar-type stars, and multiple *IUE* exposures suggest that the C IV flux is variable in late F-type stars but not by more than a factor of 4. The degree of variability of D_3 and C IV in the hotter F-type stars is not known. The strength of the D_3 line correlates equally well with C II and other lower excitation ultraviolet lines, all of which are strongly correlated with each other.

Figure 2 shows all of the stars in our sample for which $uvby\beta$ photometry is available so that we can derive an absolute bolometric magnitude. Those stars in which the equivalent width of D_3 exceeds 10 mÅ or the C IV flux exceeds 5×10^4 ergs cm^{-2} s^{-1} are designated as active.

Several interesting properties of activity in F-type stars are illustrated in Figure 2. First, the observations clearly define the point at which the onset of activity occurs. All but one (σ Boo) of the stars in the temperature range $6600 < T_{eff} \leq 7300$ K show helium absorption or chromospheric and transition region emission lines, and even σ Boo, with a D_3 equivalent width of 8 mÅ may be weakly active. None of the stars hotter than $T_{eff} = 7300$ K exhibits measurable activity. The corresponding color index is $(B-V) \approx 0.28$, given the temperature calibration adopted here, and the spectral type is $\sim$F0.

Existing X-ray data are consistent with this definition of the high temperature boundary for the onset of activity. In a

TABLE 3

Ultraviolet Emission-Line Surface Fluxes (10^4 ergs cm^{-2} s^{-1})

Star	$10^{-17} \times F/f$	*N* V λ1240	O I λ1305	C II λ1335	Si IV λ1400	C IV λ1549	He II λ1640	C I λ1657	Notes
α Tri	0.79	11.	16.	29.	23.	50.	10.	13.	1, 2
τ^1 Eri	2.0	≤0.44	1.4	6.5	5.2	11.	...	...	1
τ^6 Eri	1.9	1.4	2.1	3.6	...	4.4[a]	<0.95	...	2
45 Tau	8.8	5.2	8.8	18.	16.	40.	...	...	2
γ Lep	0.84	≤0.45	1.5[a]	≤0.49	...	≤0.65	...	...	2
ξ Gem	0.85	1.3	5.3	13.	8.2	14.	...	...	1
χ Cnc	3.9	1.8[a]	...	3.1[a]	5.1[a]	≤0.74	...	...	1
10 UMa	1.4	2.2	3.9	7.5	5.5	10.	...	...	2
τ^1 Hya	2.3	1.2	2.5	6.4	4.4	10.	...	...	2
θ UMa	0.59	0.76	1.4	0.88	...	1.0[a]	0.29[a]	...	1
HR 3991	5.8	8.1	9.3	13.	11.	23.	...	...	2
40 Leo	2.5	≤1.6	2.2	4.8	...	6.3	...	...	2
τ Boo	2.2	≤0.58	...	≤1.1	≤4.1	≤4.1	...	...	2
ι Vir	1.1	1.2	2.3	5.6	2.1	8.3	2.5	3.1	1, 2
σ Boo	2.9	≤1.7	<4.6	6.6	11.[a]	≤11.	...	...	1, 2
γ Ser	0.90	...	≤1.1	≤0.84	≤0.89	≤0.64	...	...	2
20 Oph	2.2	3.5	3.7	6.6	5.9	10.	...	3.1	1
χ Dra	0.85	<0.48	1.4[a]	1.0[a]	...	≤0.52	...	...	2
110 Her	1.8	...	1.8	6.0	2.6	10.	≤1.8	...	2
θ Cyg	2.8	...	5.6	8.1	7.6	15.	2.7	...	2
ψ Cap	2.0	3.2	5.1	12.	16.	26.	5.7	6.9	2
HR 7955	1.8	0.22	1.1	1.8	1.4[a]	≤0.90	≤1.7	2.2	1, 2
μ^1 Cyg	3.1	1.2	≤1.6	2.9	4.1	3.1	2.7[a]	...	1
ι Peg	1.2	≤0.63	<1.4	2.8	1.9[a]	2.6[a]	2.7[a]	...	2
ξ Peg	1.6	0.67	0.94[a]	0.67	...	1.1	...	...	2
ι Psc	1.4	...	1.6[a]	≤0.84	...	≤2.8	2.0[a]	3.3	2

[a] Uncertain flux.

Notes.—(1) New observation, this study. (2) Image from *IUE* achives. These observations are from the Guest Observer programs of C. Blanco, E. Böhm-Vitense, M. Giampapa, K. Hallam, L. Kuhi, J. Linsky, K. Nicolas, and D. Soderblom.

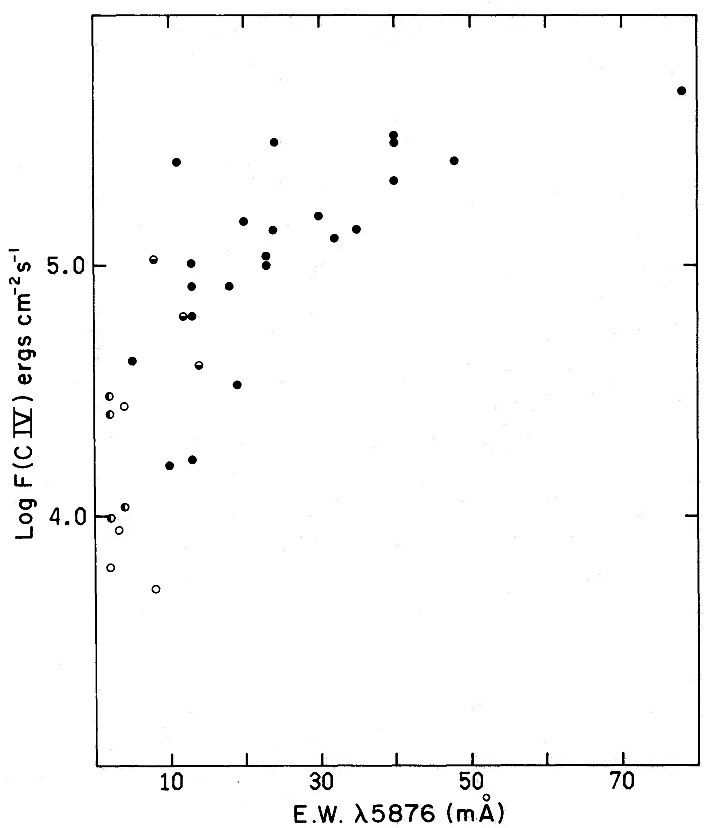

Fig. 1.—Correlation between the flux emitted in C IV λ1549 and absorption by He I λ5876. Filled circles represent measured values for both quantities; half-filled (*horizontal*) circles indicate upper limits in C IV; half-filled (*vertical*) circles represent upper limits in D_3. Open circles indicate that only upper limits were measured for both quantities.

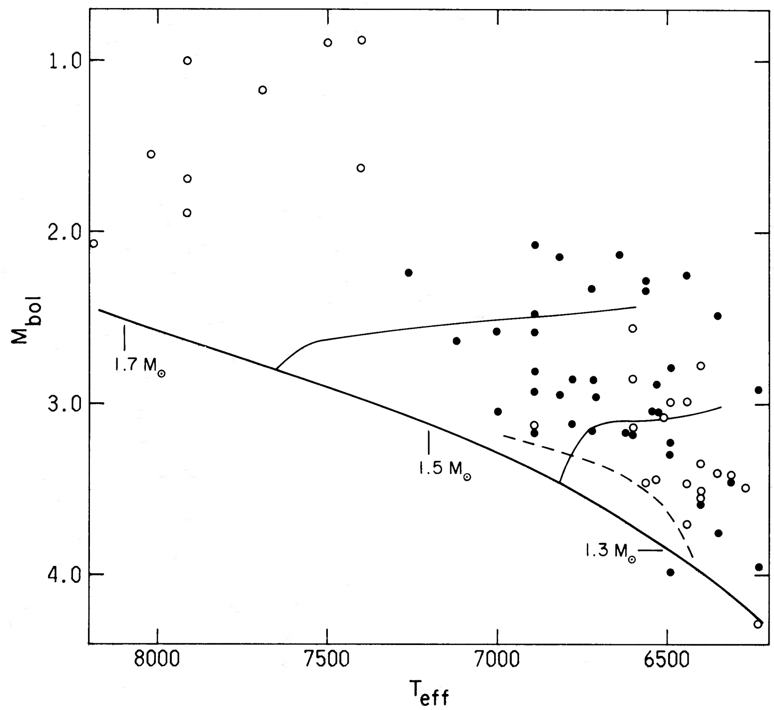

FIG. 2.—Observed stars in the magnitude-temperature plane. Filled circles represent active stars; open circles represent stars in which activity was not detected. The theoretical zero-age main sequence (VandenBerg 1985) and evolutionary tracks for stars of 1.4 $M_{\odot}$ and 1.6 $M_{\odot}$ are shown by solid lines. The dashed line is the observed ZAMS (Crawford 1975).

survey of F-type stars, Schmitt *et al.* (1985) detect X-ray emission in many stars with $(B-V) \gtrsim 0.26$–0.30 but report only a few detections and primarily upper limits for stars with $(B-V) \lesssim 0.26$–0.30. Most of these few detections are probably of binary systems, in which the X-ray emission arises from a late-type companion, but the nearby apparently single star α Aql (A7 V; $B-V = 0.22$) *is* an X-ray source. A sharper definition of the boundary between active and inactive stars cannot be obtained from X-ray data alone since in the case of a detection there is always ambiguity about whether the X-rays originate from the A- or F-type primary or are produced by a late-type companion.

We have observed relatively few stars in the color interval $0.24 < (B-V) < 0.34$ (or equivalently 7000 K $< T_{eff} <$ 7600 K) where the onset of activity occurs. It proved difficult to find late A- and early F-type stars that rotate slowly enough ($v \sin i < 100$ km s^{-1}) so that we could measure D_3. This paucity of stars may be, in fact, a direct consequence of the onset of activity. On theoretical grounds, Böhm-Vitense and Canterna (1974) predict that there should be a gap in the distribution of stars in the color-magnitude diagram caused by the abrupt onset of convection. Convective energy transport will redden a star because once convection becomes important, the temperatures in the atmospheric layers that dominate the contribution to the surface flux in U and B will decrease. The change in color depends on the amount of flux carried by convection, but is predicted to be in the range 0.05–0.10. Böhm-Vitense and Canterna go on to offer evidence that a gap of this magnitude occurs at $(B-V) \approx 0.25$ in the number distribution of both field stars and members of open clusters.

More recent calculations support the hypothesis that the onset of detectable levels of activity coincides with the onset of convection. For example, VandenBerg and Bridges (1984) find that envelope convection disappears at a mass of about 1.6 $M_{\odot}$, or at $T_{eff} = 7600$ K for their ZAMS models.

b) *Nature of Activity in Early and Late F-Type Stars*

Figure 2 shows that there is a significant difference in the character of activity in early and late F-type stars. All but one of the stars in the temperature range 6600 K $< T_{eff} <$ 7300 K is active according to the criteria that the equivalent width of D_3 must exceed 10 mÅ and/or the C IV flux must exceed 5×10^4 ergs cm^{-2} s^{-1}. For σ Boo, the equivalent width of D_3 is only 8 mÅ, and the upper limit to the C IV flux is 1.07×10^5 ergs cm^{-2} s^{-1}, and so weak activity may be present. The star HR 5529 is only moderately active ($W_{\lambda} = 12$ mÅ for D_3). All of the remaining stars in the temperature range 6600 K $< T_{eff} <$ 7300 K are highly active, with D_3 equivalent widths in the range 25–50 mÅ or C IV fluxes in excess of 10^5 ergs cm^{-2} s^{-1}.

At temperatures less than 6600 K, we observe a range in activity levels, and more than half of the stars exhibit no evidence of activity. In these cooler F-type stars, there is a strong correlation between apparent rotational velocity $v \sin i$ and activity level (cf. Figure 3, which shows the results for C IV), and so the differences in activity levels seem to be related to differences in rotational velocity. An independent study of C II and C IV emission (Walter 1985; Walter and Linsky 1986) agrees with these results in showing that surface fluxes correlate with rotation only for stars with $B-V \geq 0.42$–0.45. This work also shows no decrease in surface flux with increasing temperature for stars with $B-V > 0.30$.

The value of $T_{eff} = 6600$ K, which divides the regions where activity is ubiquitous and where activity levels vary widely depending on rotation, coincides fairly closely with the temperature that marks the sharp decline in the rotational velo-

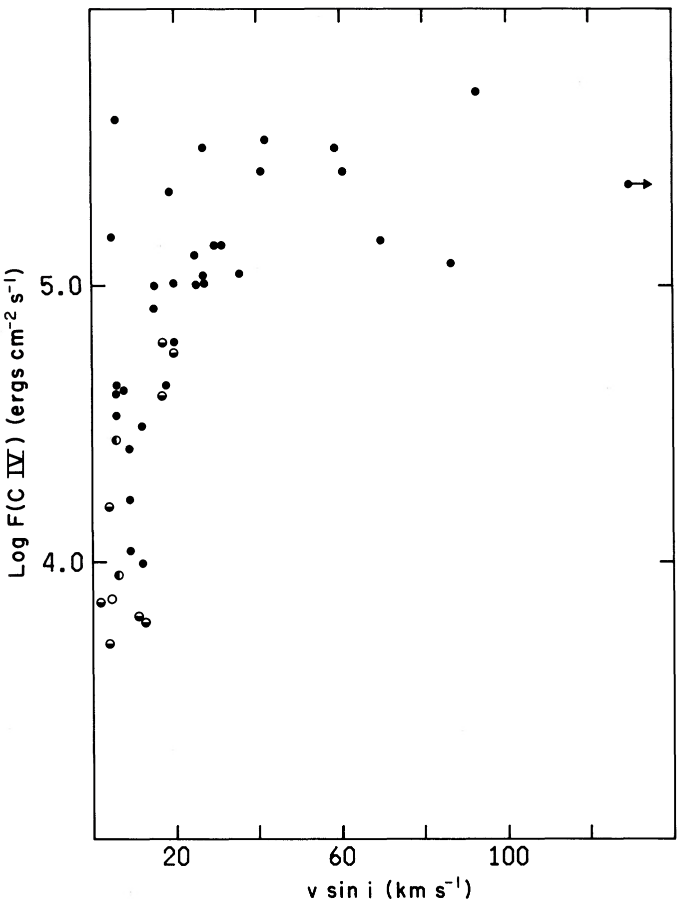

FIG. 3.—Relationship between the flux emitted in C IV λ1549 and apparent rotational velocity for stars with $T_{\rm eff}$ < 6600 K. Symbols are same as in Fig. 1.

cities of main-sequence stars (Wilson 1966; Kraft 1967). Because of the discontinuity in rotational velocities and the disappearance of Ca II H and K emission near spectral type F5, Wilson argued that convection zones also disappeared at this point in the H-R diagram. In fact, our observations show no discontinuity in either the levels of UV activity or the strength of D_3 at F5. The disappearance of H and K emission is presumably due to a loss of contrast between chromospheric emission and photospheric background.

Early and late F-type stars differ not only in the frequency of activity but in the range of activity levels. The range in the X-ray flux and the C IV flux of early F-type stars is no more than an order of magnitude while at G0 the range in X-ray flux is three orders of magnitude (Walter 1983; Schmitt *et al.* 1985) and in C IV surface flux is at least two orders of magnitude (Simon, Herbig, and Boesgaard 1985). It seems unlikely that the uniformly high levels of X-ray and C IV flux in early F-type stars can be explained in terms of selection effects. The stellar continuum flux at the wavelength of the C IV line is still very weak at spectral types F1 and F2, and the detection limits for X-ray fluxes do not depend on $T_{\rm eff}$.

The broad range of activity among stars cooler than F8 reflects the dependence of activity on rotation rate (through the Rossby relation) and the decay of rotation with age as stars lose angular momentum through coronal winds, mass loss, and magnetic braking, as originally proposed by Schatzman (1962). Little decline in X-ray and C IV flux is seen until stars are more than 2 billion years old. The uniformly high flux levels in early F-type stars may then be attributable to their short main-sequence lifetimes, to the absence of magnetic dynamos and coronal winds (see below), or both.

c) Relation of Activity to Lithium and Beryllium Abundances

Following the early work of van den Heuvel and Conti (1971) on the Li abundance-rotation-age connection and Skumanich (1972) on the Li-rotation-age-activity connection in solar-type stars, there has been much work in this area of research (e.g., Duncan 1981; Soderblom 1983; Baliunas and Vaughan 1985). In our investigation of activity in F stars we have concentrated on stars for which the Li and/or Be abundances are known in order to examine the connection, if any, between activity and light element abundance in stars more massive than the Sun. Lithium is destroyed in stars where the temperature reaches about 2×10^6 K and Be at about 3×10^6 K, so the abundances of these elements provide excellent probes of the stellar structure in the outer (approximately 5% by mass) parts of these stars. Thus we hoped to examine the relationship of stellar activity in F stars to the convection zone depth, the generation of the dynamo, and the influence of rotation on convection through the Li and Be abundance.

Abundances of Li and Be from many sources have been collected and are presented in Table 4. In one sense Be provides an important diagnostic of subphotospheric velocity fields because the abundance of Be has a bimodal distribution: it is either solar (Be/H = 1.4×10^{-11}) or else the upper limits on the Be abundance are much less than solar (by factors of 5–100).

The stars in the present sample can be grouped by position in the H-R diagram according to the divisions observed in $T_{\rm eff}$ discussed above. Among the cooler stars ($T_{\rm eff}$ < 6600 K) 11 of 18 stars (61%) have solar beryllium, while about one-third are undepleted in Li. Of the 9 beryllium normal stars only two (θ Per and τ^1 Eri) are active, whereas $\frac{2}{3}$ of the stars (seven of 11) severely depleted in Li and/or Be are active. In the temperature group 6600–7300 K, where virtually all the stars show some activity, three (α CMi, σ Boo, and θ Cyg) are Li- and Be-deficient, five are severely depleted in Li (no Be data are available), while five others have solar Be and their original Li/H of 10^{-9}. Thus, there appears to be no relation between light element abundances and activity for the hotter stars, but a possible association of activity with beryllium deficiency for the cooler stars (see Fig. 4). Definite conclusions require a larger sample size.

Gilliland (1985) has shown that the convective turnover time, τ_c, increases for stars more massive than the Sun when they evolve off the main sequence. This increase is caused by an increase in scale height and a decrease in convective velocity. This change in τ_c may both slow down the transport of Li and Be to regions in the interior where it can be destroyed and also cause an increase in stellar activity, as Gilliland proposes for ι Vir. We find, however, that stars cooler than 6600 K with normal beryllium apparently are *less* likely to be active than the beryllium-deficient ones. Perhaps a more intriguing idea to account for the possible association of beryllium deficiency with activity is that proposed by Parker (1984) to account for the solar lithium deficiency: magnetic inhomogeneities below the convection zone may set up thermal shadows producing convective-like transport of light elements to higher temperatures and nuclear destruction. Those sub–convection zone magnetic fields might also contribute to surface magnetic activity. Another possibility might be that Be deficiency is corre-

TABLE 4

LITHIUM AND BERYLLIUM ABUNDANCES

Star	[Be/H][a]	Reference	log N(Li)[b]	Reference
6 Cet	...	...	2.51	1
α Tri	...	...	1.92	1
HR 784	...	...	2.13	1
θ Per	0.31	2	2.48	1
τ^1 Eri	−0.05	2	2.13	1
τ^6 Eri	−0.15	2	...	...
45 Tau	−0.01	2	3.16	3
γ Lep	−0.10	2	2.54	1
ξ Gem	...	...	<2.19	1
α CMi	≤ −1.66	2	<1.95	1
χ Cnc	0.18	2	...	...
10 UMa	...	...	≤1.5, 2.2:	4
τ^1 Hya	...	...	<2.10	1
θ UMa	+0.20	2	3.09	1
40 Leo	≤ −1.33	5	<1.67	1
ι Leo	−0.3	5	2.9	6
62 UMa	...	...	≤0.90	4
β Vir	−0.20	7	2.04	7
γ Vir N	−0.15	2	3.00	4
γ Vir S	−0.27	2	3.00	4
HR 4934	...	...	≤1.52	4
HR 5156	...	...	≤1.00	4
τ Boo	≤ −1.10	7	≤0.6	7
ι Vir	≤ −1.85	7	<0.72	7
θ Boo	...	...	<2.15	1
σ Boo	≤ −0.77	7	<1.51	7
HR 5529	...	...	≤1.06	4
γ Ser	−0.31	7	2.04	7
20 Oph	< −1.60	2	"low"	8
19 Dra	...	...	2.40	1
HR 6541	...	...	≤1.36	4
HR 6670	...	...	≤1.08	4
99 Her	...	...	2.26	1
HR 6797	...	...	≤1.32	4
HR 6985	...	...	3.1, ≤1.9	4
110 Her	−0.82	7	1.15	7
θ Cyg	≤ −1.05	7	<1.0	7
17 Cyg	−0.15	7	2.16	7
HR 7925	...	...	≤1.36	4
Ψ Cap	...	...	≤1.18	4
HR 7955	≤ −1.35	2	≤0.40	7
μ^1 Cyg	≤ −1.08	2	≤0.3	7
16 Cep	...	...	1.98	4
ι Peg	+0.18	2	2.53	1
ξ Peg	−0.01	7	2.00	7
ι Psc	−0.21	7	2.01	7

[a] Be-deficient stars are those with [Be/H] ≤ −0.70, a factor of 5 less than normal solar/stellar Be/H = 1.3×10^{-11}.

[b] Stars with Li depletions of a factor of 5 or more have log N(Li) ≤ 2.3.

REFERENCES.—(1) Duncan 1981. (2) Boesgaard 1976. (3) Boesgaard and Tripicco 1986*a*. (4) Boesgaard and Tripicco 1986*b*. (5) Boesgaard and Chesley 1976. (6) Danziger and Conti 1966. (7) Boesgaard and Lavery 1986. (8) Herbig and Wolff 1966.

lated with rotation, which might encourage the necessary mixing, and rotation and activity are, of course, correlated in stars cooler than $T_{\rm eff} = 6600$ K. Unfortunately, the stars for which Be abundances have been derived have all been selected to have sharp lines ($v \sin i \lesssim 25$ km s^{-1}) to minimize blending, and this possibility cannot be tested at the present time.

d) Activity and Rossby Number

The observations presented here raise a basic question about activity in F-type stars. Does the ubiquity of activity and narrow range of activity levels indicate that the physical mechanism responsible for nonradiative heating in early F-type stars is not the same as in cooler stars? Or alternatively, are the physical characteristics of the early F-type stars such as to produce, within the framework of the dynamo theory, high and nearly uniform levels of activity?

Recently, it has been shown that the levels of chromospheric, transition region, and coronal activity correlate better with the Rossby number than with rotational velocity alone (Mangeney and Praderie 1984; Noyes *et al.* 1984). The Rossby number is defined to be

$$\mathrm{Ro} = P_{\rm rot}/\tau_c , \qquad (1)$$

where $P_{\rm rot}$ is the stellar rotational period and τ_c is a measure of the convective overturn time near the bottom of the convective zone where the dynamo is presumed to operate. The quantity τ_c is, in turn, defined by the equation

$$\tau_c = \Lambda/v_{\rm conv} , \qquad (2)$$

where Λ is the mixing length and $v_{\rm conv}$ is the convective velocity. In essence, the Rossby number provides a measure of the importance of Coriolis forces in introducing helicity into convective motions. The Rossby number is also approximately equal to $N_D^{-1/2}$, where the dynamo number N_D is essentially the ratio between magnetic field generation and diffusion terms for the convection zone.

In order to calculate Ro for the stars in the present sample, we have used our values of $T_{\rm eff}$ and the models for ZAMS stars by VandenBerg and Bridges (1984) to estimate the stellar radius. We have used the relationship between $B-V$ and τ_c given by Noyes *et al.* (1984) to derive the convective overturn time. Since we know only $v \sin i$ and not rotation period for most of the stars in our sample, we have calculated Ro from the relationship

$$\mathrm{Ro} = \frac{\pi^2}{2} \frac{r}{(v \sin i)\tau_c} , \qquad (3)$$

where the stellar radius r is given in km and τ_c is expressed in units of seconds of time. In equation (3), the quantity $v \sin i$ has been multiplied by $(4/\pi)$ to allow for the mean inclination. While this approach is not valid for an individual star, it is correct for an ensemble of stars and allows us to compare the relationship between Ro and activity for the F-type stars with that derived for cooler stars for which rotational periods are known (see Fig. 5).

It is true, of course, that most of our stars do not lie on the ZAMS and both r and τ_c change with time. Gilliland (1985) has calculated the change in τ_c along evolutionary tracks for stars in the mass range considered here. The estimates we have derived for τ_c and Ro should be fairly accurate for late F-type stars within 0.7 mag of the ZAMS. For early F-type stars, the calculated values of τ_c for evolved stars are, within the uncertainties of the theory, the same as those of unevolved stars with the same $(B-V)$. The derived values of Ro are listed in the final column of Table 1.

Figure 5 shows the relationship between Ro and

$$\log R(\text{C IV}) = \log [F(\text{C IV})/\sigma T_{\rm eff}^4] . \qquad (4)$$

The F-type stars cooler than 6600 K follow quite closely the relationship derived by Simon, Herbig, and Boesgaard (1985) for stars with spectral types of F8 and later and with rotational periods that were either measured directly or calculated from the Ca II H and K fluxes. The hotter stars do not follow this relationship. Although the values of Ro for the hotter stars range over nearly a factor of 100, the C IV flux is uniformly

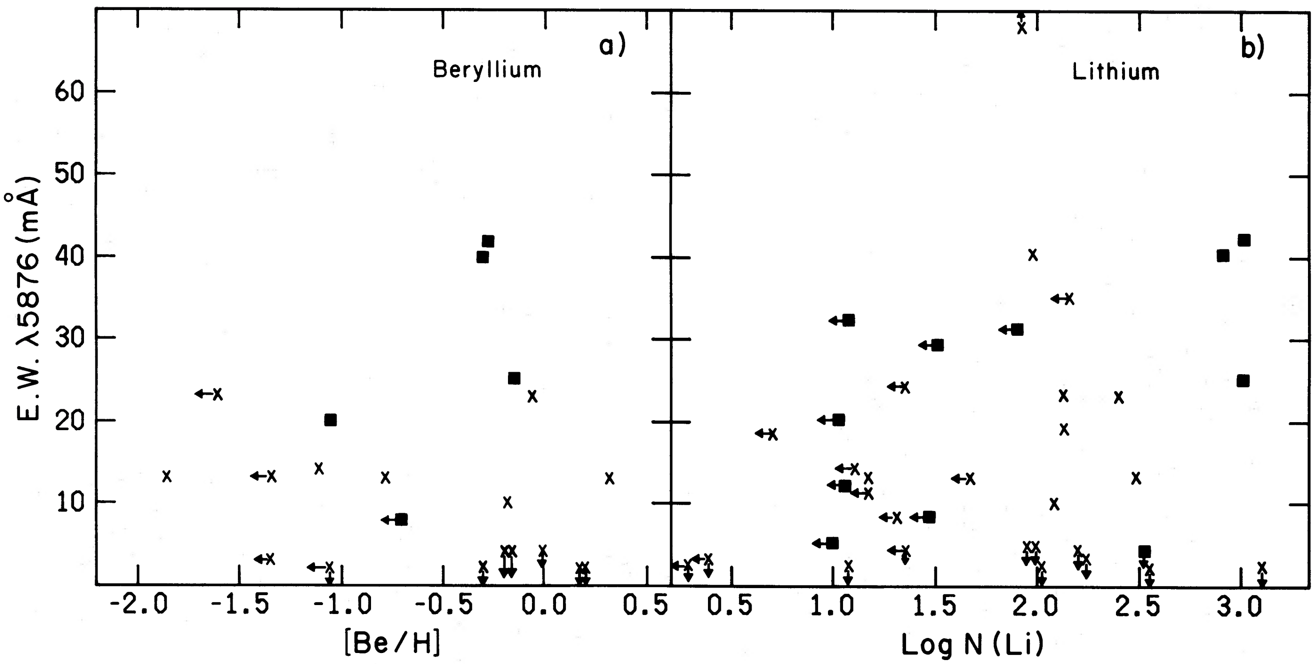

FIG. 4.—The relationship between activity as measured by He I λ5876 and the light element abundances of $[Be/H] = \log(Be/H)_* - \log(Be/H)_\odot$ (*a*) and $\log N(Li)$ on the scale where $\log N(H) = 12.00$ (*b*). Crosses denote stars with $T_{eff} < 6600$ K; squares denote stars with $T_{eff} \geq 6600$ K.

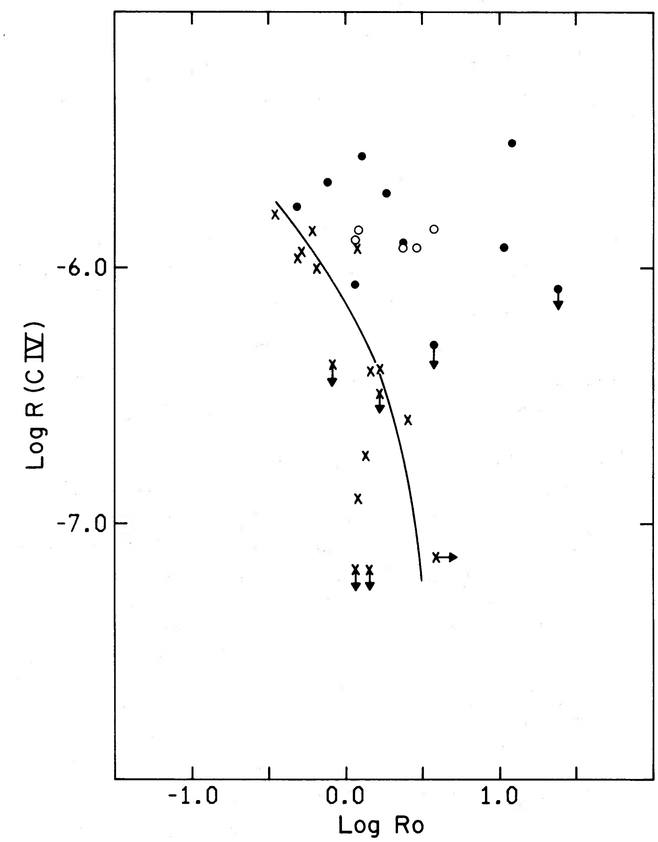

FIG. 5.—Relationship between $R(\text{C IV}) = F(\text{C IV})/\sigma T_{eff}^4$ and Rossby number. Crosses represent stars with $T_{eff} < 6600$ K; filled circles represent stars with $T_{eff} > 6600$ K, for which C IV fluxes have been measured; open circles represent stars with $T_{eff} > 6600$ K for which the C IV flux was inferred from the equivalent width of He I λ5876 (see text). Solid line represents relationship derived for stars with measured or calculated periods and spectral types F8 and later (Simon, Herbig, and Boesgaard 1985).

high and is independent of Ro. In order to strengthen this point we have included in Figure 5 those hot stars for which we have measured only D_3 line strengths. From Figure 1, it seems reasonable to assume that for any star in which the equivalent width of λ5876 exceeds 25 mÅ, the C IV flux is at least as large as 1.5×10^5 ergs cm^{-2} s^{-1}. We have then normalized this value by dividing by the value of $\sigma T_{eff}{}^4$ for each individual star. The values of R (C IV) derived in this way are listed in the parentheses in the ninth column of Table 1.

The failure of the Rossby number to provide an adequate characterization of the activity of early F-type stars could have been anticipated from the raw data. The mean $v \sin i$ for the early F-type stars observed here is only a factor of 2 higher than the $\langle v \sin i \rangle$ for the late F-type stars. The convective turnover time, in contrast, changes by more than a factor of 100 between $T_{eff} = 6600$ K and $T_{eff} = 7300$ K, which is approximately the high-temperature cutoff for activity. This one-parameter characterization of activity by means of the Rossby number fails to account for the high levels of activity seen in virtually all early F-type stars.

The basic question, of course, is whether the failure of this simple approach is a consequence of the inadequacy of the models for treating stars with shallow convection zones or, alternatively, whether nonradiative heating in early F-type stars is produced in a fundamentally different way.

In emphasizing the small range of X-ray flux and the high minimum activity level of the early F dwarfs despite their significant range in rotational velocity, Walter (1983) argued that perhaps the activity depended on some invariant property of these stars. One speculation that he offered was the possibility that the activity was associated with a primordial magnetic field and not with one generated by a currently active dynamo.

An alternative possibility is that acoustic heating may play a significant role in early F-type stars. It is obvious that acoustic waves cannot be the dominant source of coronal and chromospheric heating in all active main sequence stars (e.g., Vaiana *et* *al.* 1981). While acoustic heating models predict weak or no coronal soft X-ray emission in early A stars, peak emission near F0, with a rapid drop in flux between G5 to K0 (de Loore 1970; Mewe 1979), observations are in strong conflict with these predictions. X-ray luminosity, L_x, peaks among the G-type stars (e.g., Vaiana *et al.* 1981; Caillault and Helfand 1985), and about 30% of K dwarfs have values of L_x comparable to those of F- and G-type dwarfs. The ratio L_x/L_{bol} peaks among M dwarfs. Acoustic heating models also cannot account for systematically higher X-ray flux levels seen in younger stars (e.g., Stern *et al.* 1981; Walter *et al.* 1984), or the spatial inhomogeneity of the solar corona. On the other hand, calculations do predict a maximum near spectral type F0 in the flux produced by acoustic waves. If dynamo action is not the exclusive or dominant source of activity in the early F stars, acoustic heating might offer an attractive alternative.

One of the standard arguments against acoustic heating has been that, if this process is dominant, one should see very little spread in the X-ray flux, L_x, or in $L_{\rm C\,IV}$ at a given position in the H-R diagram since the acoustic energy is determined by $T_{\rm eff}$ and log g. In other words, the acoustic power should depend only on properties of the convection zone, which should be identical for all stars with a given $T_{\rm eff}$ and log g. Does the small spread in L_x and $L_{\rm C\,IV}$ in early F-type stars, relative to the spread in solar-type stars, offer support for acoustic heating as a relevant mechanism? Or does the fact that the fluxes vary by at least an order of magnitude for stars of similar temperature argue against acoustic heating? Or do the conditions under which star formation occurs allow differences in the subphotospheric velocity fields in stars of similar temperature and surface gravity? If the nonradiative heating is due to primordial fields (or to MHD "slow mode heating" in which magnetic fields channel acoustic waves to the atmosphere from the convective zone), then a range in magnetic field strengths in stars born in different molecular clouds (or in different regions of the same cloud) might account for the observed dispersion in C IV and X-ray flux and in the equivalent width of D_3 at a given spectral type. Obviously, many questions remain about the cause of nonradiative heating in early F-type stars and about how acoustic and magnetic heating modes vary in importance along the main sequence.

e) *Evolutionary Effects*

Gilliland (1985) has presented calculations that show that evolutionary effects can be of substantial importance in determining the value of τ_c in stars in the mass range 1.1–1.5 $M_\odot$. In a 1.25 $M_\odot$ star, for example, the value of τ_c drops by about 20% during initial evolution away from the main sequence because of a decrease in the scale height and an increase in the convective velocity. During subsequent evolution, both trends reverse themselves, and increases in scale height and decreases in $v_{\rm conv}$ are of great enough magnitude to produce a large increase in τ_c.

For the evolved stars in the present sample, Gilliland predicts that τ_c should be larger for any given star than it was on the ZAMS but smaller by a factor of 2 or more than it is for ZAMS stars with the same $(B-V)$. If we use ZAMS values for the stellar radius and for τ_c, we should therefore underestimate Ro for evolved stars. In other words, the observed levels of activity in evolved stars should be too low for the calculated value of Ro.

Figure 6 shows the relationship between the C IV flux and Ro for unevolved (within 0.7 mag of the theoretical ZAMS)

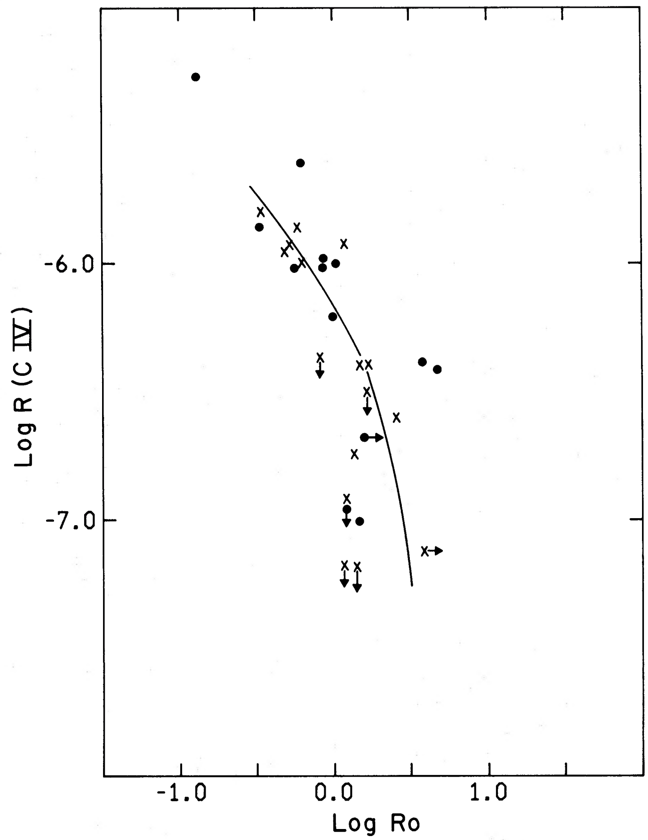

FIG. 6.—Relationship between Rossby number and R(C IV) = F(C IV)$/\sigma T_{eff}{}^4$ for stars with $T_{\rm eff} < 6600$ K. Filled circles represent stars that lie more than 0.7 mag above the ZAMS. Crosses represent stars within 0.7 mag of the ZAMS.

and evolved stars, respectively, that are also cooler than $T_{\rm eff}$ = 6600 K. There is no obvious difference in the relationship between flux level and Ro for the two groups of stars. Evolutionary effects are evidently not large enough relative to other theoretical and observational uncertainties to be detectable.

This result should certainly not be taken to mean that evolutionary effects are unimportant. Gilliland calls attention to ι Vir, which is a chromospherically active subgiant with a mass of 1.25 $M_\odot$ and a rather short rotational period of 7.6 days (Noyes *et al.* 1984). There are several other rapidly rotating subgiants in our present sample. Gilliland suggests that these stars may have been inactive on the main sequence but the increase in τ_c with evolution is responsible for (new) dynamo action. Indeed, Gilliland argues that it may be difficult to explain the existence of stars with rapid rotation, advanced age, and moderate activity level unless dynamo activity has only recently been turned on as a consequence of evolutionary changes. As the evolutionary tracks in Figure 2 show, active subgiants like ι Vir originate from positions on the main sequence where $T_{\rm eff}$ exceeds 6600 K and where activity is uniformly high. These high levels of activity may simply carry over into the subgiant phase of evolution and may not provide evidence of a rejuvenation of activity and of dynamo action. For stars earlier than F5 V there is no evidence that the high level of activity depends on rotation or that either rotation or activity decline systematically with *early* evolution away from the ZAMS, as is observed for stars later than F5 V (Kraft 1967; Wilson 1966; Simon, Herbig, and Boesgaard 1985).

IV. SUMMARY

Measurements of He I λ5876, of chromospheric and transition region emission lines, and of X-ray flux all demonstrate that activity is common among stars with spectral types F0–F9. Up to $T_{\text{eff}} = 6600$ K (spectral type ≈ F5), the level of activity can be explained adequately in terms of the dynamo models that apply to stars of solar type. In these late F-type stars, activity depends on rotation, and the level of activity in C IV can be accounted for by the same one-parameter relationship between Rossby number and surface flux derived for stars with known periods and types later than F8. The higher temperature boundary of the region where the dynamo model appears to be applicable coincides very closely with the discontinuity in rotational velocities that has long been known to occur near spectral type F5. The F-type stars for which the dynamo model appears to be applicable and which are deficient in beryllium are somewhat more likely to be active than those with normal beryllium.

While there is no discontinuity in the maximum level of activity at $T_{\text{eff}} = 6600$ K, there is a fundamental change in the observed properties of active stars. Virtually all stars with temperatures in the range 6600 K < T_{eff} < 7300 K are highly active. Whether the diagnostic used is D_3, C IV, or X-ray emission, there are few stars in which the activity is either low or unmeasurable. The range of activity levels is smaller for the early F-type stars than for the solar-type stars. There is no correlation between activity level and Rossby number, and the activity levels in these early F-type stars are higher than predicted by the standard Rossby number formulation. It may prove necessary to resort to a heating mechanism other than that associated with a magnetic dynamo to explain the activity in these stars with shallow convection zones, with acoustic heating being one possibility.

We would like to thank Don Martin for obtaining the observations made with the McMath Solar Telescope. We are grateful to the CFHT and to Michael Tripicco and John Varsik for their help in obtaining and reducing the D_3 observations. We are also indebted to Dr. Y. Kondo and the staff of the *IUE Observatory* for their assistance with the acquisition of these data. T. S. gratefully acknowledges support of National Aeronautics and Space Administration grant NAG S-146. A. M. B. was supported in part by a grant (AST 82-16192) from the National Science Foundation.

Note added in manuscript.—Zarro and Zirin (1986) have reported a strong correlation between λ10830 and fractional X-ray luminosities (L_x/L_{bol}) for dwarfs later than F7 in spectral type but not for early F dwarfs. They argue that this difference is directly related to the changing depth of the stellar convection zone in this temperature region. In comparing their data with our own, we find that the strength of λ10830 for the early F dwarfs does not correlate with either the flux in C IV or with the equivalent width of λ5876, but as noted here the latter two quantities are well correlated. We do not have enough stars to determine whether or not X-ray flux and the equivalent width of λ5876 are well correlated in hot F dwarfs. Obviously, many observational and theoretical questions remain to be resolved about the nature of stellar activity in the hotter F-type main-sequence stars.

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