THE ASTROPHYSICAL JOURNAL, **250**:293–299, 1981 November 1

THE COOL HALF OF THE H-R DIAGRAM IN SOFT X-RAYS

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Received 1980 December 15; accepted 1981 May 8

ABSTRACT

We report results of an *Einstein* Guest Observing program to map the occurrence of soft X-ray emission, which is a signature of hot stellar coronae ($T > 10^6$ K), in the cool half of the Hertzsprung Russell (H-R) diagram. We detect X-rays from F–M dwarfs and late F through early K giants, but not from the cooler giants, other than the spectroscopic binary ϵ Car (K0 II + B), or from any supergiants, other than Canopus (F0 Ib–II). The empirical separation of the cool half of the H-R diagram into a region where stellar soft X-ray emission is a common phenomenon, and a region where hot coronae are rare, if present at all among single stars, is similar to that found previously by Linsky and Haisch for C IV $\lambda\lambda$1548,1551 emission ($T \approx 10^5$ K) and by Stencel and Mullan for the onset of rapid mass loss in strong, cool ($T \lesssim 10^4$ K) stellar winds. We discuss the energy balance in the outer atmospheres of the coronal stars, the likely absorption of X-ray emission by cool winds in the "hybrid-spectrum" supergiants, a rotation-activity connection among the G dwarfs, and possible evolutionary origins of the structure seen in the cool half of the X-ray H-R diagram.

Subject headings: stars: coronae — stars: late-type — stars: magnetic — stars: rotation — stars: winds — X-rays: sources

I. INTRODUCTION

We present the results of a collaborative *Einstein* Guest Observing program to map the occurrence of hot coronae ($T > 10^6$ K) in the cool half of the Hertzsprung-Russell (H-R) diagram. Our study was stimulated in part by the work of Linsky and Haisch (1979), who proposed, on the basis of *IUE* spectra of some 20 stars, that the cool half of the H-R diagram could be divided into two distinct regions. One region includes the F–M dwarfs and late F through early K giants and is characterized by the presence of prominent chromospheric ($T \lesssim 10^4$ K) and higher temperature (2×10^4–2×10^5 K) emission lines in far-ultraviolet spectra. The second region includes red giants later than about K2 III and supergiants later than about G5 Ib and is characterized by generally weaker chromospheric emission and little or no evidence for higher temperature species. Furthermore, the red giants of the second region typically exhibit the spectroscopic signatures of strong, cool stellar winds (Stencel 1978; Stencel and Mullan 1980).

In the particularly well-studied case of the Sun, 10^5 K plasma is thought to occur almost exclusively in thermal interfaces (the "transition region") between the multimillion degree corona and the 6000 K chromospheric layers (e.g., Withbroe and Noyes 1977). If the solar analogy is at all viable in the broader stellar context, the division of the H-R diagram seen in C IV should map directly onto a similar boundary in the occurrence frequency of solar-like hot coronae. Since the soft X-ray imaging instruments on the *Einstein* Observatory are sensitive to the thermal emission from such coronae, one goal of our program was to test whether the C IV division also is seen in soft X-rays. Of particular interest in this regard are the so-called hybrid-spectrum supergiants (Hartmann, Dupree, and Raymond 1980) that show evidence for 10^5 K plasma *and* for cool winds, since the close correspondence of the C IV and wind boundaries among the ordinary giants suggested that the apparent disappearance of hot coronae might be causally related to the onset of strong, chromospheric winds (Linsky and Haisch 1979).

A second goal of our program was to identify the stellar parameters that distinguish the strong from the weak coronal X-ray sources. We anticipated that such parameters might reflect the *magnetic* properties of stars, because magnetic structures appear to be the fundamental building blocks of the solar corona (e.g., Vaiana and Rosner 1978).

II. OBSERVATIONS

Giacconi *et al.* (1979) have described the *Einstein* Observatory, and Vaiana *et al.* (1981) have reported the

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TABLE 1

SUMMARY OF TARGET STARS, X-RAY FLUXES, AND ULTRAVIOLET EMISSION PROPERTIES

Star (1)	HR No. (2)	Spectral Type (3)	V (mag) (4)	$(V-R)$[a] (mag) (5)	l_{bol} (10^{-7} ergs cm^{-2} s^{-1}) (6)	f_x/l_{bol} (10^{-7}) (7)	$f_{Mg\,II}/l_{bol}$[b,c] (10^{-7}) (8)	$f_{C\,IV}/l_{bol}$[c] (10^{-7}) (9)	$f_{He\,II}/l_{bol}$[c] (10^{-7}) (10)
				Dwarfs					
μ Dra	6369, 70	dF6+dF6	+5.06	(+0.40)	2.4	170	...	...	...
β Vir	4540	F8 V	+3.60	+0.48	9.7	20	...	...	...
π^1 UMa	3391	G0 V	+5.64	+0.52	1.5	420	...	...	...
β Com	4983	G0 V	+4.26	+0.49	5.3	40	...	...	...
Sun	...	G2 V	−26.77	(+0.53)	1.37×10^{13}	(1.5–4)[c]	200–280[c]	0.9–2.1[c]	0.2–0.8[c]
α Cen A	5459	G2 V	−0.01	(+0.53)	270	2[d,e]	180	1.0	0.3
τ Cet	509	G8 V	+3.50	+0.62	12	<4[f]	...	...	...
70 Oph	6752	K0 V+K5 V	+4.03	+0.65	7.4	100[f]	...	...	...
α Cen B	5460	K1 V	+1.33	(+0.7)	95	14[d,e]	250	1.2	0.2
ϵ Eri	1084	K2 V	+3.73	+0.72	10	150[f]	750	9.8	5.3
61 Cyg	8085, 86	K5 V+K7 V	+4.80	+1.08	6.1	40[f]	...	...	...
				Subgiants					
δ Pav	7665	G5 IV	+3.56	+0.61	11	3[d]	...	...	...
				Giants					
α Aur Ab	1708	F9? III	+0.96	(+0.46)	110	90[d,e]	1100	32	4.5
β Lep	1829	G5 III	+2.84	+0.65	23	1[d]	...	...	...
μ Vel	4216	G5 III	+2.69	+0.68	27	80	380	3.7	2.1
β Crv	4786	G5 III	+2.64	+0.61	26	<1	...	...	...
χ Per	662	gG6	+6.00	(+0.78)	1.4	25[d,e]	...	...	...
η Dra	6132	G8 III+dK	+2.74	+0.61	24	0.6[d]	...	...	...
β Gem	2990	K0 III	+1.14	+0.75	120	0.4	93	...	...
ϵ Cyg	7949	K0 III	+2.46	+0.73	35	<0.4	...	...	...
β Cet	188	K1 III	+2.02	+0.72	52	40	260	1.0	1.1
α Ari	617	K2 III	+2.00	+0.84	62	<0.2[d]	81	...	...
α Boo	5340	K2 III	−0.05	+0.97	490	<0.03	95	<0.2	<0.3
α Ser	5854	K2 III	+2.64	+0.81	33	0.3[d]	67	0.6	<0.3
ϵ Sco	6241	K2 III–IV	+2.29	+0.86	48	0.3[d]	71	0.6	<0.3
α Tau	1457	K5 III	+0.86	+1.23	360	<0.04	...	...	...
				Bright Giants					
β Dra	6536	G2 II	+2.78	+0.68	24	30	660	10	2.0
ϵ Car	3307	K0 II+B	+1.85	(+0.92)	74	0.2	...	...	...
α Cas	168	K0 II–III	+2.23	+0.78	46	<0.3	82	...	...
α UMa	4301	K0 II–III+?	+1.79	+0.81	68	<0.2[d]	100	<0.9	<0.5
β Peg	8775	M1 II–III	+2.42	+1.50	160	<0.2[d]	36	...	...
				Supergiants					
α Car	2326	F0 Ib–II	−0.75	+0.24	480	0.6	...	...	...
η Aql	7570	F6 Ib+?	+3.50	(+0.55)	11	<1	...	...	...
δ CMa	2693	F8 Ia	+1.84	+0.51	50	<0.3	62	...	...
β Aqr	8232	G0 Ib	+2.87	+0.61	20	<1	260	1.5	0.6
α Aqr	8414	G2 Ib	+2.93	+0.66	20	<1	590	1.6	1.0
9 Peg	8313	G5 Ib	+4.31	+0.80	6.6	<2	260	...	...
ϵ Gem	2473	G8 Ib	+2.98	+0.96	29	<0.6	280	<0.3	...
12 Peg	8321	K0 Ib	+5.29	(+0.99)	3.6	<3	...	...	...
ϵ Peg	8308	K2 Ib	+2.39	+1.05	58	<0.2	210	...	...
ξ Cyg	8079	K5 Ib	+3.70	+1.20	24	<0.4	100	...	...
α Sco	6134	M1 Ib+B	+0.91	+1.55	710	<0.02[d]	...	...	...
α Ori	2061	M2 Iab	+0.42	+1.64	1400	<0.03[d]	32	<0.01	...

[a] Values in parentheses are obtained from $(B-V)$, or from Thomas, Hyland, and Robinson 1973 for the Sun and α Cen A.
[b] Stencel *et al.* 1980 and Basri and Linsky 1979.
[c] Ayres, Marstad, and Linsky 1981.
[d] Vaiana *et al.* 1981.
[e] High Resolution Imager.
[f] Johnson 1981.

initial survey of stellar soft X-ray emission. Our program includes many targets that were not in the first survey and which were chosen specifically to address the problems outlined in § I, above.

Table 1 summarizes our observations. Several of the stars are from Vaiana *et al.* (1981) and from Johnson's (1981) survey of nearby cool dwarfs. Most of the targets were observed with the Imaging Proportional Counter (IPC), but a few were observed with the High Resolution Imager (HRI), as noted. Source fluxes were determined from the measured count rates using the conversion factors cited by Vaiana *et al.* (1981). We established upper limits (3 σ) for empty fields according to a detectability criterion based on the effective exposure time (see Vaiana *et al.* 1981), which was typically about 1700 s for each target. Because most of the detected sources are located within a few hundred parsecs of the Sun, we made no corrections for interstellar absorption.

The soft X-ray detections, or upper limits, are given in Table 1 as flux ratios, f_x/l_{bol}, where f_x is the X-ray intensity measured at the Earth (ergs cm^{-2} s^{-1}) in the nominal IPC (or HRI) band (typically 0.1–4 keV), and l_{bol} is the bolometric emission of the star, measured in flux units at the Earth[3] (The fluxes, f_x, of the sources at the Earth can be recovered by multiplying the flux ratios by l_{bol}, which is tabulated in col. 6 of Table 1.) The flux ratios—which are analogous to surface fluxes—are a fair way to compare the emission levels of stars having very different surface areas and can be derived independently of uncertain stellar distances when interstellar absorption corrections are negligible.

We determine bolometric fluxes as follows (see, e.g., Ayres, Marstad, and Linsky 1980):

$$l_{\text{bol}} = 2.7 \times 10^{-5} \text{ dex } (-m_{\text{bol}}/2.5), \quad \text{ergs cm}^{-2}\text{ s}^{-1} \text{ at the Earth}, \qquad (1)$$

where

$$m_{\text{bol}} = V + \text{B.C.}$$

is the bolometric magnitude, V is the stellar visual-band apparent magnitude, and B.C. is a bolometric correction. We adopt the B.C.–$(V - R)$ relations given by Johnson (1966), and the V magnitudes and $(V - R)$ colors tabulated by Johnson *et al.* (1966). If not available in the latter, V is taken from Hoffleit (1964) while $(V - R)$ is estimated from the $(B - V)$ color and the $(B - V)$–$(V - R)$ transformations proposed by Johnson (1966). We have not applied reddening corrections to the supergiants of the sample. However, if the mean density of hydrogen along the line of sight is of order 0.1 cm^{-3}, then the interstellar absorption in the $\frac{1}{4}$ keV band will be comparable to the visual extinction (Allen 1973); consequently, the flux ratio f_x/l_{bol} will be unaffected.

[3] We distinguish here between comparatively narrow-band fluxes, such as in soft X-rays or the optical V filter, and truly broad-band measures such as the bolometric luminosity. We designate the former by f and the latter by l. Lower case symbols denote fluxes measured at the Earth.

The "solar" values given for comparison in Table 1 are derived from the sunspot cycle minimum and maximum X-ray spectra cited by Manson (1977), and the broad band fluxes given by Kreplin *et al.* (1977), with the caveat that the detailed response of the IPC (and HRI) to the solar X-ray spectrum is poorly known. The factor of ≈ 3 variation of the mean coronal emission over the sunspot cycle is probably reasonable for the $E < \frac{1}{2}$ keV region that dominates the solar soft X-ray spectrum, although order of magnitude or larger enhancements are typical for the harder X-ray bands (Kreplin *et al.* 1977). Note that the X-ray flux ratio of α Cen A (G2 V), a near twin of the Sun in many respects (Flannery and Ayres 1978), is similar to that estimated for the mean Sun.

The f_x/l_{bol} ratios are depicted in Figure 1 on an H-R diagram. The abscissa is the $(V - R)$ color, which is a useful empirical measure of stellar effective temperature (e.g., Barnes and Evans 1976). The flux ratios are presented as bubbles whose areas are proportional to observed values (*open circles*) or estimated upper limits (*hatched circles*).

III. DISCUSSION

a) Coronal Emission in the Cool Half of the H-R Diagram

With our larger sample of targets, we can extend and amplify the picture outlined by Vaiana *et al.* (1981). On the one hand, we have detected soft X-ray emission from essentially all of the late-type dwarfs (F–K) that we have surveyed. In fact, Johnson (1981) and Vaiana *et al.* (1981) have measured coronal X-ray emission in red dwarfs as late as M8. On the other hand, the *Einstein* pointings have yielded only upper limits on soft X-ray emission from supergiants, with the exception of Canopus (F0 Ib–II), and giants redder than $(V - R) = 0.84$ (α Ari), with the exception of ϵ Car [$(V - R) = 0.92$]. However, the latter is a spectroscopic binary (K0 II + B) that may not be representative of the typical coronal behavior of single stars.

We call attention to the rapid decrease in the maximum f_x/l_{bol} levels as one proceeds from $(V - R) \approx 0.7$ to $\gtrsim 0.85$ in the giant branch. The giants of our sample lying in the color band $(V - R) \lesssim 0.7$ have values of f_x/l_{bol} up to $\approx 10^{-5}$ and three exceed 10^{-6}. By contrast, the single giants with $(V - R) \gtrsim 0.85$ all have upper limits $< 0.2 \times 10^{-7}$, while α Boo [$(V - R) = 0.97$] and α Tau [$(V - R) = 1.23$] both have upper limits $\lesssim 0.04 \times 10^{-7}$. [Note that α Boo and α Tau are considerably redder in $(V - R)$, and therefore are cooler than α Ser and ϵ Sco, despite their similar spectral type assignments.] Although the sample is not large, we feel that the *Einstein* data clearly indicate a fundamental weakening of soft X-ray activity (as measured by f_x/l_{bol}) in the single giants redward of $(V - R) \approx 0.85$ compared with those blueward of $(V - R) \approx 0.70$.

It is essential to consider carefully the implications of the X-ray upper limits for the supergiants and the cooler giants. First, the upper limits on f_x/l_{bol} are often considerably smaller than that of the mean Sun or the solar

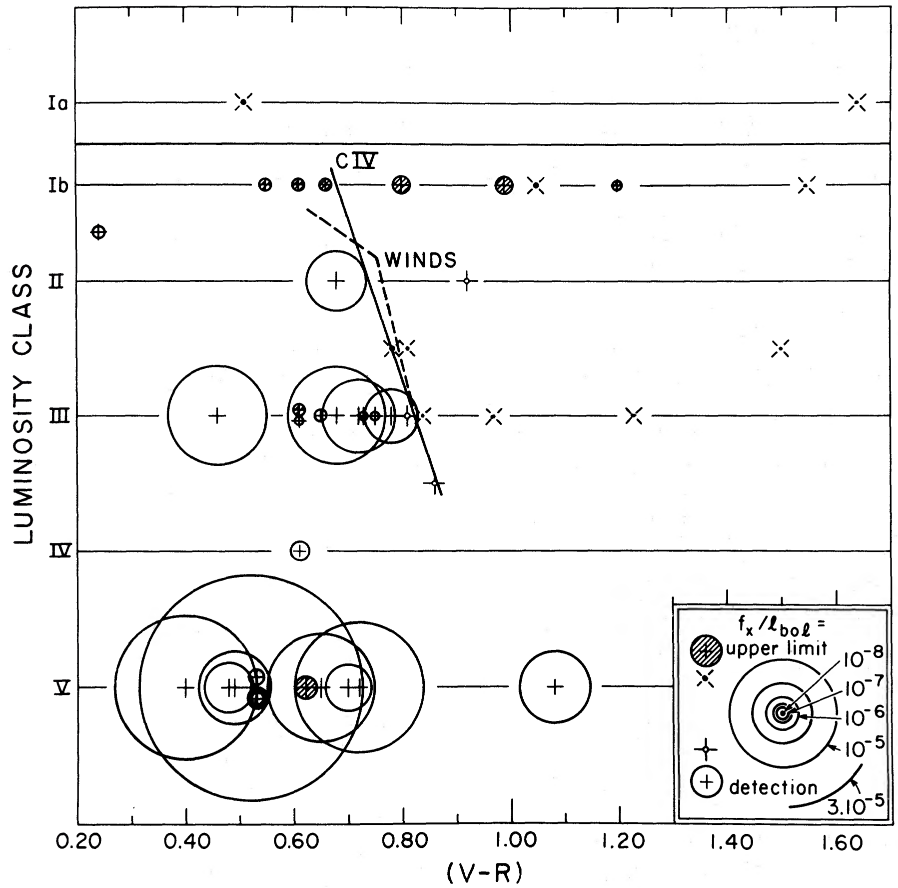

FIG. 1.—An H-R diagram in which soft X-ray detections (*open circles*) and upper limits (*hatched circles*) are plotted as bubbles whose areas are proportional to f_x/l_{bol}. The Sun is represented as a donut: the inner and outer radii correspond to sunspot minimum and maximum coronal activity levels, respectively. The line marked "C IV" separates the region where stellar 10^5 K emission usually is prominent (to the left) from that where it is usually not prominent (above and to the right). Also plotted is a boundary marked "Winds," which separates stars having weak stellar winds (to the left) and strong winds (above and to the right) as established by Mg II emission core asymmetries. Aside from the early G supergiants and ϵ Car (see text), the C IV and wind boundaries appear to coincide with the weakening of coronal soft X-ray emission.

twin α Cen A, both of which are comparatively "quiet" for typical early G dwarfs. For example, upper limits for α Ari (K2 III), α UMa (K0 II–III), and ϵ Peg (K2 Ib) are one-tenth that of the Sun or α Cen A, while those for α Boo (K2 III), α Sco (M1 Ib+B) and α Ori (M2 Iab) are only about $\frac{1}{100}$. Note, however, that the upper limits for α Aqr (G2 Ib) and β Aqr (G0 Ib) are more nearly comparable to the f_x/l_{bol} ratios of the quiet chromosphere G dwarfs.

Second, Ayres, Marstad, and Linsky (1981) have proposed correlations between the flux ratios, f_L/l_{bol}, of emission lines formed in different thermal regimes of the stellar outer atmosphere. It is significant that the f_x/l_{bol} upper limits for both α Boo and α Aqr lie a factor of 10 or more below one such correlation—$f_x/l_{bol} \sim (f_{Mg\,II}/l_{bol})^3$—which was established by typical G–K dwarfs and giants that *are* coronal X-ray sources.

Finally, the sensitivity of the *Einstein* IPC decreases precipitously from 0.25 keV to 0.10 keV. As a result, the IPC has poor sensitivity to thermal X-ray emission when the coronal temperature is cooler than about 10^6 K. Consequently, the absence of X-ray detections among the supergiants and red giants does not rule out the existence of "cool" coronae ($T < 10^6$ K).

b) *Comparison with* C IV *and Wind Boundaries*

As mentioned previously, Linsky and Haisch (1979) proposed a boundary in the H-R diagram separating stars that exhibit prominent 10^5 K emission signatures—C IV $\lambda\lambda$1548,1551 in particular—from those that do not. We have depicted in Figure 1 a C IV boundary based on more recent *IUE* survey material than was available to Linsky and Haisch (e.g., Ayres, Marstad, and Linsky 1981; Simon, Linsky, and Stencel 1981). We call attention to the correspondence in the H-R diagram between the C IV boundary and the region where coronal soft X-ray sources begin to disappear, owing either to the absence of any material hotter than 10^6 K, or to a significant decrease in the amount of such material present. However, the lack of coronal detections among the early G supergiants, despite their moderate C IV fluxes, presents a puzzle which we will consider in greater detail below.

Stencel (1978) and Stencel and Mullan (1980) have noted that the chromospheric Ca II and Mg II emission cores become strongly asymmetric, in a sense consistent with the onset of rapid mass loss by strong, cool stellar winds, along a boundary that is nearly vertical through the K giants. The Mg II asymmetry boundary, based on the recent study by Stencel *et al.* (1980), also is depicted in Figure 1. It is clear that among the ordinary single giants, the appearance of cool winds coincides with the disappearance (or weakening) of hot coronae as initially suggested by Linsky and Haisch (1979).

c) *The Hybrid-Spectrum Supergiants*

Hartmann, Dupree, and Raymond (1980) have noted that the yellow supergiants α Aqr (G2 Ib) and β Aqr (G0 Ib) exhibit prominent wind signatures—violet-shifted circumstellar absorption components in the Mg II resonance lines—as well as emission in 10^5 K species. The behavior of these supergiants is inconsistent with the suggestion of Linsky and Haisch (1979) that 10^5 K material and strong, cool stellar winds are mutually exclusive. As a rule, we have found that those cool stars which are detected in soft X-rays always have measurable C IV emission. However, among the 16 stars in Table 1 for which C IV and soft X-ray data are both available, only two disobey the *reverse* of this rule—α Aqr and β Aqr. One possibility is that the maximum coronal temperatures for α Aqr and β Aqr are somewhat cooler than 10^6 K; consequently, the X-ray emission is too soft to be detected by the *Einstein* IPC. Nevertheless, the coronal temperatures must be $\geq 2 \times 10^5$ K, because the N V λ1240 doublet observed by *IUE* does not appear to be enhanced anomalously. Furthermore, β Dra (G2 II) has very similar chromospheric emission levels ($f_{\rm Mg\,II}/l_{\rm bol}$) to α Aqr (G2 Ib), yet the $f_x/l_{\rm bol}$ detection of β Dra is a factor of 30 larger than the upper limits on $f_x/l_{\rm bol}$ for either α Aqr or β Aqr.

A second possibility is that absorption by cool gas in the extended winds of the G supergiants attenuates the soft X-ray emission from hot coronal structures in the lower atmosphere. In fact, the solar example might provide a useful prototype here (e.g., Linsky 1980). The solar corona is composed of two distinct morphological classes of magnetic structures: closed-field regions (loops) that contain the high temperature material we usually consider to be "coronal," and open-field regions (coronal holes) that are cooler and appear to be the acceleration sites of the weak solar wind (e.g., Vaiana and Rosner 1978). The loops likely are cooled mainly by radiation and thermal conduction back to the chromosphere, while the coronal holes are cooled mainly by the kinetic and enthalpy fluxes of the wind (Withbroe and Noyes 1977).

We can test the plausibility of the wind absorption hypothesis as follows. We assume that magnetic loops containing X-ray emitting plasma extend only to a radial distance R_0, and above that height the flow of cool wind from diverging open-field regions is spherically symmetric and has reached a terminal velocity V_0. The mass flux is then

$$\dot{\mathscr{M}} = 4\pi R_0{}^2\ 1.4 m_{\rm H} n_0 V_0\ , \qquad (2)$$

where n_0 is the hydrogen number density (protons plus neutrals) at R_0 and a 10% helium abundance has been assumed. Above R_0 the radial soft X-ray optical depth is

$$\tau = \int_{R_0}^{\infty} \sigma n_0 \zeta_{\rm H} \left(\frac{r}{R_0}\right)^{-2} dr = \sigma n_0 \bar{\zeta}_{\rm H} R_0\ , \qquad (3)$$

where $\sigma = 5 \times 10^{-21}$ cm^2 per neutral hydrogen atom is the absorptivity of cosmic abundance gas at $\frac{1}{4}$ keV (Cruddace *et al.* 1974), and $\bar{\zeta}_{\rm H}$ is the mean fractional abundance of neutral hydrogen along the line of sight. Since n_0 cannot be estimated easily, we eliminate it from these equations and obtain

$$\dot{\mathscr{M}} = 7 \times 10^{-9} \left(\frac{R_0}{100 R_\odot}\right)\left(\frac{V_0}{100\ {\rm km\ s^{-1}}}\right)\frac{\tau}{\bar{\zeta}_{\rm H}}\, \mathscr{M}_\odot\ {\rm yr}^{-1}\ . \qquad (4)$$

Hartmann, Dupree, and Raymond (1980) estimate that the photospheric radii of α Aqr and β Aqr are about 100 $R_\odot$, while the terminal velocity of the cool gas in the supergiant winds is about 100 km s^{-1} (as suggested by the violet-shifted absorption components in the Mg II emission cores). Hartmann, Dupree, and Raymond (1980) also estimate a mass loss rate $\dot{\mathscr{M}} \sim 2 \times 10^{-8}\ \mathscr{M}_\odot$ yr^{-1} from Sanner's (1976) scaling law. Therefore if R_0 is of order a stellar radius or less and the cool wind is largely neutral, then $\tau > 1$ at $\frac{1}{4}$ keV and larger at lower energies. We conclude that the supergiant winds can significantly attenuate soft X-rays emitted by compact coronal structures embedded at the base of the flow. Consequently, the absence of measurable soft X-ray emission from the hybrid-spectrum supergiants does not necessarily imply that hot coronal material also is absent.

d) *Energy Balance*

The energy balance of the stellar outer atmosphere is an important, but complex, question that will be considered at length elsewhere (e.g., Ayres, Marstad, and Linsky 1981; Linsky *et al.* 1981). Here we wish to make only a few comments. Table 1 compares available flux ratios of the Mg II (λλ2796, 2803) and C IV (λλ1548, 1551) doublets with $f_x/l_{\rm bol}$. The $f_{\rm Mg\,II}/l_{\rm bol}$ ratio is related to the chromospheric radiative cooling near 6000 K (Linsky and Ayres 1978); the $f_{\rm C\,IV}/l_{\rm bol}$ ratio is a measure of the radiative cooling near 10^5 K; and the X-ray flux ratio is proportional to the coronal radiative cooling. The emission rates, in turn, provide lower limits to the energy *deposition* rates in the different atmospheric layers.

Ayres, Marstad, and Linsky (1981) find that $f_{\rm C\,IV}/l_{\rm bol} \sim (f_{\rm Mg\,II}/l_{\rm bol})^{1.5}$ and $f_x/l_{\rm bol} \sim (f_{\rm Mg\,II}/l_{\rm bol})^3$, although the magnitude of $f_{\rm Mg\,II}/l_{\rm bol}$ usually exceeds the corresponding ratios for C IV and coronal soft X-rays, even among active chromosphere spectroscopic binaries. Since the flux ratios for chromospheric, transition region, and coronal emissions are correlated, the distinct thermal regimes of the stellar outer atmosphere very likely are physically associated. Given the clear example of our Sun, it does not require a great leap of imagination to suppose that the unifying characteristic of these atmospheric layers is the magnetic field (Withbroe and Noyes 1977; Vaiana and Rosner 1978). However, because the C IV and X-ray flux ratios are more than simply proportional to the Mg II flux ratios, it is quite possible that the heating mechanisms in the different atmospheric layers are qualitatively different. Finally, because the Mg II flux ratio is usually larger, and often is substantially larger, than the C IV or X-ray ratios, the chromospheric heating mechanism must be considerably more potent than those of the overlying atmosphere, at least among the stars for which kinetic and enthalpy losses in a massive wind is not an important cooling process.

e) *Stellar Rotation and Coronae*

If magnetic activity is indeed at the heart of chromosphere-corona activity among cool stars in general, as appears to be true for the Sun in particular, then one might expect to find a connection between coronal emission levels and stellar parameters that are related to magnetic field production. One obvious parameter is surface rotation rate (cf. dynamo action: Parker 1970).

However, because the primary goal of our program was to explore the corona-wind boundary, most of the stars in our sample are giants and supergiants, which typically are moderate or slow rotators ($V \sin i \lesssim 10$ km s^{-1}). Rotational velocities for such stars are difficult to assess spectroscopically, especially because other sources of nonthermal Doppler motions—macroturbulence, for example—often contribute more to the line broadening than rotation (see discussion by Smith 1979). Consequently, we defer the question of rotation-activity correlations to a separate study (Pallavicini *et al.* 1981), which includes a more comprehensive sample of dwarf stars and addresses the issues of rotational velocity measurements and possible selection effects in a more complete manner than space permits here. However, we do wish to comment on four early G dwarfs in our survey: π^1UMa (G0 V); β Com (G0 V); α Cen A (G2 V); and the Sun (G2 V). The f_x/l_{bol} ratios for these stars (in units of 10^{-7}) are, respectively, 420, 40, 2, and 3 ± 0.25 dex, and their *projected* rotational velocities (see Smith 1979, Table 1) are $V \sin i = 11$, 6, 5, and 2 km s^{-1}. Unlike the other stars, the value of $V \sin i = 5$ km s^{-1} for α Cen A is not based on a Fourier deconvolution of measured profiles, but instead on the gross appearance of the α Cen A spectrum compared to that of integrated sunlight (see Smith 1979, footnote 3). Since Boesgaard and Hagen (1974) remark that the α Cen A Fraunhofer lines at 1.7 Å mm^{-1} dispersion appear to be only about 10% broader than their solar counterparts, we feel that the conclusion that the α Cen A $V \sin i$ is ≈ 2.5 times the solar value is premature, particularly because a modest increase in the stellar macroturbulent broadening could account easily for the small increase in the stellar line widths. In fact, preliminary results from a far-ultraviolet monitoring program (Hallam and Wolff 1981) suggest that α Cen A rotates even more slowly than the Sun. Our useful data sample is limited, but it is consistent with the emerging picture (e.g., Ayres and Linsky 1980; Pallavicini *et al.* 1981) that rotation and f_x/l_{bol} are positively—and sensitively—correlated, at least among stars having similar convection zone properties.

f) *Evolutionary Considerations*

The yellow giants $[0.4 \lesssim (V-R) \lesssim 0.8]$ likely have evolved nearly horizontally in the H-R diagram from late B or early A stars on the main sequence ($\mathcal{M} \approx 3\ \mathcal{M}_\odot$). By contrast, the red giants $[(V-R) \gtrsim 0.85]$ are thought to have evolved from less massive ($\mathcal{M} \approx 1\ \mathcal{M}_\odot$) main sequence stars on tracks more nearly vertical in the H-R diagram (e.g., Iben 1967). Because the massive stars probably left the main sequence as more rapid rotators and have expanded less in radius than the solar mass stars, the yellow giants are likely to be faster rotators with more vigorous dynamos than the red giants. The evolutionary bifurcation is consistent with the gross differences in f_x/l_{bol} levels between those two groups. However, some of the yellow giants, such as β Crv (G5 III) and β Lep (G5 III), have f_x/l_{bol} ratios or upper limits nearly two orders of magnitude smaller than other yellow giants, such as μ Vel (G5 III) and χ Per (gG6). A similarly large disparity, but in $f_{C\,IV}/l_{bol}$, is seen within one binary system, Capella (α Aur A; G6 III + F9 III): the primary is a slow rotator and a weak *IUE* ultraviolet source, whereas the fast rotating secondary dominates the composite ultraviolet emission-line spectrum (Ayres and Linsky 1980).

The large range in f_x/l_{bol} and $f_{C\,IV}/l_{bol}$ seen among the yellow giants in general, and between the components of Capella in particular, could be explained in several ways. One possibility is a large dispersion in the initial angular momenta of the main sequence progenitors. A second possibility is slow angular momentum loss by a weak, solar-type coronal wind that is magnetically coupled to the stellar surface out to a large Alfvén radius (Durney 1972). In this situation, the fast rotating yellow giants very likely developed coronal winds only recently and are still spinning down. The slow rotators would be comparatively "old" yellow giants that have possessed such winds, and the attendant angular momentum loss, for a comparatively longer time. A third possibility is that the stronger yellow giant coronal sources are stars on their first ascent of the giant branch, whereas the weaker sources are post–helium-flash stars on their second ascent, after perhaps having lost angular momentum precipitously by ejecting shells at helium flash (Iben 1965), or by rapid mass loss during a brief incursion into the cool wind dominated red giant region. (Alpha Aqr and β Aqr may well be supergiant analogs of the latter mechanism currently in progress.)

IV. FOR THE FUTURE

The *Einstein* observations reported here and elsewhere have enriched our understanding of the diversity of chromospheric and coronal behavior exhibited by stars in the cool half of the H-R diagram. Nevertheless, several key questions remain to be answered:

1. What is the influence of circumstellar shell absorption in obscuring soft X-ray emission from stars having extended, cool winds?

2. Do warm coronae ($T \approx$ few $\times 10^5$ K) exist in the supergiant that would not be detected by the *Einstein* IPC?

3. How faint are the red giants such as α Tau and α Boo in soft X-rays? Are small coronal activity centers present on such stars, or are hot coronae in some sense forbidden on the low gravity, cool giants?

4. What are the detailed relationships between coronal activity and fundamental stellar properties such as rotation and convection-zone depth?

These questions are by no means exhaustive. Much theoretical work remains to be done concerning the production of magnetic fields in cool stars, as well as the heating and confinement of chromospheric and coronal material in magnetic structures such as loops. Considerable guidance in this regard likely will be provided by high resolution studies of magnetic activity on the Sun: ultimately, the Sun must be the prototype for establishing the physical connections among magnetic fields, mechanical heating, and coronal emission, because from no other star can measurements of sufficient morphological and spectral detail be obtained.

We acknowledge support by the National Aeronautics and Space Administration through grants to the University of Colorado and to the Harvard-Smithsonian Center for Astrophysics.

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