CHROMOSPHERIC AND CORONAL INDICATORS OF STELLAR MAGNETIC STRUCTURE

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1. INTRODUCTION: SOLAR AND STELLAR MAGNETIC STRUCTURE

This paper discusses attempts to derive information on magnetic structure in late-type stars, only from emission fluxes in the cores of the Ca II H and K lines, in UV emission lines and in soft X-rays - and from relations between these emission fluxes. However simpleminded and indirect this approach may seem, it brings out stimulating results. Studies of this kind are guided by solar research, so let us look first at the solar data.

The emission from the solar chromosphere and corona originates in an intricate magnetic structure. Chromospheric spectroheliograms obtained in the cores of the Ca II and Mg II resonance lines or in chromospheric UV lines show the active regions and the magnetic network - these spectroheliograms resemble magnetograms but with no indication of the polarity. Apparently chromospheric emission flux is a measure for the total magnetic flux in the chromosphere.

In soft X-rays the "coronal condensations" in active regions are very bright, yet much of the solar X-ray emission originates from fainter coronal structure outside active regions. Comparison between X-ray heliograms and calculated coronal magnetic field structure shows that the coronal emission is strongest from *closed* magnetic loops, whereas the emission is much weaker from magnetic structure that is open to the interstellar space, such as coronal holes (see Vaiana and Rosner (1978)). The X-ray flux is a measure for the magnetic flux in the solar atmosphere, but in a more complicated fashion than the chromospheric flux.

If indeed the structure of the chromospheres and coronae of late-type stars is similar to that in the Sun, then some positive albeit crude correlation is to be expected between the coronal emission flux and the chromospheric flux. In principle such a relation may depend on parameters characterizing the global stellar structure (T_{eff} and g).

The simplest measure for chromospheric and coronal emission is the energy flux per unit area at the stellar surface. This surface flux measures the average product of the brightness and the fraction

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of the stellar surfac covered by features emitting in the particular wavelength band.

The "filling factor" α, which is the fraction of the stellar surface covered with a particular feature, is another useful measure for magnetic activity. The magnetic filling factor α_B in the photosphere, which is the fraction of the area covered by a strong field of either polarity, is well defined. For the Sun α_B may be derived from magnetographic measurements, and for stars from analysis of the profiles of magnetically sensitive lines (see Marcy's invited paper during this symposium). In the photosphere the magnetic filling factor α_B approaches 1.0 only in sunspots; in dense plages within active regions it is estimated to be $0.1 \lesssim \alpha_B \lesssim 0.3$. Over the area of a mature active region we estimate $0.05 \lesssim \alpha_B \lesssim 0.10$. For the quiet network, and for the quiet sun as a whole, a rough estimate is $\alpha_B \lesssim 0.005$, and for the solar disk at sunspot maximum $\alpha_B \approx 0.01$.

Because of the fanning of the fluxtubes the filling factor α_B increases with height. Hence we expect that the filling factor for the structure that is bright in the Ca II H and K line cores, α_{H+K}, is a few times larger than the photospheric factor α_B. (Note that in routine measurements the Ca II plage areas are overestimated because of the lack of spatial resolution).

In the corona the magnetic pressure exceeds the gas pressure, hence the magnetic filling factor is unity. However, the coronal soft X-ray emission depends both on the strength and the geometry of the magnetic field, hence filling factors must be specified for each of the various features that show up in coronal emission.

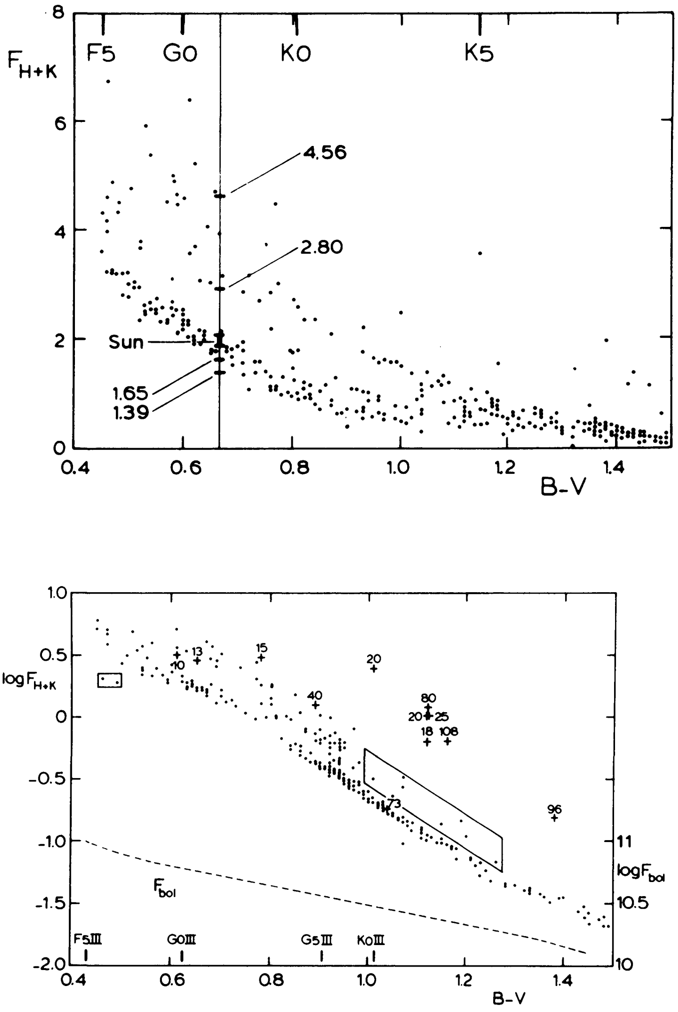
2. CHROMOSPHERIC STRUCTURE; CA II H AND K EMISSION

Figs. 1a. and b. show the Ca II H and K line-core flux F_{H+K} against color (B-V) for samples of F-, G- and K-type stars. The surface flux F_{H+K} has been derived by Middelkoop (1982a,b,c) from the H and K line-core index S measured at Mt. Wilson Observatory by various observers. (The unit of F_{H+K} is approximately $7.6\ 10^5$ erg $cm^{-2}s^{-1}$). These diagrams show:

(i) Both for main-sequence stars (Fig. 1a) and for evolved stars (Fig. 1b) there are lower limits $F_{H+K,min}$(B-V) to the distributions of F_{H+K} against (B-V). (There are some points significantly below $F_{H+K,min}$ (B-V), but probably all of these are due to peculiar stars, such as subdwarfs or (sub-) giants with peculiar abundances).

(ii) There is a large spread in F_{H+K} upward from $F_{H+K,min}$. The spread in the fluxes F_{H+K} for stars of similar spectral type and luminosity class has been attributed to a spread in stellar rotation rate. Recently some quantitative relations between Ca II H and K flux and rotation rate have been derived for main-sequence stars (Vaughan et al. 1981, Middelkoop, 1981a). These matters will be discussed in session 2 of this symposium.

In this context let us try to relate the F_{H+K} values for main-sequence stars at (B-V) $\approx$ 0.66 (see Fig. 1a) with solar Ca II K line profile data collected by Oranje (1982a,b). Between summer 1979



Figs. 1a and b: The Ca II H and K line-core flux F_{H+K} (in units of 7.6 10^5 erg cm^{-2} s^{-1}) versus color (B-V):

a. Main-sequence stars (adapted from Middelkoop, 1982a,b). The flux levels indicated at (B-V) = 0.66 are discussed in the text.

b. Giants (Middelkoop 1982b,c). The crosses refer to spectroscopic binaries with periods P < 120 days, indicated in days. The data points enclosed in boxes refer to intrinsically bright giants.

and summer 1982 about two hundred Ca II K line profiles of the full solar disk have been recorded. Fig. 2 shows one mean profile for about ten particularly active days and one mean profile for relatively quiet days. In addition, Fig. 2 presents a profile for the part of the disk remaining when the active regions are blocked off in the

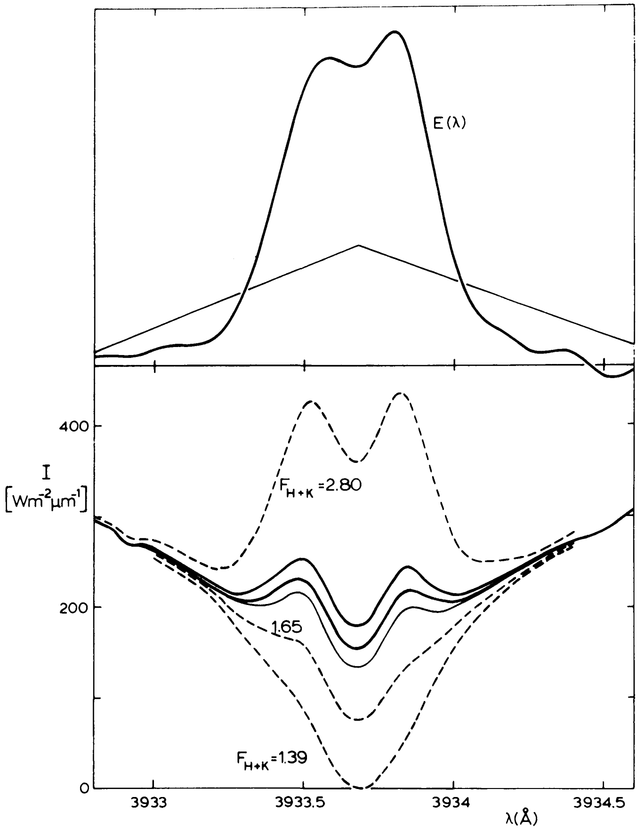


Fig. 2. Profiles of the Ca II K line core derived from full-disk solar spectra by Oranje (1982a,b). The two heavy full curves in the lower frame are average profiles, one for very active days, and one for relatively quiet days in the period summer 1979 - summer 1982. The thin line is the profile for the part of the disk remaining when the plages are blocked off. The top frame shows the emission profile E(λ) which is obtained by subtracting observed profiles. The dashed lines are profiles computed by extrapolating the solar data; the associated fluxes F_{H+K} *are indicated (and also shown in Fig. 1a). The thin triangular curve is the transmission profile of the Mt. Wilson Ca II H and K photometer.*

intermediate image. The resulting profile is within the error of measurement identical with the Ca II K profile in the atlas of the solar flux spectrum (Beckers et al. 1976), which has been recorded during a day without a trace of activity on the disk. This suggests that the flux from the chromospheric network does not vary significantly during the solar cycle.

The comparison of the Ca II K profiles shows that any of these profiles $I_i(\lambda)$ can be obtained from any other profile $I_j(\lambda)$ by adding (or subtracting) the *same emission profile* E(λ) multiplied with a wavelength-independent factor A_{ij}:

$$I_i(\lambda) = I_j(\lambda) + A_{ij}\ E(\lambda) \tag{1}$$

Apparently the emission profile $E(\lambda)$, shown in Fig. 2, represents the emission added by chromospheric plages to the line profile of the quiet disk. Clearly, the emission profile is an average over the solar disk. Note that the familiar two emission peaks in the Ca II K profile can be reproduced by adding the emission profile $E(\lambda)$ to a V-shaped absorption profile. Note that in the emission profile itself the depression between the two maxima is barely visible.

The factor A_{ij} is proportional to the difference of the filling factors for the plages representative for the profiles $I_i(\lambda)$ and $I_j(\lambda)$.

Oranje (1982b) assumed that main-sequence stars with $(B-V) \approx 0.66$ differ from the Sun by the filling factor of the plages α_p, but that the emission profile is identical. If so, then the set of solar Ca II K profiles may be extrapolated to the case of stars that are more active than the Sun. Fig. 2 shows the profile for a star with $F_{H+K} = 2.80$, situated just above the Vaughan-Preston gap (see Fig. 1a). For a very active star, with $F_{H+K} = 4.56$ (see Fig. 1a), the Ca II K emission peaks reach a level between 800 and 900 W m^{-2} μm^{-1}.

In order to compute profiles that may represent stars less active than the Sun, Oranje introduced the additional assumption that the emission profile for the elements of the chromospheric network is identical to the emission profile for plages. Two profiles are shown in Fig. 2: the one labeled $F_{H+K} = 1.65$ represents a star with the lower-limit flux $F_{H+K,min}$ (see Fig. 1a). The profile $F_{H+K} = 1.39$ yields a black line core; the physical meaning of this slightly asymmetric profile depends on the soundness of the extrapolation procedure. In any case, the large corresponding flux $F_{H+K} = 1.39$ reminds us that the instrumental profile of the Mt. Wilson Ca II H and K photometer transmits quite some radiation in the line wings.

Estimates for the filling factors for plages on stellar surfaces may be obtained from the comparison between the stellar fluxes, the flux $F_{H+K} = 2.09$ associated with the upper solar profile in Fig. 2, and the flux $F_{H+K} = 1.92$ from the solar disk without active regions. We find that for the star with $F_{H+K} = 2.80$ the plage filling factor is about 5 times the plage filling factor for the active Sun. For an extremely active star with $F_{H+K} = 4.56$ (see Fig. 1a) the plage filling factor is 15 times larger than for the active Sun. Since the plage filling factor for the Sun during days of large magnetic activity is about 0.04, for an extremely active star we estimate $\alpha_p \approx 0.60$. It may seem difficult to reconcile this large filling factor with the rotational modulation observed for very active stars (Vaughan et al. 1981). Recall, however, that the magnetic filling factor of solar chromospheric plages is quite small, less than 0.1, hence the plages on active stars may be more compact.

An estimate for the filling factor of the chromospheric network may be obtained by assuming that the lower-limit $F_{H+K,min} = 1.65$ represents stars without a trace of magnetic structure left. Then comparison with the quiet Sun (F_{H+K} = 1.92) and the active Sun (F_{H+K} = 2.09) suggests that the network filling factor is about 1.5 times the filling factor of the plages during sunspot maximum.

The F_{H+K} (B-V) diagram for evolved stars (Fig. 1b) differs in several ways from the diagram for main-sequence stars (Fig. 1a). The lower limit $F_{H+K,min}$ (B-V) drops off very quickly with increasing (B-V). There is a considerable upward spread for G-type giants (B-V < 1.0). Most of the K-type giants are confined to a narrow band along the lower limit. There are two groups of evolved K-type stars that are more active: (i) many of the intrinsically bright ($M_V < +1.0$) early K-type giants, and (ii) synchronized spectroscopic binaries (for details and interpretation see Middelkoop 1982b,c).

3. EMISSION FROM CORONAE, TRANSITION REGIONS AND CHROMOSPHERES

According to the expectation in Sect. 1, a crude positive correlation is found between the soft X-ray surface flux F_x and the Ca II H and K line-core flux F_{H+K} (Mewe and Zwaan, 1980). The correlation is greatly improved by plotting F_x against the Ca II H and K *excess* flux ΔF_{H+K}, defined as

$$\Delta F_{H+K} \equiv F_{H+K} - F_{H+K,min} \text{ (B-V)} \qquad (2)$$

where $F_{H+K,min}$(B-V) is the lower-limit flux introduced in Sect. 2 (Mewe et al. 1981). Fig. 3 includes recent results derived from observations obtained with the imaging proportional counter onboard the HEAO-2 Einstein Observatory. It is surprising that all stars in the available sample follow the same relation: single stars of different spectral type and luminosity class, and synchronized spectroscopic binaries. A statistical common-factor analysis yields the relation

$$F_x = 2.4\ 10^{-3}\ \Delta F_{H+K}^{1.4} \qquad (3)$$

(Schrijver et al. 1982); this relation does not depend on parameters determining the global stellar structure (e.g., radius or mass).

Note that some less active giants show a mean flux F_x that is smaller than the flux from a solar coronal hole.

Probably the spread in Fig. 3 is mainly due to the variability of the emission fluxes (the X-ray and the Ca II H and K measurements have not been obtained simultaneously). Moreover, for stars of a low activity level the excess flux ΔF_{H+K} is inaccurate.

These causes of scatter do not apply in the comparison of fluxes in various chromospheric and transition-region (TR) lines observed simultaneously with IUE in the 1200 - 2000 Å region. In order to reduce the noise we define the chromospheric flux F_{chrom} by the sum of the fluxes in lines of Si II (1808, 1817 Å) and of O I (1304 Å), and the transition-region flux by the sum of the fluxes in lines of Si IV (1394, 1403 Å), C IV (1550 Å) and N V (1204 Å) - see Oranje, Zwaan and

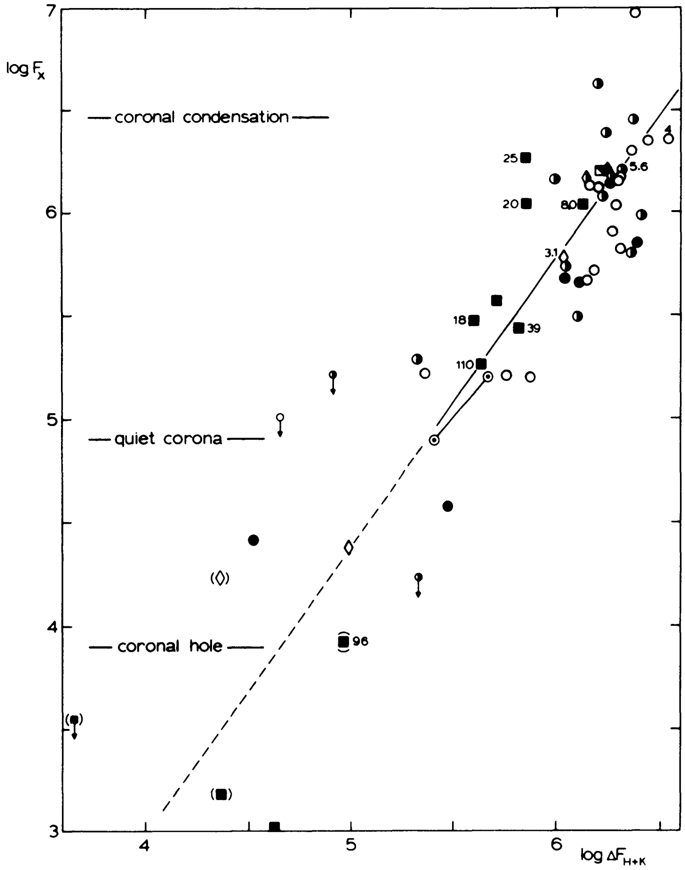


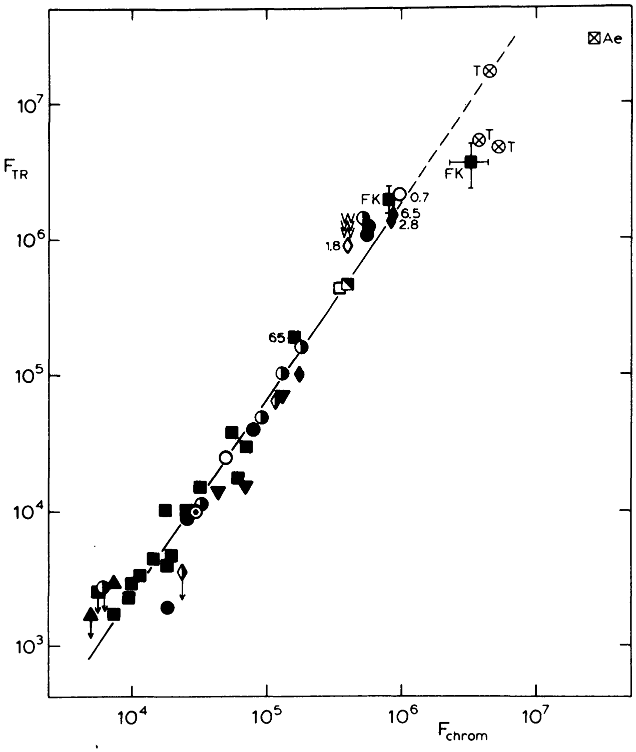
Fig. 3: Soft X-ray flux F_x versus excess Ca II line-core flux ΔF_{H+K} (surface fluxes in erg cm^{-2}s^{-1}). Symbols:

B-V LC	≤ 0.60	0.60...≤ 0.80	> 0.80
V	○ F6 - G2	◑ G0 - K0 ◉ Sun	● K1 - K5
IV	◇ G0	◆ G4,G5	◆ G8,K2
III,II	-	▧ G5	■ G5 - K2

Arrows indicate upper limits, brackets mark uncertain values. For short-period spectroscopic binaries the periods are given in days. For the sources of F_x, ΔF_{H+K} data: see Schrijver et al. (1982). The solar data are from Vaiana and Rosner (1978). The line represents relation (3).

Figs. 4: Transition-region flux F_{TR} versus chromospheric flux F_{chrom} (surface fluxes in erg cm^{-2} s^{-1}): a. (below): dwarfs, yellow giants and supergiants, specific active stars; b. (opposite page): orange and red giants and supergiants, Ke and Me dwarfs, superimposed on the data points from Fig. 4a.
The line represents relation (4). Short-period binaries are marked by their period in days. Arrows indicate upper or lower limits.

Fig. 4a:



B-V LC	< 0.60	0.6...≤ 0.8	0.8...≤ 1.0	> 1.0	
V	○ G0	◐ G2,G8	● K1,K2	● K5	
IV	◇ F6	⬖ G4,G5	◆ (G2,G5)	-	see Fig. 4b
III	□ F9	◩ G0	■ G5 - K0	-	
II	-	-	▲ G8,K2	-	
I	-	-	▼ G0,G2	-	

Sources: Ayres, Marstad and Linsky (1981); Ayres et al. (1982); de Castro et al. (1981); Hartmann, Dupree and Raymond (1982); Linsky et al. (1982); Mullan and Stencel (1982); Oranje (1982b); Oranje, Zwaan and Middelkoop (1982); Simon, Linsky and Stencel (1982).

W ◐ or W ● : W UMa stars: Rucinski and Vilhu (1982)
FK ■ : FK Com stars: Bopp and Stencel (1981)
T ⊗ : T Tau stars: Cram et al. (1980); Tjin A Die (1982)
Ae ☒ : Herbig Ae star: Tjin A Die et al. (1982)

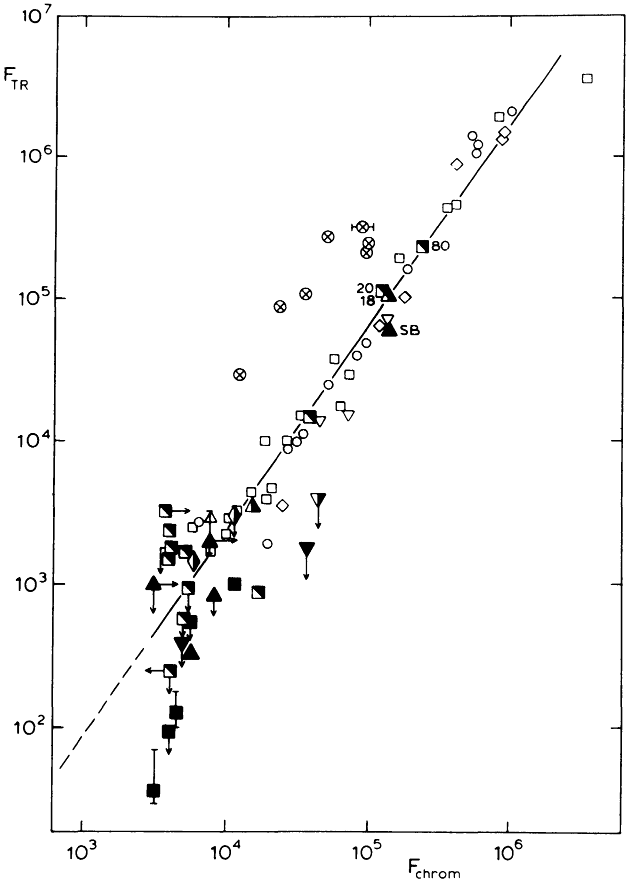


Fig. 4b: Small open symbols: data points from Fig. 4a.

LC	B-V 1.0...≤ 1.2	> 1.2	
IV	⬗ G8 - K2	-	sources: see caption Fig. 4a
III	◩ K0 - K2	■ K3 - K5	
II	◭ K0,K1	▲ K0,K3	
I	⧨ G5	▼ G8,K5	

V ⊗ *dKe, dMe stars: Linsky et al. (1982)*

Middelkoop (1982). The results are shown in Figs. 4a and 4b.

Fig. 4a shows main-sequence stars (except the Ke and Me dwarfs) and evolved stars with (B-V) < 1.00. The fluxes F_{TR} and F_{chrom} are closely related. The data are fitted well by the relation suggested by Oranje et al. (1982):

$$F_{TR} = 4.3\ 10^{-3}\ F_{chrom}^{1.44} \tag{4}$$

The W UMa contact binaries and the very active FK Com stars follow the same relation. Even the pre-main-sequence stars, the T Tau stars (in the quiescent stage) and the Herbig Ae star HR 5999 (A 7 IIIe), seem to fit to the top of the relation (Tjin A Die, 1982).

Fig. 4b shows the evolved stars with $(B-V) > 1.00$, superimposed on the data in Fig. 4a. The bin $1.00 < B-V \leq 1.20$ is chosen to enclose the region $(V-R) \approx 0.80$. There a dividing line has been suggested (Linsky and Haisch, 1979), separating yellow giants, which may show evidence of 10^5 K plasma, from red giants and supergiants which show no evidence of plasma hotter than 10^4 K. The bin $(B-V) > 1.20$ is well beyond $(V-R) \approx 0.80$.

Fig. 4b shows that some of the K-type giants follow nicely the trend indicated by Fig. 4a - all the synchronized spectroscopic binaries do. However, the K-type evolved stars of low activity clearly fall below the relation (4), which suggests a vertical asymptote near $F_{chrom} \approx 3\ 10^3$; the flux measurements from IUE spectra by Simon, Linsky and Stencel (1982) provide most of the data for this result. The present data suggest that there is a lower limit to the UV chromospheric emission, a ubiquitous emission which is not associated with a detectable TR emission at $T \approx 10^5$ K. We point out that this finding is similar to the lower-limit for the Ca II H and K flux.

The present sample supports the notion of a lower-limit chromospheric flux associated with disappearing transition-region flux only for red giants and supergiants. It is not yet known whether such a lower-limit F_{chrom} exists for extremely quiet yellow (sub-)giants or for main-sequence stars. The present sample is too limited to find a possible dependence of the lower-limit F_{chrom} on T_{eff} or g, although there is a hint in Fig. 4b that the lower-limit F_{chrom} is larger for supergiants than for giants.

There is one category of stars that markedly deviates from the relation in Figs. 4a and 4b: the Ke and Me dwarfs (Linsky et al. 1982). These active stars show transition-region lines which are enhanced with respect to the chromospheric lines (see Fig. 4b).

4. DISCUSSION

Stars with convective envelopes show a wide range of chromospheric and coronal activity: the data discussed in this paper cover 3 decades in chromospheric surface flux, 5 decades in transition-region flux and 4 decades in coronal soft X-ray flux (Figs. 3, 4a, 4b).

There are surprisingly close relations between the chromospheric, transition-region and coronal fluxes. These relations by themselves do not depend on the parameters characterising the global stellar structure; only the Ke and Me dwarfs depart clearly from the relations. So, if one of the fluxes ΔF_{H+K}, F_{chrom}, F_{TR} or F_X is given, the other fluxes may be estimated with reasonable accuracy.

Apparently there is one "activity parameter" which determines the structure of the outer stellar atmosphere, as far as the emission fluxes from the various atmospheric components are concerned. Probably this activity parameter is entirely determined by the magnetic structure in the atmosphere, for instance by the mean magnetic flux density. It is now generally accepted that the activity parameter depends strongly on the stellar rotation rate. The wide range of activity levels among the G-type main-sequence stars and giants is readily explained by the large range of rotation rates among these stars. However, it is to be expected that the classical parameters characterizing the global stellar structure, the effective temperature T_{eff} and surface gravity g, also enter into the activity parameter. For instance, the stellar dynamo probably depends on the (relative) depth of the convective envelope, hence on T_{eff} and g. Moreover, the part of the coronal magnetic structure that consists of closed loops, and the parameters characterizing these loops, are expected to depend on the surface gravity g (see contributed paper by Mewe et al. during session 2).

In order to obtain a close and general relation between the X-ray flux and the Ca II H and K line-core flux (Fig. 3) it is necessary to subtract a lower-limit flux which depends on (B-V) and luminosity class. The discussion in Sect. 2 shows that at least for solar-type main-sequence stars a substantial fraction of this lower-limit flux is due to photospheric radiation in the Ca II H and K line wings. However, there is a truly chromospheric component. In Fig. 4b we find an indication that there is a lower-limit chromospheric flux in the UV emission lines which is not associated with a detectable flux in transition-region lines, at least for red giants and supergiants. We suggest that these lower-limit fluxes come from *ubiquitous* chromospheric emission that may originate from the part of the magnetic network that is connected with coronal holes, and from the non-magnetic part of the chromosphere.

Both the X-ray flux and the transition-region flux increase with the chromospheric flux to a power $\alpha \approx 1.4 > 1$. Similar non-linearities, with somewhat different exponents, have been found by others, e.g. by Ayres, Marstad and Linsky (1981). Qualitatively this non-linearity may be understood: the number of closed coronal loops (origins of F_x and, indirectly, of F_{TR}) increases faster than linearly with the number of magnetic poles in the photosphere and chromosphere (origins of ΔF_{H+K} and F_{chrom}). However, quantitatively the closeness of the relations with $\alpha \approx 1.4$ over the wide range of activity levels is surprising and yet unexplained.

Finally, let us consider some observational studies that may set the interpretation of the chromospheric and coronal activity on a quantitative footing.

The first problem is the calibration of the "chromospheric magnetometers" F_{H+K} and F_{chrom}. This requires solar studies comparing magnetic flux densities measured with a magnetograph and simultaneously measured chromospheric fluxes F_{H+K} and F_{chrom} in young, mature and old active regions, and in the network, at various positions on the disk. Does the relation between chromospheric and magnetic flux depend on the type of the region? Results obtained in this way may be generalized to stars that are very similar to the Sun. Clearly, this job should be supplemented by a stellar program simultaneously measuring chromospheric fluxes (e.g. F_{H+K}) and magnetic fields in active stars, as described by Dr. Marcy during this symposium).

The interpretation of the close relations between F_x, F_{TR} and F_{chrom} or F_{H+K} for stars asks for a renewed study of coronal, transition-region and chromospheric emissions from various solar regions at various positions on the disk. These regions should be selected according to coronal criteria, such that a coherent coronal area is covered, for instance a complete coronal condensation, a large area in a coronal hole, etc. From these data "solar-type stars" may be synthesized for comparison with real stars. This program may be a considerable job of teamwork, but the results will be rewarding. I take it that the necessary observational data are in the ATM archives.

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DISCUSSION

HAISCH: With regard to the determination of chromospheric fluxes from the strength of the O I triplet (1302–1305 Å), I would like to point out that, especially for giant stars, this line is pumped by hydrogen Lyman α and thus may not be a valid chromospheric diagnostic.

ZWAAN: The use of the O I triplet is questionable. However, there are very few strong, low-temperature lines in the $\lambda < 2000$ Å region, and we were happy to see from the work of Ayres, Marstad, and Linsky that the O I complex appears to behave as a chromospheric line.

BASRI: Can you comment on the fact that your results do not agree with the results I have presented here, or those of Ayres, Marstad, and Linsky. These show, for example, a much steeper dependence of X-rays on chromospheric flux.

ZWAAN: We have noticed the differences, but as yet we have no explanation. Oranje is analysing the relations between the fluxes in the Ca II H and K, Mg II h and k, and the chromospheric lines with $\lambda < 2000$ Å.

DUPREE: The search for an "activity parameter" is complicated by observations of the four Hyades giant stars (~ K0 III) by Baliunas, Hartmann, and Dupree, which show a factor > 6 in the range of C IV flux, and > 10 in soft X-ray flux for the three giants observed by Stern et al. Since these stars are thought to be similar in most physical parameters (T_{eff}, g, age, chemical composition, and rotation rate), such observations strongly suggest that a long-term activity cycle may be present that is similar to the one known in the sun.