CORONAL ACTIVITY IN F-, G-, AND K-TYPE STARS; EMPIRICAL RELATIONS BETWEEN STELLAR PARAMETERS

R. Mewe, C.J. Schrijver, E.H.B.M. Gronenschild, C. Zwaan
The Astronomical Institute, Space Research Laboratory
Beneluxlaan 21, 3527 HS Utrecht, The Netherlands.

ABSTRACT. For a sample of 58 late type stars we analyse the relations between the soft X-ray flux density F_X, the Ca II H and K line-core flux density F_{H+K}, and parameters determining the global stellar structure. By analysing the soft X-ray spectra from 15 stars we determine the coronal temperatures T and specific emission measures per unit area ζ. We discuss the dependence of T on B-V, F_X and stellar radius R. The diagram of the specific emission measure ζ against the temperature T is interpreted in terms of a coronal model consisting of static loops. Also, a search for time variations in the X-ray flux has been performed.

1. OBSERVATIONS; TEMPORAL VARIABILITY

The X-ray observations (see Table 1 and Schrijver *et al.*, 1982) were obtained with the imaging proportional counter (IPC) onboard the HEAO-2 Einstein observatory (see Giacconi *et al.*, 1979). IPC counting rates are converted to X-ray fluxes f_X at Earth (0.15-4 keV) using a factor of 1.7 10^{-11} erg cm^{-2} ct^{-1} (see Schrijver *et al.*, 1982, Schrijver, 1982). X-ray and Ca II fluxes per unit area at the stellar surface are

TABLE 1. Characteristics of the stars used in the common-factor analysis. The number of stars in each class for which temperatures and emission measures are known is given between brackets.

Spectral type	Luminosity III	IV	V
F5 - F9			11 (3)
G0 - G4	1 (1)	1	10 (1)
G5 - G9	8 (2)	2	9 (3)
K0 - K4	7 (1)		6 (3)
K5 - K9			3 (1)

(Sources: see Schrijver, 1982)

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derived from fluxes at Earth using the bolometric flux at Earth and the stellar effective temperature.

An analysis in time and frequency (Fourier) domains did not reveal any significant variability for our sample of 12 stars (with typical observing times ranging from 1 to 3 ks and a total observing time of nearly 7 hours). The 3σ detection limit for variations on a 2 (15) min timescale ranges from 30 (10) % to 90 (30) % of the mean total X-ray intensity.

2. RELATION BETWEEN X-RAY AND CA II FLUXES

In Fig. 1 the stellar X-ray flux F_x (see Schrijver *et al.*, 1982; Schrijver, 1982; solar data from L. Golub, this conference) is plotted against the Ca II H+K line-core excess flux ΔF_{H+K} obtained by subtracting an observational lower-limit flux from the total line-core flux F_{H+K} (see Mewe *et al.*, 1981; Schrijver *et al.*, 1982; Schrijver, 1982; Skumanich and Eddy, 1981). It is seen that these parameters are closely related; the correlation coefficient is 0.82. A statistical common-factor analysis shows that they obey the relation (with fluxes in erg cm^{-2} s^{-1})

$$F_x = 2.4\ 10^{-3}\ F_{H+K}^{1.4} \qquad (1)$$

(Schrijver *et al.*, 1982). The relation does not depend on parameters determining the internal stellar structure (mass and radius). Upper limits for faint X-ray sources are consistent with the relation (1).

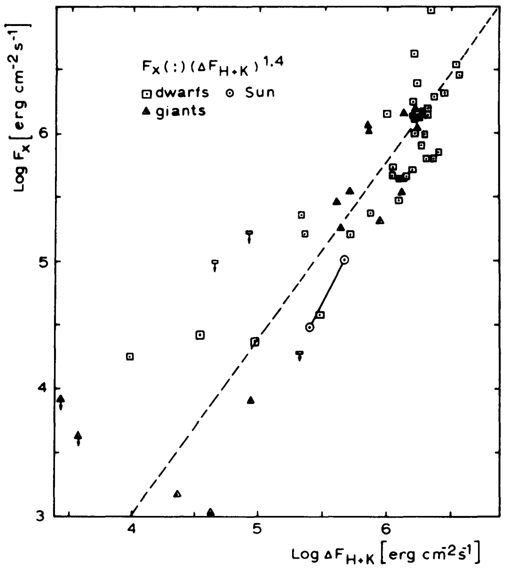

Fig. 1. Soft X-ray flux F_x vs the Ca II H and K excess flux ΔF_{H+K}. The line represents the relation resulting from the common-factor analysis.

3. SPECTRAL ANALYSIS: TEMPERATURES AND EMISSION MEASURES

In order to analyse the observed IPC X-ray spectra we convoluted theoretical line and continuum spectra (Mewe and Gronenschild, 1981) for cosmic abundances with the instrumental response function. A χ^2 analysis yields effective coronal X-ray temperatures T and emission measures $\varepsilon = \int n_e^2\, dV$. We have assumed negligible interstellar absorption. We found that the uncertainty due to the gain variations across the field of the IPC (≈7%) is generally much larger than the error due to counting statistics, so that only the gain uncertainty is considered.

In Fig. 2 T is plotted against (B-V). The vertical bar for the Sun indicates the range of temperatures for quiet and active regions (Vaiana

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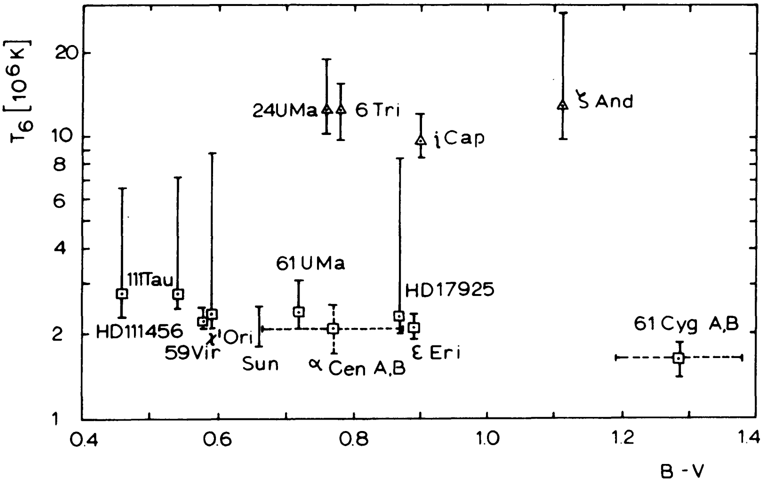

Fig. 2. Coronal X-ray temperature T vs color B-V (⊡ dwarfs; ▲ giants).

and Rosner, 1978). The datum for α Cen is taken from Golub *et al.* (1982). For our sample coronae around giants are significantly hotter (1 to 2 10^7 K) than those around dwarfs (1 to 4 10^6 K). Fig. 2 suggests a weak dependence of the coronal temperature on B-V for dwarfs.

We use the specific emission measure $\zeta = \varepsilon/(4\pi R^2)$ as an empirical parameter representing the stellar coronal activity. Mewe *et al.* (1981) have shown that ζ correlates strongly with the Ca II excess flux ΔF_{H+K} for the stars in our sample (see Table 1). In Fig. 3 we plot the obtained values of ζ_{27} (in units of 10^{27} cm^{-5}) against the X-ray temperature T_6 (in MK). The data for α Cen are taken from Golub *et al.* (1982). X-ray luminosities for the average Sun are taken from Manson (1977) and temperatures from Vaiana and Rosner (1978). The other solar data were derived from Skylab S054 observations (Pallavicini *et al.*, 1981).

In interpreting the spectral results we assume conditions in the outer atmospheres of the observed stars to be similar to those on the Sun: a corona highly structured by magnetic fields, in which the observed X-ray emission largely originates from plasma in closed magnetic loops. The model of a static, uniformly heated loop in local energy balance yields (Rosner *et al.*, 1978; Serio *et al.*, 1981):

$$T = 1400\ e^{-0.04L/H_p}\ (pL)^{1/3} \approx 1400\ (pL)^{1/3} \quad , \qquad (2)$$

where T is the (maximal) temperature, p is the (base) pressure, L is the halflength of the loop, and H_p is the pressure scale height (in cm) $H_p = 5\ 10^3\ T\ (g/g_\odot)^{-1}$. This scaling relation has been discussed by Pallavicini *et al.* (1981) on the basis of the Skylab observations. They found that, flare loops excluded, all features ranging from short, dense loops in active regions (L ≈ 3 10^9 cm, p ≈ 5 dyn cm^{-2}; CARL in Fig. 3) to the long, tenuous loops connecting different active regions (L ≈ 2 10^{10} cm, p ≈ 0.2 dyn cm^{-2}; LSL in Fig. 3) fit the scaling law

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well (see also Raymond and Rosner, 1981). Note that the point EARL in Fig. 3 corresponds to an 'equivalent' loop that matches the average of an active region on the Sun ($L \approx 9\ 10^9$ cm, $p \approx 1.5$ dyn cm^{-2}).

For a corona of N identical loops we find (Mewe *et al.*, 1980, 1982):

$$\zeta = G\,F\,p^2\,(2kT)^{-2}\ell \quad , \qquad (3)$$

where G is a geometry factor (1-G is the fraction of the corona occulted by the star; we take G = 0.7), $F = 2NA/(4\pi R^2)$ is the coronal filling factor, A is the average cross section of the loops and ℓ is the emission scale length, which is limited either by the loop size ($\ell \approx L$ for $L \leqslant H_p/2$ with L the loops' halflength), or by the pressure scale height ($\ell \approx H_p/2$) (Mewe *et al.*, 1980, 1982). Combining Eqs. (2) and (3) with the limiting values for ℓ (with L_{10} in 10^{10} cm):

$$\zeta_{27} = 0.12\ (L_{10}/F)^{-1}\,T_6^4 \qquad (L \leqslant H_p/2) \quad , \qquad (4a)$$

$$\zeta_{27} = 0.03\ (L_{10}/F)^{-2}F^{-1}(g/g_{\odot})^{-1}\,T_6^5 \qquad (L \geqslant H_p/2) \quad . \qquad (4b)$$

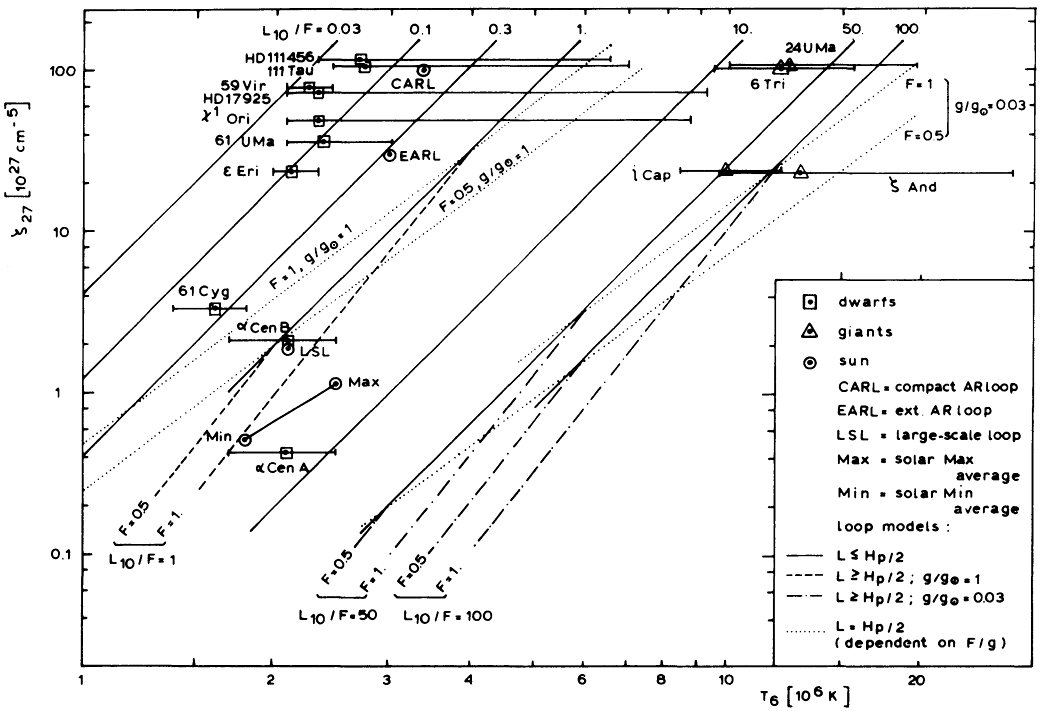

Fig. 3. Specific emission measure ζ vs coronal X-ray temperature T. The drawn curves represent theoretical relations for coronal loop models.

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4. DISCUSSION

Curves calculated with Eqs. (4a,b) are drawn in Fig. 3. The dotted lines represent cases in which the loop halflength equals half the pressure scale height, with the filling factor F as a free parameter.

We see that the data for the average Sun and for α Cen A and B are compatible with a star covered for a large fraction with large-scale loops with $L \approx H_p/2 \approx 5\ 10^9$ cm ≈ 0.1 R. We know that the emission of these loops dominates the total solar emission because the filling factor for active regions (AR's) is small ($F \sim 10^{-3}$ to 10^{-2}, Vaiana and Rosner, 1978). The active dwarfs, however, lie in the region $L_{10}/F \approx 0.1$, where $L << H_p$. As $F \leqslant 1$ it follows that the majority of the loops on active dwarfs must be very compact, at least as compact as the loops in solar AR's. A search for rotation modulation in X-rays could give a clue on the values of the filling factors, and hence on loop lengths.

The active giants fall in the region $L_{10}/F \approx 50$, so we obtain as an upper limit $L \approx H_p/2 \approx$ R. In the case of small filling factors the loops will be much smaller than H_p and R.

Thus, the observations indicate coronae with loops of different relative sizes. It is surprising that all these observations obey the same relation between F_x and ΔF_{H+K}.

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DISCUSSION

GIAMPAPA: Have you attempted coronal loop modelling with multiple components? That is, could you achieve some of the same results with a combination of "active" compact ($L < H_p$) loops and "quiet" loops ($L \gtrsim H_p$)?

MEWE: Not with the observations made with the imaging proportional counter (IPC) on the *Einstein* Observatory, because these are too inaccurate to allow such a procedure. However, on Capella, a giant with an activity comparable to that shown by the giants considered, we have performed high-resolution spectral measurements with the objective grating spectrometer (OGS) on *Einstein*. The resulting data are best fitted with two temperature components, which have the following characteristic parameters (assuming that Capella Ab is the X-ray source):
$T_1 = 5 \times 10^6 K$, $(L_{10}/F)_1 \approx 10$ (i.e., $L \ll H_p$), $(pF)_1 \approx 0.6$ dyn cm^{-2}, and
$T_2 = 10^7 K$, $(L_{10}/F)_2 \approx 100$ ($L \approx FH_p$), $(pF)_2 \approx 0.5$ dyn cm^{-2}.

VILHU: Are you able somehow (at least in principle) to determine the filling factor?

MEWE: A search for rotational modulation in X-rays (which has not yet been performed) could give us a clue to the values of the *coronal* filling factors (hence to the loop lengths). From the results for the magnetic area coverage factor of active dwarfs (G.W. Marcy, these proceedings) we may expect filling factors close to unity, which in that case would imply that modulations in X-rays are difficult to detect.

VAIANA: First a comment about the possibility of getting a filling factor from X-ray data. Of course any model that we have developed is able to give filling factors. There are two filling factors: one is the ratio of the area covered by coronal loops with respect to the total surface of the star; the other is a magnetic filling factor that is something like $\langle B_z \rangle / B_{equipart.} = f_m$. They are model dependent and will require independent determinations: The first from rotational modulation for instance, the second from direct magnetic field measurements.

Now I have a question. In your F_x vs. F_k figure, the scatter is acceptable only at high values of F_x and over a small region (perhaps one order of magnitude). At low fluxes the scatter is very large. Are you not worried that your correlation may be an artifact of this somewhat arbitrary subtraction technique?

MEWE: For stars with X-ray surface fluxes ranging from about 10^7 down to at least 10^5 erg cm^{-2} s^{-1} we had no problems in subtracting the Ca II H and K lower limit, but for fainter stars (with activity comparable to the sun or weaker) indeed this procedure becomes uncertain.