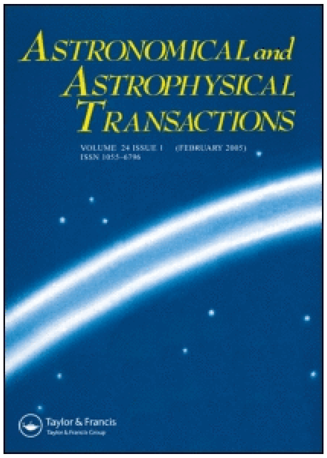

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THE POSSIBILITY OF SIMULATION OF THE CHROMOSPHERIC VARIATIONS FOR MAIN-SEQUENCE STARS

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We present a method of chromospheric flux simulation for 13 late-type main-sequence stars. These Sun-like stars have well-determined cyclic flux variations similar to an 11 year solar activity cycle. Our flux prediction is based on chromospheric HK emission time series measurements from Mount Wilson Observatory and comparable solar data. We show that solar three-component modelling explains the stellar observations well. We find that 5–10% of the disc surfaces of K stars are occupied by bright active regions.

Keywords: Late-type stars, Chromospheric variations, Modelling of chromospheric emission

1 INTRODUCTION

This paper continues a study of variability among Sun-like stars. Here the purpose is to assess the possibility of modelling the behaviour of the chromospheric emission of a star in the future or for periods of time without measurements.

Observations of chromospheric variability are necessary for at least a decade to reveal variations with time scales on the 11 year solar cycle.

Such a program was initiated by Wilson (1978) who discovered the widespread occurrence of activity cycles by monitoring Ca II H and K variations in 91 stars on or near the lower main sequence over 12 years. Two sets of measurements (called the HK project) have been combined to make records of stellar chromospheric activity covering more than 30 years. Wilson made observations from 1966 to 1977 at monthly intervals on the 2.5 m telescope at Mount Wilson Observatory. The survey moved in 1977 to a 1.5 m telescope with an instrument whose measurements can be compared with those of Wilson's system. Some new stars were added to Wilson's 91 stars to bring the total in the monitoring programme to 111 stars (Baliunas *et al.*, 1995). Ca II H (396.8 nm) and K (393.4 nm) emission is observed in stars later than approximately F2V, that is less massive than about 1.5 M. Areas of concentrated magnetic fields on the Sun and Sun-like stars emit Ca II H and K emission more intensely than areas with a lower magnetic field present. So the contrast of emission from active regions (ARs) (where the local magnetic fields are more than a few orders of magnitude higher than the

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average global magnetic field) in these Ca II lines changes from 1.2 to 1.5 with a change in the chromospheric activity cycle phase.

Comparison of the variability in H and K emission in main-sequence stars should provide important validation for theories of magnetic activity, as well as providing a general perspective for solar activity.

The influence of the photospheric flux on the total solar or star irradiance can be interpreted as the cyclic flux variations caused by a slight imbalance between the flux deficit produced by dark sunspots and the excess flux produced by bright faculae.

Besides structures such as ARs in the solar and star chromosphere there is another regular structure, namely the chromospheric network (connecting with supergranulation). Its relative brightness also varies with the chromospheric activity cycle.

It should be noted that the maximum amplitude of photospheric flux variability in the 11 year solar cycle may be as much as 1–3% of the average photospheric flux level but the maximum amplitude of the Ca II chromospheric flux may be as much as 20% of the average level. These values are our estimations for the maximum amplitudes of the 11 year variations of the photospheric and chromospheric fluxes of Sun-like stars.

2 THE THREE-COMPONENT MODEL OF STELLAR CHROMOSPHERIC EMISSION AS AN ANALOGUE OF THE THREE-COMPONENT MODEL OF SOLAR CHROMOSPHERIC EMISSION

The processes in the solar atmosphere causing emission in different spectral intervals and lines have been well studied. However, it is very difficult to take into account the contribution of all the different structures that are emitted from the solar surface. As a successful example of solar flux model calculations in spectral intervals of 40–140 nm (which are in agreement with SKYLAB's observations) we can point out the should mention the data obtained by Vernazza *et al*. (1981).

The calculations made by Vernazza *et al*. take into account the influence of six main different components on the solar surface and their contributions to the total emission in this spectral interval. These components are the dark areas inside the chromospheric network cells, the centres of networks, the areas of quiet Sun, the average level of the network emission region, the bright areas of the network and the brightest areas of the network. When observations of all phase structures are not made with high accuracy, we see the quiet Sun average emission (which varies with an 11 year chromospheric cycle).

These structures contribute significantly to the full flux emitted from the quiet Sun chromospheric average emission.

The next most important source of solar chromosphere emission is the AR emission. Skylab observations show that the brightnesses of ARs are 1.5–2.5 times greater the average quiet surface brightness (Schriver *et al*., 1985). This AR brightness contrast depends on the wavelength. Schriver *et al*. also note that the AR surface brightness depends on the AR area and the number of spots that the AR consists of.

The three-component model (used for the 40–140 nm spectral interval) based on Nimbus 7 observations by Lean and Scumanich (1983) assumed that the full flux from the chromosphere is determined by three main components. These components are as follows: firstly, the constant component with uniform distributed sources on the solar surface; secondly, the active network component (uniformly distributed too but also connected with destroyed parts of previous ARs and so is proportional to the total AR areas); thirdly, the AR component.

Therefore one can use the Lean–Scumanich formulae for calculating the flux in chromospheric lines:

$$I = I_{\lambda Q}[1 + f_N(C_{\lambda N} - 1)] + 2_{\pi} F_{\lambda Q}(1) \sum A_i \mu_i R_\lambda(\mu_i)(C_{p\lambda} W_i - 1), \quad (1)$$

where I is the full chromospheric emission flux, $I_{\lambda Q}$ is the contribution of the constant component (basal), $C_{p\lambda}$ is the value of AR contrast (similar to the contrasts obtained by Cook *et al.* (1980)), $C_{N\lambda}$ is the value of the active network contrast (equal to 0.5 $C_{p\lambda}$ for the continuum and to $1/3$ $C_{p\lambda}$ for lines) and f_N is the part of the disc (without AR) that is occupied by the 'active' network.

The second term on the right-hand side of Eq. (1) describes emission from all the ARs on the disc; A_i are the values of their squares, μ_i describes the AR position and is given by $\mu_i = \cos\phi_i \cos\theta_i$ (where ϕ_i and θ_i are the coordinates of the ARi), and $R_\lambda(\mu_i)$ describes the relative change on the surface brightness $F_{\lambda Q}(\mu_i)$ on moving from the centre to the edge of the disc. The relative added AR contributions to the full flux from the different ARs is determined by the factor W_i which is linearly changed from the value 0.76 to 1.6 depending on the brightness sphere of the flocculae (according to changes in the brightness sphere of flocculae from 1 to 5).

So the 'active' network part of the total surface without ARs is determined by the AR decay; the relationship between f_N at the time moment t and the average values A_i in earlier time is

$$f_N(t) = 13.3 \times 10^{-5} \left\langle \sum A_i(t - 27) \right\rangle, \quad (2)$$

where time averaging is carried out for seven previous rotation periods; A_i is measured in 106 parts of the disc.

To analysed the long-time variations in the Ca II H and K flux for Sun-like stars we assume that full flux $S_{\mathrm{Ca\,II}}(t)$ consists of the following components: firstly, the constant part (the so-called basal component in solar physics) (we call this component P_{min}; secondly, the 'phone' component which does not change much (we call this component $P_{\mathrm{Ca\,II}}(t)$); thirdly, ARs on the disc of the star (we call this component $S_{\mathrm{AR}}(t)$).

So the full flux will be

$$S_{\mathrm{Ca\,II}}(t) = P_{\mathrm{Ca\,II}}(t) + S_{\mathrm{AR}}(t).$$

The second component $P_{\mathrm{Ca\,II}}(t)$ consists of the constant basal component P_{min} and a pseudo-sinuoidal component which does not change much and which we can see from observations of the Sun's we shall describe it approximately later.

It is evident (from solar observations and their interpretations) that there is a close connection between the values $S_{\mathrm{Ca\,II}}(t)$ and $P_{\mathrm{Ca\,II}}(t)$.

According to Borovik *et al.* (1997) the average amplitude of flux variations may be 20% in the maximum phase of the chromospheric cycle. This point of view agrees reasonably well with the Lean–Scumanich (1983) model for the solar line (in this case the maximum amplitude of flux variation in different 11 year cycles reached a value of 20%).

Than we determine the analogous coefficient k for a star's chromospheric cycle as equal to ratio of the maximum amplitude of the so-called 'phone' component to the maximum amplitude of the full flux in a long-term activity cycle:

$$k = \frac{P_{\mathrm{Ca\,II}}^{\mathrm{max}} - P_{\mathrm{min}}}{S_{\mathrm{Ca\,II}}^{\mathrm{max}} - P_{\mathrm{min}}}. \quad (3)$$

We consider that k is a constant ratio of $P_{\mathrm{Ca\,II}}(t)$ to $S_{\mathrm{Ca\,II}}(t)$ for all moments during star's cycle.

We also assume that $P_{\mathrm{Ca\,II}}^{\max} = 1.2P_{\min}$.

It is evident from our previous consideration that $P_{\min}$ is a constant value during all long-term cycles but differs for different stars and the Sun. It is most likely that the value $P_{\min}$ characterizes the average level of the outer atmosphere activity of stars and may correlate with ROSAT observations of their X-ray fluxes (X-ray luminosities are observed on ROSAT for 65% of the HK project stars only).

According to these data, we connect the full flux value $S_{\mathrm{Ca\,II}}(t)$ and the 'phone' flux value $P_{\mathrm{Ca\,II}}(t)$ by the analogous coefficient k (equation (3));

$$P_{\mathrm{Ca\,II}}(t) = kS_{\mathrm{Ca\,II}}(t). \tag{4}$$

The $S_{\mathrm{Ca\,II}}(t)$ values may be taken from observations by Baliunas *et al.* (1995). In Figure 1, we can see records of relative Ca II H + K emission fluxes $S_{\mathrm{Ca\,II}}$ for 13 stars of the excellent' class of Balivnas *et al.* of the Sun for 30 years from 1965 to 1995. Also in Figure 1 we can see the Henry Draper (HD) Catalogue numbers of stars and their $B - V$ values.

It is evident (from solar observations in different spectral intervals) that $P_{\mathrm{Ca\,II}}(t)$ and $S_{\mathrm{Ca\,II}}(t)$ have similar behaviours in the chromospheric cycle. We have calculated the regression coefficients a and b (Table I) for the regression relation

$$S_{\mathrm{Ca\,II}}(t) = aP_{\mathrm{Ca\,II}}(t) + b. \tag{5}$$

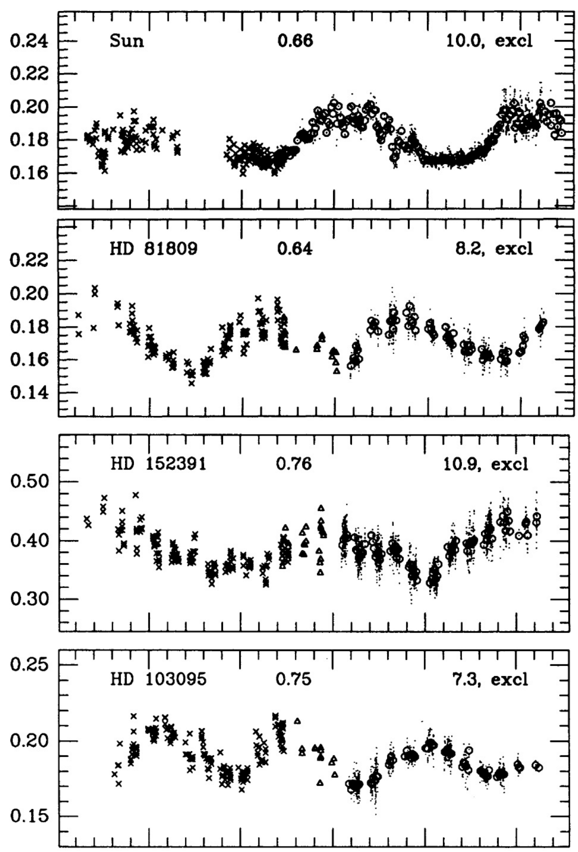

FIGURE 1 Records of relative Ca II H + K emission fluxes $S_{\mathrm{Ca\,II}}$ for 13 stars of the 'excellent' class of Baliunas *et al.* and for the Sun for 30 years from 1965 to 1995, HD numbers of stars and their $B - V$ values. The basal $P_{\min}$ levels is shown as a dashed line.

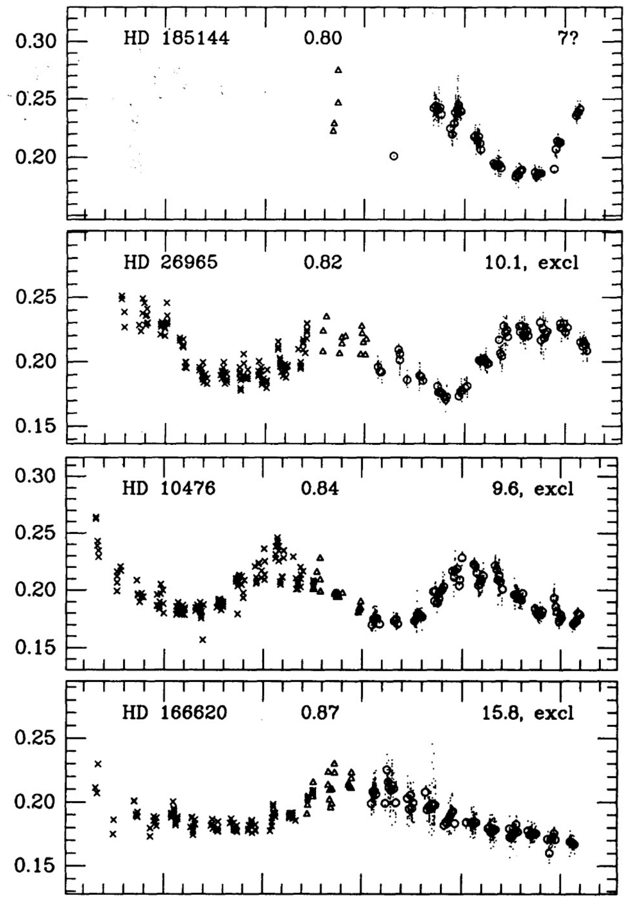

FIGURE 1 Continued.

To make a 'phone' flux-prediction we employ the method used by Bocharova *et al.* (1983) for the solar 'phone' flux variations in 11 year cycle. Using the Bocharova *et al.* method we have obtained the next approximation for the 'phone' flux $P_{\mathrm{Ca\,II}}(t)$ (Bruevich, 1997):

$$P_{\mathrm{Ca\,II}}(t) = P_{\min}\left[1 + \sin^4\left(\frac{\pi t}{T}\right) \mathrm{e}^{-\pi t/T}\right], \tag{6}$$

where $P_{\min}$ is the minimum value of the 'phone' flux which is equal to the basal flux. It corresponds to the minimum 'phone' flux value for the star and it is constant for all observed long-term cycles, (see Fig. 1).

T is the period of long-term chromospheric cycle calculated by Baliunas *et al.* (1995), and t is the time expressed in parts of period T:

$$t = 0.1T, 0.2T, \ldots$$

There are two methods of for calculating the 'phone' flux: firstly, from observation records using Eqs. (3) and (4) (see Fig. 1); secondly, from analytical approximation (6) using $P_{\min}$ only. Note that both methods give us very identifiable values of $P_{\mathrm{Ca\,II}}(t)$ which differ by only a few per cent.

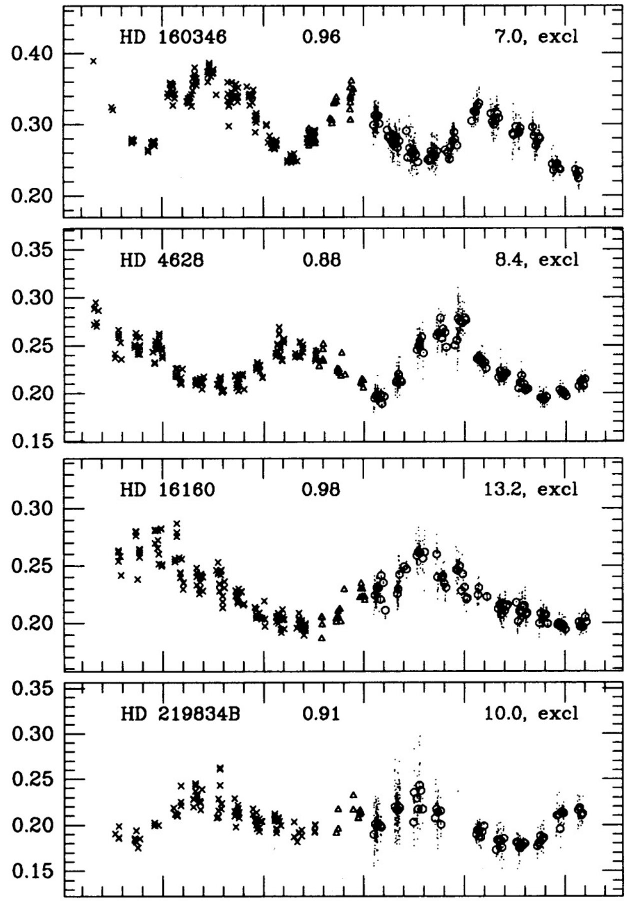

FIGURE 1 Continued.

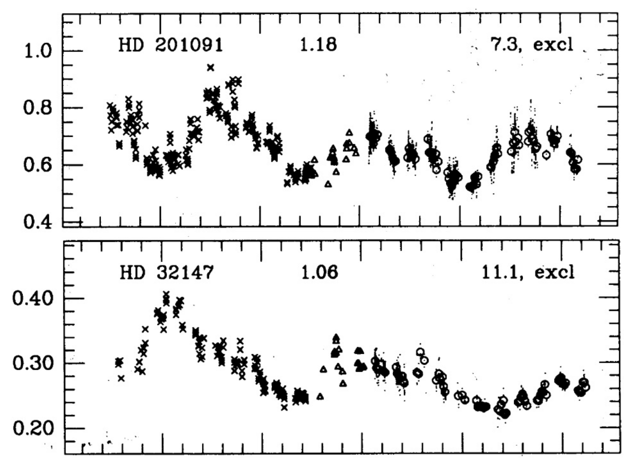

FIGURE 1 Continued.

TABLE I

Object	*Name*	$B-V$	T_{cyc} *(years)*	P_{min}	a	b	$\Delta S^{max}_{Ca\,II}/P_{min}$ %	$\Delta S^{max}_{AR}/P_{min}$ %
Sun		0.66	10	0.162	1.19	−0.031	23.4	3.4
HD 81809		0.64	8.2	0.155	1.13	−0.020	22.6	2.6
HD 152391	V2292Oph	0.76	10.9	0.32	1.56	−0.180	31.6	11.3
HD 103095	Grmb1830	0.75	7.3	0.17	1.23	−0.040	24.7	4.7
HD 185144		0.80	7(?)	0.19	1.45	−0.085	28.9	8.9
HD 26965	o^2 EriA	0.82	10.1	0.18	1.39	−0.07	27.8	7.8
HD 10476	107Psc	0.84	9.4	0.17	1.61	−0.104	32.4	12.3
HD 166620		0.87	15.8	0.175	1.43	−0.075	28.6	8.6
HD 160346		0.96	7.0	0.24	1.88	−0.21	37.5	17.5
HD 4628		0.88	8.4	0.19	1.96	−0.183	39.4	19.4
HD 16160		0.98	13.2	0.19	1.61	−0.116	32.6	12.6
HD 219834B	94 AqrB	0.91	10.0	0.17	1.92	−0.157	38.2	18.2
HD 201091	61 CygA	1.18	7.3	0.51	1.85	−0.434	37.2	17.2
HD 32147		1.06	11.1	0.22	1.67	−0.147	45.4	25.4

So, if we want to predict the chromospheric flux, we can calculate $S_{\mathrm{Ca\,II}}(t)$ with the help of equation (5) using the coefficients a and b, which are calculated earlier with the help of standard regression methods and the presented in Table I.

In Table I we also present the relative full flux variation $\Delta S^{\max}_{\mathrm{Ca\,II}}/P_{\min}$ in the activity cycle maximum and the relative AR-added flux $\Delta S^{\max}_{\mathrm{AR}}/P_{\min}$ in the activity cycle maximum. The value $P_{\min}$, which is equal to the basal emission for different objects can be determined from the data obtained by Balivnas *et al*. (Fig. 1).

The data in Table I may be employed in our full flux chromospheric predictions; at a certain moment t (t is the time expressed in parts of the period T) we can calculate the value $P_{\mathrm{Ca\,II}}(t)$ from equation (6). Then from equation (5) at the moment t and for the star's $P_{\min}$ value we can calculate the predicted flux $S_{\mathrm{Ca\,II}}(t)$.

3 SUMMARY AND CONCLUSIONS

When we analyse results of our predictions (in Table I we presented the observed values that are being discussed and our estimations as $\Delta S^{\max}_{\mathrm{Ca\,II}}/P_{\min}$ and $\Delta S^{\max}_{\mathrm{AR}}/P_{\min}$), some conclusions can be made.

K-stars of the 'excellent' class of Baliunas *et al*., that is stars with the most evident chromospheric activity cycle, have many ARs at their surfaces and these ARs can emit an additional flux of nearly 10–20% of the full flux in the chromospheric cycle maximum (see Table I). So we can see that in K-stars the brightest flocculae (its flux is twice that of the average chromosphere flux) may occupy almost 5–10% of a star's disc. It is necessary to note that this value of 5–10% belongs to the cycle-dependent variable part of the flocculae squares. So the period of this variability is closed to period T of the chromospheric cycle. Observations of other active stars (Neff *et al*., 1995) allow us to suppose that the flux changes that we have analysed relate to the central part of the Ca II line profiles only. The flux changes measured in a wide-spectral interval show a more significant amplitude of flux variations and so this leads to a larger part of flocculae squares.

This 10–20% of AR additional flux ('phone' flux evaluation) is shown in Figure 1. The star's 'phone' flux (smoothly changing in the chromospheric cycle) and basal component (constant in the chromospheric cycle) can also be seen.

Note that all our three components can be seen in Figure 1 (HK project observations of excellent class stars) according to the solar case (Lean and Scumanich 1983).

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