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Ca II K EMISSION FROM THE SOLAR CHROMOSPHERE

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Abstract

The role of the Ca II K line as a reliable diagnostic of the chromospheric activity on the Sun is reviewed. The chromospheric structures seen in this line serve as good indicators of the photospheric magnetic structures and also mimic the morphological changes in the surface magnetic features associated with the solar cycle. Similar changes can be expected to take place in other sun-like stars and could therefore be used as a diagnostic for inferring the kind of structures of surface magnetic fields in them.

The term 'chromosphere was coined to denote the bright, thin coloured ring seen around the solar limb soon after the thin crescent is obscured by the advancing moon at the time of total solar eclipse. The spectrum of the chromosphere also known as the flash spectrum consists of emission lines some of which persist to such great heights that at least their cores originate in the chromosphere. These chromospheric emission lines appear in absorption when seen over the solar disc. The main problems of the chromosphere were the anamolously large emission scale heights and the presence of emission lines of singly ionized atoms that demand temperatures higher than for a radiative equilibrium model. Thomas and Athay (1961) introduced the concept of the non radiative energy source to heat up the chromosphere and the non LTE methodology to explain the large extent of the chromosphere. The chromosphere, thus is an example of the failure of the classical stellar atmospheric theory particularly the radiative equilibrium. In the case of cool giants and super giants, direct momentum transfer by mechanical waves or Ly-alpha radiation pressure may be important sources of heating. The chromosphere can therefore be defined as a region where non-radiative heating dominates the energy balance i.e. where there is an outward increase of T_e as a result of the dissipation of non-radiative energy.

As indicators of the chromosphere, we have the H and K lines of Ca II, the h and k lines of Mg II, He I lines at 10, 830 A and 5876 A, OI lines at 1305 A and 1355 A and so on. Among these, the Ca II H and K lines are the most widely used for the following reasons. In the case of the sun, the H and K lines have been demonstrated as one of the most useful indicators of the features of the chromosphere in the visible region by D'Azambuza, Hale and Delanders and are also the ones employed vastly for the study of the solar chromosphere until the present day. Secondly, the discovery that the logarithm of the emission widths of any one of the two lines is proportional to the luminosity of the stars later than F2 and that such a relation is valid over a range of magnitudes as large as 15, (Wilson and Bappu 1957) have made these lines the most favoured ones both among the solar and stellar astronomers. The sun also obeys this relation as much as any other star and this had opened up the possibility of looking for solar phenomena in those stars that obey the W-B relation.

A two dimensional image of the sun in the Ca II K line under high spatial resolution shows that the three agencies responsible for Ca II emission are the bright points, the network and the plage areas. Their properties are summarized in Table I. One important point is that the spatial correlation between areas of chromospheric emission and the photospheric magnetic fields is well established and this relation holds good from plages down to features as small as a few arc seconds across (Babcock and Babcock 1955;

Table I

Properties of the three agencies of K emission

Bright points	Network	Plages
Populate interior of the network; size 1"-2", life time 100-200 sec. Brightness fluctuates with the above periodicity; enhancement as much as 50% common in K_2V, K_3. V/R asymmetry a common feature. Width at half intensity point from many profiles ~34 km/sec. There is one to one correspondence with the photospheric inner network magnetic elements. Associated fields 20-25 gauss. 70 gauss and above are also possible.	Size 20,000 km. Cospatial with the underlying super granular network. Magnetic fields are swept by the super granular motion and piled up at the boundaries. Excess Ca II emission cospatial with excess magnetic field. Width at half intensity point intermediate between bright points and plages.	Show Ca II excess emission. One to one correspondence with regions of strong magnetic fields at the photospheric level. Brightness varies linearly with magnetic field over the plages. The profiles vary in shape and width. Width at half intensity point is greater than that for the bright point and proportional to magnetic field.
Solar rotation:		
Cannot be recognised if bright points alone populated the entire sun.	Cannot be recognised.	Shows rotation well.
Solar cycle:		
Number of bright points increases 40% during the solar maximum compared to solar minimum.	Estimated contributions 10% or less.	Large and impressive changes confined to 1Å band. Increase as much as 40% possible during solar maximum over minimum.

Leighton 1959; Sivaraman and Livingston 1983). Such a correlation has been put on a quantitative basis by Skumanich et al. (1975) from simultaneous measurements of photospheric magnetic fields and the emission in the K-line.

Let us now examine the K-line profiles of the three chromospheric features. A typical bright point has a profile as shown in Fig.1. It shows a V/R asymmetry and has a K_2 width (~34 km/sec) which is the full width at the half maximum (FWHM) of the K_2 emission peaks measured above the K_1 minima. The K profile over a plage region has interesting properties. Besides enhanced K_2V, K_{2R} and K_3 emission the width at the half intensity level is also greater than for a bright point. In Fig.2 we show profiles corresponding to two plages of increasing brightness obtained with the Kodaikanal solar tower spectrograph. The K_2V, K_{2R} and K_3 intensities increase rapidly with the increasing brightness of the plage so that for the brightest plage K_2V is almost 45% of the continuum whereas the line wings are identical for the strong and weak plages but significantly above the quiet sun level. Thus the sun has a variety of chromospheres but only two kinds of photospheres. Another interesting point is that the K_2 width as defined above increases along with the brightness of the plage. The profile of the network boundary is intermediate between the profiles of the bright point and a weak plage.

On the sun individual chromospheric features and their K profiles can be studied under high spatial resolution. These spatially resolved profiles can now be synthesised according to their weighted contributions. These contributions would depend on the area they occupy on the solar surface and their emission contrast against the chromospheric background. Such profiles over a solar cycle would bring out the variations in their relative contributions that are solar cycle related. The identification of the chromospheric features (and hence the magnetic structures) can be done in the K profiles of the sun viewed as a star with ease by comparing them with the synthesised profiles. This establishes a way to look for the signatures of the chromospheric structures (and hence the associated magnetic structures) if the K profiles of the sun as a star were alone available and infer their presence. Then by an extension of this association to other sun like stars, the possible existence of structures in their chromospheres similar to the sun can be inferred by analogy. By the same argument, the identification of the chromospheric features in these stars will also establish the presence of the corresponding magnetic features in their photospheres.

There is an on going programme at the Kodaikanal solar tower started in 1969 to monitor the disc averaged K-line profile to study the variations over solar cycle time scales. The disc averaged profile of the quiet sun has a width identical to that of the bright point and based on this Bappu and Sivaraman (1971) concluded that these bright points provide the sun the appropriate width needed to follow the W-B relation. Two typical profiles from this large collection one representing the solar maximum and the other the solar minimum are shown in Fig.3. During the maximum the contribution from the plage becomes overwhelmingly large compared to the other two contributors and this would explain most of the enhanced emission at the maximum over the minimum. Also, this enhancement in intensity is confined to a bandwidth of 1Å centred round K and so the sun viewed through a 1A band width filter will appear as a variable in the K-line (Fig.4). Similar solar cycle associated variations are also seen in the plot of the intensities of K_3, K_{2V}, K_{2R}, K_{1V}, K_{1R} and the K_2 width over this period. The enhancement in the 1Å flux during the maximum depends on the peak level of the activity of the individual solar maximum and can be 20-25% as in 1970 to as much as 30-35% as in 1980. (White and Livingston 1981; Sivaraman et al. 1985). The 1Å flux monitored for the sun shows also the rotation modulation very well. As the sun rotates the plages on the solar surface are taken away and brought into view and thus the plage area over a period of time shows the rotational modulation, demonstrated first by Bappu and Sivaraman (1971) as a convenient method of measuring rotation in slow rotators (Fig.5). The emission from the plages being dominant, the 1Å flux averaged over the solar disc also shows this rotational modulation. Wilson (1978), Preston and Vaughan (1980) have monitored the 1Å flux of many stars and have detected rotation in slow rotators and also established solar like cycles in many LMS stars.

Let us now examine the way the K-line emission rotation and magnetic activity are related to the very long time scale parameter namely the age. Skumanich (1972) showed that the K-line emission and rotation, decline with the age of the star (T in years) at a rate proportional to $T^{-1/2}$. The basic parameter that determines the level of magnetic activity in stars with convection zones is the star's rotation period. The steady spin down is caused by the loss of angular momentum through stellar winds. The magnetic activity in the sun and the LMS stars is believed to be caused by the coupling of rotation and convection producing the dynamo action and if so a decrease in this emission with decrease in rotation rate and with increasing age is to be expected. In other words the surface magnetic activity also decreases with increasing age presumably at the same rate, namely $T^{-1/2}$. Linsky (1981) has illustrated the rate of emergence of magnetic flux (dB/dt) for young and old stars as a function of spectral type through a diagram (reproduced here as Fig.6) in terms of Ω, the angular velocity of the star and d_c/R_* the ratio of the convective zone depth to the stellar radius. He used a function of the form

$$\frac{dB}{dt} = \Omega^{\alpha}\left(\frac{d_c}{R_*}\right)^{\beta} \qquad \text{where } \alpha \approx 1; \;\; \beta > 0 .$$

The rapid increase in the flux emergence in early F stars by the dynamo action decreases fast into the G stars due to the rapid spin down for all ages. The increase in M stars due to the increase in the depth of the convection zone is described well in this figure. Also (dB/dt) is far greater for young than for the old stars of each spectral class. Such a demarcation is also obvious from the plot of the chromospheric emission for about 400 solar neighbourhood field stars by Vaughn and Preston (1980). They find that there is a gap in the K line emission at the intermediate age of 1 to 2 billion years. All stars above this gap that have large K-emission are young and those below with weak emission are old (Vaughan 1980). If this gap is real it would mean that at a certain stage during evolution there is a sudden and steep decrease in the production of surface fields and hence a similar decrease in the K emission. Also, other parameters like rotation, cyclic activity are different for the two groups. These facts are set out in Table II.

Table II

Comparison of the properties of young and old stars

		Young stars	Old stars
1.	Ca II K Emission	Strong	Weak
2.	Rotation	Fast (can be detected from line profiles)	Slow (detected from 1Å index)
3.	Solar like cycles	Not present	Present
4.	Convection zone depth	Small	Large
5.	Emission width	Small	Large

(1) & (2) show that magnetic activity is high in younger stars and low in old stars.
(3) & (5) indicate that the organisation of surface magnetic fields (activity) in younger stars appear to differ from that in older stars.
(5) indicates young stars contain structures essentially in the form of bright points.

A possible logical conclusion would be that the organisation of surface magnetic field structure could be different for the young and the old stars due to different modes of field generation in the two cases. Among the large sample of stars monitored by Wilson (1978) those below the Vaughn gap showed smoothly varying clear solar like cycles in the K emission while those above the gap showed irregular fluctuations without signs of any periodicity. The absence of solar like cycles or a rotational modulation can happen if the surface of the star is populated with only the bright points and the chromospheric network, whereas a star which has plage like structures on its surface will exhibit rotational modulation and solar like cyclic activity. Thus as the star ages, there is an accompanying change in the pattern of chrmospheric structures and with this, the predominant agency responsible for the chromospheric emission also changes. When young, the bright points and the network provide the necessary emission, while in old stars it is the plage like structures that provide the emission. The formation of such compound structure is also probably aided by the increase in the depth of the convection zone. If the sun is a typical star possessing the above characteristics, then a speculative scenario of the evolutionary history of its magnetic activity and the chromospheric structure providing K-emission could be something like the following:

When the sun was younger (age $\sim 1\text{-}2 \times 10^9$ years) it would have been a rapid rotator ($T < 10\text{-}12$ days) showing high levels of surface magnetic activity characterized by pronounced chromospheric and coronal emission. Also at that time, it would not have showed clear solar like cycles and if ever present would have been masked by irregular fluctuations. This could mean that the magnetic field structures were in the form of bright points over the entire surface associated with strong magnetic fields. With increasing age, when the rotation rate decreased ($T > 10$ days) the field production rate also dropped down systematically. With this the level of activity also dropped down, giving rise to solar cycle phenomenon in magnetic activity. The magnetic structures once in the form of strong and tiny structures turned into the form of plages showing rotational modulation and the 11-year solar cycle.

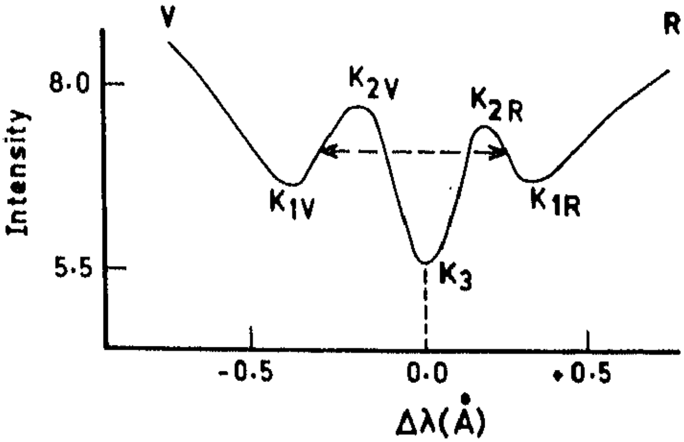

Fig.1. K-line profile of a typical bright point. The intensity is in per cent of the continuum. Notice the V/R asymmetry. The K_2 width (at the FWHM) is shown by the dashed line and is reckoned from the K_2 emission peak and K_1 minima.

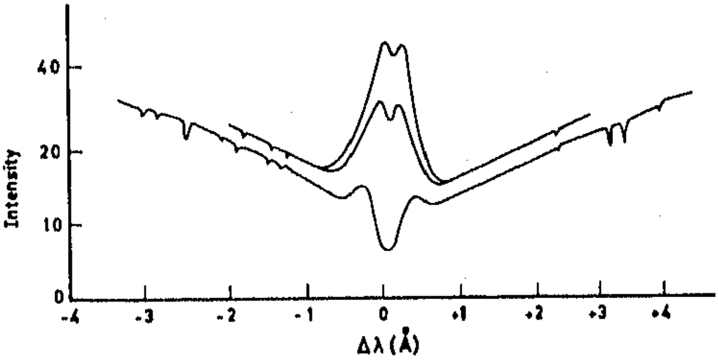

Fig.2. K-profiles of the quiet sun (profile 1) and those of plages (2 & 3). Notice as the intensity of the plage increases the K_2 width at the half intensity level also increases. The intensity is in per cent of the continuum.

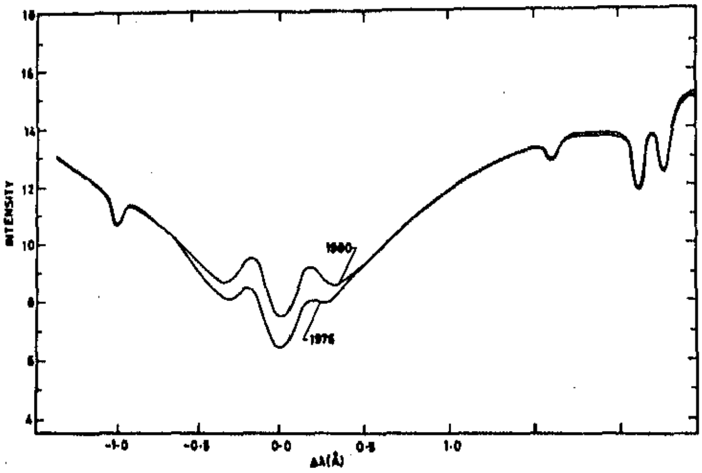

Fig.3. K-line profiles of the disc averaged sun on 11-7-1976 (solar minimum) and 24-6-1980 (solar maximum). Notice that the enhancement in emission is mainly confined to 1Å window centred round the line core.

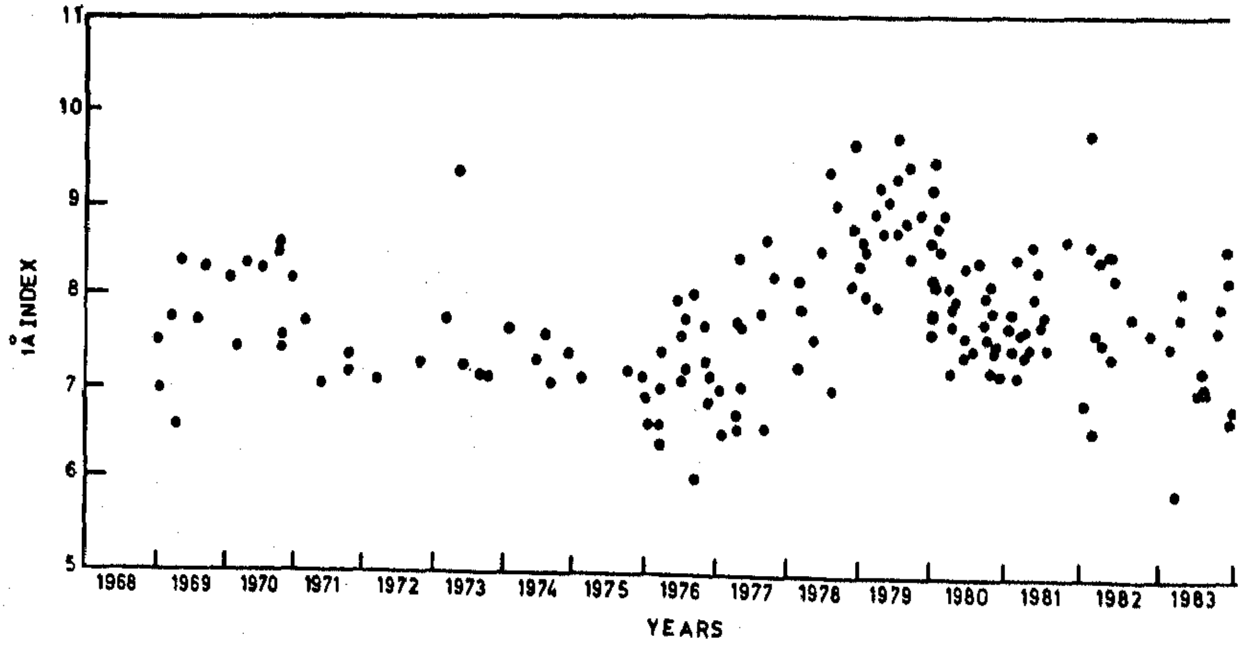

Fig.4. Plot of 1Å index for the disc averaged sun for the years 1969-1984 from the Kodaikanal data. The 1Å index is proportional to the 1Å flux centred round the K-line core.

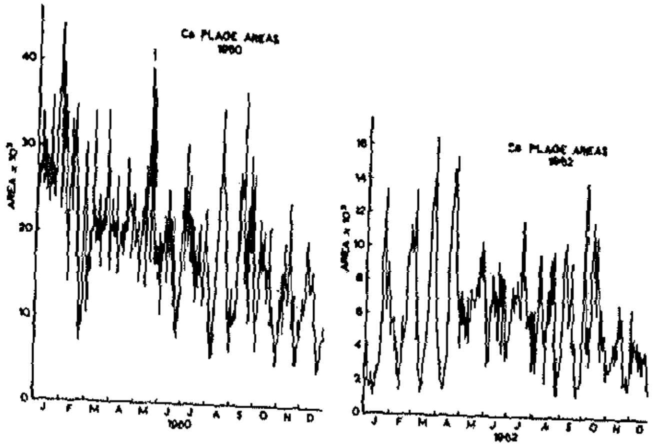

Fig.5. Plot of the daily plage areas from Kodaikanal K spectroheliograms for the years 1960 to 1962 to demonstrate the rotation modulation. The rotation is obvious at solar minimum when the number of plages are less.

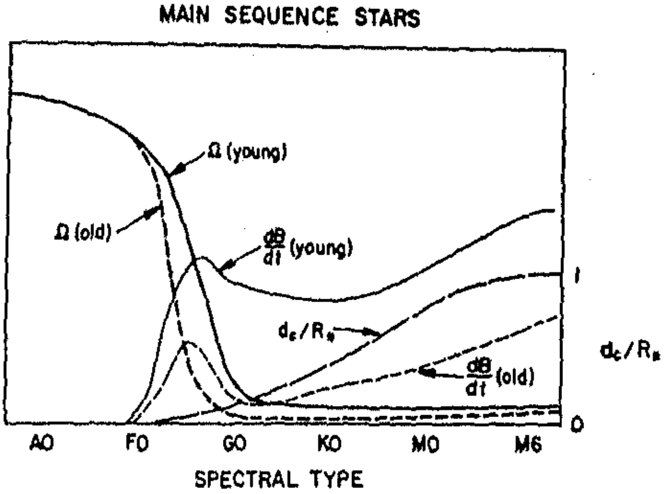

Fig.6. A schematic representation of dB/dt (the rate of emergence of magnetic flux per unit area) as function of d_c/R_X (the ratio of the convective zone depth to stellar radius), Ω (the angular velocity of the star), spectral type and age. Young stars are those on the zero age main sequence and the old stars are those about to leave the main sequence. From Linsky (1981).

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