CHROMOSPHERIC EMISSION INTENSITIES AND STELLAR EVOLUTION

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An age dependence of chromospheric emission intensities, especially for stars on the main sequence, has been known for some time.[1,2] These observations of intensity measures of the resonance lines of ionized calcium in the spectra of known members of the well known galactic clusters, the Pleiades and the Hyades, have shown the subtle difference in chromospheric flux caused by a difference in ages of the two clusters. Indeed, the intensity criterion has been used effectively by Kraft and Greenstein[3] to identify faint members of the Pleiades cluster from the background of field stars. Skumanich[4] has placed this relation on a quantitative basis by using flux values, reduced to a common spectral type, of the Sun, and also the Hyades, Ursa Major and Pleiades groups. An emission decay that follows the inverse square root of age is found, a pattern that is closely similar to that exhibited by rotational decay along the main sequence, as well as by the curve for lithium depletion.

The association of Ca^+ emission intensity with longitudinal magnetic field has been a well-established correlation for surface features on the Sun. Frazier's study[5] of the emission flux in a band 1·0 Å wide demonstrates the validity of a linear dependence on surface magnetic field strength to measureable low values. Viewed in this context the net chromospheric emission flux is an index of the average surface magnetic field of the star. The proportionality to the rotational braking curve indicates a decay with age of the "dynamo" processes responsible for the surface fields. The chromospheric emission characteristic assumes a new role in our understanding of the subtleties of association between several phenomena that originate over nearly the stellar radius and beyond.

The integrated radiation from the Sun as a star displays a weak Ca^+ emission component that can be seen with the high dispersion instruments of present-day stellar spectroscopy. Three contributors to this flux of radiation are the bright mottle, the Ca^+ network with its aggregate of mottles resolved and unresolved, and the plage that locates an active region.[6] The bright mottle of size 1000 km, in the solar case, is the principal contributor to the integrated radiation. It has been shown[7] that the Sun follows the Wilson-Bappu relation essentially because of the dominant characteristic of the bright mottle. The bright mottle has a range of intensities; its mean characteristic profile and total mean radiated flux are correlated with the luminosity of the star and its age. A substantial variation in the mean mottle flux comes about only over a large time-scale, when the general parameters of mean mottle brightness decays; the present indications are that the general surface magnetic field is a major controlling factor of the brightness.

The network emission outlines the supergranular cell of convective flow. The radial outflow, from a centre, of matter piles up a magnetic field near the boundary of the cell. We find here, besides an excess population of the normal bright mottle, a background of incipient emission that is a consequence of the accumulated magnetic field. Observations of the solar network have shown how when active regions disperse in the final stages of their evolution, there is an enhancement of intensity in the nearby network.[8] There is therefore, a noticeable but small enhancement of the general intensity of the network near the maximum of solar activity when plage dispersal is more common. There is also a measurable decrease in the size of the network at this time[9] caused perhaps by the effect of the dispersing magnetic fields on the properties of convective flow that governs the network size scale.

The plages, that so strikingly locate the centres of activity on the solar surface have a time dependence of number on the phase of the solar cycle. For the sun, these are not too numerous and hence their areal extent is limited. But since they are of high intensity, their contribution to the integrated flux is appreciable. They bring to any study a characteristic time-dependent variation that is a function of the solar cycle. In the stars we may witness manifestations of greater variety of these plages that lead to the possibility of Ca^+ light curves of large amplitude which reveal stellar cycles of activity in much the same way as we witness on the Sun.

The bright mottles on the solar disk seen in the K line of Ca^+ have a spacing of about 7000 km between each other and a life-time of about 200 seconds.[7] The change in emission line profile of any individual mottle as a function of time[10] depicts the propagation of an upward disturbance that produces an intensity perturbation by virtue of local heating of the chromosphere.[11] I have speculated[12] on the circumstantial evidence that permits the association of bright points with localized regions of weak magnetic field concentrations such as those shown by Harvey[13] within a network cell. The number density and distribution of both, lend confidence to such reasoning. There has been no published conclusive study made as yet, of the simultaneous magnetic field value and Ca^+ emission intensity, in order to unambiguously identify the correlation. Very recently Sivaraman and Livingston[14] found that bright mottles occur only in localized magnetic concentrations that are higher than the background level and that the peak intensity of a mottle depends directly on the field strength of the concentration. These investigators also confirm the mixed polarities of the field concentrations so strikingly seen in figure 5 of Harvey's paper.[13] However, one should bear in mind the demonstration by Ramsey *et al.*[15] that while much localized structure in the longitudinal magnetic field pattern exists within a network cell, a close coupling of mixed polarities, as shown by Harvey, is not noticeable. It is obvious that detection techniques and errors of compensation have a substantial role to play in exacting measurements of this kind and that confirmation of the mixed polarity awaits further study with a different experimental arrangement.

To sum up, we recognize on the solar analogue, that any aspect of short-time scale behaviour must necessarily be ascribed to variation of a total plage intensity. It is the time variation that exposes the "active" chromosphere of the star. The bright mottle and the network together on the other hand, have a more long-lived aspect of intensity. Variations that we encounter from these two contributors are on the time scale of evolution of the star.

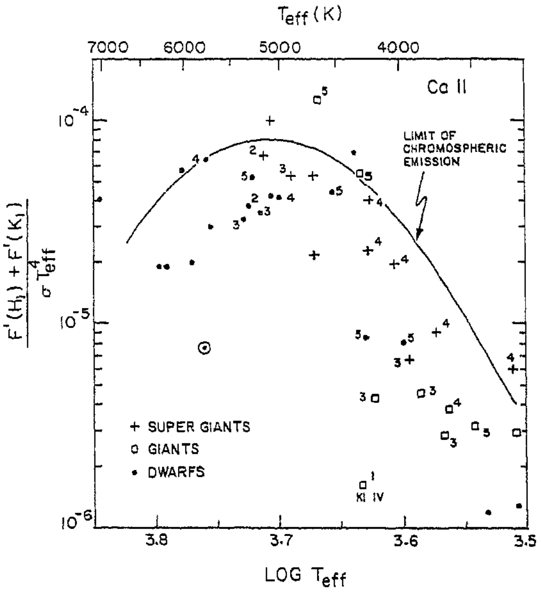
If we now extend to the stars these aspects of K-line emission that we have learnt from the Sun, we find that well-known stellar chromospheric phenomena like the *K*-line width-absolute magnitude relation and the decay curve of chromospheric flux in main sequence stars are essentially the performance of the bright mottle. We have found very little difference between the emission profile of the single bright mottle on the Sun and its integrated spectrum.[16] This is so atleast for the quiet Sun. The presence of active regions and hence of calcium plages provide an enhancement not only of the *K*-line emission but also of its width. The high precision data of White and Livingston[17] illustrate strikingly the plage contribution, especially the increase in width of emission over a period of time covering the rising part of the solar activity curve, from sunspot minimum to sunspot maximum. A very interesting feature noticeable in their curves of line width variation over the years 1975-80 is the modulation by rotation that resembles the modulation demonstrated by the Ca^+ plage areas.[7] Intrinsic to this data lies also the fact that the line widths of the bright mottle must be experiencing a similar enhancement as one goes towards the sunspot maximum. We reach this conclusion from the consideration that the lower limit of line widths measured in 1980 are atleast 2% higher than those obtained around 1975. This is also noticeable in their measures of separation of the K_1 minima. These investigators also have measures of Ca^+ emission flux that show a general background enhancement of 9% between sunspot maximum and minimum, with even flux value increasing upto 22% at times of high plage incidence. It is interesting to compare these values with the 10% value obtained by plage intensity measures from spectroheligrams carried out to demonstrate the use of the *K* emission intensity variation as an index of activity cycles in other stars.[18]

It seems, therefore, that on the short time scale that encompasses the duration of an activity cycle of a few years, the mean bright mottle demonstrates a marginal change in intensity and mean width; if we were to examine a star of identical characteristics to the Sun with the current techniques used for the study of the stellar chromospheric activity, these subtle changes may even go undetected. Of interest, however, lies the fact that much of this change comes about from the dispersal of magnetic fields from active centres and hence is an effective demonstration of the intensity of Ca^+ chromospheric emission as an index to the surface magnetic field strengths of the star.

The case of Canopus is an illustration of enhanced local magnetic fields that cause deviations from a normal characteristic. As an early F supergiant it would hardly have any Ca^+ emission. However, Warner[19] observed Ca^+ that had a width which deviated substantially from the Wilson-Bappu value that is consistent with its visual absolute magnitude. In the six years that we have monitored the Ca^+ *K* line with high dispersion equipment[20] we have never had any success in detecting Ca^+ emission in *K*-line core that was comparable to the Warner observation of 1965. Here is an illustration of plage-stimulated emission that is highly temporal in nature and which by virtue of its intrinsic association with a plage and not the bright mottle, has widths that deviate from the *K* linewidth- M_v relation, that is so well established for normal stars.

The most exhaustive source of information currently available of *K*-line widths and eye estimates of *K*-line emission intensity is the Wilson catalogue[21] of over 700 late type objects. Most of these objects are of high luminosity. Using Wilson's eye estimates I have shown[12] that many of the field red giants come from progenitors of low mass. These stars spend a substantial part of their lives on the main sequence, losing in the process much of their chromospheric emission, thus bringing it down to levels comparable or even lower than the solar case. At the dispersions used to study stellar chromospheres, we would fail to detect any emission in the *K*-line cores of these stars. And yet they have appreciable chromospheric fluxes as we see them today in the red giant phase. Clearly, therefore, one must conclude that the star, during the course of its subgiant, giant phase of evolution has experienced a restructuring that has revitalized its chromospheric emission. The bright mottle in the giant phase operates with greater intensity and larger line width consistent with the increase in luminosity of the star. The intensification of surface magnetic fields provides the enhancement of intensity; the consequences of the structural changes in the outermost stellar layers bring out the changes in source function and turbulent broadening, that cause the increase in line width. The magnetic fields take time to build up, for, these evolutionary phases are on time scales of 10^8 years. If so, a star in the subgiant phase would have less chromospheric emission than when it becomes a giant.

Ideally, flux measurements corrected for spectral type dependence are necessary for evaluation of the net chromospheric radiation losses. Our conclusions outlined above are based on eye estimates only, that are uncorrected for spectral class. But they serve to demonstrate the trend and provide the stimulus for a programme of more flux evaluation of stars with well known ages. For the present, the limited data of flux values for Ca^+ obtained from ground based observatories, together with many more available of Mg^+ from the International Ultraviolet Explorer studies, provide us with a few gleanings.



In figure 1 we have a plot of the ratio of chromospheric flux in the Ca^+ lines to the bolometric luminosity for dwarfs, giants and supergiants. The Ca^+ radiative loss rates are taken from Linsky *et al.*[22] The number adjacent to each point indicates an eye estimate of intensity of *K*-line emission on a scale of 1-5 (5 is the most intense) that is taken from the Wilson compilation. These intensity estimates are made against a background that decreases as one goes to lower effective temperatures. However, in any narrow zone of effective temperature, the pattern of variation of the eye estimates must be similar to the variation of the chromospheric flux values. The highest values of flux are shared by main sequence objects, the supergiants and some of the giants. Indeed, it would be difficult to show any absolute dependence on luminosity of the chromospheric flux. It is possible to draw an upper envelope of chromospheric emission above which the normal star, be it of any of the luminosity classes I, III or V, can seldom be located. The drawing of this curve at low effective temperatures is aided by the intensity estimates, since we know by experience that brighter cases than those marked in the diagram are seldom seen amongst the large number of stars that we are familiar with in the solar neighbourhood. If now we examine two narrow vertical sections of the diagram, one near log $T_e = 3{\cdot}75$ that passes through the point representing the quiet sun and the other at log $T_e = 3{\cdot}63$, that cuts through the lone point of a K_1 subgiant, we find two opposite trends in the age effects. When we follow the main sequence objects at log $T_e = 3{\cdot}75$, we find that the decrease in intensity with age is represented by the departure from the curve that defines the limit of Chromospheric Emission (LCE), with the sun at one extreme and objects like Zeta Bootis A near the limiting curve. At log $T_e = 3{\cdot}63$ we find the supergiants near the LCE, the K_1 subgiant with a maximum departure and the giants interspersed in between. A star at this post-main sequence phase of evolution builds up its chromospheric emission and moves towards the LCE, though with the sparse data we now have it will not be possible to indicate whether in this second phase of chromospheric revitalization they reach the LCE. The supergiants hover around the LCE since they have the chromospheric emission originate from magnetic fields available at birth and which have not had time enough to decay, together with the new source acquired by virtue of the evolutionary changes of post-main sequence existence.

The concept of renewal of chromospheric emission as a consequence of post-main sequence emission can perhaps best be assessed by observations of the subgiant and giant branch in old galactic clusters. The cluster M67 offers the best possibility: its distance and consequent faintness of the objects of interest are such as to keep it still within the reach of current techniques for such detection.

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