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Facular Structures on Cool Stars

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Abstract

Activity has many manifestations, from dark spots to bright regions, to the presence of the heated chromosphere, to the superheated corona. Sunspots are extended, strongly magnetic regions on the Sun. Photospheric faculae are generally visible only at the limb. Polar faculae are smaller than the main-zone faculae. The contributions of the active region faculae and the facular network are at least as important as the solar spots in augmenting the solar emission.

1. Introduction

Since black spots were observed on the solar disk, there has been interest in the activity that takes place on the atmospheres of cool stars. It has many manifestations, from dark spots to bright active regions, to the presence of the heated chromosphere, to the superheated corona which extends far away from the surface and gives rise to the wind leaving the star. While we can see the solar disk and have easy access to these signatures of activity on the Sun, it was much less obvious that such activity also takes place on other stars. As this century progressed it became increasingly clear that some variable stars were variable because of the passage of enormous analogs of sunspots across their visible faces. The contrast between stellar surface and the active atmosphere becomes increasingly large as one moves to UV and X-ray wavelengths, which are also the spectral regions at which most of the emission from active plasma occurs. The term magnetic activity generally describes a stellar atmosphere within which many of the phenomena of activity described below are found.

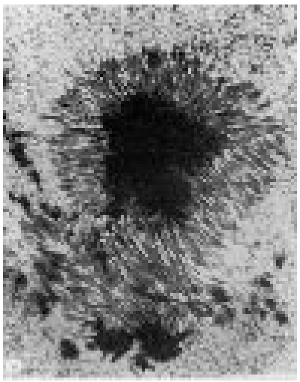

Figure 1. A typical sunspot exhibits a dark central region, the umbra, surrounded by an annular region, consisting of alternately bright and dark radial filaments, called the penumbra (Obs. du Pic-du-Midi).

2. Solar Activity Patterns

2.1. Sunspots

Sunspots are extended, strongly magnetic regions on the Sun which, owing to their reduced temperatures (3000-3500 K) radiate less visible light than the undisturbed photosphere (5800 K). These provide the most dramatic examples of activity and of the non-uniform structure of the photosphere. Larger spots usually consist of an umbra and penumbra. A spectacular example is shown in Figure 1.

The umbra is the dark core of a spot. The penumbra surrounds the umbra, and consists of bright and dark filaments connected radially to the umbra.

Sunspots usually occur in groups. Large groups often show a clustering of spots around two primary spots, which are termed bipolar. Lifetimes of sunspots may range from a few days to several solar rotations. The occurrence of a spot group is linked to other phenomena tied to solar activity such as faculae, prominences, and flares, all of which are caused by magnetic fields. The development of these phenomena is of different speeds and also different in each spot region.

2.2. Photospheric Faculae

Bright veins or streaks of light can be observed almost every day on the surface of the Sun. These phenomena are the photospheric faculae which form over the entire solar surface, although in white light they are generally visible only at the limb. Their observability is thus very limited. The faculae on the Sun are all associated with the sunspots.

When the Sun is observed through mono-chromatic filters, such as in the Calcium H-and-K lines or in the hydrogen $H\alpha - line$, faculae can also been seen outside the disk.

These chromospheric faculae, which represent the protrusion of photospheric faculae into the chromosphere, are to be described later.

Faculae consist of aligned mottles 5 000 to 10 000 km wide and up to 50 000 km long. They in turn are composed of oval-shaped coarse mottles with diameters of about 5 000 km. The coarse mottles are made up of the faculae granules, about 1 000 km in size.

Faculae -and almost all solar surface phenomena- are spawned by magnetic fields, and characterize a region of enhanced activity in which sunspots can also appear. Faculae not only presage sunspots but they also outlive them, often by several weeks. The average lifetime of photospheric faculae is 90 days. Their integrated area is substantially larger than that of associated spot group. Photospheric faculae appear in increased numbers in a region prior to the emergence of sunspots and remain for a rotation or more after the spots have decayed. Because they are brighter than their surroundings, they are believed to be hotter (the temperature in faculae is several hundred (degrees) Kelvin higher than that of the quiet, undisturbed photosphere) and thus to radiate more energy. The faculae are, for this reason, important to the energy balance between sunspots and the photosphere.

2.3. Filigree

The smallest structures which have been resolved on the solar disk are the filigree. These structures are cospital with, but much smaller than, the faculae and are believed to delineate the magnetic field network associated with faculae.

2.4. Polar Faculae

It is widely known that sunspot activity occurs not uniformly across the entire solar surface, but in two zones parallel to the equator and extending to about $\pm 45°$ of heliographic latitude. The same holds true for the faculae which can be observed daily on the Sun. Nevertheless, there do exist polar faculae in regions of high heliographic latitudes.

Polar faculae are smaller than the main-zone faculae; their average diameter is around 2300 km. Their shape is point-like or oval. Their lifetimes range from a few minutes to some hours, but the decisive difference from the main-zone faculae lies in their activity cycle. When spots and faculae of the main zone are at minimum, the polar faculae have their maximum activity, and vice versa. The latter thus go through the activity cycle in opposite phase.

2.5. Choromospheric Faculae

When the Sun is observed in the monochromatic light of $H\alpha$ or CaII K-line, faculae are observed over the entire solar disk; these are chromospheric faculae (Figure 2), an extension of photospheric faculae into the chromosphere. A definitive explanation of their precise connection with the features of photospheric faculae is still lacking.

The observation chromospheric faculae or plages is of great interest for several reasons. Plage phenomenon heralds the appearance of sunspots. Therefore, if plages can

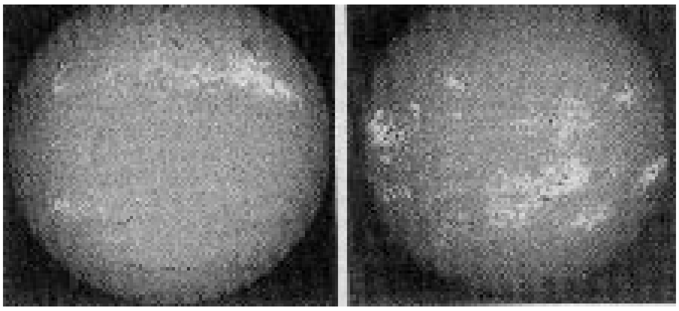

Figure 2. The Sun in monochromatic light; left: in H_α light; right: in Ca II light.

be observed over the entire solar disk, then it is possible to predict the positions of new activity centers.

3. The Solar-Stellar Connection

Although the Sun permits the detailed two-dimensional study of its activity phenomena, it exhibits only a single set of stellar parameters, since its mass, size, composition, and state of evolution are necessarily fixed at this point of time. On the other hand, stars, as observed from earth, are essentially one-dimensional objects, but they offer a wide range of physical parameters which permit a more through testing of theories and conjectures regarding common phenomena than is possible for the Sun alone. The solar-stellar connection aims to bring these two lines of investigation together in order to further our understanding of the properties of the Sun and other late-type stars.

Even before the solar-stellar connection methodology became recognized as such, there were many examples of successful application of solar results to stellar investigations. In the 1940s and 50s, for example, the chromosphere and corona were thought to be unique to the Sun, but, later with the application of improved techniques from space research, equivalent regions have since been identified in the atmospheres of many stars.

3.1. Starspots

The possibility that luminosity fluctuations in stars of order 20% over periods of days, or a few weeks, might indicate that the surface of such stars was not uniformly bright was first suggested more than a century ago by Pickering, who assumed that the star' s rotation carried these variable or spotted regions on and off the visible hemisphere, giving rise to a brightness or colour modulation of its continuous spectrum. Since 1970, many people have carried out photometric studies of a variety of cool stars, including the RS CVn subgiants, such as II Peg, which occur in binary pairs, and the BY Draconis dwarf stars (with luminosities $< \frac{L_\odot}{2}$, such as AU Mic, and have developed geometrical models in order to explain the light and colour variations. They find that the starspot model, usually invoking.

In the early stages of these studies, there was some doubt as to whether starspots were hotter or cooler than their surroundings, and, more recently, Peterson, Hawley and Fisher [1] have reiterated these concerns. However, detailed studies of the shape and size of both the light and colour variations have yielded typical effective spot temperatures near 3400 ± 200 K, generally 1000-1200 K cooler than the unspotted regions. If starspots have an umbra-penumbra structure similar to sunspots, where typically 97 percentage of the flux comes from the penumbra, this result would imply umbral temperatures of $\sim$ 2600 K. Starspots are therefore both actually and relatively cooler than sunspots, in which umbral and penumbral temperatures of 4000 K and 5300 K must be compared with a solar photospheric temperature of 5800 K.

3.2. Spot Cycles and Facular Structures

A growing number of RS CVn and BY Dra stars have been systematically observed with photometry for over a decade or more. Many of these stars show evidence of long-term variation in the light amplitudes and in the mean light levels of their light curves that could be due to solar-like activity cycles. Evidence of activity cycles in RS CVn and BY Dra stars is given, for example, by Rodono [2]; Dorren and Guinan [3]; Evren [4]; İbanoğlu [5]; Maceroni et al. [6]; Olah [7] and Henry et al. [8]. Most cycles are between 6 and 14 years.

An interesting example of evidence for an activity cycle in an active RS CVn star is given by Dorren and Guinan [9] for V711 Tauri. Figure 3 from this paper shows a plot of the seasonal mean values of $H\alpha$ index, V-magnitude, colour index, and C IV λ 1550 emission line flux over time. The light variation appears to show a systematic rise and fall suggesting the presence of an activity cycle with a period of 11-14 yrs. However, as shown in the figure, the $H\alpha$ index and colour index measured for this binary do not seem to correlate well with the observed brightness changes. Moreover, the C IV λ 1550 emission flux, which arise from the transition-region, appears to rise and fall a few years out of step with the star's luminosity. This study indicates that the star was brightest when the activity levels inferred from the transition region lines was greatest. This effect is opposite to what would be expected if the starspots were the only contribution to the long-term brightness variations.

These results are interpreted as evidence of a significant facular (white light faculae) contribution to the star's luminosity. They suggest that the C IV λ 1550 line emission yields a more direct measure of magnetic activity while the long-term light variation is produced by competition between the blocking effect of the dark starspots and enhancements in luminosity from white light faculae and a facular network similar to that observed in the Sun.

Dorren and Guinan [9] believe that it is now possible to have a clearer understanding of these results in light of the work of Foukal and Lean [10-13] on the factors affecting the solar irradiance. They showed conclusively in the visible band. The contributions of the active region faculae and the facular network are at least as important in augmenting the

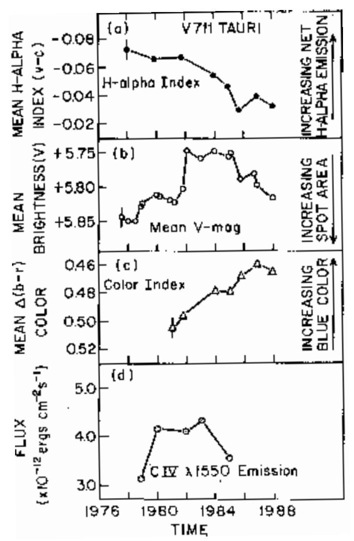

Figure 3. Variation with time of (a) the mean H_α index, (b) the mean brightness of the system, (c) the mean (b-r) color index, and (d) the C IV 1550 Å emission flux. After Dorren & Guinan [9]

solar emission as the spots are in diminishing it. Indeed, they concluded that at the last solar activity maximum the irradiance was also a maximum, contrary to what would be expected if the spots were the sole factor affecting the visible band luminosity. The loss of light due to the increased spot area at the peak of activity was more than compensated for by the growth of the contribution of the faculae and facular network. During the decline of activity from 1981 to 1984 following solar maximum, the solar irradiance also declined; they showed that this was due to a decline both the active region faculae and in the facular network. As shown in Figure 4, a study of the last three solar cycles, 19-21, led these authors to conclude that the Sun is consistently brighter at solar maximum, due to the faculae and facular network overcompensating for the reduced emission from the spots. They also found that the evolution of large active facular complexes is responsible for variations on the time scale of a few months.

The solar chromosphere and corona are usually viewed as regions of the solar atmosphere whose physical conditions are controlled by magnetic heating process originating below the photosphere. The energy content and gas density of these outer regions are orders of magnitude lower than those prevailing in the underlying photosphere. Thus photospheric processes determine the magnetic configurations which control both the heating of the corona and its morphology. To a very close approximation the chromosphere and corona have no effect on the solar photosphere. Although the same processes which heat the outer layers may give rise to heating effects visible at near-photospheric levels (e.g. white-light faculae).

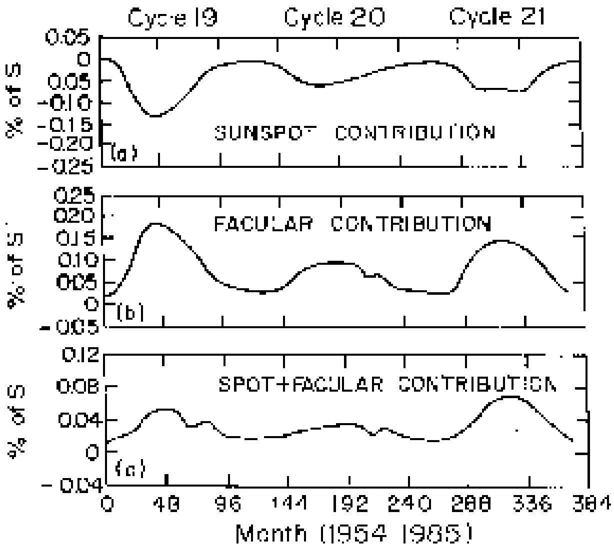

Figure 4. Percentage contributions to the solar irradiance S from sunspots and faculae over the last three solar cycles 1954-1985 (from Fig.4 of Lean and Foukal, [13]). Plot (a) shows the sunspot contribution to total irradiance; (b) is the facular contribution; and (c) is the summed sunspot+facular contributions showing the brightening at solar maximum.

Chromospherically active late-type stars exhibit all of the panoply of solar activity but on scales several orders of magnitude larger. The solar paradigm is widely (and successfully) adopted in interpreting such phenomena. It is implicity assumed that the stellar photosphere underlying these outer atmospheric effects may be regarded as similar to that of a quiescent star of similar spectral type, at least in a global sense.

Excesses in the mean global blue colours of some young open cluster stars have been detected for some time now. Turner [14] measured an UV excess in the members of the young Pleiades open cluster. He explained this as being due to an effect of metallicity. Stauffer [15] examined the turn-on point of pre-main sequence objects in the Pleiades. He explained this ultraviolet excess as due to flaring. He reasoned that, since many of this stars are flare stars, this might affect the blue colours, making them look bluer and, thus, producing the excess.

This UV excess has been observed in some other types of stars. So, up to now, there have been a few attempts at explaining this excess (UV excess) seen in the blue colours of some stars. In the study published by Amado and Byrne [16], they examined several classes of chromospherically active late-type stars for evidence of an effect of activity on the mean global photospheric colours. The question that immediately arises from this investigation is, what produces this UV excess? They considered the following possibilities: (i) flaring, (ii) chromospheric emission, (iii) x-ray back-heating, and (iv) faculae. In active stars, the higher brightness and hotter temperature of faculae and plages over those of the photosphere would affect the colours of the star shifting them towards the blue, thus producing on UV excess. This effect, of course, will be more enhanced for stars with lower effective temperature for which the contrast between the faculae and the photosphere will be larger.

In the Sun, the white-light faculae as a photospheric phenomena are intimately connected with spots; they often appear before the sunspot and persist after the disappearance of the spot. There is also a facular network which corresponds closely to the chromospheric network. Their precise contribution to the solar irradiance is only now being clarified through the investigations of Foukal and Lean [10-13].

The possibility of a facular network contribution to the optical brightness of **RS CVn** stars has until now been ignored, because of the lack of understanding of the role that the solar faculae play, and also because of the impossibility of extracting information about a facular contribution from the light curves alone.

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