THE SPATIAL ASSOCIATION OF SPOTS AND PLAGES

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Abstract. We review the evidence, from rotational modulation, for association of plages and spots on active binaries. We find reasonably convincing support for such an association from IUE SWP observations of RS CVn stars, but little or no evidence from MgII line fluxes. There is a similar lack of evidence for BY Dra systems. The results can be interpreted as evidence for: (a) the presence of *active longitudes* which persist on some RS CVn stars for several years, (b) high filling factors in MgII emission and (c) lower filling factors, and therefore greater contrast, in SWP emission. There is a suggestion that the association between plages and spots is more clearly seen in longer period RS CVn stars than the very active, short period, systems favoured by IUE observers.

1. Introduction – the solar picture

Cool dark spots on the surface of the Sun are the most widely known feature of solar activity. Sunspots can occur singly or in groups and have lifetimes of up to a solar rotation period. Many characteristics of sunspots have been described since systematic monitoring began in the early 19th century, (see Kiepenhauer, 1953). For instance we may mention: their tendency to appear at certain preferred longitudes, the cyclic changes in their latitude as evidenced by the *butterfly diagram*, and the approximately eleven year periodicity in their frequency (the *Schwabe Cycle*). Other well known solar cycles related to sunspots are the 22 year magnetic cycle and the much longer, approximately 80 year, periodicity in the amplitude of the Schwabe Cycle, known as the *Gleissberg Cycle*.

Less conspicuous in white light, but quite prominent in some emission lines (e.g. CaII and Hα) are the bright, extended, patches known as faculae.

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They are believed to delineate the regions where magnetic heating is occurring in the upper photosphere and chromosphere and are most clearly seen in white light when close to the solar limb. When observed in Hα, or the K line, they are visible, undiminished, across the solar disk. They often form prior to the emergence of sunspots, are constantly evident in the presence of sunspots, and survive for some days after the sunspots have disappeared. Whilst faculae can exist without sunspots, the reverse is apparently never true. In older literature, the term *faculae* is used for both photospheric (white light) and chromospheric (Hα and CaII K) emission regions. As this terminology can cause confusion we shall, in the rest of this article, refer to the chromospheric faculae, by their alternative name *plages*, which alludes both to their brightness and their proximity to sunspots.

The most dramatic manifestations of solar activity are the brief, but energetic, flares. Flares commonly occur in the vicinity of sunspots and are believed to result from the reconnection of the strong magnetic fields associated with them. However, in 10% of solar flares there is no neighbouring dark spot. Nevertheless, flares invariably occur in facular regions.

The regions of the Sun's surface where one or more of the above apparitions: spots, flares and faculae, occur are known as *active regions*. In general, though often discussed separately, the panoply of phenomena that occurs in active regions are all believed to originate from the effects of magnetic fields.

2. Rotational modulation – a key to spatial relationships between spots and plages on stars

On the Solar model, we would naturally expect a similar set of features on late-type stars, however, as few, if any, such stars can be directly imaged, we are forced to resort to secondary methods to establish their presence. Three such techniques are currently available: eclipse imaging, where surface inhomogeneities on the eclipsed star betray their presence in small distortions of the eclipse light curve; Doppler imaging, where small cyclic deformations of line-profiles are attributed to the presence of inhomogeneities as they move across the line profile due to the rotation of the star; and, lastly, rotational modulation, where the presence of an inhomogeneity is inferred from the variability of the star's brightness as it rotates. All three of these methods have their own peculiar shortcomings. Firstly, eclipse imaging, though probably suitable for RS CVn stars which include giant and subgiant components, can rarely be used on dwarfs due to the small number of such stars that eclipse. Similarly, Doppler imaging, which is restricted to stars with high equatorial velocities, is more suitable for RS CVn stars than dwarfs. Rotational modulation, on the other hand, can be used on either class of active star, RS CVn or BY Dra variables. The drawback is that it suffers from non-uniqueness, for it is found that almost all observed optical light curves of active stars can be fitted by simple, two-spot models. Bearing in mind the solar picture this would seem to be a drastic oversimplification of the true situation. Nevertheless, because the technique is available for all stars with inclined axes of rotation, it has been the one most commonly used for the identification of surface inhomogeneities. Therefore, we shall base the remainder of our discussion on the results of this technique.

Rotational modulation of an inhomogeneous stellar surface can only be used successfully when the distribution of inhomogeneities is non uniform. Both a large polar spot, or an uniform distribution of spots around the star, will simply result in a change in the overall brightness of the star and not in rotational modulation. Thus in using this technique we only see the non-uniform component of the distribution of spots.

A further problem with the rotational modulation method lies in the difficulty in assessing the brightness of the unspotted star. Often, investigators assume that the unspotted or *immaculate* star has the brightest magnitude at which the star was ever observed. For very active stars, it is quite possible, that spots are always present, and therefore the assumed *immaculate* level is too faint. In this situation the size of the spots will be underestimated. Also, we may note, from space-based measurements over recent decades, that the Sun is brighter overall during sunspot maximum, than sunspot minimum. If the same is true for an active star then, at times when there is no rotational modulation (i.e. it is assumed spotless), the magnitude assumed for the immaculate star would be expected to be too faint. As no allowance for this is usually made in spot modelling of late type stars, the size of the spots will again be underestimated. These reservations need to be borne in mind when discussing the results of studies using rotational modulation.

In order to assess the spatial relationships between the photospheric spots and plage-like regions on late type stars we need to look at the relative phase of the depressions in the optical light curve (assumed caused by dark spots) to the increase in the flux of the chromospheric emission lines which accompany plages. If spots and plages on stars are spatially associated, as on the Sun, then the phase of the optical minimum will coincide with the peak flux of the emission lines.

Due to the very low ultraviolet continuum flux from late type stars and the strength of the prominent emission lines of ionised carbon, oxygen, helium, nitrogen and magnesium, IUE has been commonly used to detect rotational modulation of plages. When combined with the photometric studies, usually carried out in the V band, we can assess the relative phase of plages and spots for these stars. Though initially the data tended to strongly favour the solar picture, later data cast some doubts on the earlier conclusions. Here we try to review the overall picture after nearly two decades of IUE observations. We shall discuss RS CVn stars and BY Dra stars separately.

3. RS CVn stars

The first attempt, using IUE data, to establish whether or not a spatial association exists between spots and plages was made by Baliunas and Dupree (1982) in their study of the long period RS CVn star λ Andromeda. Their results showed a general increase in the strength of the IUE (SWP) emission lines at optical minimum (spot maximum). This result, though based on very few spectra, supported the solar model. However, it was quickly realised that, for such highly variable stars which show evidence not only of spots but also frequent and prolonged flares, many more observations would be required if the solar paradigm was to be confirmed.

At that time, IUE was operated by: NASA, ESA and the UK Science Research Council, and in order to obtain a consecutive sequence of observations for a period in excess of 40 hours, it was necessary to gain approval by all three agencies. This lead to the establishment of an international consortium involving collaborators based at the Universities of Colorado and Catania and Armagh Observatory.

In their extensive campaign in 1981, three RS CVn and two BY Dra variables were observed for at least one complete rotational cycle, (see Rodono et al. 1987). For one star, II Peg, there appeared to be dramatic confirmation of the solar model, with a strong enhancement in all the IUE emission lines coinciding with the minimum of the optical light curve. The interpretation of the enhancement in the IUE lines as a plage-like region was reinforced by the following points: (1) The enhancement was observed over two successive cycles. (2) The light curves of the emission lines showed a steep rise as the region of enhanced emission came into view, and a sudden drop as it disappeared over the limb, half a rotation later.

Nevertheless, a followup study in 1983, published by Andrews et al. (1988), cast some doubt on this interpretation. The later observations showed evidence for two large flares during the IUE run, both of which occurred during the phase interval during which the plage-like enhancement had been seen two years earlier. The fact that the amplitudes of the flare enhancements in 1983 were almost identical to that of the supposed plage-like enhancement in 1981, suggested that perhaps the 1981 enhancements were also due to flares. In fact, either interpretation is plausible and whichever is the true explanation they would both confirm a solar-type model, with active regions (as evidenced by flares or plages) coming into

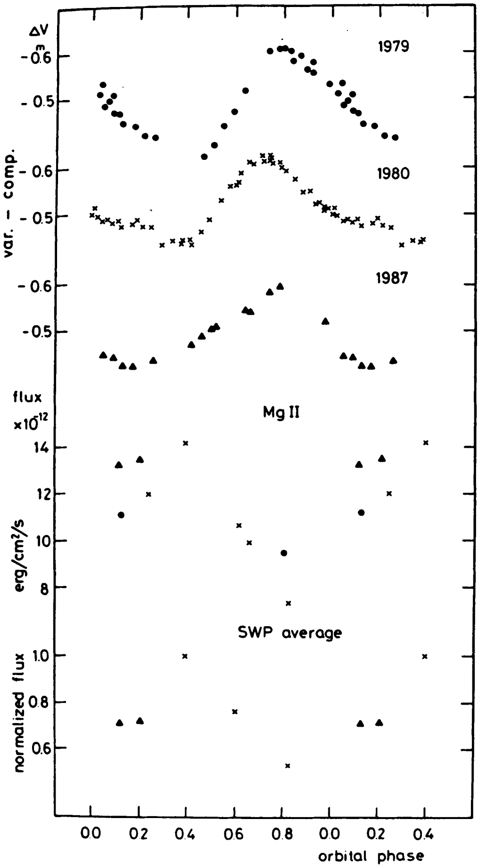

Figure 1. The comparison of the V-band light curve and IUE fluxes for HK Lac. Note the stability of the optical curve and its anti-correlation with the IUE emission line fluxes.

view at optical minimum. In the later papers by Andrews et al. (1988) and Doyle (1988) the earlier conclusions are modified to some extent and the observations seen as evidence for the emergence of active regions at certain *preferred longitudes* on II Peg, where these active regions manifest themselves through spots, plages or flares. Similar active longitudes, which can persist for many rotations, have been noted on the Sun (see Wolfer, 1899 and Losh, 1939). In the case of II Peg, the active longitudes appear to persist for a number of years.

In addition to II Peg, the above mentioned consortium also observed HR 1099, one of the most active RS CVn stars, and AR Lac which is an eclipsing system. Both systems show marginal evidence for an increase in the SWP emission line fluxes at optical minimum, however, a large flare on

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HR 1099, and incomplete coverage of AR Lac, resulted in a less convincing case than for II Peg. Further observations in 1983, reported by Andrews et al. (1988) and in 1984, reported by Dorren and Guinan (1990), gave a similarly marginal result for HR 1099.

TABLE 1. Association between Spots and Plages on RS CVn Stars - SWP lines

Star	P_{orb}	P_{phot}	Year	Spot & Plage in phase	Reference	Comments
λ And	20.5	54	1978/9	+	Baliunas & Dupree 1982	
II Peg	6.72	6.72	1981	++	Rodono et al. 1987	flares ?
			1983	+	Andrews et al. 1988	flares ?
			1986	+	Doyle et al. 1989	
			1990		Doyle et al. 1993	flare
HR 1099	2.84	2.84	1981	+	Rodono et al. 1987	
			1983	+	Andrews et al. 1988	
			1984	+	Dorren & Guinan, 1990	
			1992		Neff et al. 1995	
AR Lac	1.98	1.98	1981	+	Rodono et al. 1987	
HK Lac	24.4	24.4	1979-87	++	Olah et al. 1992	

In Table 1, we summarise the evidence for a spatial association of spots and plages on RS CVn stars from the IUE SWP lines. A single plus sign in the fifth column indicates a marginally positive correlation between plages and spots; a double plus sign a good correlation; a negative sign a marginal anti-correlation; a double negative sign a strong anti-correlation; and if the field is blank, there is no evidence either way. The overall conclusion is that there is significant evidence in favour of the association of spots and plages as seen in the SWP lines.

If we look at the evidence from the MgII emission lines, at $\lambda \sim$2800A, seen in the LWR/LWP spectra from IUE, the position is much less clear. In Table 2, we list the publications from which a comparison of the MgII and optical light curves is possible. In many cases no conclusions can be reached, either way, and in some cases, for example in II Peg in 1986 reported by Doyle et al. (1989), we see evidence for the opposite of the solar picture. Thus we conclude that the MgII emission flux does not confirm a solar-type plage distribution. Indeed, as has been suggested by Linsky et al.

TABLE 2. Association between Spots and Plages on RS CVn Stars - MgII

Star	P_{orb}	P_{phot}	Year	Spot & Plage in phase	Reference	Comments
II Peg	6.72	6.72	1981	++	Rodono et al. 1987	flares ?
			1983		Andrews et al. 1988	
			1986	−−	Doyle et al. 1989	
			1990		Doyle et al. 1993	flares
HR 1099	2.84	2.84	1981		Rodono et al. 1987	
			1983		Andrews et al. 1988	
			1992		Neff et al. 1995	
AR Lac	1.98	1.98	1981	−	Rodono et al. 1987	
HK Lac	24.4	24.4	1979-87	++	Olah et al. 1992	small N_{obs}

(1982) and subsequently by other authors, the very high activity levels in RS CVn stars may result in such widespread plage-like regions that the entire surface of the star is completely covered. In this case, no rotational modulation would occur, only a very high surface flux.

The case of HK Lacertae is an interesting one, as it points to a possible observational selection effect in the above data. HK Lac is a member of the long period group of RS CVn stars with a well established optical light curve. The optical data (see Olah et al. 1991) confirms that an active longitude has persisted for a number of years. IUE observations, in both SWP and LWP/LWR spectral regions, made over several years, showed a generally solar-like association between spots and plages on this star. In Figure 1 (from Olah et al. 1992) we show the clear anti-correlation of the optical and IUE light curves, (i.e. the positive correlation between spots and plages) on this star. The fact that the two members of the long period group included in Tables 1 and 2, namely λ And and HK Lac, show reasonably convincing evidence of an association between spots and plages, suggests: (1) that the spatial association is more clearly seen in stars from the, less active, long period group than amongst stars from the, highly active, short period group, and (2), that the perceived, somewhat confused, picture, may have arisen, partly, from the preference by IUE observers for short period systems. More observations of members from the long period group would help to clarify whether the above conclusions are justified.

The generally clearer, and more solar-like, picture seen in the higher temperature upper chromosphere and transition region lines observed in the IUE SWP range, as opposed to the lower temperature MgII lines seen in the LWP/LWR range, probably results from the greater contrast of the SWP lines and their more concentrated spatial distribution (i.e. smaller filling factor) compared to the MgII lines.

TABLE 3. Association between Spots and Plages on BY Dra Stars

Star	P_{orb}	P_{phot}	Year	Spot & Plage in phase	Reference	Comments
SWP lines						
BY Dra	5.98	3.83	1981	+	Butler et al. 1987	V-band low ampl.
AU Mic	-	4.86	1981		Butler et al. 1987	flares, poor phase coverage
MgII lines						
BY Dra	5.98	3.83	1981		Butler et al. 1987	
AU Mic	-	4.86	1981		Butler et al. 1987	
			1986		Quin et al. 1993	$\Delta V \sim 0^m.04$

4. BY Draconis variables

Compared to the RS CVn stars, there have been relatively few rotational modulation studies with IUE of the BY Draconis variables. This is probably due to their substantially lower fluxes. In Table 3, we give details of observations of two of the brightest BY Dra variables, BY Dra itself, and AU Mic, which is unusual for its class in that it is a single star. Only in the SWP observations of BY Dra, is there any clear suggestion of a rotational modulation which is consistent with the solar picture. The SWP observations of AU Mic, on the other hand, are so complicated by frequent flaring, that it is quite impossible to see any underlying slow modulation that could be attributed to rotation.

In the MgII lines, again it seems that frequent flaring and large filling factors may be responsible for the lack of any convincing rotational modulation. The conclusion that large filling factors resulting in complete coverage of the surface with plages are responsible for the lack of rotational modulation, receives some support from a study by Mathioudakis et al. (1992). They showed that the MgII surface fluxes of the dMe stars lie at the upper limit of the distribution in the *flux - (B-V)* diagram. The conclusion was that stars at this level are completely covered with MgII plages.

Some additional evidence for very high filling factors for MgII plages on the very active dMe stars is also seen in the MgII light curve of YY Gem during eclipse. We note that the MgII fluxes obtained by Butler et al. (1995) can be fitted by the V-band light curve from which the influence of spots has been removed. This strongly suggests that the MgII emission is indeed uniformly distributed over the surface of the eclipsed star.

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References

Andrews, A.D., Rodono, M., Linsky, J.L., Brown, A., Butler, C.J., Catalano, S., Scaltriti, F., Busso, M., Il-Seong Nha, Oh, J.Y., Henry, M.C.D., Hopkins, J.L., Landis, H.J. and Engelbrekston, S. 1988, A&A 204, 177.

Baliunas, S.L. and Dupree, A.K. 1982, ApJ 252, 668.

Butler, C.J., Doyle, J.G., Andrews, A.D., Byrne, P.B., Linsky, J.L., Bornmann, P.L., Rodonó, M., Pazzani, V. and Simon, T. 1987, A&A 174, 139.

Butler, C.J., Doyle, J.G., Budding, E. and Foing, B. 1995, *Proc. 4th MUSICOS Workshop*, L. Huang, D. Zhai, C. Catala and B. Foing (eds), Beijing, June 1994, ESA, p 207.

Dorren, J.D. and Guinan, E.F. 1990, ApJ 348, 703.

Doyle, J.G. 1988, A&A 192, 281.

Doyle, J.G., Butler, C.J., Byrne, P.B., Rodonó, M., Swank, J. and Fowles, W. 1989, A&A 223, 219.

Kiepenhauer, K.O. 1953, *The Solar System* **1**, *The Sun*, G.P. Kuiper (ed), Chicago, p. 322.

Linsky, J.L., Bornmann, P.L., Carpenter, K.G., Wing, R.F., Giampapa, M.S., Worden, S.P. and Hege, E.K. 1982, ApJ 260, 670.

Losh, H.M. 1939, *Pub. Zürich Obs.* **2**.

Neff, J.E., Pagano, I. and Rodonó, M. 1995, *Proc. 4th MUSICOS Workshop*, L. Huang, D. Zhai, C. Catala and B. Foing (eds), Beijing, June 1994, ESA, p. 157.

Olah, K. Hall, D.S. and Henry, G.W. 1991, A&A 251, 531.

Olah, K., Budding, E., Butler, C.J., Houdebine, E.R., Giminez, A. and Zeilik, M. 1992, MNRAS 259, 302.

Quin, D.A., Doyle, J.G., Butler, C.J., Byrne, P.B. and Swank, J.H. 1993, A&A 272, 477.

Rodono, M., Byrne, P.B., Neff, J.E., Linsky, J.L., Simon, T., Butler, C.J., Catalano, S. Cutispoto, G., Doyle, J.G. and Gibson, D.M. 1987, A&A 176, 267.

Wolfer, A. 1899, Pub. Obs. Univ. Michigan 7, 127.

The Italian-Greek connection. *From left to right:* A. Lanza, ?, M. Rodonó, S. Catalano, E. Antonopoulou, P. Niarchos.

Female power. Andrea Dupree (*left*), Mercedes Richards (*middle*), and Kimberly Leka (*right*).

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