STARSPOTS AND PLAGES

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ABSTRACT

The general methodology to detect and study solar-like surface inhomogeneities on stars is presented. The most significant observations and typical results are discussed with particular emphasis on the inferred physical characteristics of starspots and plages and differential rotation, as compared to solar values. On account of the present observation and modelling limits, the need for complementary photometry and spectroscopy with space-born instruments is stressed, as well as the scientific relevance of the so-called solar-stellar connection studies in today's Astrophysics.

1. INTRODUCTION

The concept that activity phenomena may develop on stars, other than the Sun, has deep roots in the astronomical literature (cf. Goldberg 1983, Rodono' 1985a and references therein). However, only recently has the problem of stellar activity been quantitatively and systematically addressed (cf. Shatzmann 1967, Godoli 1968). Stellar activity refers collectively to all those phenomena produced by such instabilities, usually of nonthermal origin, that show up as localized and transient modifications of the normal atmospheric structure, and give rise to a temporary enhancement or suppression of the quiescent flux. These activity phenomena occur on a variety of timescales, from seconds to several tens of days, or even years. Unsold (1955) correctly argued that "all this evidence of stellar activity [on late type stars] is ultimately of magnetodrydynamic character". Any other star is too far away to give direct spatially-resolved information on active

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regions. Moreover, active phenomena on stars are observed against a relatively bright background, the quiescent star, so that only the most intense events or, more generally, those favoured by contrast effects in specific spectral regions or lines can be detected. If at stellar distance, also the Sun, the best known active star, would appear rather quiescent: the most long-lived and largest sunspot groups affect the total solar energy output at optical wavelengths by only 0.1 per cent or less. The most intense flares and plages might be detected, however, from Ca II and hydrogen Balmer line enhancements or at X-ray, UV and radio wavelengths. This situation could appear an unfortunate one for the purpose of understanding solar and stellar activity in a common physical framework. On the contrary, it turns out to be a favourable one. From an observational point of view, both solar and stellar studies have benefited and, very likely, will benefit from ever improving instrumental capability, leaving almost unchanged the dividing gap between them. What has finally changed in the recent past is the attitude both of solar and stellar astronomers: the solar laboratory, where stellar phenomena can be studied in minute details, and the stellar laboratory, where huge solar-like phenomena occur in different physical environments, are not any more isolated islands. A busy "two-way street" has now been opened up and certainly will greatly help in fully exploiting, the so-called solar-stellar connection. The various facets and implications of this new approach have been thoroughly addressed at the first IAU-sponsored meetings on that topic (Byrne and Rodono' 1983, Stenflo 1983) as well as in the series of Cambridge Workshops on Cool Stars, Stellar Systems and the Sun (Dupree 1980, Hartmann and Golub 1982, Baliunas and Hartmann 1984; cf. also Bonnet and Dupree 1981).

2. SEARCHING FOR SURFACE INHOMOGENEITIES

The presence of surface inhomogeneities on stellar surfaces produces both photometric and spectroscopic effects. As a consequence of cool spot formation, the continuum flux decreases, so that, if a solar-like activity cycle occurs, long-term cyclic light changes should result. The discovery of such cycles implies long-term studies, as those carried out using the archival Harvard plate collection (Phillips and Hartman 1978; Hartmann et al. 1979).

Spots and plages will also give rise to flux variation in absorption and emission lines, respectively. The equivalent width of absorption lines decreases due to the presence of cool spots on the photosphere, while the integrated flux in emission lines increases due to the presence of bright plages at chromospheric and upper atmospheric levels (Wilson

1978, Vaugan and Baliunas 1985). Generally, plages overlie spots, so that anti-correlated variations of wide-band photometry and integrated emission line flux are expected. From long-term studies useful information on activity cycles can be derived, but very little on the characteristics of individual spots and plages. Activity cycles form the subject matter of another paper in this volume (Dravins 1986) and will not be considered here. The present review deals with the evidence, interpretation and derived physical parameters of small-scale structures on stellar atmospheres, such as cool photospheric starspots and chromospheric and transition region plages.

The typical accuracy of photometric and spectroscopic observations is of the order of 0.1 to 1 per cent, depending on the apparent magnitude of the star itself and on the instrument/detector used. Therefore, only huge starspots and plages on intrinsically faint stars - so that contrast effects are optimized - can be detected.

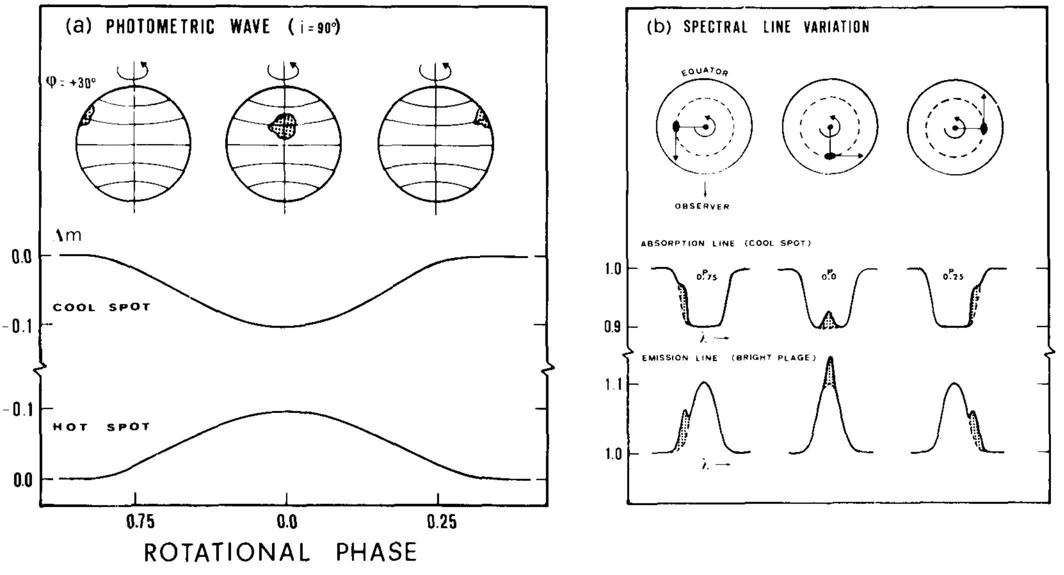

Figure 1. Schematic illustration of (a) photometric (b) spectroscopic effects due to solar-like features on a rotating star.

The star rotation plays an important role for two principal reasons. Firstly, rotation is a necessary ingredient for the generation of strong magnetic fields, which underlie all activity phenomena. The $\alpha-\omega$ dynamo mechanism (cf. Parker 1985, Weiss 1986) requires the coupling of rapid rotation and deep convection. The consequent differential rotation is the basic requirement for producing and reinforcing a toroidal magnetic field from an original poloidal field. Secondly, the star rotation periodically modulates the visibility of surface features on the hemisphere facing the observer. Consequently, and more important, both its projected area and its radial velocity will undergo periodic changes versus rotation phase reaching a maximum and a minimum, respectively, when the surface feature is at the central star meridian or, as sometimes referred to, is at the sub-solar point. The change of the projected area, as surface features cross the star disk and disappear behind the limb, leads to cyclic modulation of wide-band and integrated emission line fluxes (Figure 1a).

Also the line profiles, both in absorption and emission, are affected by the star rotation. Due to the cyclic changes of projected radial velocity of surface features, Doppler shifted "emission bumps" are observed, which migrates on the star's rotationally broadened lines (Figure 1b). By studying the Doppler-induced line profile variation, a technique first applied to Fe absorption lines by Vogt and Penrod (1983) and to Mg II h and k emission lines by Walter et al. (1984) and Neff et al. (1984), it is possible to map the active features on the star surface. Following Vogt and Penrod (1983), this technique is now generally referred to as Doppler Imaging. High-resolution spectra, well distributed in phase, are required to fully exploit this technique, so that Doppler Imaging studies of absorption and emission lines have been carried out so far only for V 711 Tau = HR 1099 and AR Lac, respectively.

Sometimes, the relative importance of spectroscopy versus photometry, and viceversa, has been endlessly debated. What can be stated with confidence is that, by simultaneously acquiring radial velocity and photometric data on transient activity features, firm constraints on theoretical models can be provided.

Another promising, but still almost unexplored technique to resolve surface features on active stars is offered by eclipsing binary systems. During the course of secondary eclipses, the hotter and, usually, unspotted star progressively eclipses the cooler spotted companion so that, as a moving screen, it scans the spotted areas on the latter. At primary eclipse, especially during totality phases, only the cooler spotted component remains entirely visible. Therefore, any spot coming into view at those phases produces a light "dip", which is easier to detect against the depressed background level. These observations are, however, at the limit of the presently available photometric precision of ground-based observations (Rodono'

1985b).

For the sake of completeness, polarimetric measurements should be mentioned. Actually, since starspots are presumably characterized by strong magnetic fields, as sunspots are, their large covering factors favour the detection of polarization effects, both in wide-band photometry and in profile changes of magnetic sensitive lines. Several polarization detections have been later questioned or disproved. However, recent refined techniques, which are primarily devoted to the measurement of surface magnetic fields (cf. Robinson 1985) are now successfully being employed. As far as starspot diagnostic is concerned, rotational modulation of percent polarization would significantly complement photometric and spectroscopic observations.

3. OBSERVATIONS AND TYPICAL RESULTS

Quasi-periodic low-amplitude UBV light variations, commonly referred to as photometric waves, are observed on several K-M emission-line dwarfs and subgiants, the majority of which are members of binary systems. The peak-to-peak amplitudes and periods are of the order of 0.1 magnitudes and a few days, respectively. The light curve shape is sometimes almost sinusoidal, but, sooner or later, the amplitude and shape undergo striking changes (Figure 2). Strong asymmetry often develops and phase shifts of the entire light curve may occur on time scales of the order of 10-100 periods. No significant variations of U-B, B-V and V-R colors are usually observed, while V-I clearly indicates a reddening at light minimum. This suggests that the observed variability can be attributed to cool photospheric spots, whose projected area and visibility are modulated by the star rotation. The light variability of eclipsing systems is more complex due to the intervening photometric eclipses and other proximity effects, such as reflection and ellipticity effects (Figure 2c). The latter effect arises because the projected surface of tidally distorted ellipsoidal stars varies as a function of orbital phase. Sometimes, the spot induced photometric waves are often referred to as distortion waves, to emphasize their distorting effect on the light curves of eclipsing binaries.

Simple geometrical models of spotted stars have been worked out to produce the observed photometric waves, as first done by Torres and Ferray-Mello (1973). Several improved modelling methods are now available, which lead to what presumably are more accurate surface maps of starspots (Poe and Eaton 1985, Vogt 1983, Rodono' et al. 1985a, Rodono' 1985b and references therein). The model parameters

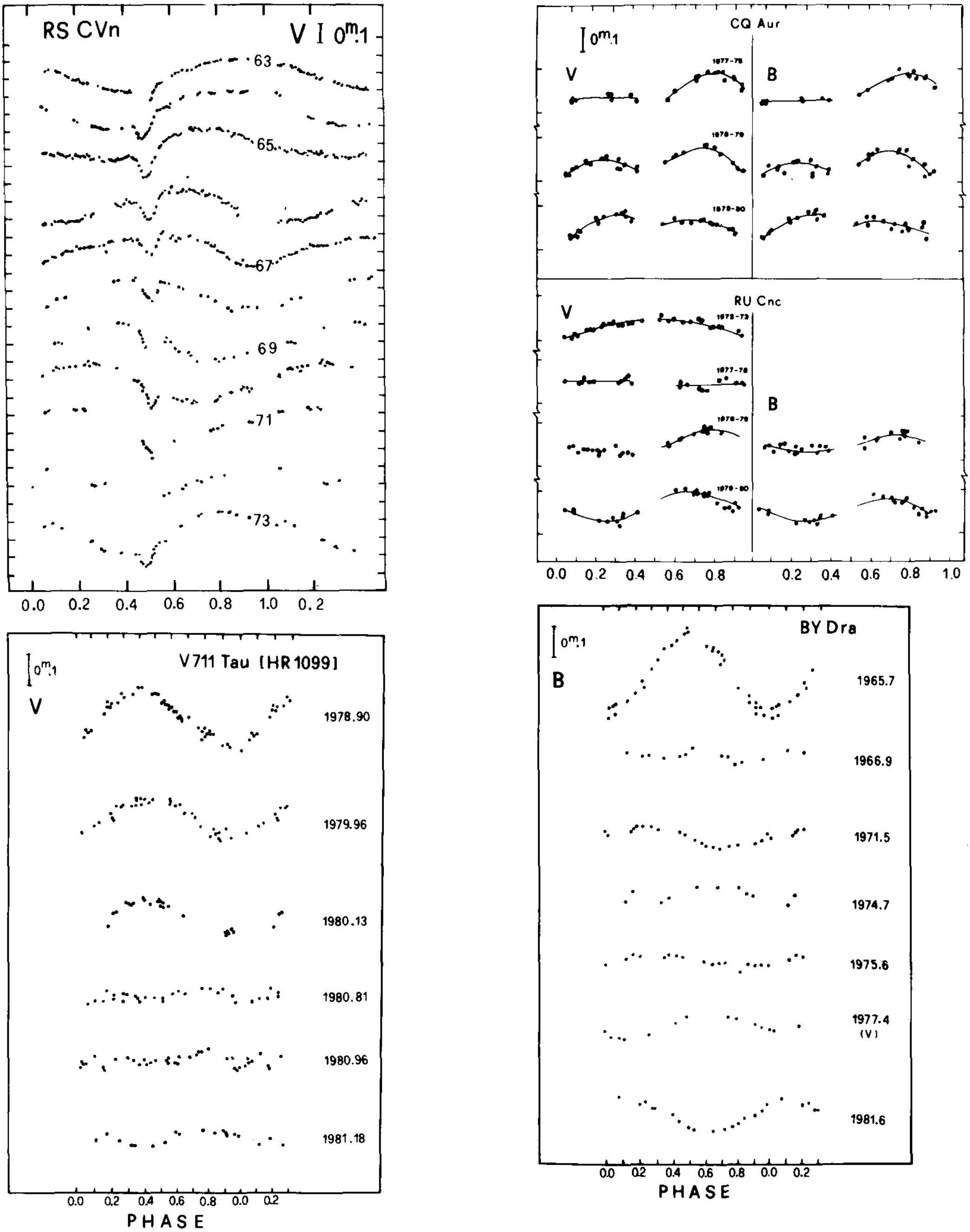

Figure 2. (a) The migrating slowly changing distortion wave on RS CVn V light curve (Catalano et al. 1980). (b) The remarkable changes of the distortion wave for the eclipsing RS CVn systems CQ Aur and RU Cnc (Blanco et al. 1983a). Eclipse data are not plotted. (c, d) Synoptic photometric waves for the non- eclipsing systems V 711 Tau and BY Dra (Rodono' 1983).

- inclination of the star rotation axis to the line of sight, spot location, extension and temperature ratio with respect to the imperturbed photosphere, and limb darkening coefficient - do not permit unique solutions (Figure 3). However, if one or more parameters are estimated independently, such as the inclination of the rotation axis from the solution of eclipsing binary light curves or the spot temperature from color variations, reasonably significant solutions can be derived. This is particularly true if synoptic studies are carried out. By modelling the slow modification of the photometric wave versus time, together with a careful monitoring of rotation period variation, important information on spot evolution and on the migration of the spot forming region, i.e. on stellar differential rotation, may be obtained.

Typically, from modelling observed photometric waves (cf. Figure 4) spotted area covering factors from 5 to 35 per cent of the projected stellar disk and spot temperatures cooler than the supposedly immaculate photosphere of about 400-1500 degrees have been inferred (cf. Rodono' 1983, Poe and Eaton 1985 and references therein). Although these are important typical results, they should not be regarded at all as typical starspot parameters. As a matter of fact, starspot temperatures and dimensions are clearly affected by observational selection: smaller and/or relatively hotter spots would give rise to flux variations of less than one per cent that would be difficult to detect with presently available techniques. On the other hand, assuming solar activity as a valid guideline, small solar-like spots should occur also in stars. Therefore, the known range of "observed" starspot parameters is likely to be biased towards larger dimensions and cooler temperatures.

Starspot temperatures appear to be hotter than those of sunspot umbrae and cooler than penumbrae, with a slight preference towards the latter temperatures. This might suggest that the derived starspot temperatures are weighted averages of large spotted areas, which include a fraction of undisturbed photosphere or penumbra region. Actually, the huge extension of "observed" starspots, might be only a consequence of the limited geometrical resolution that is allowed us by the presently available observation precision and spot modelling methods. Indirect evidence, which supports the suggestion that large spotted areas actually consist of extended complex structures, is given by the difficulty in modelling some photometric waves with simple one- or two-spot models (Eaton and Hall 1979) and by some observations of photometric eclipses involving spotted stars. The small light dips, which are seen during the course of well observed primary eclipses of AR Lac (Figure 5), are suggestive of the progressive emergence at the

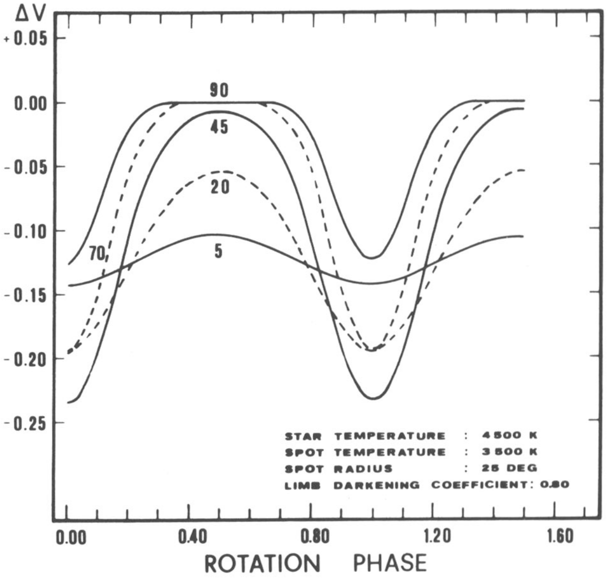

Figure 3. Computer generated photometric waves due to starspots for different inclinations of the rotation axis and one spot on the star equator or different spot colatitudes on an equator on star. This ambiguity is a major difficulty in modelling spot-induced light variations.

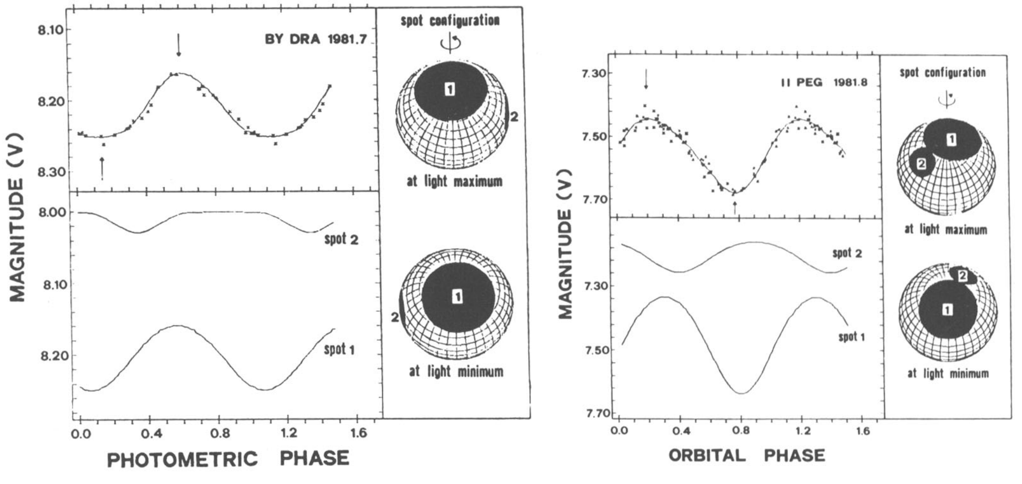

Figure 4. Two-spot models for BY Dra and II Peg from Rodono' et al. (1985a). The spot configurations at light maximum and minimum (arrows) are shown on the right-hand panels.

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advancing star limb of small solar-like spots.

Surface inhomogeneities are not confined to photospheric levels. Several programs to study rotational variability of chromospheric lines are being carried out successfully (cf. Vaughan 1983, Vaughan et al. 1981). Unfortunately, the rotational modulation of line fluxes is marginal or even absent at high flux levels, probably because the emission arises from large plage areas that never disappear completely from the projected stellar disk as the star rotates.

The International Ultraviolet Explorer (IUE) is now offering unsurpassed opportunities for studying stellar plages up to transition region levels by monitoring the numerous diagnostic emission lines in the wavelength region 1200-3200 A. Since 1980, three groups at Armagh (N. Ireland), Boulder (USA) and Catania (Italy) have jointly organized international coordinated programs for simultaneous IUE and ground-based observations. Their observations have clearly shown that chromospheric and transition region plages are spatially correlated with photospheric spots as in the Sun, but plages are much more compact than solar ones (cf. Rodono' 1983; Linsky 1983a, 1983b; and references therein). Figure 6 from Rodono' et al. (1985b) clearly shows anti-correlated variations of integrated emission fluxes in several chromospheric/transition-region lines with optical V-band flux for the non-eclipsing binaries II Peg (K2-3 IV-V) and V 711 Tau (G5 V + K1 V).

Pure plage UV spectra, which were obtained by subtracting the average quiescent spectra from those at active phases (cf. Linsky 1983a, Rodono' et al. 1985b) show transition region line fluxes enhanced by a factor of 5, while chromospheric ones by only a factor of 2 relative to the quiescent level. The increase of the line enhancement with the temperature of formation is also typical of solar plages and indicates that non-radiative energy dissipation plays an increasingly important role as temperature increases, i.e. towards the outermost atmospheric levels. A quantitative comparison of solar and stellar behaviour shows that, even at seemingly quiescent phases, the line flux from active stars is larger than from very active solar regions and becomes increasingly larger, as the atmospheric level increases (cf. Rodono' 1985a). Clearly, active star surfaces are covered by intense solar-like plages, which affect even their relatively quiescent hemispheres.

The structuring of stellar atmospheres extends up to coronal levels. X-ray and radio observations have provided definite evidence of coronae in late-type stars (Vaiana et al. 1981, Golub 1983, Gibson 1983) and of solar-like highly structured

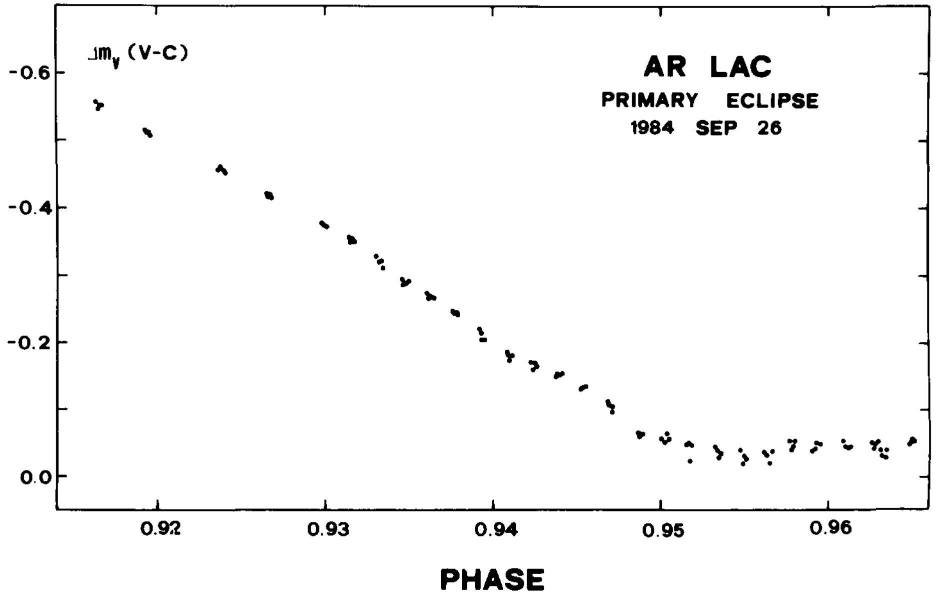

Figure 5. Light dips during one primary total eclipse of the RS CVn binary AR Lac (Cutispoto and Rodono', unpublished)

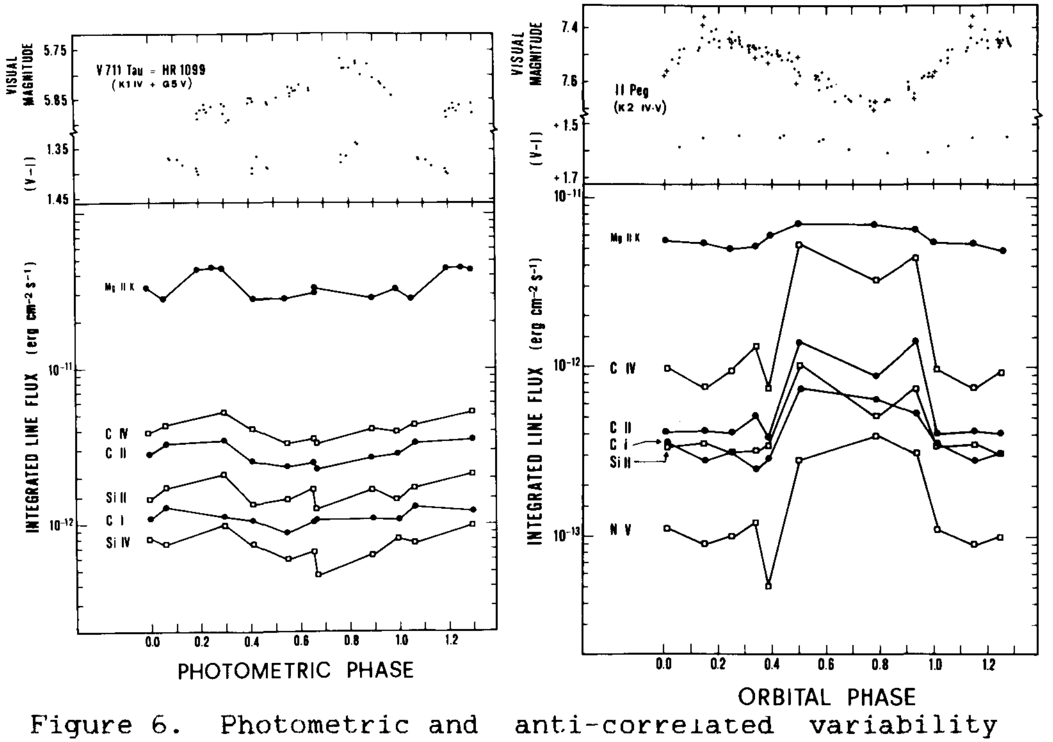

Figure 6. Photometric and anti-correlated variability of integrated UV emission line fluxes for the RS CVn systems II Peg and V 711 Tau (Rodono'et al. 1985b)

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coronae (Pettersen et al. 1981, Walter et al. 1983).

4. DIFFERENTIAL ROTATION

Accurate data on differential rotation could be obtained, at least in principle, from actually modelling synoptic photometric waves and studying the resulting spot maps versus time. But a statistically significant number of stars have not yet been studied using this method.

Assuming that the variation of the photometric period is due to latitude migration of the region of spot formation in a differentially rotating star, from long-term studies of period variation, the $\Delta P/P$ immediately give an estimate of differential rotation being $|\Delta P/P| \propto |(1/\Omega^2)\Delta\Omega \;/(1/\Omega)| \propto |\Delta\Omega/\Omega|$.

Similarly, the change of the migration rate of a distortion or photometric wave on the light curve of an eclipsing binary can be used. As shown by Rodono' (1985b), a) on active close binaries, stellar differential rotation appears surprisingly lower (0.001-0.01) than on the Sun (0.1), b) there is a general tendency for a decrease of differential rotation towards later spectral types, contrary to what $\alpha-\omega$ dynamo model predicts (cf. Belvedere et al. 1980), and c) log ($\Delta P/P$) and log P are linearly correlated implying that $\Delta\Omega/\Omega \propto \Omega^{\alpha}$, with $\alpha < 1$, while dynamo models predict $\alpha = 1$ (cf. Catalano 1983). These results deserve further attention both from an observational and theoretical point of view. One reason for the discrepancy between predicted and "observed" differential rotation may be the binary nature of the majority of active stars. For example, Schalermann (1981, 1982) has shown how strongly the differential rotation regime in close binaries is affected by tidal interaction. It is certainly indicative that, for one single star, the differential rotation rate is comparable to the solar one (Guinan 1985). On the other hand, tidal interaction between close binary components enforces higher-than-normal rotation velocity, which is a basic ingredient for the development of activity phenomena.

5. CONCLUSION

The presently available ground-based and space observations have already provided important insights into the study of stellar activity, especially as far as average physical parameters of starspots, plages and activity cycles are concerned. Nevertheless, additional fundamental questions could be adequately answered only if the photometric precision and the long-term monitoring attainable with space-born instruments become available. Activity phenomena give rise to transient, non-repeating, and, sometimes, short-lived variability. Therefore, the required observation accurary cannot be achieved by increasing the integration-time, otherwise the resulting time-resolution would be inadequate. Moreover, the energy emission affects almost simultaneously a wide range of wavelengths, from X-ray to radio spectral domains. The obvious implication is that significant progress in the study of stellar activity will be achieved only if ground-based observations are complemented with dedicated observations from space-born instruments, and simultaneous photometry and spectroscopy is carried out.

The astrophysical relevance of stellar activity studies is well beyond what might appear at first glance to be "stellar cometics". Actually, activity phenomena are likely tracers of surface magnetic fields, whose initial production and strengthening take place deep inside the stellar interior (cf. Parker 1985, Weiss 1985). Therefore, stellar activity studies supply basic information on the internal structure of stars and may offer important clues on stellar evolution.

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