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OBSERVATIONAL STUDIES OF MAGNETICALLY ACTIVE STARS

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ABSTRACT

Multi-wavelength observing has been particularly fruitful in cool star research. There have been some well-observed examples, eg AB Dor, though ambiguity remains. This raises issues of data information content and model parameter determinacy, which are examined firstly in an optical context. We then widen the discussion to show how multi-site and multi-wavelength data can be combined to point to better constrained models. Particular cases, involving near-simultaneous radiometry and photometry, are discussed to clarify such modelling.

I. ACTIVE STARS

There are extensive sources of recent information on this rapidly expanding subject (see e.g. *Stellar Surface Structure* eds. K. Strassmeier and J. L. Linsky, 1996). The present account can only sketch, with its own particular slant, some salient points, though a few new results will be ventured.

Stellar 'activity' is strongly associated with stars showing phenomena similar to those of the close binary system RS CVn (Ramsey, 1990; Strassmeier *et al.*, 1993). One such star, YY Gem, caused the photometry pioneer G. Kron to invoke the 'starspot' idea (Kron, 1952). While slow in gaining general acceptance, the weight of extensively combined data have now led to a widely supported picture of effects resembling those of solar activity, but with key parameters generally scaled up by one or two orders of magnitude. Starspots are among the more readily accessible features of this picture, observationally and in broad concept. Starspot (sometimes 'maculation') photometry was reviewed by Budding (1996). The general scale of stellar maculæ must involve relatively large (i.e. up to 20-30 deg diameter) umbral magnetic concentrations at ∼1000 K cooler than surrounding photospheres (Vogt, 1981; Zeilik *et al.*, 1990; Strassmeier & Oláh, 1992), having surface fields of ∼several × 1000 gauss (Saar, 1991).

Recent advances in automated photometric capabilities ('APTs'), which are becoming more widely networked, offer distinct lines of progress (cf. e.g. Eaton, 1992). The higher data accuracy capability of APTs (Young, 1993) implies an inherently better parametrization, while fuller time coverage, independent data checks and more data generally can be expected from 'multi-site campaigns' of networked telescopes (cf. Henry *et al.*, 1995a). But modern studies of stellar activity frequently refer to observational data from beyond the optical domain. Such 'multi-wavelength' methods can be effective in resolving the ambiguities of photometric analysis. This will be presented herein, particularly via the combination of optical photometry and microwave radiometry, as applied to some brighter RS CVn binaries.

II. SURFACE INHOMOGENEITY RESOLUTION

Budding and Zeilik (1987) developed an approach to light curve analysis for RS CVn type stars that has proved reasonably productive in obtaining consistent basic stellar parameter sets, and also characterizing the gross trends of maculation effects. The previously mentioned cool reference star YY Gem was recently studied in this way (Butler *et al.*, 1996).

Details of the surface phenomena of RS CVn stars are, however, still far from clear. Starspots could be the large single entities used to model photometric data sets (e.g. Oláh, *et al.*, 1991), or they could be close clusterings of smaller ones, like those on the Sun. Such structure is below what can be resolved with currently available photometric precision. Neither is the global organization of starspots settled. Either a predominantly poloidal arrangement, or solar-type toroidal structures, could be possible from photometric evidence.

For a data set having a photometric error measure δl (as a proportion of full light) the smallest discernible spot has radius γ of order $\sqrt{\delta l}$. The Fourier transform of the theoretical photometric 'wave' due to such a spot shows it to be dominated by a small number of low order cosine terms centred on the wave minimum to accuracies of order 0.001 mag. Putting spots on the surface is then equivalent to adding in short Fourier expressions of the form

$$\begin{aligned} l &= a_0 + a_1\cos(\theta+\epsilon_1) + a_2\cos(2(\theta+\epsilon_2)) \\ &\quad + a_3\cos(3(\theta+\epsilon_3)) + \ldots, \end{aligned} \qquad (1)$$

with given amplitudes and phases. Since this is equivalent to changes in only the amplitudes of a few terms of the resultant low order series, it follows that the inverse problem of retrieving information on spot distributions from maculation waves at 'typical' photometric accuracies is going to be restricted to a half dozen or so independent quantities, i.e. at most two circular spots. If, however, photometric accuracies could consistently attain 0.001 mag, the question of whether there is any predominantly poloidal preference would become determinable, since there then would be clear determinacies of up to three separate major maculæ groupings, however arranged.

The radius of a spot γ, whose area is effectively the same as that of a darkened region, giving rise to a maculation wave of amplitude Δl, can be specified to $\delta\gamma/\gamma \sim \delta l/2\Delta l$. Its longitude is fixed to within $\delta\lambda \sim \delta l/\sqrt{n}\Delta l$, with n points distributed in the wave. The latitude error $\delta\beta$ should be of order $\delta\lambda \tan i \cos\beta$ (Budding, 1977). The effects of observational errors on parameter determination have been investigated in more detail by Rhodes (1990) and Kővári (1996).

The use of spectroscopic techniques, e.g. Doppler or Zeeman imaging, is also in vigourous development in the quest for information on active stars. Multiplying the phase-derivative of the photometric darkening function by suitable trigonometric function of the phase recovers the effect of a Doppler-shifted darkened area of surface on a line profile. In practice, there is a trade-off, in terms of information content, between the ability of a spectrum to 'snapshot' the entire hemisphere in one exposure, and the extent to which features may have changed in the much longer 'exposure' associated with the production of a light curve, but there has been no establishing that the $\delta l/\sqrt{n}$ factor is significantly different from spectral line to photometric wave contexts.

III. MULTI-SITE CAMPAIGNS

This field gave rise to the Strasbourg Conference on *Coordination of Observational Projects* (eds. C. Jaschek and C. Sterken, 1988), and has figured in numerous other compendia including *Multiwavelength Astrophysics* (ed. F. Córdova, 1988), *The Study of Variable Stars Using Small Telescopes* (ed. J. R. Percy, 1986; Sections 5 & 7), *Stellar Photometry — Current Techniques & Future Developments* (eds. C. J. Butler & I. Elliott, 1993; Section 5), as well as various individual papers (e.g. Nather *et al.*, 1990; Butler, 1994).

Small ($D \lesssim$ 1m) and highly automated telescopes together can be productively linked into multi-component observing 'campaigns'. Such campaigns are frequently organized to cover active stars intensively, spearheaded by a Principal Investigator at a 'megascience' facility (Michalowski, 1996) over a short period ($\sim$ a day or so), with background small telescope photometry for the surrounding week or so. In the context of widely distributed computers and the Internet, rapid electronic interactions based around multi-site data collection have taken place. A recent example is the April-May 1996 HST-led campaign on V824 Ara, organized by R. Dempsey of the Space Science Institute, which included the participation of a half-dozen small telescope photometrists in Australasia.

Developing such interactions via an organization such as the 'Global Network of Automated Telescopes' (GNAT — cf. Crawford, 1994) has been periodically reviewed in recent years (e.g. Budding *et al.*, 1996). An approximate evaluation can be made from the V824 Arae campaign results. Typical ~5-parameter information content light curves of bright stars at small telescope precisions involve data sets of about, say, 300 points at an accuracy of ~0.01 mag. Such complementary information retrieval is a real possibility for total operational costs $\gtrsim$1% of those on the megascience facility allocation. In view of the interpretative value of such parameter sets, this can be seen as a very cost-effective component of a properly planned campaign.

Adequate lead-time planning and communications are important features of such campaigns, however (de Jager, 1988). Certainly, the latter is becoming much easier with the growth of electronic mail links. Concerning organizational difficulty — multi-contributor campaigns which are relatively short and require only a small number of specific and relatively simple tasks for individual participants are clearly advantageous. Some other economics-related aspects were reviewed by Budding (1995).

IV. COMBINING PHOTOMETRY AND RADIOMETRY

A key point about the radioastronomy of active stars emerged from Lim *et al.*'s (1994) study of AB Dor. This concerned the implication, from the relatively short down-up-down timescale ($\lesssim$ 0.25 orbital period) of the smooth undulatory variations seen, that one is here observing small sources of extremely high temperature (T up to 10^{12}K). Lim *et al.* found these undulatory microwave flux variations tend to anticorrelate with photometric minima observed near-contemporaneously for AB Dor. Similar effects have been observed for a number of the nearer RS CVn stars, including UX Ari (Elias *et al.*, 1995), and V471 Tau (Patterson *et al.*, 1993), although strong correlations have not always been clear (Chambliss *et al.*, 1978).

Probably the most straightforward interpretation of these undulatory flux variations is in terms of a fully relativistic (Lorentz factor $\gamma \gtrsim$10) electron acceleration regime, with the source area less than that of the stellar disk (Lim *et al.* 1994). Radiation from such a source would then be relativisitically 'beamed' in the direction of motion of the electrons involved, i.e. near perpendicular to loop axes in the case of those electrons confined in the magnetic field near the tops of such loops by large pitch angles. This model accounts for both the relatively short timescale of the flux variations and their shape, and is self-consistent with the required high temperatures. If correct, it has the potential to be more informative about the geometry of the active regions, particularly when alternative ranges of observation can bear on the same physical structures. The

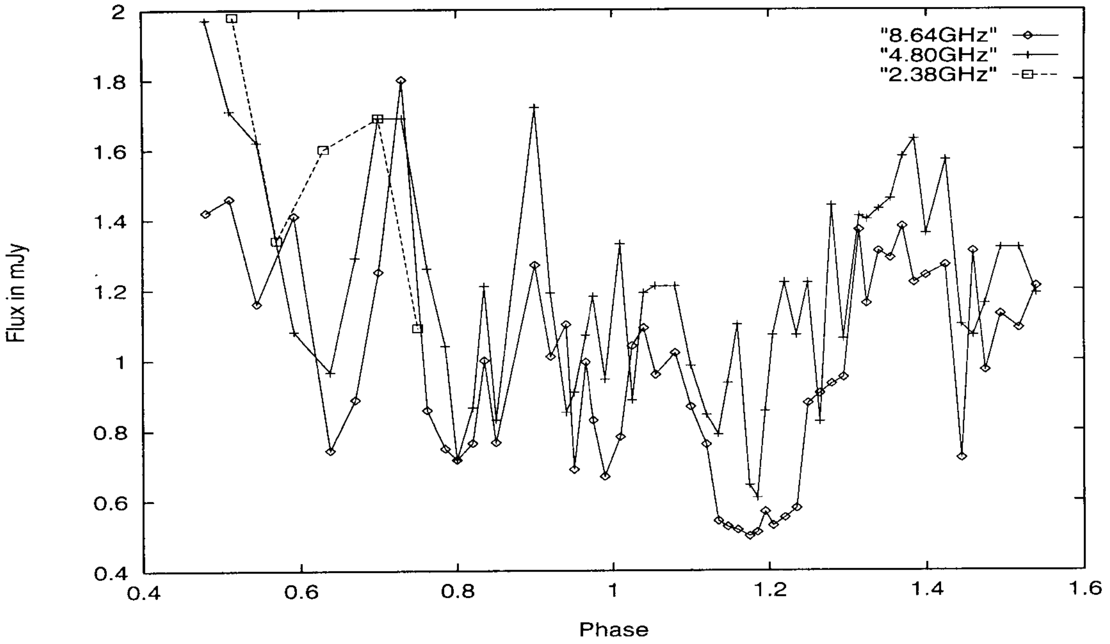

Fig. 1.— 1996 June microwave radiometry of CF Tuc. MIRIAD analysis of this ATCA data indicates data precision of about 0.015 mJy in X and C and about 0.02 in S bands.

combination of different data samples relatable by common parameters enhances their determinacy, as would the relativistic foreshortening constraining the geometrical requirements for visibility.

Lim *et al.*'s (1994) picture has been applied by the present authors to several cases of near-contemporaneous optical and radio light curves of RS CVn stars, including YY Gem, ER Vul and CF Tuc. An improved information yield potential has been confirmed in these empirical studies, although it would be strongly desirable to have a better physical picture overall of the electron acceleration processes. Supportive observations from other widely separated spectral regions are probably necessary for this purpose. For example, X-ray (or UV) data can separately constrain electron energies, as in Vilhu *et al.*'s (1993) multi-site, multi-wavelength campaign on AB Dor (cf. also e.g. Linsky *et al.*, 1989).

In the case of CF Tuc, activity is associated with the secondary, subgiant component (Cameron *et al.*, 1981, Coates *et al.*, 1983), as has been general for the RS CVn and Algol type binaries. Photometric effects are then ascribed to one or two large regions on the cooler star (Budding and Zeilik, 1996), usually set at higher latitudes than starspots on the Sun, though there may be some analysis-related bias in this finding. There have been various indications that certain longitude ranges tend to be preferred for active starspot formations on RS CVn stars. More extensive investigations of particular cases, however, show starspots drifting with respect to the basic orbital period, presumably due to differential rotation (cf. Henry *et al.*, 1995b).

Gunn *et al.* (1995) observed CF Tuc using the Compact Array of the Australia Telescope (ATCA) at 3.6 and 6 cm (X and C bands) in 1994 August. They did not find the stellar eclipses would resolve the active region locations, but their C and X band light curves do show a fairly smoothly varying hump in the phase range ~0.4-0.7 of up to ~2-3 mJy, rising above the background level of 1-2 mJy in both frequencies. T. Rounthwaite's independent photometry of CF Tuc in 1994 August, around the time of the Gunn *et al.* observations, indicates a maculation type depression centring itself in that same phase range ~0.4-0.7.

In June 1996 another optical and microwave multi-component campaign on CF Tuc took place, with C and X (and some L and S) band data gathered at the Compact Array of the Australia Telescope National Facility at Culgoora involving the present authors. Preliminary microwave light curves are presented as Figure 1. Near-simultaneous optical photometry, and some high resolution spectroscopy, has been attempted from a variety of sites, amateur and professional, around Australasia. Rounthwaite's photometric data of ~ 6 months previous to these observations indicate a sizeable depression centred at a phase around 0.6, but it is yet to be confirmed whether this maculation effect has drifted down to about 0.4 by the time of the recent AT observations, though this would be consistent with previously known behaviour.

V. FINAL REMARKS

Multi-site, multi-wavelength methods of observing are proving effective in penetrating the physical nature of the magnetodynamic activity of RS CVn stars. The wide range of astronomical collaboration and cross-fertilization is an interesting point to note in this context.

Radio observations can probe an active region in its third or vertical dimension, thereby complementing the two dimensional surface modelling of photometric starspots. The observed microwave radiation appears to require very highly energized electrons in the large coronal loop models which have been applied (Rosner *et al.*, 1985; Cameron & Robinson, 1989; Lim *et al.*, 1994). Large-structured active regions gather support from the argument that small spots produce only small vertical extensions into the corona, whereas coherent structures of size an appreciable fraction of the stellar radius would give rise to a loop of at least this order of size (cf. Mullan, 1985). The evidence of UV and X-rays backs this extensive scale, at least for certain stars (Vilhu *et al.*, 1993). The very fast rise-time large flares, that are sometimes observed, point to correspondingly large surface field concentrations. This high energy loop model has parameters that directly relate to the optical inverse problem, so the whole picture tends to be confirmed or denied by its separate parts.

Optical precisions really need to advance towards the 0.1% level per datum in order to properly resolve surface structure, however. Complete light curves obtained with such precision within a week or two, in which main features remain within their resolution limits, could be usefully combined with high-quality line profile studies to properly establish their characteristics. An effective multi-site organization, utilizing, say, a dozen new generation, but still small, telescopes is better placed to achieve this photometry than single large facilities.

Targets are still essentially the relatively brighter RS CVn stars. In the past, certain bright Algols have also been included in this general context, though it is not established that the radio emission from Algols is due to just the same processes as regular RS CVn stars. Re-analysis of survey data on stellar radio emission currently underway indicates that previously reported longitude preferences for the emission has a more distinctive character for classical Algols than RS CVn stars. This may be a signature of the mass-transferring stream interaction particular to Algols. This is then another new topic within the field of studies of magnetically active stars to continue the need for further data.

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