Starspots: The Zebra Effect

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ABSTRACT

Recent observations of brightness variations on the Sun during the solar cycle have motivated us to re-examine the widely held view that cool, dark starspots, covering a significant fraction of the star, are the centers of magnetic activity on BY Dra stars. We propose that the magnetic regions are better described by a bright facular network, and that the dark areas which give rise to photometric rotational modulation are actually regions where the underlying quiet photosphere is seen. This interpretation is consistent with recent observations of late-type stars that show that bright areas covering much of the star have magnetic fields with strengths of several thousand gauss. It resolves several problems with the current model, including the size, location and stability of the starspots required to match photometric and Doppler imaging observations. It also has interesting observational implications for the correlation of photometric rotational modulation and long term brightness variations with other surface activity, and for the positions of magnetically active stars in the H-R diagram.

I. INTRODUCTION

Stellar activity is associated with strong magnetic fields in main sequence stars of solar type and later. In late type stars, the presence of magnetic flux at the stellar surface, and subsequent heating of the atmosphere, results in chromospheric, transition region, and coronal emission similar to that observed from magnetically active regions on the Sun. It is natural, then, to interpret observations of stellar activity using a solar analogue; that is, by assuming that the surface phenomena that can be resolved on the Sun are occurring in a similar, though perhaps scaled, way on active stars. For example, the discovery of periodic photometric brightness variations on late type dwarfs (*e.g.* BY Dra stars) and subgiants (*e.g.* RS CVn systems) that were known to be magnetically active from their chromospheric emission has led to the currently popular "starspot" model of magnetic activity on these stars. In this model, dark regions analogous to sunspots, but many times larger, are postulated as the centers of magnetic activity and are presumed to be responsible for the brightness changes through rotational modulation as the spot passes in and out of view. Long term variations (*i.e.* on an activity cycle time, some few to tens of years) in the mean brightness level are explained by varying the size and location of the spots. The starspot model has been used with some degree of success to explain observations of late type stars in nearly all stages of evolution, including pre-MS T Tauri stars, main sequence F-M dwarfs and subgiants in RS CVn systems.

It is important to remember however, that the solar manifestations of magnetic activity in the photosphere consist not just of dark sunspots but also of bright facular areas in the active regions and an extended bright magnetic network that covers much of the Sun. In fact, recent satellite measurements (Willson *et al.* 1986, Willson and Hudson 1988) have shown that as the Sun becomes more active during its 11 year cycle, the (suitably time averaged) solar irradiance *increases* even though the spot coverage has also increased. This is attributed to an excess of radiation from the bright facular network which evidently increases in strength by a larger amount than the (increased) sunspot deficit (Chapman 1987, Hudson 1988, Lean and Foukal 1988, Foukal and Lean 1988). Furthermore, although spots initially produce a large brightness deficit (*e.g.* in the UV), the rotational modulation of an active region over several rotation periods is manifested instead as a brightening, because of the much longer lived effect of the faculae associated with it. The connection between spots and brightness variations on the Sun is therefore not as straightforward as predicted by the starspot paradigm.

A further complexity has been introduced by recent observations of solar- like stars (Radick, Lockwood and Baliunas 1990). Though still preliminary, their data suggests that relatively inactive stars show the solar effect – a brightness *increase* as activity increases, while more active stars show the opposite effect – a brightness *decrease* as activity increases. This latter effect is what is predicted by a starspot model. The indication, therefore, is that the total amount of activity can influence the relative importance of the dark spot areas and the bright facular areas in contributing to the observed stellar luminosity. Unfortunately the data are not yet available for any but G and early K dwarfs, so investigation of this effect for later type stars must await further study.

Stars at other stages of evolution also exhibit complex activity-related behavior. For example, T Tauri stars have shown *bright* spots correlated with ultraviolet emission lines (Simon, Vrba and Herbst 1990), while RS CVn stars have been modeled successfully with multi-component starspot and plage models (Neff *et al.* 1989). However, Dorren and Guinan (1990) found that over long (several year) timescales, the transition region emission lines correlated with photometric brightness on the RS CVn star V711 Tau, suggesting that faculae may play an important role on these stars.

The variety of magnetic phenomena that have been observed in detail on the Sun, and the complexity of interpreting the data from other stars, leads us to suggest that the current model of dark spots being solely responsible for the observed photometric modulation and long term brightness variations on late type stars is too simplified. Rather, we believe that the interplay between bright facular elements and dark spot regions is a complex function of activity level, stellar interior and atmospheric structure, and probably other, as yet unrecognized, parameters.

In this paper we will concentrate on some specific problems encountered by applying the simple starspot model to BY Dra stars. In particular, we will explore the possibility that, as in the solar case, the bright facular elements play a dominant role in the observed brightness variations, and discuss the implications and consequences of such an interpretation.

II. The BY Dra Stars

The BY Dra stars are a class of late K and M type dwarfs which exhibit photometric rotational modulation of a few hundredths to a few tenths of a magnitude (Bopp and Evans 1973, Vogt 1975). They are unique as a place to investigate magnetic activity because it is now possible to measure their surface magnetic field strengths directly. As summarized in Saar (1990), field strengths of some 1000- 5000 G and filling factors of 20-80% are typical of these stars. (Solanki (1992) notes that the simplicity of the models may result in overestimates of the filling factors. See also Basri, Marcy and Valenti 1990 for further discussion of measuring magnetic fields on late type stars.) The values refer to bright areas on the star, not to "starspots" because the "spots" are cool and hence do not contribute significantly to the total light. The problem then becomes identifying the nature of these bright regions. In the usual starspot model, the dark areas on the star are the sites of enhanced magnetic activity while the bright regions represent undisturbed photosphere. However, on the Sun, the filling factor of magnetic flux tubes in the quiet photosphere is very small and thus the average field from those areas is negligible. Larger filling factors are found in the bright network elements with typical field strengths of 1000-1500 G. If magnetic activity is similarly organized on the BY Dra stars, then the following picture of stellar activity emerges:

The magnetically active star has an extended facular network similar to that surrounding active regions on the Sun, which acts to raise the apparent brightness of the star. This network covers a considerable fraction of the star and replaces what was considered to be the photosphere in the historical starspot model. The remainder of the stellar surface consists of quiet photosphere, which is seen as dark in comparison to the bright facular regions. This relatively field free photospheric region is what was previously attributed to starspots. Spots may well exist within the facular network, but on such small size scales and short timescales that their presence is not currently detectable, except by proxy during flares. *In essence what we are proposing is a "Zebra Effect", where the magnetically active regions are the bright areas and the quiet photosphere constitutes the dark areas; the opposite of the current starspot model.*

How does this interpretation of the stellar surface features – namely small area coverage of normal photosphere and large area coverage of bright magnetic network – fit in with the other available data on these stars? The data comprise both photometric light curves, which show modulation on the rotational timescale of the star, and Doppler imaging analyses, which reveal systematic changes in line profiles over the rotation period. When interpreted with a starspot model (Rodono 1986, Rodono *et al.* 1986, Vogt 1981,1983), the general characteristics that fit both types of observations include:

(1) The starspots are cooler than the surrounding photosphere, with $\Delta T \sim 500$ - 1500K;

(2) Large spotted areas are required, e.g. some 10 - 50% of the visible hemisphere;

(3) Starspots are stable and live for many, sometimes several hundred, stellar rotations;

(4) Starspots exist both near the equator and near the pole; and

(5) Long term variations in the photometric brightness are explained by a change in the spot area coverage.

The data and models make no *a priori* assumption about which area of the star is magnetically active, so the same modelling techniques that were previously used are still appropriate. If we adopt the Zebra interpretation, which was inspired by the direct magnetic field measurements, we identify the previous "spot" areas as quiet photosphere and the rest of the star (which is brighter) as the magnetic network region. In fact, Vogt (1983) noted that what were being called starspots were perhaps more analogous to solar coronal holes. It may be that the solar photospheric counterpart to coronal holes is quiet photosphere which appears dark in the Zebra model of stellar activity.

With the Zebra interpretation, the characteristics discussed above in the context of a spot model become: the undisturbed photosphere is cooler than the surrounding bright network, covers some 10-50% of the star, is stable and exists for many rotations, exists near the equator and near the pole, and varying area coverage of photosphere and bright network gives rise to long term brightness variations. All of these are characteristics easily recognized on the Sun, the only spatially resolved star we can observe. Furthermore, several problems with the spot model, *e.g.* flux redistribution from very large spots (Mullan 1983), polar or high latitude spots which are seldom observed on the Sun, and long lived spots which are also not observed on the Sun, are alleviated in the Zebra approach.

III. Consequences and Implications of the Zebra Effect

In this section we discuss the implications of the Zebra interpretation for the correlation of other emission from the magnetically heated atmosphere with the photometric rotational modulation and long term brightness variations. We also discuss the consequences of the model for the positions of these stars in the Hertzsprung - Russell diagram.

a) Rotational Effects

The large filling factor of bright magnetic regions suggests that chromospheric and transition region emission lines will show only weak, if any, rotational modulation; this is also the case for coronal X-ray emission. In addition, the emission will be correlated with the photometric brightness in the sense that more emission is expected when the star is bright. Local enhancements, such as the decreased brightness on the Sun that is associated with the appearance of a new large sunspot, may cause a temporary variability. We expect that within the network there will be many "active regions" (AR) with associated spots, plages, etc., so the effect of any one region (except possibly during flares) will be small. Further, if the evolution of the AR progresses as on the Sun, the rotation effects will be noticeable for only one or a few rotations. Contemporaneous observations of chromospheric emission and photometric rotational modulation tend to support this view since, in most cases, no obvious correlation is found (Butler *et al.* 1987, Ambruster *et al.* 1992). Where correlations do exist, they could be explained by a coincidental longitudinal alignment of a dark (photospheric) area and a new plage area.

On other active stars, some rotational modulation has been claimed. The widely studied RS CVn system II Peg appeared to show chromospheric and transition region emission lines varying in anti-phase with the photometric variability (as predicted by the starspot model) according to Rodono *et al.* (1987). However, Andrews *et al.* (1988) found that most of the line enhancements they observed on II Peg could be attributed to flare activity, while Doyle *et al.* (1989) saw chromospheric emission *correlated* with the photometric light curve, which would support the Zebra model. A study of the pre-main sequence star BP Tau by Simon, Vrba and Herbst (1990) also found rotational modulation of the line emission correlated with the photometric variability. The rotational effects on even well observed active stars are thus controversial and far from understood.

In addition to causing temporary variability that might be mistaken for rotational modulation in the emission lines, flares also provide a means for correlating activity with longitudinal variations in brightness. In the starspot model, an increase in flare activity was expected when a dark area was toward the observer. Spots at high latitude complicate the issue, especially when the star is observed at low inclination (Pettersen, Kern and Evans 1983). No obvious correlations have been found but the available data is sparse and the results are inconclusive (Doyle 1987, Andrews 1983, Chugainov 1974). Under the Zebra interpretation, no preferred longitude for flaring, and hence no rotational modulation correlation, is expected.

b) Long Term Brightness Variations

In addition to the rotational modulation of the photometric brightness, a long term variation is present in BY Dra stars observed over long (many years) timescales (e.g. Phillips and Hartmann 1978). The traditional interpretation is that large spotted areas suppress the brightness to low levels, and that the star returns to its immaculate brightness level when the spots disappear. In the Zebra model, however, the faintest brightness level is identified as being closest to the immaculate level (largest coverage of non-magnetic photosphere). This leads to the observable consequence that other magnetic activity indicators such as chromospheric and transition region emission lines (Hα, Ca II H and K, Mg II, C IV), coronal (soft X-ray) emission, and the occurrence of flares should correlate with the photometric brightness, in the sense that the star would be most active when it is brightest. This expectation is opposite of what is expected from the usual starspot model, but is exactly analogous to the solar case. As mentioned above, on other types of stars the evidence is mixed: the Radick *et al.* (1990) study of G and K dwarfs compares Ca II H and K emission with photometric brightness, with the result that active stars seem to fit the starspot prediction while less active stars behave like the Sun, but the results of the Dorren and Guinan study of the active RS CVn system V711 Tau showed that it behaved like the Sun (more activity when photometrically brighter).

Very little data exist on BY Dra stars to test the model prediction. On BY Dra itself, there is sufficient data to construct a lightcurve over the past 60 years. During this time, the faintest B magnitude was 9.7 in 1965-66, while a few years later it had increased to B=9.2, a level also reached in 1930. Under the Zebra interpretation, a facular network coverage of about 50% of the visible hemisphere with an average temperature 500 K above the photospheric temperature of 4000 K is sufficient to produce this brightening. Further, BY Dra has had strong Hα emission lines since 1975 (when it has been bright) and reports of Hα absorption (Vogt 1980) at earlier epochs (when it was fainter). These observations support the Zebra model, but are only suggestive. Much more data is necessary before any conclusive result can be obtained. We also expect more and larger flares during the periods when the star is bright; the data are not yet sufficient to test this hypothesis.

c) Effects in the Hertzsprung - Russell Diagram

Spruit and Weiss (1986) considered the effects of starspots on the luminosity and surface temperature of late-type stars. For activity time scales which are short compared to the thermal timescale of the convection zone (*e.g.* 10^5 years for the Sun), the stellar luminosity decreases while the surface temperature remains nearly constant. However, activity that persists over long timescales affects the energy generation directly through the convective coupling between the surface and central temperatures. Thus, continued spot coverage results in a decrease in the luminosity and an increase in the surface temperature.

In the Zebra model, the photometric signature of activity results from bright facular regions rather than starspots. If we assume that the Spruit and Weiss models can be extrapolated to bright, rather than dark, features, then we find that on short timescales the active star will appear more luminous than its inactive counterpart, while the temperature is nearly unchanged. On long timescales the active star will show an increase in luminosity and a decrease in surface temperature. Its true photospheric characteristics can be determined only at times when the star is near brightness minimum. There is some indication that dMe stars have brighter absolute magnitudes at the same spectral type (Joy and Abt 1974, Leggett 1992); this effect has generally been attributed to youth in the sense that the dMe stars may be younger, hence they may still be descending on their pre-main sequence tracks to the ZAMS. Improved mass and temperature determinations for M dwarfs are needed to sort out which effects dominate, and whether there are practical applications of a possible activity-luminosity correlation.

Acknowledgments

Our thanks to H. Hudson, B. LaBonte, J. Linsky, J. Neff, R. Radick, S. Saar and S. Solanki for interesting and useful discussions and to O. Duhalde and W. Krzeminski for their hospitality at Las Campanas Observatory where we began writing this paper during a snowstorm. We also thank the referee for pointing out the complicated rotational behavior of II Peg. This work was supported by NASA grant NAGW-2547 and NSF grant ATM-90-22385 (SLH), NSF grant ATM-91-06052, NASA grants NAGW-864 and NAGW-2969, and AFOSR grant AFOSR-90-0116 (GHF) and grants from the Norwegian Research Council for Science and the Humanities (BRP). SLH was partially supported by NASA through Grant No. HF-1017.01-91A awarded to the Space Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under Contract No. NAS5-26555. Part of the research was done at the Lawrence Livermore National Laboratory under the auspices of the United States Department of Energy, through Contract No. W-7405ENG-48.

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