SESSION II

OBSERVED ACTIVITY IN RED-DWARFS

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SPOTS, SPOT-CYCLES, AND MAGNETIC FIELDS OF LATE-TYPE DWARFS

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ABSTRACT

A review is presented of the current state of observational knowledge concerning spots, spot-cycles and surface magnetic fields on active late-type dwarfs. The discussion centers primarily on the physical characteristics of starspots on BY Dra-type stars, including spot sizes, temperatures, structural morphology, migratory motions, and activity cycles. The discussion will also include some references to similar spot phenomena on the RS CVn stars. Observational evidence for surface magnetic fields on these stars, and on chromospherically-active G and K dwarfs, is also reviewed.

1. INTRODUCTION

I will attempt to present a review of spots, spot cycles, and magnetic fields in late-type dwarfs, specifically the BY Dra stars. As most of you well know, these are UV Ceti flare stars of dKe and dMe spectral types which, outside of periods of flaring, show periodic variations in light of several tenths of a magnitude attributable to large, cool "starspots" on their surfaces. Starspots are also generally accepted as the explanation for the distortion waves on light curves of the RS CVn stars (Hall 1976). There is no doubt in my mind that the mechanism for the periodic light variations of both the BY Dra's and the RS CVn's is one and the same: starspots. In fact, spots seem to be present on any late-type star with an appreciable convection zone and sufficient angular velocity, regardless of evolutionary state. The BY Dra's are mostly spotted pre-main-sequence dwarfs, whereas the RS CVn's are spotted post-main-sequence subgiants and giants. Recently another group of spotted stars was discovered in the Pleiades - rapidly rotating K stars with periods in the $0^{d}.4$-$1^{d}.2$ interval and ranges of 0.04-0.06 in V-magnitude. These will be discussed later in the meeting by others. Their sinusoidal light curves are strikingly similar to BY Dra light curves and they are evidently an even younger form of BY Dra stars still approaching the main sequence.

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The observational and theoretical evidence is now overwhelming that spots are a direct consequence of deep convection zones, and rapid angular velocity. While spotted stars occur most frequently in close binaries, this is only because the rotation rate of a convective star in a binary system can be maintained against magnetic braking forces through tidal interaction. It has been shown quite clearly (Bopp et al. 1981; Bopp et al. 1980; Bopp and Fekel 1977; Bopp and Espenak 1977) that relatively rapid rotation ($V \geq 5$ km s^{1}) is the underlying cause for spots on late-type dwarfs, and that membership in a close binary system is only a sufficient, but not necessary condition for spots. Recent V sin i measures by Vogt, Soderblom and Penrod (1982) also support this view by demonstrating that apparently single spotted stars rotate at much higher than normal rates ($V = 5$-15 km s^{-1}).

Many excellent and still current reviews of the spot phenomenon, both theoretical and observational, exist in the literature (Hall 1976; Rodono 1980, 1981; Gershberg 1978; Mullan 1976a,b and refs. cited therein). The field of starspot research has grown enormously since I became involved some ten years ago and it is a hopeless task to do it justice in a mere 40 minute review. Rather, I intend to concentrate primarily on the highlights of our present observational knowledge of the physical character of spots and associated magnetic activity, citing key references where appropriate. I feel compelled to offer the usual apologies to the many hundreds of researchers whose references were not cited explicitly in this work, but upon which this discussion was based.

Almost every paper published these days on starspot phenomena starts with a lengthy defense of the spot hypothesis with all the usual references cited. As recently as two years ago Hall (1980) remarked that "...the case for spots is largely circumstantial or, at best indirect. We should work to find sufficient direct evidence to convince the devil's advocate that such spots exist." Similarly, Rodono (1980) considered the spot model of RS CVn binaries as "a working one probably leading in the right direction ... questions remain to be answered before it can be accepted with confidence." By the end of this review, after I have shown you a movie of spatially resolved images of starspots obtained through a new technique we call Doppler Imaging, I expect to have convinced you that it is time once and for all to put aside our noble skepticism about the reality of starspots. We no longer should feel embarrassed or defensive about the ease with which the spot hypothesis accounts for all the observational results. That is not to imply that these starspots are direct analogs of sunspots. Rather, I will present evidence that starspots on RS CVn and BY Dra stars are actually much more analogous to solar coronal holes and solar complexes than to sunspots as regards sizes, shapes, lifetimes, and migratory motions. If true, they are probably more of a manifestation of global-scale processes occurring deep within the star, than are spots on the Sun.

2. PHYSICAL CHARACTERISTICS OF STARSPOTS

Most of our knowledge of the physical characteristics of starspots has been gleaned from modeling the photometric variations. These variations are typically a few hundredths to several tenths of a magnitude in range, and vary in shape, period, phase, and mean light level. They involve small but often detectable color variations, a circumstance which allows us to derive spot temperatures. The light curves often show discontinuities in mean light and phase, easily explainable by subtle changes in the spot area and/or distribution on the star. The light curves of the BY Dra's and the "distortion waves" of the RS CVn's are quite similar in most respects though the evidence for systematic period variations in the latter is much stronger due to the larger body of data available.

2.1 Geometric Spot Models

Geometric spot models to date have been of three basic types: single-circular spot, two circular or rectangular spots, and equatorial bands. The single circular spot model approach is only valid in cases where the light curve is symmetrical and where it is known (e.g., II Peg in 1977) from the immaculate light level that the spot passes completely out of view at some phases. In situations where the light curve is asymmetric, two spots (either circular or bounded by parallels of longitude and latitude) separated in longitude are able to provide reasonable fits to the light curves. This approach has been used extensively by Dorren and Guinan (1982a), Guinan et al. (1982), Dorren et al. (1981), Bopp and Noah (1980), and others. Here, there are many more free parameters and solution nonuniqueness problems become much more severe. The third approach (Eaton and Hall, 1979), is to assume (by solar analogy) that spots are distributed nonuniformly in longitude in mid-latitude bands symmetric about the equator. The spot area covered is assumed to follow a simple cosine dependence with longitude.

In all of these approaches, there are definite problems with non-uniqueness as regards spot sizes, temperatures, shapes, and locations. Realistic spot modeling requires, at the minimum, knowledge of the inclination of the system, proper accounting of the behavior of the mean light level and the presence of an unspotted (?) companion, and actual detection of color variations in the light curves (to decouple temperature effects from geometrical ones).

The single circular spot assumption allows a major simplification to be realized in computing light curves to model the observations. In fact the machine computation is fast enough that a dense grid of light curves covering the full range of spot size and latitude can be computed and regions of best fit to the observed light curve can be identified in spot (size, latitude) space. Figure 1 illustrates this approach for the 1977 light curve of II Peg (Vogt 1981a). Here we have plotted the goodness of fit (vertical axis) of synthetic light curves generated at different combinations of spot location (latitude) and size. The best

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fitting solutions occur farthest above the plane and regions below the third of fourth vertical contour from the plane represent unacceptable fits to the light curve as regards shape, amplitude, or mean light level. Similar planes can also be computed for a range of inclinations and spot temperatures, and the regions of acceptable fit can then be combined onto a single 2-d plot as in Figure 2 to produce a reasonably unique spot model within the bounds of the original single circular spot assumption. Here we have combined regions of acceptable fit from a large number of surfaces like that of Figure 1 spanning the full range of stellar inclination and three different spot temperatures. The pronounced N-S latitude ambiguity in Figure 2 arises because of the unknown inclination.

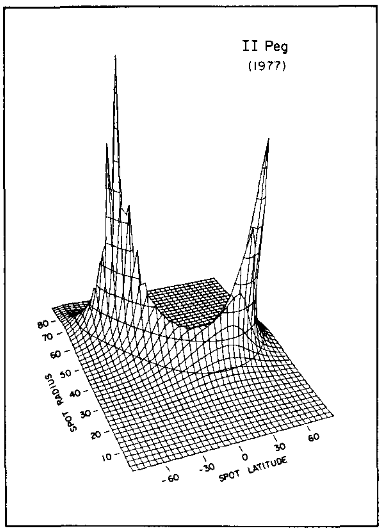


FIGURE 1

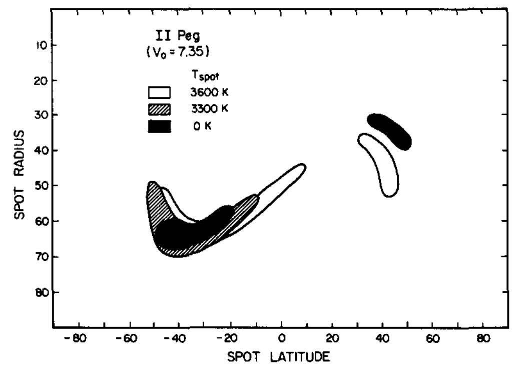


FIGURE 2

In many cases where the light curve is asymmetrical and a two-spot approach is required, the uniqueness problem becomes much more difficult. Often the two spots are assumed to be the same size and to lie at the same latitude, and in several well referenced cases neither the inclination nor the spot temperature was known.

Despite problems of nonuniqueness in the geometrical models, it is clear that starspots, be they circular, triangular, elongated, or whatever shape, are quite large, often covering up to 20% of the stellar surface. This is a simple inescapable fact of the observed amplitudes of light variation and is quite independent of solution uniqueness.

2.2 Spot Temperature Modeling

There is a fundamental trade-off between spot temperature and area. Small, cool spots can produce similar light curves to larger, warmer spots. Because of this, any serious model requires knowledge of color variations in the photometry to decouple temperature effects from geometrical ones. Many of the original spot models published simply ignored this effect and their results should not be taken seriously.

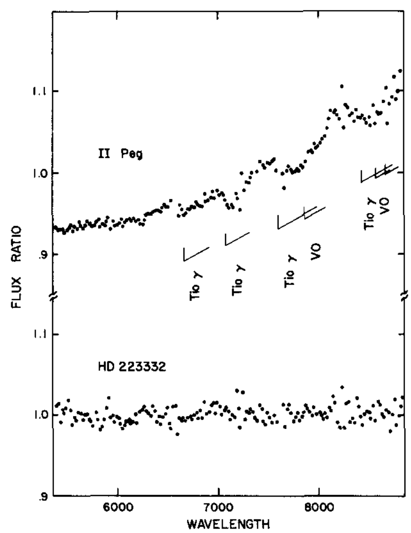
Most spot models employ Planckian energy distributions or actual measured stellar energy distributions for star and spot to reproduce color variations. Limb darkening coefficients are taken from published compilations and the coefficient for star and spot are generally assumed to be similar. These analyses generally yield spot temperatures which are 800 to 1200 K cooler than the surrounding photosphere. Unfortunately, the energy distributions of late-type stellar atmospheres are remarkably non-Planckian, and there are problems combining stellar energy distributions accurately on a proper flux scale, requiring integrations of the published distributions through the estimated photometer response functions. To avoid these problems, I developed a technique (Vogt 1981a) for deriving accurate spot temperatures using the Barnes-Evans visual surface brightness relation (Barnes, Evans, and Moffett 1978). This method allows direct determination of the (V-R) color difference and hence temperature difference ΔT between spot and surrounding photosphere. It consistently yields spot temperatures near 3500 K.

Other methods of determining spot temperatures involve direct detection of spectral features from the spot. Figure 3 shows a low resolution spectrum from 5000-8000Å of the spot on II Peg (Vogt 1981b) which shows a steep rise in flux to the red and pronounced absorption features of the TiO γ-system. These features led to an estimate of $\sim$M6 for the spot's equivalent spectral type, or T(spot) $\sim$ 3400 K. Ramsey and Nations (1980) also detected enhancement of the λ8860 bandhead of TiO in HR 1099 as the spot moved into view and derived a spot temperature of $\sim$3750 K or less.

From the set of all published determinations of spot temperature, it might appear (as noted by Bopp and Noah, 1980) that there is no single ΔT which can be applied to all spotted stars. Published ΔT's range from a few hundred degrees to about 1200 K, and for the star BY Dra, ΔT can decrease or even become negative (hot spot) as the cool spot disappears (Vogt 1975, 1981a; Oskanyan et al. 1977). Some of this scatter in ΔT is undoubtedly a result of solution nonuniqueness however, and some is due to differences in T(star). I have attempted to collect all of the reliable determinations of spot temperatures in Table 1. Only those determinations were used whose spot models were reasonably unique (known inclination, accounting for secondary star and/or mean light level) or where color variations were actually detected.

From this collection of reasonably well-determined spot temperatures, it is clear that most fall very near a value of 3600±200 K. The only significant exception is λ And, though neither the inclination nor the immaculate light level for this star is known and some trade-off between spot temperature and area may be allowable which could further lower T(spot). Also, there is a well-known case, BY Dra, where a large, cool spot dissolved after migrating toward the pole, leaving a plage-like remnant which remained for 5-6 years (Vogt 1981a; Oskanyan et al. 1977). A spot temperature of 3900 K was determined for this remnant by Davidson and Neff (1977) and a temperature of 4200-4300 K was derived by Vogt (1975). Clearly these temperatures do not refer to the large cool features we call starspots, but rather to some active remnant. It would be of great interest to follow accurately the change in temperature and area as one of these great spots formed or dissolved. The evidence at hand however points to a fairly consistent, well defined temperature of 3600±200 K for large cool starspots. Table 1 also shows that regardless of the temperature of the star, over the range from 4100 K to 4950 K, the spot temperature remains fairly well fixed, thus giving rise to differing ΔT's noted by Bopp and Noah (1980). This tendency for large cool spots to share a common temperature regardless of star temperature is probably an important clue as to their physical structure.

FIGURE 3



I have also included two columns which list the ratios of T(spot)/T(star) and ΔT/T(star) for comparison with sunspots. In either case, starspots look much more like sunspot umbrae than sunspot penumbrae. If starspots are morphologically similar to sunspots, but just larger, our derived temperatures must refer to the penumbral region, since this contributes 97% of the total flux of a sunspot. That the derived spot temperatures more closely resemble sunspot umbrae is an indication, I believe, that the two are not morphologically similar, but rather that starspots are more like giant umbrae, with little or no penumbrae.

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TABLE 1

Temperatures of Stars and their Starspots

Star	Sp.Type	T(star)	T(spot)	ΔT(star-spot)	T(spot)/T(star)	ΔT/T(star)	Ref.
BY Dra	M0 V	4100	3500 ± 450	600	0.85	0.15	1
II Peg	K2 IV	4600	3400 ± 100	1200	0.74	0.26	1
HR 1099	K1 IV	4700	<3800	>900	<0.81	>0.19	2
			3450	1250	0.73	0.27	3
			<3700	>1000	<0.79	>0.21	4
SZ Psc	K1 IV	4700	3500 ± 400	1200	0.74	0.26	5
DK Dra	K0 III	4700	3600 ± 150	1100	0.77	0.23	6
HD 209813	K0 III	4790	<3840	>950	<0.8	>0.2	1
HD 32918	K2 III	4950	3750 ± 100	1200	0.76	0.24	7
λ And	G8 III-IV	5000:	4200	800	0.84	0.16	8
Sun	G2 V	6050	4240 (umbra)	1810	0.70	0.30	9
Sun			5680 (penumbra)	370	0.94	0.06	9

1 - Vogt (1981a)
2 - Dorren et al. (1981)
3 - Antonopoulou and Williams (1980)
4 - Ramsey and Nations (1980)
5 - Eaton and Hall (1979)
6 - Guinan et al. (1982)
7 - Collier (1982) - this star is an FK Com-like variable
8 - Bopp and Noah (1980)
9 - Allen (1973)

2.3 Spot Shapes

It is often found in the geometrical models that spots are characterized by very large extents in longitude. Spot light curves are only rarely seen to have flat portions, indicative of a spot which passes completely out of view, and the smooth, sinusoidal shape of the light curves in stars of high inclination (like eclipsing systems) argues strongly for great longitude extents, often exceeding 150°. Of course, models invoking spots bounded by parallels of latitude and meridians of longitude (Bopp and Noah, 1980) or bands of spots (Eaton and Hall 1979) seem to favor spots quite elongated in the longitudinal direction, whereas circular spot models by their very nature do not allow for this.

Many of the spotted stars however are at low inclination, and we are often seeing circumpolar spots which can remain in view for much, if not all, of the rotation cycle. Here, it is almost impossible to distinguish elongated spots from circular ones, and the derived spot shape is more a reflection of the model assumptions than anything implied by the light curve. Later in this meeting, I will demonstrate some actual images derived of several spotted stars using a new technique called Doppler Imaging which is quite sensitive to spot shape and shows large spots very near the pole (like polar coronal holes) and spots which are greatly extended in latitude, with almost no extent in longitude. At present then, I can only summarize by saying that there is strong evidence for all three types of shape: spots extended predominantly in longitude, or in latitude, or spots which are roughly circular in shape. If I had to second guess future results of the Doppler Imaging technique, I would say that low latitude spots are preferentially extended in longitude, whereas high latitude spots are preferentially circular or elongated in latitude.

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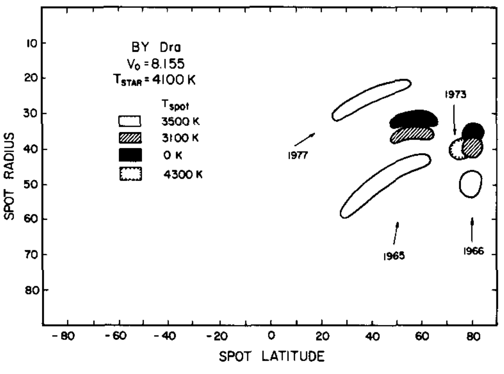
It is also not yet clear whether large spots are single entities, or groups of smaller spots. All existing models provide no information on this question. We expect the Doppler Imaging technique to make some progress in this area.

2.4 Spot Locations and Migrations

The spot models show a definite tendency for many spots to form at intermediate latitudes and then to drift either poleward or toward the equator. One of the best examples of this was BY Dra, a spotted star of well known inclination whose photometric behavior from 1965 to 1973 is well-modeled by a large cool spot which formed at an intermediate latitude and drifted poleward before dissolving into a plage-like region. This is illustrated in Figure 4 (a plot similar to Figure 2). Here we see that a large spot, some 40°-50° in radius formed at a latitude of 55° in 1965 and then drifted at constant radius to a latitude nearer 80°, where it then dissolved leaving a bright remnant in 1973. While the spot geometry is admittedly somewhat nonunique and idealized, it is clear that from our viewing angle, we witnessed a poleward motion of the latitude centroid of spot area. This particular episode is in fact strikingly similar to the poleward migration of high latitude solar coronal holes, then resulting in a large polar coronal hole (straddling the pole) which eventually dies away leaving an active region remnant.

FIGURE 4



More remarkably, the period change on BY Dra associated with this latitude drift implied a latitudinal shear of the same sign, and very nearly the same value (within 30%) of that observed on the Sun (Vogt 1981a). While the reality of such period changes has been justifiably questioned by Hartmann and Rosner (1979) it is a well-documented effect in the RS CVn's and is becoming increasingly hard to explain away on the BY Dra's in terms of observational uncertainty as the photometric data base improves. The RS CVn stars show longitudinal migrations of spots in both directions, indicative of period changes to values both greater and less than the orbital one (Rodono 1981). The standard interpretation (Hall 1972) is that spotted stars, like the Sun, rotate faster at the equator than at the poles, and thus spots below the latitude of co-rotation rotate faster than the orbit (retrograde migration), and spots

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above this latitude rotate slower than the orbital motion (direct migration). Occasionally spots drift across the latitude of corotation and spot migration can change from retrograde to direct or vice versa (AR Lac, SS Boo, HR 1099, UX Ari). While changes in both directions have been well observed on several RS CVn's, only poleward migration has yet been detected on the BY Dra's. Probably migration in both directions is occurring, with all spots above some intermediate latitude migrating poleward, and those below that latitude migrating toward the equator.

Often the migration rate shows discontinuities or sudden accelerations (e.g., Eaton et al. 1980). Such behavior is easily explained by subtle changes in the areal distribution of spot groups, with new spots forming as old ones decay away. Noticeable changes in the areal distribution can occur on time scales as short as five stellar rotations. This makes accurate spot modeling extremely difficult and requires intensive cooperation and coverage by spot photometrists.

2.5 Association of Spots with Chromospheric Emission and Flaring

There is now much evidence to suggest that large dark starspots are spatially associated with regions of enhanced chromospheric emission and flaring. Weiler (1978) found a correlation between the strength of Hα and phase of photometric minimum in several RS CVn's. Kodaira and Ichimura (1982) found periodic variations of the emission at Hβ from YY Gem whose maximum corresponded precisely with photometric minimum (dark spot most in view). Dorren and Guinan (1982b) found among a sample of G8-K7V stars an anti-correlation between strength of CaII and Hα emission and mean brightness. Baliunas and Dupree (1982) found for λ And that the phase of maximum spot visibility corresponds with enhancement of both CaII K emission and the ultraviolet transition-region lines. Vogt (1981b) found a strong correlation between Hα strength and spot visibility on II Peg. There are many other reports of such correlations between chromospheric emission and spot visibility.

Generally, the correlation, though certainly present, is much weaker than hoped for, implying that, while the emission is certainly enhanced near the dark spot, it also arises more or less globally. The relatively high mean level of emission on these stars with only subtle modulations also implies that a large fraction of the stellar surface must be covered with plage-like regions. Presumably these plage-like regions, like those on the Sun, have a shallower $T(\tau)$ relation than non-active regions and, if area coverage was great enough, could dilute the quiescent photosphere's line spectrum enough to explain the anomalous underabundances often found for the active members of RS CVn systems. This would nicely explain why only the active component ever has "anomalous underabundances", and implies a large areal filling factor for these plages.

The association of spots with flares is much harder to establish, though intriguing correlations have been noticed. Young et al. (1982)

found a strong correlation between the times of flare events and phase of photometric minimum in V471 Tau, an eclipsing binary system consisting of a white dwarf and a K dwarf which shows BY Dra-like spot behavior. Busko and Torres (1978) also found that the flaring rate of AU Mic, a spotted dM0e star, was marginally higher when the dark spot was in view.

3. SPOT AND ACTIVITY CYCLES

A fundamental goal of spot monitoring is to search for evidence of periodic cycles or patterns in spot activity. These cycles could be repeated patterns of any observable quantity such as spot area, spot latitude, spot longitude, magnetic field strength, chromospheric emission strength, or others. By analogy with the well-known solar cycle, one expects to find cyclical variations in at least several of these observables which can serve as a probe of the interior structure of the star as well as of the dynamo mechanisms generally thought to be responsible for the activity. Already, many hints of "clocks" running in active late-type dwarfs and subgiants have been detected. The CaII K line monitoring work of Wilson (1978), Vaughan and Preston (1980), Vaughan (1980), and Vaughan et al. (1981) has shown very clear evidence of 7 to 14 year cycles in chromospheric emission from F5-M2 dwarfs. Thus far, only the older stars of the sample show smooth cyclic variations at the K line; these are stars with rotation periods greater than about 20 days. The cycle periods in these stars are apparently uncorrelated with rotation period. There seem to be two distinct levels of activity among the F, G dwarfs: either high or low, with a deficiency of F, G dwarfs exhibiting intermediate K-line emission (the "Vaughan-Preston" gap). This gap has been explained by Durney, Mihalas, and Robinson (1981) as an abrupt transition from a multi-mode to a single-mode dynamo as rotational velocity decreases. Knobloch, Rosner, and Weiss (1981) offer another explanation for this gap in which the convection pattern switches from rolls predominantly parallel to the rotation axis, to normal convection cells as the angular velocity is decreased past a critical rotation period ($\sim$20 days). Whatever the explanation, it seems clear that these cyclic K-line variations are an important tool for understanding the global-scale properties of the star's convection and/or dynamo mechanism.

The RS CVn stars also show evidence of cycles, though the situation is much more complex, and several clocks seem to be present. Haslag (1977) has reported a very striking 30 year cycle in the wave amplitude of RT Lac. Hall (1972) found strong evidence for a 23.5 year cycle of wave amplitude on RS CVn. Bohusz and Udalski (1981) have detected an 8-10 year periodic variation in the phases of photometric minima in II Peg, a transition case between the BY Dra and RS CVn stars. Dorren and Guinan (1982a) found variations in spot area, latitude and longitude for spots on HR 1099, but thus far, none of these patterns have repeated, implying a lower limit of 5 years for any spot cycle period. Rodono (1980) cites evidence of several RS CVn's whose cycles of about 5 years are in evidence. There are numerous other reports of suspected or detected cycles of activity in the RS CVn's. The migration period of a spot in longitude, typically on the order of 5 years or more, might also represent some true cycle of internal activity. The situation is further confused by characteristic several year time scales for the appearance or disappearance of a given spot group which is often misinterpreted as evidence for a cycle.

In short, there is strong evidence for spot activity cycles ranging from as short as 5 years to as long as 30 years on the RS CVn's. At present, the longer cycles seem to me most striking and well defined. Clearly many more years of dedicated photometry will be required to fully identify the various clocks within the star.

The BY Dra stars also show very clear evidence of periodic starspot activity. Lee Hartmann and co-workers have been using the Harvard archival plate collection to study the long-term behavior of the mean light of several BY Dra and RS CVn systems. Phillips and Hartmann (1978) found evidence for a 50-60 year periodic variation in the mean light of BY Dra and CC Eri. Hartmann et al. (1981) found even stronger evidence for a 60 year cycle on Gliese 171.2A, a dK5e spotted star. I present their results in Figure 5 as an example of this type of periodic behavior. Such activity variations may occasionally cease altogether as for II Peg (Hartmann, Londono, and Phillips 1979) where the mean light was essentially constant for about 40 years before beginning to exhibit variations on both short and long time scales. This suggests that the BY Dra and RS CVn stars may undergo periods of relative spot inactivity much like the solar Maunder minimum.

It appears then that clocks of various rates reside in all the groups of stars: the active late-type dwarfs, the BY Dra spotted flare stars and the RS CVn systems and it is interesting to compare these rates and their dependences on spectral type and rotation period with theoretical predictions. For example, Belvedere et al. (1982) developed an $\alpha\omega$-dynamo operating in the convection zone which predicts an increasing dynamo cycle period with advancing spectral type from F5 to M0. When adjusted to fit the 22 year period of the Sun, this model nicely reproduces the 50-60 year periods of the dK5 and dM0 stars Gliese 171.2A and BY Dra. Robinson and Durney (1982) on the other hand predict a dynamo cycle period which decreases with advancing spectral type at a given rotation period for G0 to M5 dwarfs. Their model assumes that the rise time of a magnetic flux tube due to buoyancy is equal to the e-folding amplification time for the dynamo.

For the purposes of comparison with observation, I have assembled in Table 2 and Figure 6 a collection of known or suspected spot cycle candidates from various sources. I make no guarantee of completeness of this compilation, nor of the reality or physical interpretation of the given "cycle" periods, but I have tried to use only the cases where the cycle time (whatever it may be caused by) and rotation periods are accurately known. In addition, there may be some ambiguity by factors of two involving true cycle periods analogous to the 11 year vs. 22 year

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components of the solar cycle. For the lower group in Table 2, I have simply quoted the time interval between successive minima.

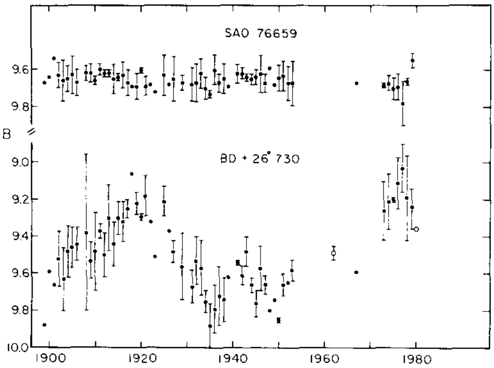


FIGURE 5

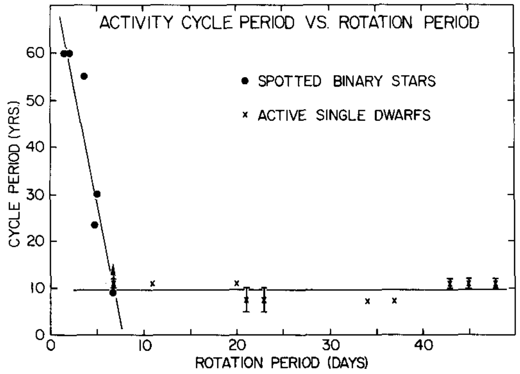


FIGURE 6

TABLE 2

Activity Cycles and Rotation Periods

Star	Sp.Type	Binary	$P(rot)^d$	$P(cycle)^{yr}$	Ref.
CC Eri	dK7e	*	1.56	60	Phillips and Hartmann (1978)
Gl 171.2A	dK5e	*	1.9	60	Hartmann et al. (1981)
BY Dra	dM0e	*	3.8	55	Phillips and Hartmann (1978)
RS CVn	K0 IV	*	4.8	23.5	Hall (1972)
RT Lac	K1 IV	*	5.1	30	Haslag (1977)
II Peg	K2 IV	*	6.72	8-10	Bohusz and Udalski (1981)
HD 17925	dK0		6.9	>10-12	Vaughan et al. (1981)
HD 152391	dG8		11	11	"
HD 4628	dK4		20	10-12	"
HD 155886	dK1		21	5-10	"
HD 155885	dK1		23	5-10	"
HD 160346	dK3		34	7	"
HD 201091	dK5		37	7	"
HD 166620	dK2		43	10-12	"
HD 16160	dK4		45	10-12	"
HD 201092	dK7		48	10-12	"

Table 2 and Figure 6 reveal several interesting facts. First, all these stars occur in the G8 to M0 spectral range. Though observational selection effects are certainly present, the mechanism producing such behavior seems to prefer this mix of convection zone depth and rotational velocity. The upper group (spotted binaries) includes both RS CVn's and BY Dra's and shows a very pronounced, essentially linear correlation between cycle time and rotation period in the sense that faster rotation means longer cycle periods. These spotted binaries also show a definite tendency for cycle period to increase with (B-V) though the correlation is not as strong. This latter behavior coincides with the predictions of Belvedere et al. (1982) that cycle period should increase with (B-V). However, these authors assumed that the rotational period was fixed and this is not true among the sample in Table 2, so the comparison should not yet be taken too seriously. Secondly, the single chromospherically active dwarfs of the lower group in Table 2 show no dependence of cycle period with rotation period (as already pointed out by Vaughan et al. 1981), or with (B-V). Instead, these stars all show periods in the 7-12 year range, presumably the analog of the 11 year solar cycle.

From these data, it is clear that some process related to angular velocity turns on abruptly inside the star at a rotation period of about 6-7 days and leads to large spots and cyclic spot activity. Stars rotating slower than this show very little evidence of starspots, and essentially identical chromospheric emission cycle periods very near the solar period of 11 years. Stars rotating faster than this (all binaries in this sample) exhibit cycle periods which increase essentially linearly with angular velocity. Vaughan et al. (1981) point out that, in their sample, 10-12 year activity cycles are found almost exclusively among stars with rotation periods longer than 20 days. However, much of this is probably a selection effect since their monitoring time base is only 13 years now and they are not yet sensitive to the longer activity cycles. As the time base increases, cycles longer than the canonical 11 years length will probably be found on stars with rotation periods below 20 days. Indeed, HD 17925, which has a rotation period of only 6.9 days, shows a steady decline in activity over the 10 year baseline, implying a cycle much longer than 10-12 years.

To summarize, both the single chromospherically active K dwarfs and the spotted RS CVn and BY Dra binaries show clear evidence of dynamo cycles. For rotation periods longer than about 6-7 days the cycle length is essentially constant at 10 ± 3 years and is independent of both spectral type (from G8-M0) and rotation period. Stars with rotational periods shorter than this 6-7 day breakpoint show large cool spots and spot cycles whose periods increase linearly with angular velocity. The 6-7 day breakpoint corresponds to an equatorial velocity of 5 km s^{-1} for a K5 dwarf and it is certainly no mere coincidence that this is exactly the critical velocity specified by Bopp and co-workers (Section 1) above which the BY Dra syndrome (spots) turns on. Perhaps, in this latter group, we are witnessing the effects of Coriolis forces which inhibit the buoyant emergence of magnetic flux and thus serve to amplify field strength as well as to increase cycle periods, (Penrod, 1982). The striking difference in Table 2 between starspot cycles of the spotted binaries and the solar-like 10-12 year cycles of the active dwarfs suggests again that starspots are not very close analogs to sunspots, but instead, like solar coronal holes and solar complexes are manifestations of a more global-scale process occurring deeper within the star than the relatively shallow mechanism responsible for spots on the Sun.

4. MAGNETIC FIELDS

Much effort over the past 8 years has gone into a search for the magnetic fields suspected on these active dwarfs. The original approach used the time-honored Babcock method to search for longitudinal or line-of-sight fields. The search included work by a number of researchers, including myself and all yielded essentially null results down to the 100-150 gauss level. These noble efforts are only of historical interest now so I will not dwell on them further except to say that, by analogy with the Sun (whose fields are locally bipolar on relatively small spatial scales), it is not surprising that the searches for longitudinal field all failed. Obviously, the small-scale bipolar networks spread uniformly across the disk cancel circular polarization to a very high degree. Recently, Borra and Mayor (private communication) have used the CORAVEL spectrometer at Geneva Observatory and a pockels cell analyzer to push the uncertainties of this technique down to the 3-5 gauss level. To date, after surveying over 30 stars, including RS CVn's, BY Dra's, and active single dwarfs, no evidence of coherent longitudinal fields above the 3 gauss error bars has been detected.

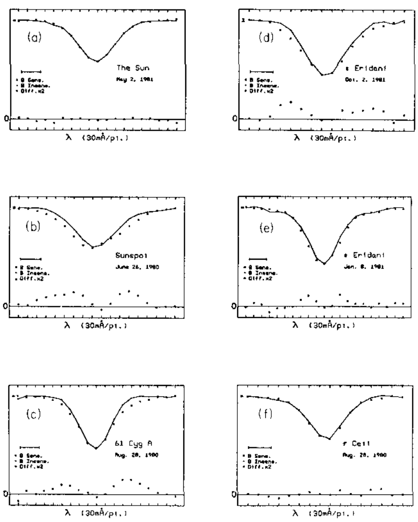
Though circular polarization is largely cancelled by spatially noncoherent fields, the Zeeman splitting of the spectral lines remains and manifests itself as a line broadening which correlates with Landé g factor - the splitting sensitivity of each line. The first convincing detection of this magnetic broadening was reported by Robinson et al. (1980) based on a fourier deconvolution method pioneered by Robinson (1980). Basically the method compares the profiles of two carefully selected lines which are as similar as possible in all respects except for Landé g factor where they are as dissimilar as possible. Generally the magnetically sensitive line is 2.5 times more sensitive to a given field than the insensitive line. The insensitive line is treated, to first order, as an approximation of a totally insensitive line profile to extract the degree of Zeeman broadening from the sensitive line profile. Both the average field strength and the fractional surface area covered by field can be estimated from this technique; the field strength coming from the separation of sigma components in the deconvolved profile, and the area coverage coming from the ratio of sigma to pi component line depths. Using the technique, Robinson et al. (1980) reported detection of a 1900 gauss field covering 10% of 70 Oph A, and a 2500 gauss field covering 20 to 45% of Xi Boo A.

Several groups are now apparently vigorously pursuing magnetic field measures in active dwarfs with similar techniques. One such effort (Marcy 1981), which is now quite well along and with which I am most familiar, is the work of Geoffrey Marcy, a graduate student at Lick Observatory. Marcy's results were presented at the IAU Symposium No.102 in Zurich several weeks ago, and will soon appear in the Astrophysical Journal. I would like to quickly summarize this work for you.

For the past 2 years, Marcy has surveyed a sample of 29 G0V-K5V stars for magnetic activity. This range in spectral type is bounded at the GOV end by decreasing line strength and increasing V sin i, and at the K5V end by line blending and line saturation problems. He uses the 24" coudé auxiliary telescope (CAT) and coudé echelle scanner (Soderblom et al. 1978) to obtain 100:1 signal-to-noise line profiles at 60 milli-angstrom resolution of λ6173 FeI (the magnetically sensitive line: g = 2.5) and λ6240 FeI (the insensitive line: g = 1.0). With the CAT, he can work to V = 5.5 in 3 hours per line or 6 hours per line pair. With the Shane 3-meter telescope, V = 7.5 is about the practical limit.

Figure 7 shows a fairly representative sample of observed line profiles from Marcy's work. The insensitive line in each panel is denoted by the solid line, while the crosses represent the sensitive line.

FIGURE 7



At the bottom of each panel, the vertically magnified difference profile is shown to enhance the visibility of the sigma components in the excess broadening of the sensitive line profile. The separation of these sigma components yields the field strength, while the area coverage is derived in the deconvolution by determining the ratio of sigma to pi component depths.

4.1 Results

Of the 29 stars surveyed, 19 show obvious fields; 30% of these in the 800-1000 gauss range with another 35% in the 1000-1500 gauss range. The derived area coverage is somewhat model dependent but area filling factors of 60 to 80% of the visible hemisphere are not uncommon. This is to be compared with filling factors of 1-2% for the Sun. The resultant magnetic surface flux for these stars is then $2\text{-}4 \times 10^{25}$ Mx, a factor of about 20 to 40 greater than the solar flux.

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The fields show time variability in several stars in both field strength and area coverage. For example, in Figure 7, the two ε Eri panels show markedly different field strengths as evidenced by the change in separation of the sigma components in the magnified difference. Such variations could be evidence of magnetic flux ropes appearing at the surface and then diffusing away. Monitoring of these field variations should produce some fascinating results in the next few years.

Marcy has attempted to determine the correlation of chromospheric emission at the CaII H, K lines with B and Teff to try to differentiate between acoustic, Alfvén, slow- and fast-mode MHD waves as the origin of this emission. He finds that the corrected H, K emission flux F' is proportional to $\sqrt{BT^4}$, roughly the dependence expected for slow-mode MHD waves, and he is effectively able to rule out Alfvén and fast-mode waves as the dominant chromospheric heating mechanism.

Marcy also finds a good correlation between the X-ray flux [log(F_x/F_{BOL})] and area filling factor. This is in agreement with models which involve large coronal loop structures anchored to magnetic regions at the surface to energize the corona. He also finds that F_x/F_{BOL} is proportional to $B^{-1.5}$ in good agreement with Alfvén waves heating the corona.

A good correlation is also found between the log of the magnetic flux and log of the equatorial rotation velocity: $\Phi \sim V_e^{1/2}\, T_e^{-2.8}$.

Finally, I should mention that in Marcy's sample, fields are detected predominantly for those stars in the upper branch above the Vaughan-Preston gap in the Log S - (B-V) diagram (Vaughan and Preston 1980). Marcy suspects that the area filling factor drops markedly across the gap, making for quite low area coverage of fields along the lower branch of the gap and hence relative absence of detectable fields. The Sun for example has mean surface fields of 1500 gauss, but area filling factors of only 1-2% and would have totally escaped detection in such a survey.

4.2 Fields in the Spots and in Flares

Direct detection of fields within starspots has yet to be accomplished. Vogt (1981b) reported the possible detection of a -515 gauss field in the starspot of II Peg, but this result has yet to be confirmed. Geyer and Metz (1977) found for XY UMa an increase in scatter of the Stokes Q, U parameters when the spot passed into view and thus possible evidence of transverse fields within the spots.

Fields have also been indirectly inferred during flaring through circular polarization in radio observations. Various groups have reported circular polarization of up to 20% in the radio at various phases of RS CVn flares, probably attributable to synchrotron emission from the flaring region.

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5. STARSPOT RESEARCH AT LICK OBSERVATORY

In addition to the magnetic field research of Marcy's, we are developing another technique at Lick for studying spots which should provide some fairly high spatial resolution pictures of spots, and thus greatly improve upon the ambiguous spot solutions obtained from modeling light curves. The method will be presented in greater detail elsewhere in this meeting, but I would like to take these last few minutes to introduce the technique and then to show you a movie of some preliminary Doppler Imaging solutions of UX Ari and HR 1099.

Basically, the technique exploits the direct correspondence between position across the disc of a rotating star and wavelength position across the rotationally broadened spectral line. For V sin i > 40, the rotational broadening dominates and the intrinsic profile can be easily decoupled from the observed profile. Any dark spot on the surface produces an apparent emission bump in any given absorption line profile which propagates across the line as the star rotates. By modeling these bumps simultaneously with the light curve, we can derive quite detailed and unique information on spot sizes, shapes, and locations. Nominally only one dimension of spatial information is present in the line profiles and for inclinations of 90° the modeling of the bumps would be terribly nonunique. However, nature was kind enough to give us several stars at intermediate (35°-55°) inclinations, and on these stars we can actually determine some 2-d information by observing the spot at a range of phases. For example, a spot situated directly on the pole would produce a bump which remained stationary at line center. As the spot is moved to lower latitudes, its velocity excursion about the line center increases accordingly, so accurate latitudes can be obtained. We have even watched circumpolar spots chase each other around the far side of the pole. Photometric modeling of starspot light curves is basically sensitive to longitude extent, whereas our line profile observations are sensitive to latitude extent of the spots. The two methods are thus quite complementary and by combining them into a single modeling formalism, we expect to be able to derive some detailed pictures of starspots. Additionally, we intend to attempt Doppler Imaging in polarized light in an effort to detect fields within the starspots. Our goals are to be able to differentiate between single large spots vs. large groups of smaller spots, to determine the detailed spatial and magnetic structure of a spot (umbra/penumbra) and to follow the development and migration of selected spots through their cycles for determination of differential rotation and spot migration patterns. This work will be published in a more complete form in the Astrophysical Journal.

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DISCUSSION

Anon: Which spectral lines did you use?

Vogt: 6430Å, FeI, we use 6430 and 6439. 6439 is a lot harder, that's Ca. It is difficult because it is almost all CaII in the star and all CaI in the spot. So there is a great change in the line strength when you go from star to spot. This has to be accounted for in the model, so it gets very confusing.

van Leeuwen: There are great problems with these stars. Why are the spots always concentrated to one side of the star? (Next sentence lost). We have been observing K-type stars in the Pleiades and all K-type stars in the Pleiades vary in that way. So why are the spots always concentrated to one side (of the star)?

Vogt: I believe it is a selection effect and that there are many stars which have spots all over them but we can know nothing about them. Their uniform distribution of spots means that they do not vary. They may look a little too cool for their spectral type but other than that I don't think we will ever know.

van Leeuwen: But I have looked at K stars in the Pleiades and they all show varaibility.

Worden: I am worried about the assumption that solar and stellar spots are different in nature. There are two physical facts which must be considered here. The first is that one must examine the depth in the atmosphere at which your lines are being formed. The second relates to the physics of flux tubes. In standard models the flux expands as you go up into the atmosphere. If sufficient flux tubes are put together the brightening or darkening effect according to the models varies. In the Sun for instance if one looks deep enough in even a plage region it looks dark. If a few more flux tubes come together you get a pore. So it is very questionable whether there is a fundamental difference here.

Vogt: I'm not sure which statement you are questioning.

Worden: The statement that there is something different in the physics of what is going on in the sunspot and starspot and that you are seeing differences in umbra, penumbra and plage. I think it all has to do with the flux tube model.

Vogt: All that I am saying is that morphologically they do not seem similar to giant sunspots at all.

Uchida: Takoshi, Sakurai and I have recently proposed a new picture for the starspots. We propose the equivalent of a solar active longitude belt corresponds to the trough of the photometric wave rather than a simple spot. Spots are formed, drift across this belt and disappear.

Vogt: We are saying exactly the same thing.

Uchida: Yes, it is somewhat similar to your view. We have a poster paper on it.

Walter: I just want to say that in the Sun one does see active longitudes. You see a rotational 27 day period in the sunspot number. (Following partly lost) You even may see this in A stars. The other point is that the spots don't appear to go much earlier than A. Some work has been done on post-T Tauri stars and they appear to have spots on them. They are about 2×10^6 years old, about the same age as the T Tauri stars. So these phenomena appear to be with stars across their entire lifetime.

Vogt: Yes. I don't think it cares about the age of the star but only about the presence of a convection zone and rotation.

Basri: With regard to the definition of a BY Dra star, Chugainov has observed this phenomenon in HD 1835 (?) so apparently a wider range of spectral types exhibit these phenomena than previously thought.

Vogt: That might be.

Basri: There might be A, F and G dwarfs showing these effects.

Vogt: That would be very nice to look for. I did not do a complete literature search to see how early a spectral type has spots. Most of them however seem to be at G8 or later.

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