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Joel A. Eaton
Tennessee State University

Gregory W. Henry
Tennessee State University

Francis C. Fekel
Tennessee State University

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RANDOM SPOTS ON CHROMOSPHERICALLY ACTIVE STARS

Joel A. Eaton, Gregory W. Henry, and Francis C. Fekel
Center for Automated Space Science and Center of Excellence in Information Systems, Tennessee State University, Nashville, TN 37203
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ABSTRACT

We have investigated the effect of large numbers of moderately sized spots placed randomly on a differentially rotating star as the explanation of the rotational light curves of magnetically active cool stars. This hypothesis produces light variation very similar to observed light curves of RS CVn binaries, provided there are of order 10–40 spots at any time and provided individual spots have a finite lifetime.
Subject headings: stars: activity — stars: late-type — stars: variables: other (miscellaneous)

1. INTRODUCTION

Over the past few years, we have fitted light curves of many chromospherically active (CA) variable stars with a two-spot model (see Henry et al. 1995, and references therein). The actual implementation we use is a simple curve-fitting scheme, devised by Hall (see Hall, Henry, & Sowell 1990), which approximates the effect of a spot as the lower lobe of the cosine function and fits a light curve with one or two such dips to find the spots' longitudes and strengths. In spite of the obvious simplicity, derived results are comparable to those of full-blown spot solutions (see, e.g., Rodonò et al. 1986; Strassmeier et al. 1988; Strassmeier & Olah 1992) that also attempt to determine spot latitudes and radii. Such light-curve solutions for stars with many years of photometry tend to find two dark starspots at any one time, rotating with slightly different periods. The spots seem to live for about 2 yr each and to be replaced, often in pairs, by others at roughly the time they dissipate. Hall (see Hall & Henry 1993) has devised a theory explaining the spot lifetimes as being due to simple evaporation for small spots and to the shear of differential rotation for large ones. Analyses of rotational periods derived for many such spots on a given star imply differential rotation one or two orders of magnitude lower than solar (in terms of k of eq. [1]). Long-term changes in the mean brightness of these stars ($\tau \sim 10$ yr) have suggested solar-type spot cycles.

A two-spot model explains the light variation of chromospherically active stars very well. Yet there are reasons to suspect chromospherically active stars have many more than two spots on their surfaces. Solutions of light curves, especially when combined with contemporaneous line profiles, imply much more complicated spot distributions in some cases (see Noah, Bopp, & Fekel 1987; Eaton et al. 1993; Rodonò, Lanza, & Catalano 1995). Our analysis of RS CVn, for instance, found six to eight spots of roughly 14° radius, much smaller than the sizes of spots derived in a traditional two- or three-spot analysis (e.g., Kang & Wilson 1989); there could well have been more. In RS CVn, *eclipses* of spots have been detected (Eaton et al. 1993), which require only moderately large spots (29° × 16° in 1992). Furthermore, actual Doppler images of stars also tend to find a more complicated distribution of surface brightness than expected for two or three large spots only (see Strassmeier et al. 1993; Kürster et al. 1992; Hatzes 1995). In an especially good example, Kürster, Schmitt, & Cuitispoto (1994) used a two-temperature algorithm to obtain a Doppler image of the K0 V star AB Dor that showed five major spot areas. Those areas were not large coherent spots but were resolved into numerous smaller structures or spot groups. Kürster et al. argued that much of that structure was real and pointed out that smoothing constraints used in other Doppler-imaging techniques necessarily suppress much smaller structures.

If there are truly many spots on all these chromospherically active stars, are the signatures we have taken as proof of a few large, dark spots for the past 20 yr merely the necessary result of clumping in random distributions of a large number of spots? Such clumps would be concentrations in longitude of independent spots, not the coherent, cogenerate groups often mentioned somewhat disingenuously as alternatives to the one or two continental spots being imagined. In this many-spot formulation, differential rotation provides a way of rearranging the clumps of spots, thus giving new apparent large "spots" and perhaps providing some degree of apparent differential rotation for the two "spots" thus identified.

We are using this paper to present and test the idea that moderately large numbers of randomly distributed starspots cause the observed photometric variation of chromospherically active stars. To test it, we have calculated sets of light curves for 20 different random distributions each of five to 40 dark spots on a rapidly rotating star. We find this approach (1) gives rotational light curves that look like observations of chromospherically active stars; (2) provides two-spot solutions similar to those for actual stars, and with the right amount of apparent differential rotation; and (3) gives appropriate changes in mean light level from season to season if spots have a limited lifetime, of the order of 1 yr. Section 2 explains what calculations we have made, tells how we analyze the results, and gives some examples. Section 3 tests the random-spot model. Section 4 discusses implications for two-spot analyses. Section 5 summarizes our results and suggests further tests.

2. CALCULATIONS

We have calculated light curves for circular spots placed randomly over the surface of a star, letting an initial distribution of such spots evolve under differential rotation over a period of 14 yr with suitable seasonal gaps. In these calculations, spots are simulated as circular areas (angular radius r), of constant temperature (3500 K), located at longitude λ and latitude β on a spherical star (4700 K) rotating about an axis inclined i (70°) to the line of sight. Longitudes are measured in the direction of rotation from a point defining the zero of the photometric phases, and surface brightness in the V band is approximated with the Planck function calculated at 5460 Å and linear limb darkening ($x_V = 0.66$).

We assume the rotational period of the star is 10 days at latitude 30°. This latitude divides the star into equatorial and polar zones of equal area. We then choose a number of spots ($N = 5, 10, 20$, or 40) and distribute them randomly in longitude, λ, and sine of latitude, sin (β), so as to give an equal probability per unit surface area over the whole star. We assign the spots rotational periods from a solar differential-rotation law,

$$P(\beta) = P_{\rm eq}/(1 - k \sin^2 \beta) , \qquad (1)$$

where $P_{\rm eq}$ is the equatorial rotational period, and k defines the amount of differential rotation ($k = 0.03$ for most of our calculations, as discussed in § 3, but 0.18 for the Sun). The longitudes of these spots change with time with respect to the assumed 10 day mean rotation through differential rotation

$$\lambda(t) = \lambda(t = 0) + 360° \Delta t[1/P(\beta) - 1/P_{\rm ave}] . \qquad (2)$$

$P_{\rm ave}$ is the mean rotational period of the star, assumed to be 10 days. We then calculate a series of light curves for circular spots. We have taken the spot radius squared to be inversely proportional to the number of spots, and we have let the radius be $r = 15°$ for the case with 10 spots; these choices make the total spot area constant for all the calculations and give all the light curves roughly the same depression (see Table 1, col. [3]). We have used the analytical formulae of Budding (1977) in the actual calculations of light loss and have ignored overlaps of the spots, assuming that any spots coming into contact would deflect one another as though they are little magnetic islands floating in the photosphere. Also, to save time, we calculated only every fifth light curve.

One final provision of some of these calculations was destruction of existing spots and creation of new ones. We let spots disappear with a constant probability per unit time of $1/\tau$, where τ is the lifetime. These dying spots would be replaced by other randomly placed spots with a probability of N/τ, where N is the initial number of spots, to give a roughly constant number throughout the 14 yr sequence.

A typical 14 yr light curve looks like Figure 1. In the upper panel we see effects of differential rotation alone on the light of a star with 20 spots. To be sure this calculation is representative, we chose it by lot; the other 19 have essentially the same features. In the lower panel we illustrate the added effect of spot dissipation and random emergence by giving the spots a lifetime of $\tau = 1$ yr. Of particular interest is the apparent cyclical behavior (period ~6.9 yr).

Table 1 gives some statistical properties of light curves for various numbers of random spots. Column (3), $\langle \Delta V \rangle$, gives the average light loss for all 20 × 62 light curves calculated for a case (N, τ). The quoted uncertainty is the amount each 14 yr set of light curves differs from the mean of 20 sets, a measure of the variation from one random distribution of spots to another. Column (4), $\sigma_{\rm ave}$, gives the standard deviation of the mean light in each 10 day light curve from the mean of the 62 light curves in its set, averaged over the 20 sets. For calculations with a constant number of spots, this number is no more than ~0.004 mag—nonzero only because we have averaged in magnitude space. For cases allowing the creation and destruction of spots, $\sigma_{\rm ave}$ represents roughly the level of variation from season to season. Column (5), $\sigma_{\rm L.C.}$, gives the standard deviation of a calculated point from the mean magnitude of its light curve, averaged over all the light curves for case (N, τ). This number thus represents the average amount of rotational modulation expected from a given number of spots. Column (6), $F(\leq 0.03)$, gives the fraction of the 20 × 62 calculated light curves for which the maximum brightness is depressed by no more than 0.03 mag. This quantity mea-

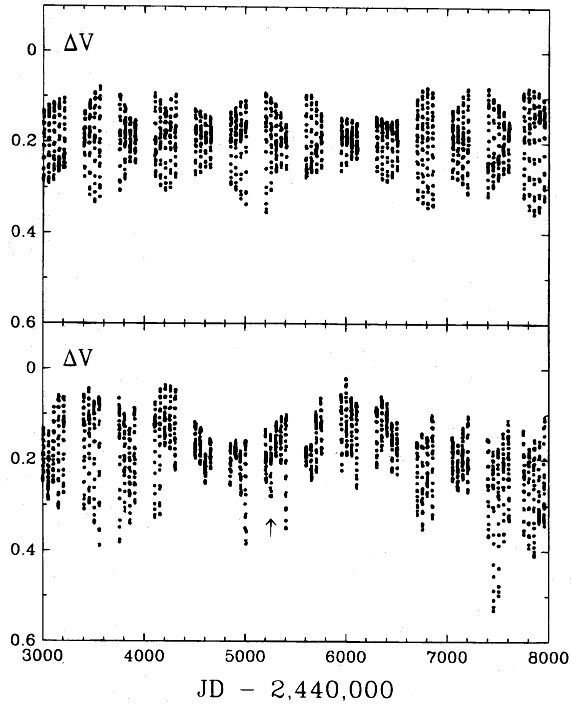

FIG. 1.—Two simulated data sets for a star with 20 spots distributed randomly over its surface. Data points represent every fifth rotational light curve over the 60% of the year we assume the star could be observed. In the upper panel, the initial complement of spots remains throughout the simulation; in the lower panel, we have let the spots come and go with a lifetime of 1 yr. Compare these figures with Figs. 2, 7, 13, and 18 of Henry et al. (1995) and Fig. 1 of Strassmeier, Hall, & Henry (1994) for actual spotted stars. Similarities are the changes in amplitude of light variation from year to year in our simulations for both constant and variable spot distributions. The changes in mean brightness seen in actual stars, however, are found only in the simulation with variable spots. Those changes show the apparent cyclic behavior often seen in real stars.

TABLE 1

STATISTICAL PROPERTIES OF RANDOM SPOTS ($i = 70°$)

N[a] (1)	τ (yr) (2)	$\langle \Delta V \rangle$ (3)	$\sigma_{\rm ave}$ (4)	$\sigma_{\rm L.C.}$ (5)	$F(\leq 0.03)$ (6)	$r_{\rm Spot}$ (7)
5	∞	0.169 ± 0.042	...	0.11	51%	21°2
10	∞	0.173 ± 0.021	...	0.08	12	15.0
20	∞	0.177 ± 0.015	...	0.06	1.0	10.6
40	∞	0.173 ± 0.010	...	0.04	< 0.1	7.5
5	1.0	0.176 ± 0.037	0.085	0.12	54	21.2
10	1.0	0.182 ± 0.028	0.061	0.09	21	15.0
20	1.0	0.174 ± 0.016	0.045	0.06	4.3	10.6
20	2.0	0.177 ± 0.018	0.035	0.06	2.3	10.6
20	4.0	0.166 ± 0.026	0.032	0.06	4.9	10.6
40	2.0	0.174 ± 0.017	0.022	0.04	~0	7.5
11 stars[b]	...	...	0.035	0.05	...	...

[a] Number of spots.

[b] Average for λ And, σ Gem, II Peg, and V711 Tau (Henry et al. 1995), HR 7275 (Strassmeier, Hall, & Henry 1994), V350 Lac (Crews et al. 1995), BM Cam (Hall et al. 1995), V835 Her (Hall & Henry 1994), V478 Lyr (Hall, Henry, & Sowell 1990), EI Eri (Strassmeier 1990), and V1149 Ori (Hall et al. 1991).

sures how likely a spotted star is to show an unspotted hemisphere. The bottom line of the table gives comparable statistics for some actual stars. This table shows in columns (3)–(5) that the variability expected of random spots decreases as the number of spots increases.

There were systematic changes in properties of the light curves as the number of spots increased. Specifically, variability is less with more spots, as expected. This can be seen in Table 1, where the range of light loss from a given number of randomly placed spots (col. [3]), the variation from light curve to light curve caused by destruction and creation of spots (col. [4]), and the rotational modulation (col. [5]) all decrease from five to 40 spots.

Once the theoretical light curves are calculated, we may solve them with the two-spot formalism described by Henry et al. (1995). In this two-spot formalism, the effect of a spot is represented by the lower dip of a cosine curve centered on the orbital phase of that "spot's" greatest visibility. Adding two of these dips together in magnitude space, translated appropriately in rotational phase and depressed by a magnitude at maximum brightness, gives a calculated light curve fitted to the observed light curve. Properties of the fit are the rotational phases of the "spots," "spot" amplitudes, and zero magnitude. Phases represent stellar longitudes of "spot" centers in the two-spot model.

3. RESULTS: FOUR TESTS

How well do the light curves calculated for random distributions of spots approximate those of actual stars? There are several criteria we may apply: First, do the calculated light curves for different numbers of random spots actually have the right shapes? Second, can series of these light curves be fitted with a two-spot model to identify "spots" that migrate in rotational phase with the right rate and persist as long as do those in actual stars? Third, do the calculated light curves have the right amplitude within a given year and from year to year as actual stars? And, fourth, do the calculations reproduce the apparent long-term cyclic variability, which has heretofore been taken to be caused by spot cycles? We will address these questions in succession below.

Correct light curves?—All of the random spot distributions we have calculated give phase variation like that seen in actual photometry of RS CVn binaries. To see this, we have plotted up about 2500 of the light curves, ΔV versus rotational phase, looking for discrepant examples. The features we saw in these calculated light curves were the same sort we have fitted in observed light curves over the years with the two-spot model. Furthermore, the dips in calculated light curves maintained themselves for at least a year, often longer, despite the fact we used a rather large differential-rotation parameter. Even the distributions of 40 spots showed these coherent dips. Only the light curves for five spots seemed inconsistent with observations, in that they tended to show too many cases with only one apparent "spot" and showed too much variation from changing numbers of spots.

The random-spot model has a further advantage over a strict two-spot model. It produces dips in light curves broader than the signatures of individual large spots (see Henry et al. 1995, Fig. 1). This is, then, the reason that such a simple approach as the double-dip model seems to work so well. Figure 2 shows a two-spot fit to a typical theoretical light curve, and Figure 3 gives the corresponding spot distribution. Figure 4 shows another such aspect of the general agreement, the gradual decay of amplitude in actual observations of V2253 Oph and in a theoretical calculation. In the two-spot model, this decay of amplitude would be caused by the slow evaporation of a spot; here, it is caused solely by differential rotation naturally rearranging spots.

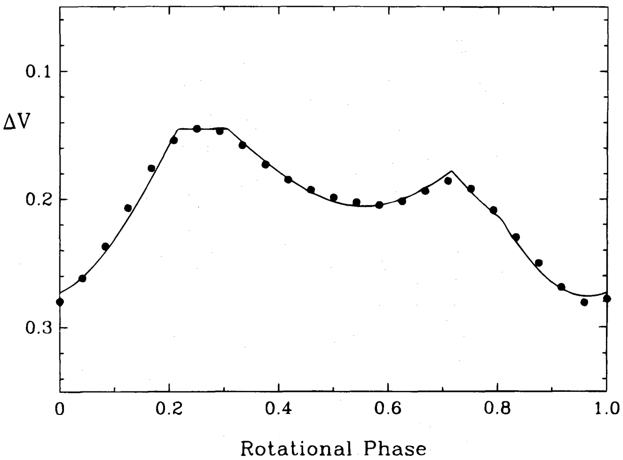

FIG. 2.—Fit of a randomly selected light curve from Fig. 1 (*bottom panel, arrow*) with the two-spot model. Compare with Figs. 3, 8, 14, and 19 of Henry et al. (1995), Figs. 2 and 3 of Strassmeier, Hall, & Henry (1994), Figs. 2–4 of Hall et al. (1991), and Figs. 2–4 of Hall, Henry, & Sowell (1990) for actual spotted stars. The fitted curve deviates from the 25 points by $\sigma = 0.004$, about the same as in actual stars with allowance for observational errors.

Correct migration curves?—This is potentially the toughest test of all, inasmuch as the changing dips in calculated light curves must remain coherent over periods of 2–3 yr (for $k \sim 0.01$ at $P = 10$ days) and must migrate through the light curve at an appropriate rate if the model is to reproduce phenomena in actual stars. Figure 5 (*upper panel*) is a migration diagram based on the two-spot model. It is so called because a spot rotating faster or slower than an assumed rotation period appears either later or sooner in successive light curves. Thus the spot *migrates* through the light curve, and this migration is what a two-spot analysis measures most reliably. The rate of migration in both two-spot and multiple random-spot models is proportional to the amount of differential rotation, k in equation (1). The bigger the differential rotation, the faster "spots" migrate, but, also, the faster the random concentrations will break up and reform (as in Fig. 4).

Thus, the sternest test is for a value of k at the top of the observed range. Equations (1) and (2) imply that the rate of migration per unit time is proportional to k/P. We can

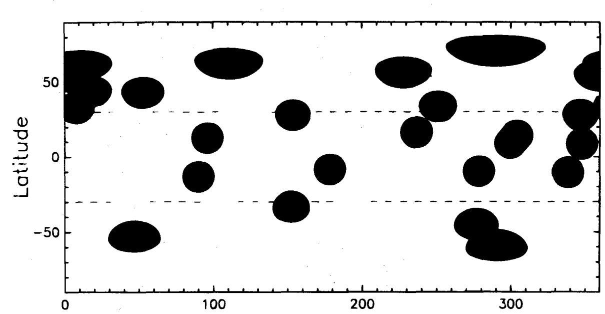

FIG. 3.—Distribution of spots used to calculate the light curve in Fig. 2. Plotted spots are all the same ($r = 10\overset{\circ}{.}6$), as assumed in this calculation.

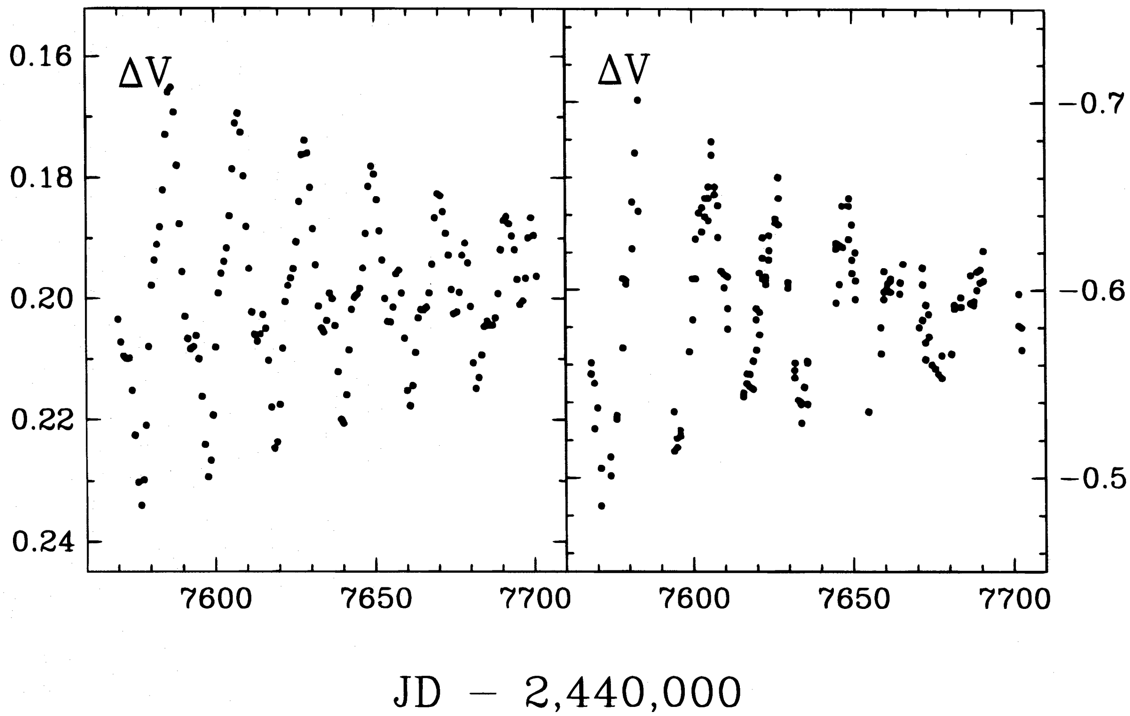

FIG. 4.—Comparison of the decaying amplitude in chromospherically active variable V2253 Oph (*right*) and in a theoretical calculation for 20 spots (*left*). In the calculation, this change results solely from rearrangement of a constant number of spots by differential rotation. In the past, this behavior in actual stars has sometimes been taken to show decay of a starspot.

therefore define a value of k that would give the same effect in our model calculations (with $P = 10$ days) as in actual stars. The values of k measured with the two-spot model for nine well-studied stars (λ And, σ Gem, II Peg, and V711 Tau [Henry et al. 1995], HR 7275 [Strassmeier, Hall, & Henry 1994], V350 Lac [Crews et al. 1995], V478 Lyr [Hall et al. 1990], V1149 Ori [Hall et al. 1991], and BM Cam [Hall et al. 1995]) range from $10k/P_{\rm Rot} = 0.007$ to 0.021, with a median value of 0.010. We have chosen to use $k = 0.03$ for our calculations, which gives a more severe test of the model. In contrast, $10k/P_{\rm Rot} = 0.067$ for the Sun.

Phasing of the "spots" in light curves without destruction or creation of spots seemed to be preserved well in the three to four cases we have fitted. For the three cases we considered with changing numbers of spots, we could identify and follow "spots" about as well as in observations of actual RS CVn binaries. Figure 5 is an example of this. "Spot" lifetimes were somewhat shorter than measured in actual stars, but this is to be expected from the large value of k we assumed; it could be remedied by changing k (in eq. [1]) from 0.03 to a more realistic 0.01 (and possibly increasing the spot lifetime). In fact, one example we did calculate with $k = 0.01$ gave "spot" lifetimes in the range 0.27–2.46 yr with a median of 1.23 yr. This is similar to the 0.2–6.5 yr range, with median of 1.5 yr, found by Henry et al. (1995) for 53 actual "spots."

Correct amplitudes of variation?—If random spots are to explain the light variations, they must provide the full range of light variation measured in chromospherically active stars. There are two aspects of this, the variation in individual light curve (Table 1, col. [5]) and the year-to-year changes (Table 1, col. [4]). In both cases, random spots produce enough variation to satisfy observations of most stars observed for numbers of spots in the range 10–40. Amplitudes of variation are most consistent with 20–30 spots.

Correct long-term cyclic variation?—Columns (3) and (4) of Table 1 imply that long-term photometric variation of chromospherically active stars is the result both of changes in the way a constant number of spots is distributed in latitude and of changes in the number of spots. Figure 1 shows an especially convincing example of long-term variation, which we have replotted in Figure 6 with actual obscrvations of λ And. Other calculations for 20 spots with lifetimes of 1 and 2 yr gave long-term variation, often with apparently a single cycle in the 14 yr span (median cycle length of 10–12 yr).

Another question related to cycles is the idea that we can occasionally observe a chromospherically active star in an unspotted state. Our calculations show that, even with 10–40 starspots, there are a few times at which differential rotation would clear almost all the spots from one hemisphere. Thus, the unspotted, immaculate magnitudes assumed in many spot solutions may have a basis in reality.

4. VALIDITY OF TWO-SPOT ANALYSES

Many stars have now been analyzed with a two-spot model that follows dips in rotational light curves, identifies spots with these dips, and derives spot lifetimes and degree of differential rotation from migration and persistence of these dips. What results of such analyses would survive the adoption of the random-spot model? The most fundamental property of two-spot analyses seems to be the amount of differential rotation. As we have seen in § 3, in four well-investigated cases, the amount of differential rotation derived from a two-spot analysis is roughly the same as that put into the multispot model analyzed. The derived differential rotation should thus be reliable to at least better than

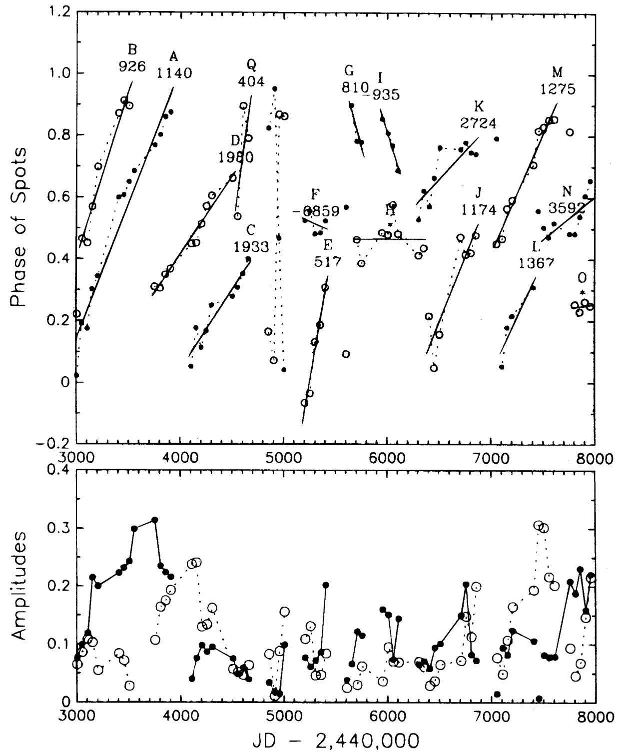

FIG. 5.—Spot migration and amplitude curves for the data of Fig. 1 (*bottom panel*). We have measured positions in orbital phase and amplitudes in magnitudes of "spots" with the two-spot model and then identified individual "spots" and measured their migration periods. A migration period (the number given below the spot symbol) is the beat period between the "spot's" actual rotational period and the assumed 10 day mean rotational period. In this example, spot E has a rotational period of 9$^{\rm d}$810 and spot I, 10$^{\rm d}$108. The range is thus 0$^{\rm d}$298, or $k = 0.030$. This value is fortuitously the same as the $k = 0.03$ used to calculate the motions of the actual randomly placed spots. Three other migration curves we have analyzed give k values of 0.021, 0.023, and 0.037. Compare with Figs. 4 and 5, 9 and 10, 15 and 16, and 20 and 21 of Henry et al. (1995), Figs. 5 and 6 of Hall, Henry, & Sowell (1995), and Fig. 4 of Strassmeier, Hall, & Henry (1994) for some actual spotted stars.

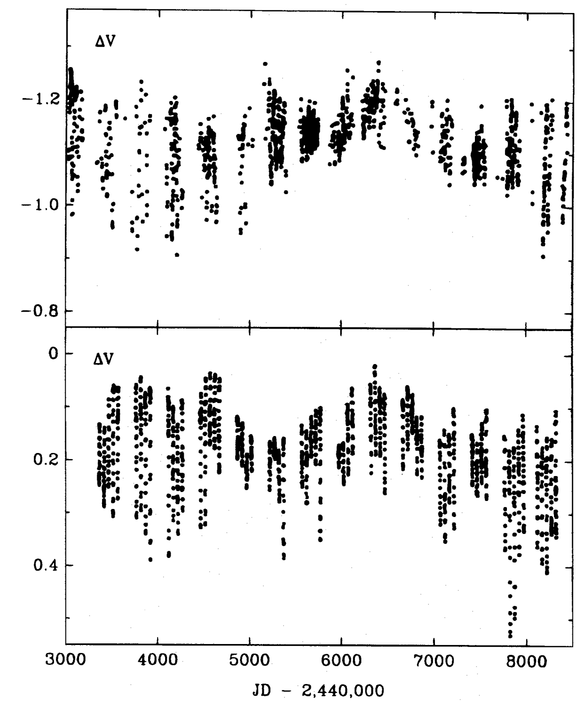

FIG. 6.—Cyclic behavior of spotted stars: λ And at the top and the theoretical calculation of Fig. 1 (shifted by 1 yr) below. Note the many features in common to both curves, some of which can actually be seen in the same season. The 11.1 yr cycle seen in λ And by Henry et al. (1995) is consistent with the 10–12 yr median cycle lengths observed in our random-spot models using 20 spots with lifetimes of 1–2 yr.

a factor of 2.

Spot lifetimes derived from migration diagrams, however, are merely an artifact of the rate at which the clumping of random spots changes; thus, they have nothing to do with actual spot lifetimes, but they do provide an independent check on degree of differential rotation. Ironically, the idea that large, dark "spots" may be created by differential rotation rearranging a random distribution of many small spots follows directly from Hall's explanation of lifetimes of big "spots." If shear of differential rotation can spread a large spot out around the star, it can inversely take spots spread in longitude and concentrate them. The apparent lifetimes (~2 yr) are the times for differential rotation to break up these concentrations and form new ones.

Magnetic cycles derived from photometric cycles are similarly suspect, since we have produced these effects entirely by letting old spots randomly decay and new ones be born on a timescale of years.

5. SUMMARY AND SUGGESTED TESTS

Our calculations show that, at least to the level of our preliminary tests, a moderately large number of moderately sized spots, randomly distributed on the surface and dissipating with a lifetime of the order of a year or so, account for all the long-term photometric changes of highly spotted magnetic stars. Even random distributions of 40 spots give rotational variation of ~0.03 mag r.m.s. in a given star. Thus, the effects of spots are hardly ever evenly distributed in longitude unless the number of random spots is greater than 40. Fewer than ~10 spots seem to give too much change from one light curve to another and too many light curves with only one apparent "spot."

The traditional two-spot approach assumes there is a deterministic cyclical mechanism forming spots. But the actual light curves require nothing more than for spots to pop up randomly on the surface of the star. This is not to say that actual dynamos of magnetically active stars do not produce spots at preferred latitudes, as the solar dynamo does, but rather, if so, there must surely be so many preferred latitudes, all operating simultaneously, that the spot emergence seems random. Durney, Mihalas, & Robinson (1991) speculated that the transition from such a complicated dynamo to the simpler solar-type dynamo may explain the Vaughan-Preston gap in Ca II emission.

So far, we cannot say how long spots live in multispot analysis. However, this may be possible in a more detailed study that looks at stochastic changes in spotted stars' light and derives migration diagrams for theoretical random-spot models with different values of τ.

Further tests of the random-spot model are (1) much better Doppler images that can resolve smaller features on spotted stars, preferably a series of such images to follow the spots identified; (2) a more thorough investigation of tens of migration curves of randomly spotted stars to determine the systematic errors of measuring differential rotation with the two-spot model; and (3) a comparison of statistical properties of spotted stars with small and large inclinations, since for stars with small values of i, we sample fewer spots on average and can expect a bigger fractional change from the death of a single spot. So far, we cannot say how long spots live in multispot analysis. However, it may be possible in a more detailed study that looks at stochastic changes in spotted stars' light and derives migration diagrams for different values of τ.

For the record, the idea that multiple spots are needed to model the behaviour of HD 163621 was proposed by Dr. Roger Griffin in 1992 to F. Fekel and G. Henry. This research has been supported by NASA grant NCCW-0085 establishing the Center for Automated Space Science and NSF grant HRD 9550561 for analysis of chromospherically active variable stars.

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