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HD 12545, a Study in Spottedness

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ABSTRACT. We have solved two sets of light curves of HD 12545 at its epoch of extreme spottedness in 1990–91, one of which coincides with an independent set analyzed recently by Strassmeier and Olah (1992). Even for the huge amplitudes observed, these light-curve solutions did not give reliable determinations of several important spot properties. Specifically, we find that we could obtain acceptable solutions for a wide range of inclination; that spot temperature depends on inclination assumed, falling in the range $\Delta T = T_{\rm star} - T_{\rm spot} = 650-1200$ K for inclinations of 70–30°; that spot latitudes derived from the light curves are unreliable; and that our independent spot solutions disagree with Strassmeier and Olah's. On a more positive note, changes in the light curve over the past five years seem to have been caused primarily by rearrangement of persisting spot groups, and we note that the high level of activity implied by its Hα emission makes HD 12545 a prime candidate for a white-light flare star.

1. INTRODUCTION

The variable HD 12545=XX Tri is a chromospherically active (CA) binary star with the distinction of having shown the largest amplitude of light variation from spots yet recorded (Nolthenius 1991). It became a CA suspect on the basis of Bidelman's (1985) survey spectra. Bopp et al. (1993) have since confirmed the high level of activity and refined the star's properties with high-dispersion spectra. They find that HD 12545 is a 23.97-day single lined spectroscopic binary, dominated by a K0 III chromospherically active component ($R \sim 9R_\odot$). This star, in fact, is so active that it has always exhibited Hα emission, like the very most chromospherically active giants, and it shows the usual ultraviolet tracers of extreme activity. Hooten and Hall (1990) found the star is a rotational spotted variable with a moderate amplitude (0.16 mag) in photometry for 1986–87, as did Skiff in unpublished photometry for late 1985 (Strassmeier and Olah 1992). Subsequent photometry by Nolthenius (1991) showed an unprecedented amplitude in rotational modulation (0.6 mag in *V*) and further photometry by Strassmeier and Olah (1992) showed the amplitude almost as large (0.5 mag in *V*).

The *BVRI* photometry of Nolthenius defines both the light and color variation of this spotted star at an epoch when it had the highest spot amplitude ever recorded. Since the star apparently does not eclipse, and since the companion contributes very little of the combined light of the binary system (Bopp et al. 1993), we have in HD 12545 the equivalent of a *single* rapidly rotating chromospherically active giant star. We therefore have the opportunity of fitting a light curve to define the temperature, latitudes, and sizes of spots in an RS CVn binary. In analyzing this star, we are concentrating on the following questions. (1) How well can the latitudes of spots be determined for stars with more than one large spot? (2) What is the spot temperature, and how well is it known? (3) How well do independent analyses agree on derived spot properties? and (4) What changes in the spots accompany changes in the light curve?

2. OBSERVATIONS

The observations we are considering consist of the Johnson/Cousins *BVRI* photometry of Nolthenius plus *BV* photometry gathered during the same observing season with the Vanderbilt/Tennessee State 16-inch robotic telescope (APT) (Henry 1995). All observations were made differentially with respect to the comparison star HD 12478. These data divide naturally into two groups, one containing the observations before JD 2,448,258, and a second consisting of the data thereafter (see Fig. 1). There seem to have been changes in the light curve that became prominent at that date; specifically, the maximum brightness was somewhat reduced in the second group. The first group (Epoch I) contains the data of Nolthenius (29 nightly means of ~3 observations per night) along with seven *V*-band data from the APT (nightly means of three observations). The second group (Epoch II) consists of 15 nightly means from the APT. Estimated uncertainties of the data are σ=0.03 mag for Nolthenius, which we are using for all the data in the first group, and σ=0.009 mag for the APT data, as derived from scatter in differential photometry of the check star, HD 14041. Because the *B*-band data had considerably more scat-

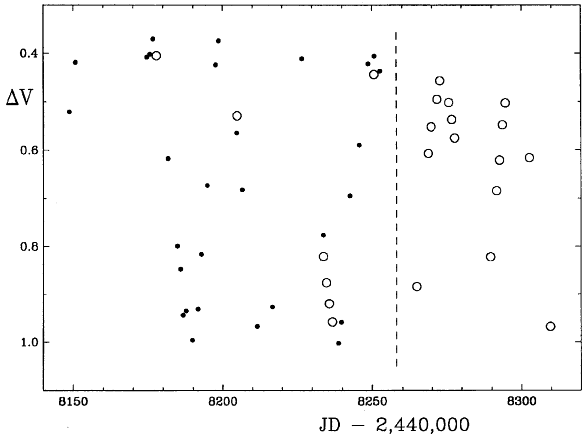

FIG. 1—The visual observations analyzed. Data from Nolthenius are plotted as dots, APT data as circles. The light variation was clearly changing during this season, with the brightness at maximum light decreasing. A vertical line at JD 2,448,258—roughly the time the change in maximum brightness became apparent—divides the data into two sets. The first set contains all the photometry of Noltenius; the second, only APT data.

ter than photometry at *VRI*, we have decided not to analyze these *B* data but to concentrate instead on fitting simultaneously the *VRI* light curves of Nolthenius (1991) and the *V* data from the robotic telescope.

We have calculated phases with a preliminary ephemeris of Fekel (1992),

$$\text{HJD (Obs.)} = 2{,}448{,}132.613 + 23.9902 \cdot \text{Phase}, \qquad (1)$$

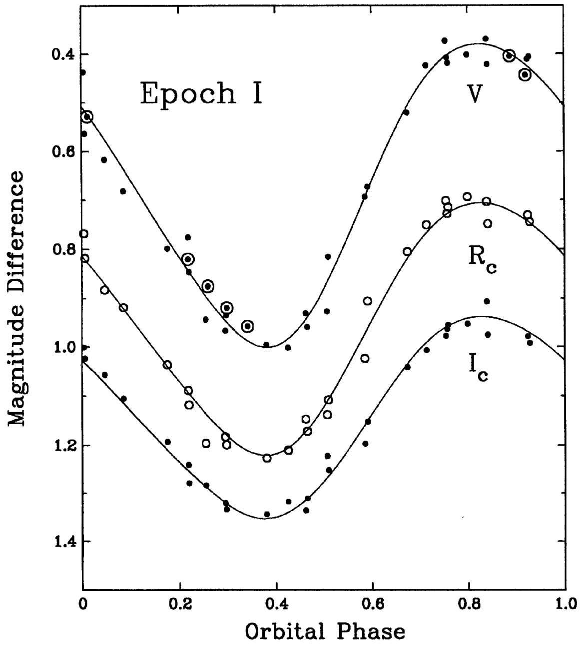

FIG. 2—Sample fits for Epoch I. Data for red and infrared bands have been displaced downward by 0.2 and 0.4 mag, respectively. The circles points for *V* are data from the APT; all other data are from Nolthenius. Solid curves represent the theoretical solution for $i = 50°$; those for 30 and 70° are equally good.

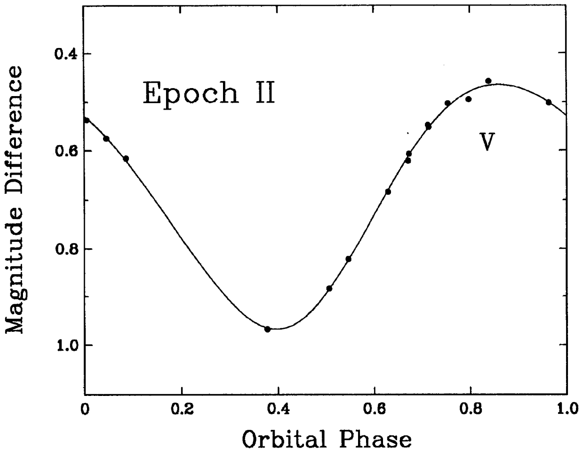

FIG. 3—The fit for Epoch II with $i = 50°$. The observed data are all from the APT.

which gives phases smaller by 0.203 cycles (73° in stellar longitude) than the ephemeris of Bopp used by Strassmeier and Olah (1992). The correspondence between stellar longitudes is more difficult to calculate, however, since we measure ours in the direction of rotation while Strassmeier and Olah seem to measure theirs in opposite rotation, but the transformation is

$$\lambda_{\rm us} = (\lambda_{\rm S\&O} + 73°). \qquad (2)$$

3. THE MODEL

We are fitting the analytical spot model of Budding (1977) to the data. In it, spots are simulated as circular areas (angular radius r) of constant temperature, located at longitude λ and latitude β on a spherical star rotating about an axis inclined i to the line of sight. Longitudes are measured in the direction of rotation from an arbitrary zero point defined by the zero of the photometric phases [i.e., of Eq. (1) for HD 12545]. If spots do not overlap, we can place an arbitrary number of them on the star; in our solutions for HD 12545, the spots graciously did not overlap. We have approximated the surface brightness in each photometric band with the Planck function calculated for the effective wavelengths, 5460, 6600, and 8250 Å, respectively, for V, R_c, and I_c.

Once the sizes and positions of the spots are specified, the light loss at any rotational phase may then be calculated. This dimming, however, is measured with respect to the brightness the star would have without any spots, a level that would hardly ever be known accurately, although there may be some hope of it (Eaton et al. 1996). This level may thus be specified *a priori* as a fixed light level, or it may be derived from solutions to the light curves as a fitted zero point in each band—ΔV_0, ΔR_0, and ΔI_0, for instance. These two approaches will lead to different spot solutions because of the way they constrain the spots allowed. If the zero point is specified *a priori*, then the maximum size of a spot is limited, and more small spots will likely be required to fit a light curve. On the other hand, if the zero points are free parameters, the spots' sizes and positions are less constrained, so that fewer spots may be required by a light curve. The unspotted star will likely be brighter in this case.

Zeilik has applied this model extensively to the short-period RS CVn binaries to find properties of their spots (Budding and Zeilik 1987; Zeilik et al. 1988; Zeilik et al. 1989; Zeilik et al. 1990a; Zeilik et al. 1990b). Since these short-period systems seem to have only one moderately large spot at any time, the Budding model would be well suited to them and has given statistically well-determined measurements of spot latitude, a property notoriously difficult to determine, for quite a number of light curves. Application to the longer-period RS CVn binaries, which almost always have asymmetrical light curves implying at least two spots or spot groups, is much more difficult. Yet we have in hand what should be two of the most restrictive light curves for such a star.

To apply the Budding model, we wrote a computer program to calculate the light loss at an arbitrary rotational phase given a set of spot properties. It calculates the light loss for a specified configuration of spots at each phase and color for which we have an observation. When the light loss is calculated for all the observed photometric data, the program chooses the zero point for each photometric band that will eliminate the sum of deviations of calculated magnitudes from observed magnitudes in that band. The program then adds these zero points to the calculated magnitudes, subtracts the calculated from observed magnitudes, and calculates χ^2. To find a solution, the program explores a wide range of parameter space, varying each spot property over a wide range of possible values and finding the minimum of χ^2. By changing the range over which the program varied the parameters, we extensively explored the possible parameter space. In practice, we varied the sizes and positions of the two spots and a spot temperature while keeping the inclination fixed.

After finding acceptable solutions, we then determined errors of the properties by calculating χ^2 around the derived value of each property and measuring how much change in the parameter is required to give a significant change in χ^2. This procedure gives lower limits to the errors since it does not allow correlations among the parameters to propagate errors among them.

4. SOLUTIONS OF THE LIGHT CURVES

Solutions for the two epochs are given in Table 1 and plotted in Figs. 2 and 3. We list in Table I properties of the two spots, zero points of the photometry in each band (the magnitude difference, var-comp., of the equivalent unspotted star), χ^2 for each solution, the number of data fitted, and the fraction of the star's total surface covered by the two spots, expressed as a percentage. Since χ^2 is comparable to the degrees of freedom (the number of observations *minus* the number of free parameters, =84 and 8 for the two epochs), and is essentially the same for all three inclinations, we must conclude that two spots fit the data adequately and that there is no preference for any particular inclination.

Some of the properties of the binary and its spots simply cannot be derived from the light curves and must be assumed. They are the effective temperature of the K0 star (4700 K), the fraction of light contributed by the unseen second star (zero), the limb-darkening coefficients and the inclination of the rotational axis to the line of sight. This inclination could be within a very large range, so we have obtained separate solutions for three possible values, 30°, 50°, and 70°. Contrary to Strassmeier and Olah (1992), we have obtained equally good solutions for all three inclinations, so it seems clear that the inclination cannot be derived reliably from the present photometry. We note that there is a difference in spot temperature, i.e., $\Delta T = T_{\rm star} - T_{\rm spot}$, between us (850 K) and Strassmeier and Olah (1100 K) at i=50°. This may be due to some extent to differences in the assumed effective temperature of a K0 star or to differences in the limb darkening assumed. We assumed 4700 K to their 4820 K, which an have only a second-order effect on the relative temperature of spots. Our limb-darkening coefficients ($x_v = 0.66$, $x_R = 0.54$, and $x_r = 0.43$), were derived from models of Carbon and Gingerich (1969) chosen early on to agree with an old G5 IV spectral type given by Strassmeier et al. (1988), since revised in Strassmeier et al. (1993). These values are low for a K0 star, but the full range of x_λ is similar to the expected range for K stars—specifically, $x_V - x_I = 0.23$ vs. the 0.25 used by Strassmeier and Olah, but this should have little effect on derived spot temperatures.

TABLE 1
Light-Curve Solutions

Epoch:	I			II		
Inclination:	30	50	70	30	50	70
λ_1	40.1±1.2	86.0±1.1	92.9±1.1	62.5±2.4	109.6±1.4	110.5±1.3
β_1	48.9±1.9	61.1±0.8	54.0±1.2	41.8±5.4	75.6±0.5	60.9±1.0
r_1	31.1±0.4	46.0±0.6	57.0±0.7	24.0±0.6	60.2±1.1	57.8±1.0
λ_2	161.9±0.7	177.1±1.2	180.1±1.9	163.0±1.2	180.9±2.2	189.9±2.0
β_2	47.5±2.0	27.8±3.0	25.0±6.3	43.3±5.6	49.2±3.3	46.8±2.4
r_2	46.0±0.4	33.0±0.4	34.9±0.5	40.0±0.4	23.1±0.4	30.4±0.6
$T_{\rm spot}$ (K)	3500±20^a	3850±13^a	4050±27^a	(3500)	(3850)	(4050)
ΔV_0	-0.021	0.237	0.327	0.281	0.085	0.383
ΔR_0	0.134	0.373	0.455	–	–	–
ΔI_0	0.204	0.418	0.491	–	–	–
χ^2	71.2	71.4	71.1	6.62	6.68	6.82
No. obs.	94	94	94	15	15	15
% spotted	22.5	23.3	31.8	16.0	29.1	30.2

Note: Values of inclination, longitude (λ_i), latitude (β_i), and spot radius (r_i) are in degrees. % spotted is the fraction of the whole surface of the star covered by spots. a. These errors quoted for $T_{\rm spot}$ are actually errors in $\Delta T = T_{\rm star} - T_{\rm spot}$ and do not reflect uncertainties in photospheric temperature.

5. DISCUSSION

The six solutions derived in the last section can be subjected to further tests of their validity and used to investigate questions about the spot model. We shall do so by addressing the questions of the following paragraphs.

What does the unspotted magnitude ΔV_0 tell about the spot distribution? We have let the unspotted brightness of the star vary in our solutions, and the values derived for it provide one test of our models. If this two-spot model is realistic, the unspotted magnetic should not change within a year and should probably always stay about the same. We notice, however, that ΔV_0 is quite different for the first two of our representative inclinations, 30 and 50°. Changes of the magnitude derived in those two solutions imply rapid creation or dissipation of spots comparable in size to some of those used to fit the light variations, or they require changes in

$(B - V)$ color of 0.04–0.07 mag between the two epochs. Both of these possibilities are unrealistic: the former because it would seem to have changed the phasing of the light curve so little, and the latter because the required changes in $(B - V)$ color, hence in surface brightness, are not seen to the required extent in measurements of HD 12545 with the APT or in other RS CVn binaries (e.g., Henry et al. 1995). That the change of ΔV_0 is relatively small for the third inclination, 70°, may be a point in its favor, but other geometrical properties of the spots change unrealistically from Epoch I to Epoch II in that solution. So, although there may be some inclination at which the unspotted magnitude does not change from epoch to epoch, the three statistically valid and equivalent solutions we have obtained are physically invalid by this test.

How well have latitudes of spots been determined in this case with two large spots? Strassmeier and Olah (1992) concluded, from disagreement between two independent analyses of the same light curve, that latitudes are poorly determined. Formally, our latitude determinations seem good, typically ±1–3°. However, solutions for the two epochs in 1990–91 are inconsistent. Solutions for $i = 50$ and 70° had one spot jump 20° in latitude, and the other moved roughly 10°. Such changes in spots, which migrate smoothly in a wide variety of stars similar to HD 12545, seem rather unlikely (Henry et al. 1995). Here, we see analyses of consecutive light curves giving discordant latitudes, so again there is evidence that latitudes cannot be reliably extracted from photometry of even light curves with high amplitudes.

What is the spot temperature? The solutions show that the spot temperature derived depends rather strongly on the inclination assumed. Actual temperature differences ranged from $\Delta T = T_{\rm star} - T_{\rm spot} = 1200$ K at $i = 30°$ to $\Delta T = 650$ K at 70°. The standard error of ΔT, as we have determined it, is quite small, just as in Strassmeier and Olah, but the inclination and spot temperature are clearly correlated in this case.

How well does our analysis for Epoch II agree with the independent analyses of Strassmeier and Olah? They agree poorly, and part of the disagreement results from different assumptions about the nature of spots. Strassmeier and Olah allowed three large spots to our two, which will necessarily fit a given light-curve distortion differently. They also constrained the unspotted magnitude difference, ΔV_0, to a value so faint that large spots would not be allowed at high visible latitudes. We, on the other hand, let the unspotted magnitude float and consequently found large spots at high latitudes for the same assumed inclination. In our solution for $i = 50°$ (the same inclination assumed by Strassmeier and Olah), we found one huge spot centered at $\beta = 75°$, while centers of the dominant spots found by Strassmeier and Olah were 28°. We note that the latitudes found from a belt model of the same epoch by Eker (1995) were ±18°. The correspondence between our spot longitudes and those of Strassmeier and Olah (1992) is likewise poor—their dominant spot A, for instance, seems to correspond to our spot No. 1, but the longitudes are 63° and 110°, respectively, in our system of coordinates. Their spot C corresponds better to our spot 2 with longitudes 181° and 174°, respectively.

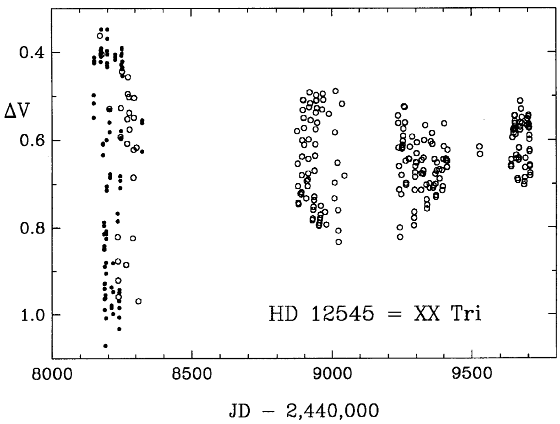

FIG. 4—Light variations since the 1990–91 extremum. As in Fig. 1, dots are for Noltenius, circles for the APT. Mark the change between the first year and the last three years. The APT data are missing for the 1991–92 season because of delays caused by upgrading the photometer (Henry 1995). Note the decrease in amplitude at constant average brightness in the first three years illustrated. The phenomenon is caused most likely by rearrangement of a constant area of spots, probably the direct result of differential rotation. The 0.05 mag brightening in the fourth year, on the other hand, implies a change in the total area of spots.

What changes in the spots caused the change in the light curve between Epoch I and Epoch II? Solutions of these light curves give little guidance. As we have seen in the last three paragraphs, there are such strong systematic differences for different reasonable assumptions about spots, that differences between solutions at the two epochs cannot be considered significant, at least for data of the quality of those in hand. The epochs we have analyzed represent an extreme for this star and has not recurred since. Figure 4 shows the brightness as measured over the past five observing seasons, 1990–91 through 1994–95. These data show phenomena common to the RS CVn binaries. It is clear that the amplitude of light variation became much less in the last three observing seasons, while the minimum brightness decreased. Average V magnitude difference, a rough measurement of total spottedness, was 0.653, 0.653, 0.660, and 0.603 for the four seasons illustrated. Thus the total amount of spottedness changed very little, at least until the final season, while the rotational modulation caused by these spots became much less. This effect can be accomplished most easily by a redistribution of a constant area of dark starspots, as we have postulated for such stars as σ Gem, II Peg, V711 Tau, EI Eri, HD 212280, DQ Leo, AY Cet, V1762 Cyg, V478 Lyr, V1149 Ori, and V1764 Cyg (Henry et al. 1995). Eaton et al. (1996) have argued that different rotation rearranging a moderately large number of spots often produces exactly this phenomenon. In fact, in the year JD2,449,200−9500 we see just the decay of rotational amplitude illustrated by Eaton et al. (1996) in their Fig. 4 and explained as the effect of differential rotation on a distribution of several tens of spots. The changes after JD 2,449,600, on the other hand, require a change in spot area, most likely accomplished by the death of one or more moderately sized spots.

Finally, we would like to stress the extremity of chromspheric activity in this star. This is one of the few *giants* that have always shown Hα emission (Bopp et al.

1993). Such persistent Hα emission makes this star a prime candidate for white-flaring light (Henry and Newsome 1995).

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