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STARSPOTS FOUND ON THE ELLIPSOIDAL VARIABLE V350 LACERTAE = HR 8575

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ABSTRACT

It has been a puzzle why this chromospherically active, strong-dynamo K2 IV-III star is not known to have the large starspots characteristic of other such stars. Published individual radial velocities, which had never been analyzed, are used to derive an orbital solution. Combined with the one older existing orbital solution, this yields an improved orbital ephemeris: time of conjunction (K star behind) = JD 2445255.47±0^{d}11 and period = 17^{d}75346±0^{d}00016. All available photoelectric photometry, from 1970.9 to 1992.5, is collected. A cos 2θ fit of the ellipticity effect yields JD 2445255.60±0^{d}06 for a time of conjunction, 17^{d}7523±0^{d}0005 for the period, and 0^{m}084 for the peak-to-peak amplitude in V. With the ellipticity effect removed, the light curve *does show* measurable starspot variability in 15 of 16 data groups, the starspot wave amplitudes ranging between 0^{m}03 and 0^{m}08. Ten starspots are identified and their rotation periods determined, the mean being 17^{d}70±0^{d}03 (confirming synchronous rotation) and the range being $\Delta P/P=0.017\pm0.006$ (indicating differential rotation). There is a slow variation in mean brightness, almost 0^{m}1 in range and at least 2 decades in length.

1. INTRODUCTION

HR 8575 = HD 213389 is a bright ($V=6^m4$) K2 giant and an SB-1 of orbital period 17^{d}755 (Northcott 1947). Though one of the earliest recognized RS CVn-type (Hall 1976) or chromospherically active (Strassmeier *et al.* 1993) binaries, no photometric variability due to large starspots has ever been established. Variability per se was discovered by Herbst (1973) but attributed to the ellipticity effect, which gave it a peak-to-peak amplitude of 0^{m}13 in V. The variable star designation is V350 Lac. From the spectroscopic orbit of Northcott (1947), the $V \sin i$ of Fekel *et al.* (1986), and the ellipticity effect amplitude, Hall (1990) determined $54° < i < 73°$ for the inclination, $0.72 < F < 0.79$ for the K star's Roche-lobe-filling fraction, $0.95 < M_1 < 1.29 \mathscr{M}_\odot$ and $9.9 < R_1 < 11.7$ $R_\odot$ for the K star, and $0.73 < M_2 < 1.14 \mathscr{M}_\odot$ for its unseen companion. This radius estimate indicates that the K2 IV-III classification of Herbst (1973) is more realistic than the K2 III seen more frequently in the literature.

Large starspots are found on the surface of the active star in virtually all known RS CVn-type binaries, in fact, in virtually all chromospherically active stars of any type. Hall (1991a, 1994) showed that large-amplitude variability (defined as $>0^m01$ in V) resulting from rotational modulation of starspots is *restricted to* the strong-dynamo stars, where a surprisingly sharp threshold between ineffective and effective dynamos lies at a Rossby number (ratio of rotation period to convective turnover time) of Ro=0.65. The $>0^m01$ cutoff had been selected as an amplitude larger by one order of magnitude than the amplitude of photometric variability caused by rotational modulation of spots on the Sun, the best-studied weak-dynamo star. Only a perplexing few strong-dynamo stars *have not shown* significant photometric variability. We can follow the recipe of Hall (1991a, 1994) to calculate the Rossby number for the K giant in V350 Lac from its known rotation period, its known $(B-V)_0$, and its IV-III luminosity class. The result is Ro=0.14, well below the Ro=0.65 threshold, meaning V350 Lac is one of these perplexing few. Our principal motivation for studying V350 Lac was to search for the large starspots we believed should be there. Photometric investigations following that of Herbst (1973) were based on only one observing season (Percy & Welch 1982), three seasons (Strassmeier *et al.* 1989), or two seasons (Demircan *et al.* 1992) and found evidence for starspot variability only suggestive.

[1]Deceased, July 1992.

TABLE 1. New photometry of V350 Lac.

observatory name	observatory location	telescope aperture	observers
Braeside	Arizona	16-inch	R.E.Fried
Dyer	Tennessee	24	G.W.Henry
Kitt Peak	Arizona	16	G.W.Henry
Landis	Georgia	8	H.J.Landis
Lines	Arizona	20	H.C.Lines + R.D.Lines
Louth	Washington	11	H.P.Louth
Mt. Hopkins	Arizona	16	D.S.Hall + G.W.Henry
Skillman	Maryland	12.5	D.R.Skillman

2. AVAILABLE PHOTOMETRY

We have made the maximum effort to assure that our investigation is based on *all* photoelectric photometry of V350 Lac which exists, both published and unpublished. Published photometry is found in Herbst (1973), Percy & Welch (1982), Boyd *et al.* (1990), and Demircan *et al.* (1992). Additional photometry, by J. A. Eaton, is found in file No. 147 of the I.A.U. Commission 27 Archive for Unpublished Observations of Variable Stars (Breger 1988). Photometry not published before now, which we make use of in this paper, was obtained with the telescopes listed in Table 1. It has been sent to the same previously mentioned Archive, where it is available as file No. 294 (Schmidt 1992). Most of this photometry was in more than one bandpass, but only the V band of the UBV system was in common to all, so we restricted our analysis to the V.

All of the available photometry was differential with respect to a comparison star, was corrected for differential atmospheric extinction, and (with one exception) was transformed to the standard V band. In most cases each "observation" was actually a mean of generally three intercomparisons between the variable and its comparison star. In making use of the 4 years of photometry from the 10 in. APT (Boyd *et al.* 1990) we added $0^{\rm m}.71$ to the ΔV values between JD 2,446,218.92 and 2,446,245.89, which had been affected by "Problem D," and we deleted the data between JD 2,446,385.69 and 2,446,443.97, which had been affected by "Problem E." Problem D had been caused by the yellow filter falling out and the correction was effectively a supplementary color-dependent transformation, especially large in this case because of the unusually large $\approx 1^{\rm m}.1$ difference in $B-V$ between the variable and its comparison star. The photometry of Percy & Welch (1982), made in the y band of the $uvby$ system and apparently not transformed to the V, lay systematically high in the light curve, so we made those 9 Δy values fainter by $0^{\rm m}.075$.

The Boyd *et al.* (1990) photometry and all of the telescopes in Table 1 except the 20 in. in Arizona used 4 Lac = HR 8541 as the comparison. The other sources of photometry used HD 213776. For both stars, several determinations of the V magnitude appear in the literature, the most accurate (in our judgement) being $V=4^{\rm m}.590$ for 4 Lac given by Rufener (1988) and $V=7^{\rm m}.708$ for HD 213776 measured by

TABLE 2. Radial velocity curve elements.

Source of data	K_1 (km/sec)	γ (km/sec)	T(conj.) (K star behind)
Northcott (1947)	40.1 ±0.5	+5.35 ±0.36	2441691.82 ±0.04
Beavers & Eitter (1986)	40.8 ±1.6	+5.88 ±1.30	2445255.47 ±0.11

J. A. Eaton (Breger 1988). We added $3^{\rm m}.12$ to all of the ΔV values made with HD 213776 as comparison.

The entire photometric dataset ranges from JD 2,440,923.6 to 2,448,798.0, which is 21.5 years, and the total number of ΔV values (after the deletions due to Problem E) is 635.

3. IMPROVED ORBITAL EPHEMERIS

To uncover starspot variability, we will need to remove the variability produced by the ellipticity effect, which is invariant in shape and amplitude for any given binary system. Moreover, because it is strictly in phase with the orbital period, we need an accurate determination of the orbital ephemeris. In principle one could remove the ellipticity effect by analysis of the photometry alone, but this would be risky due to the additional variability caused by starspots which may be present and might distort the times of minimum light used to fix the epochs of conjunction.

The only spectroscopic orbit in the literature is that of Northcott (1947), with a period of $17^{\rm d}.755 \pm 0^{\rm d}.002$. Whereas she found an eccentricity of $e=0.0226 \pm 0.0073$, Lucy & Sweeney (1971) think the orbit actually is circular. We have used Northcott's velocities to redetermine the spectroscopic orbit, fixing $e=0$, and give the elements in Table 2. Our circular solution included a new determination of the period, namely, $17^{\rm d}.7537 \pm 0^{\rm d}.0021$, which is consistent with hers.

Beavers & Eitter (1986) published 12 radial velocities obtained in 1982 but never included in an orbital solution. We used these to determine the spectroscopic orbit, again fixing $e=0$, and give the elements in Table 2. The calculated curve and observed velocities are plotted in Fig. 1. Both the semi-

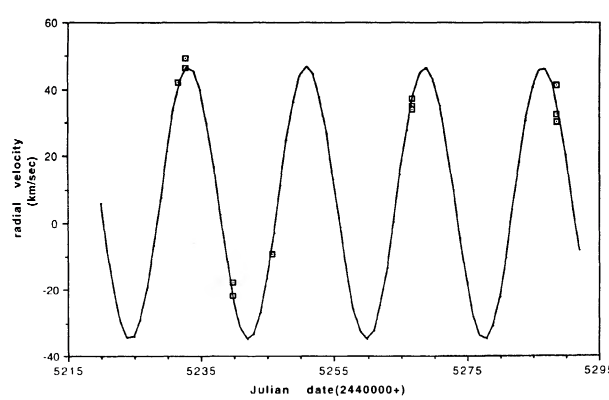

FIG. 1. Radial velocity curve of V350 Lac. Points are from Beavers & Eitter (1986) and the solid curve represents the elements in Table 2. A circular orbit has been assumed.

amplitude K_1 and the center-of-mass velocity γ are consistent with the corresponding values from our solution of Northcott's velocities. The 40-year baseline between the two lets us derive the much improved orbital ephemeris

$$\begin{aligned} \text{JD (hel.)} &= 2{,}445{,}255.47 + 17^{\mathrm{d}}\!.75346\ E \\ &\quad\ \pm 0.11 \quad \pm 0.00016 \end{aligned} \tag{1}$$

for times of conjunction with the K star behind.

4. THE ELLIPTICITY EFFECT

To represent the variability caused by the ellipticity effect, we used least squares to fit the entire photometric data base with a light curve containing $\cos\theta$ and $\cos 2\theta$ terms, where θ is phase computed with an ephemeris for times of conjunction with the K star behind. The $\cos 2\theta$ term will be the dominant one; the $\cos\theta$ term will measure any difference between the two minima, caused by the "pointed end effect" (Hall 1990). The result was

$$\begin{aligned} \Delta V &= 1^{\mathrm{m}}\!.799 + 0^{\mathrm{m}}\!.0015\ \cos\theta + 0^{\mathrm{m}}\!.0385\ \cos 2\theta, \\ &\quad \pm 0.001 \pm 0.0014 \qquad\quad \pm 0.0014 \end{aligned} \tag{2}$$

which means that the two minima had full amplitudes of $\Delta V = 0^{\mathrm{m}}\!.086 \pm 0^{\mathrm{m}}\!.003$ and $\Delta V = 0^{\mathrm{m}}\!.082 \pm 0^{\mathrm{m}}\!.003$, with the slightly deeper one at conjunction when the K star is behind and its pointed end faces Earth.

An additional result of this fit was an independent determination (from the photometry) of the orbital ephemeris,

$$\begin{aligned} \text{JD(hel.)} &= 2{,}445{,}255.60 + 17^{\mathrm{d}}\!.7523E, \\ &\quad\ \pm 0.06 \quad \pm 0.0005 \end{aligned} \tag{3}$$

which is consistent, within the errors, with the one (from the spectroscopy) in Eq. (1).

The ellipticity effect was removed from the entire photometric data base by subtracting the last two terms in Eq. (2) and the resulting "clean" light curve is plotted in Fig. 2.

5. SEARCHING FOR STARSPOT VARIABILITY

Analysis of the clean light curve in Fig. 2 should reveal any starspot variability which might be present. The range seen in the yearly data groups, over $0^{\mathrm{m}}\!.10$ in several, suggests that residual variability might be present. A slower variation, almost $0^{\mathrm{m}}\!.1$ in range and at least 2 decades in length, is also apparent.

Experience with starspot variability in many other chromospherically active or strong-dynamo stars guides our search. The K star probably rotates synchronously (Hall & Henry 1990). Any starspot on it should rotate with a period close to the $17^{\mathrm{d}}\!.75$ orbital period but may, depending on its latitude, rotate somewhat faster or slower (Hall 1991a). The expected light curve shape may be nearly sinusoidal, if one large spot is present, or more complicated if two or more spots are present and separated in longitude. Any given spot will have a lifetime of months or years, depending on various factors (Hall & Henry 1994). The finite lifetime means that the light curve shape may change abruptly within a given observing season.

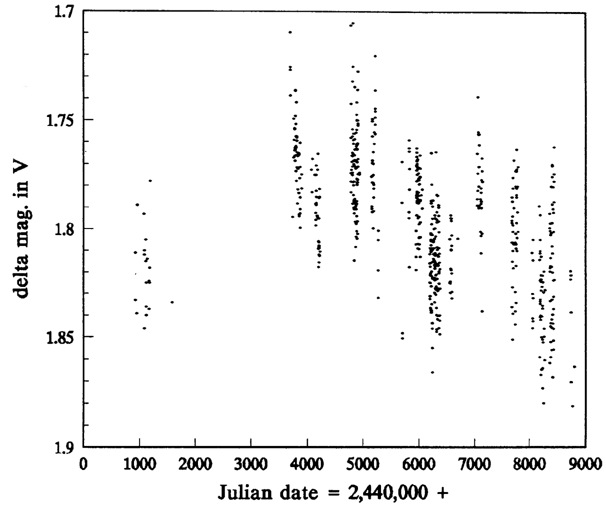

FIG. 2. The complete set of ΔV magnitudes for V350 Lac, based on 4 Lac as the comparison star, *after the variation due to the ellipticity effect has been removed.* The range seen in the yearly data groups proves to be residual variability produced by rotational modulation of starspots. A slower variation, almost $0^{\mathrm{m}}\!.1$ in range and at least 2 decades in length, is also apparent.

The 16 data groupings we adopted are given in Table 3. A convincingly smooth light variation of significant amplitude was apparent in *all but one* of them. We used the two-spot model of Hall *et al.* (1990) to fit the light curves of those 15

TABLE 3. Data groups.

data group	number of points	first/last JD=2440000+	median epoch	source
1	20	923.58 1580.60	1971.35	Herbst (1973)
2	53	3696.62 3903.65	1978.80	this
3	17	4078.78 4189.62	1979.71	this
4	19	4197.62 4227.69	1979.92	Percy & Welch (1982), this
5	97	4783.54 4934.22	1981.69	Demircan et al. (1992)
6	33	5155.38 5284.33	1982.68	Demircan et al. (1992)
7	12	5703.61 5838.95	1984.19	Boyd et al. (1990)
8	64	5957.67 6069.61	1984.86	Boyd et al. (1990), ark. 147
9	72	6197.97 6307.77	1985.51	Boyd et al. (1990)
10	49	6312.77 6384.69	1985.77	Boyd et al. (1990)
11	19	6564.97 6708.80	1986.56	Boyd et al. (1990)
12	31	7050.74 7141.66	1987.82	this
13	46	7683.94 7791.69	1989.58	this
14	47	8047.93 8272.57	1990.73	this
15	49	8357.99 8439.95	1991.38	this
16	7	8732.99 8797.95	1992.39	this

TABLE 4. Parameters of two-spot-model fits.

data group	period (days)	T(minimum) (JD=2440000+)	amplitude (mag.)	maximum (mag.)	rms (mag.)	wave (mag.)	spot name
1	17.66±0.01	926.68±0.11	0.070±0.002	1.772±0.001	0.005	0.070	A
	17.64±0.03	1180.98±0.19	0.056±0.003				B
2	17.62±0.08	3804.21±0.26	0.029±0.003	1.743±0.002	0.010	0.048	C
	18.08±0.08	3815.66±0.34	0.024±0.003				D
3	17.97±0.05	4136.64±0.17	0.026±0.002	1.766±0.001	0.003	0.027	D
	17.57±0.11	4159.81±0.22	0.023±0.001				C
4	16.90±0.53	4205.43±0.26	0.033±0.002	1.778±0.001	0.004	0.040	D
	17.77±0.71	4210.50±0.31	0.032±0.002				C
5	17.92±0.11	4866.03±0.28	0.036±0.003	1.748±0.002	0.016	0.042	C
	18.66±0.18	4861.23±0.39	0.026±0.003				D
6	18.28±0.15	5213.96±0.39	0.029±0.005	1.747±0.002	0.012	0.084	D
	16.46±0.13	5168.91±0.19	0.058±0.005				C
7	17.84±0.06	5710.10±0.39	0.069±0.010	1.765±0.005	0.014	0.069	E
8	17.77±0.09	5958.90±0.19	0.035±0.002	1.775±0.001	0.007	0.035	E
9	18.19±0.28	6244.52±0.35	0.030±0.004	1.797±0.002	0.015	0.030	E
	17.42±0.19	6271.43±0.62	0.023±0.003				F
10	17.36±0.12	6351.44±0.16	0.033±0.002	1.791±0.001	0.008	0.053	E
	17.62±0.08	6376.34±0.17	0.053±0.002				F
11	——	——	——	1.813±0.003	0.012	——	-
12	17.99±0.15	7108.91±0.34	0.034±0.006	1.762±0.002	0.010	0.054	G
	18.23±0.18	7079.34±0.38	0.026±0.004				E
13	17.68±0.06	7742.04±0.12	0.055±0.003	1.778±0.002	0.010	0.058	H
	17.95±0.16	7693.44±0.39	0.017±0.003				G
14	17.72±0.10	8231.70±0.43	0.039±0.006	1.816±0.002	0.015	0.039	I
	17.86±0.06	8059.16±0.60	0.025±0.005				H
15	17.60±0.11	8406.13±0.18	0.047±0.004	1.785±0.002	0.011	0.080	J
	17.31±0.09	8427.35±0.19	0.053±0.004				I
16	18.06±0.12	8759.77±0.19	0.055±0.003	1.822±0.002	0.002	0.055	J

data groups. The resulting parameters are given in Table 4, where the second column is the spot's rotation period, the third column is the Julian date of light minimum (when the spot faces Earth), the fourth column is the amplitude of the light loss produced by that spot, the fifth column is the value of ΔV at light maximum (when neither of the two spots is visible to Earth), the sixth column is the rms deviation of the ΔV values from the fit, and the seventh column is the total range of the light variation produced by the two spots working together, often called the starspot wave amplitude. In three of the 15, the light curve could be represented adequately with a one-spot fit.

One of the two-spot fits, data group 15, is illustrated in Fig. 3. Though each of the two produces a light loss of only $0\overset{m}{.}05$ as it turns into view, they are rather close together in longitude and thus work together to produce a total light variation or wave amplitude of $0\overset{m}{.}08$.

6. DISCUSSION AND CONCLUSIONS

We conclude that V350 Lac does vary in light by rotational modulation of starspots, in combination with the previously recognized ellipticity effect. Measurable starspots are present at virtually all epochs. In the absence of the ellipticity effect, V350 Lac's light curve would indeed show the familiar starspot wave, with a full range of $0\overset{m}{.}084$ in the extreme case, data group 6.

This finding of starspot variability does solve one little mystery. The light curve of Herbst (1973) had a total amplitude of $0\overset{m}{.}13$, which he attributed to the ellipticity effect, but no light curves published subsequently have ever shown an amplitude that large. Recall that we found a mean total amplitude of $0\overset{m}{.}084$. Our two-spot-model fit in Table 4 shows the two spots: at longitudes of 175° (very near one of the conjunctions) and 60°, and with amplitudes of $0\overset{m}{.}056$ and $0\overset{m}{.}070$. This arrangement means that the undisturbed cos 2θ curve of the ellipticity effect will have one minimum lowered by nearly the full amount of the $0\overset{m}{.}056$, the other minimum lowered by a fraction of the $0\overset{m}{.}070$, one maximum lowered, and the other maximum unchanged. As a result, the full amplitude (highest maximum to lowest minimum) of the observed light curve should be $0\overset{m}{.}084+0\overset{m}{.}056=0\overset{m}{.}14$.

From the 27 times of light minima in Table 4 we computed phases with the orbital ephemeris in Eq. (1) and pre-

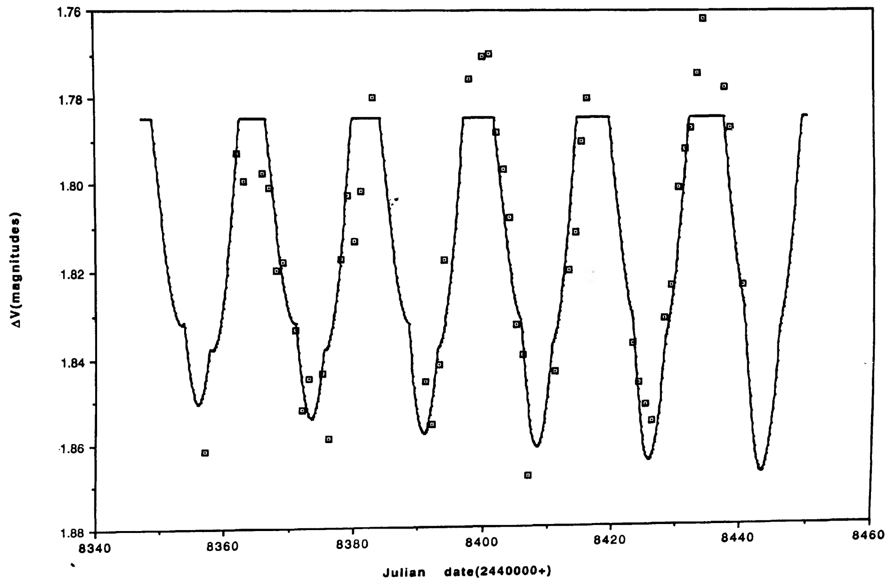

FIG. 3. The light curve of data group 15, with the ellipticity effect removed. The solid curve represents the parameters of the two-spot fit in Table 4. Though each of the two spots produces a light loss of only $0^{\rm m}.05$ as it turns into view, they are rather close together in longitude and thus work together to produce a total light variation or wave amplitude of $0^{\rm m}.08$.

pared a migration curve, i.e., fractional phase versus time, which can trace the gradual wandering of spots in longitude and identify a new spot by its sudden emergence at a very different longitude. In this way we tentatively identified spots which persisted from one data group into the next. They are designated A through J in the last column of Table 4. Note that three of the spots (C, D, and E) were especially long-lived, persisting for at least 4 years while drifting smoothly in longitude by only 60°, 90°, and 50°, respectively. These longer time spans let us derive spot rotation periods more accurate than those in Table 4, which were derived from single data groups. They are shown in Table 5. In some cases we had only two times of minimum light to work with, but we could use linear least squares when times were available from more than two data groups. Spots A and B came from a single data group but their periods were defined relatively well.

The weighted mean of the 10 spot rotation periods in Table 5 is $17^{\rm d}.70\pm0^{\rm d}.03$, very close to the orbital period and thereby confirming synchronous rotation. A chi square significance test of those 10 values and their errors indicates a very small probability (10^{-14}) that the rotation period is *not* a variable quantity. The maximum range exhibited by this sample of 10 measures is the difference between the longest value $17^{\rm d}.784\pm0^{\rm d}.012$ (ignoring the slightly longer value $17^{\rm d}.786$ with a much larger error) and the shortest value $17^{\rm d}.485\pm0^{\rm d}.107$. Expressed as a percent, the range is $\Delta P/P=1.7\%\pm0.6\%$, where the uncertainty here comes from the combination of the errors of those longest and shortest values. Given V350 Lac's known physical characteristics (rotation period and Roche-lobe-filling fraction of $F=0.75\pm0.04$), the study of differential rotation in a larger sample of stars by Hall [1991a, Eq. (2)] would have predicted $\Delta P/P=4.5\%\pm2.0\%$, *or less* if our sample of spots did not populate the entire 90° range of latitude.

The mean brightness in V is variable on a longer time scale, rising from $\Delta V=1^{\rm m}.82$ in 1971 to $\Delta V=1^{\rm m}.76$ in 1978/

TABLE 5. Rotation periods for ten starspots.

spot	period (days)	number of T(minimum)
A	17.659 ± 0.010	1
B	17.641 ± 0.033	1
C	17.714 ± 0.020	5
D	17.696 ± 0.018	5
E	17.784 ± 0.012	5
F	17.485 ± 0.107	2
G	17.713 ± 0.016	2
H	17.618 ± 0.034	2
I	17.786 ± 0.043	2
J	17.682 ± 0.013	2

1979 and falling to $\Delta V=1\overset{m}{.}84$ by 1992. This indicates an amplitude of at least $0\overset{m}{.}08$ in V and a time scale for one cycle at least 20 years long. From the data in hand we cannot say that one full cycle has been executed, nor that it will prove periodic, nor even that it will repeat in the future. Nevertheless, similar long-term cycles in mean brightness (amplitudes of $\approx 0\overset{m}{.}1$ and time scales of ≈decades) have been observed in a number of other chromospherically active stars and theory has been developed to link them to long-term magnetic cycles (Hall 1991b; Applegate 1992).

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