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NEW RADIAL VELOCITIES AND FURTHER PHOTOMETRIC OBSERVATIONS OF λ SCO AND κ SCO

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SUMMARY

Radial velocity measurements of the southern broad-lined stars λ Sco and κ Sco have confirmed their membership in the β Canis Majoris (or β Cephei) class of variables. Photometric observations of both stars were made from 1971 to 1973. These observations are investigated in addition to those obtained in 1969 and 1970, reported already in a previous paper. For λ Sco they show that neither the period nor the amplitude of the short-period variation are constant; the 10-day period is present in each year's observations. The beat period of $7^d\cdot3$ for κ Sco is confirmed, although there are significant variations in the amplitudes which are not accounted for by simple beating periods. Three colour observations were made for both stars on three nights in 1972.

Both λ Sco and κ Sco are binaries, but due to their unknown orbital parameters it has not been possible to attribute departures from periodic behaviour to the effects of the secondary.

1. INTRODUCTION

The variability of λ Scorpii and κ Scorpii was reported by Shobbrook & Lomb (1972, to be referred to as Paper I) from photometric observations made in 1969 and 1970. During those 2 years, spectrograms were also obtained and the measured radial velocities are discussed in this paper. In addition photometric observations have been made in each year since to 1973; these were mostly only in yellow light but three nights were spent in 1972 observing with the standard *UBV* filters.

The telescope mainly employed for the photometry was the 40-cm reflector at Siding Spring Observatory, Coonabarabran. The equipment and reduction procedures have been detailed in Paper I and in Shobbrook *et al.* (1969). In 1973 the stars were observed for three nights with the 60-cm telescope, with the same Corning 3384 filter and EMI 6094S photomultiplier as before, but using the Mt Stromlo capacitor and digital voltmeter integration system. The comparison stars for both variables were HR 6420, 6460, 6628 and υ Sco, the magnitudes being finally expressed with respect to HR 6628, which was measured on all nights.

The spectrograms were all taken at the coudé spectrograph of the 188-cm reflector at Mt Stromlo Observatory, at a reciprocal dispersion of 6·7 Å mm^{-1}. Three of the plates were taken by Dr R. D. Watson and the rest by RRS, who also measured the plates for radial velocities.

2. λ SCORPII

In Paper I we reported that λ Sco showed a single short periodicity of $0^d\cdot2137015$ in a light curve made markedly non-sinusoidal by the presence of its first harmonic.

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A longer period of 10·15 days was also indicated. On one night a mean magnitude was recorded which was some 0·04 mag fainter than on the other nights. We suggested that this may have been due to an eclipse, since the star is a known spectroscopic binary.

2.1 *Radial velocities*

There were 46 spectrograms of λ Sco obtained on five nights in 1969 and 1970. The spectrum shows broad lines, and although λ Sco is known to be a binary with approximately equal brightness components (Hanbury Brown, Davis & Allen 1974), only one spectrogram (that with a velocity of 92 km s^{-1}) which has strongly asymmetrical lines, gives any indication of the presence of a second spectrum. Slettebak (1975) mentions a spectrogram on which many of the lines are double with a separation of 120 km s^{-1}. At any rate, considerable effects due to blending are to be expected in the velocities. Hence, initially the plates were reduced to obtain individual line velocities only, so that these blending effects could be investigated before combining them to obtain plate velocities. The line rest wavelengths were the same as those used for α Vir (Shobbrook, Lomb & Herbison-Evans 1972).

From the photometric results of Paper I it was reasonable to assume that if there were any short period variations present in the velocities they would have a component at $0^{\mathrm{d}}{\cdot}2137015$. Therefore, a sine curve of this period was included in the model to be fitted to the velocities of each line. An inspection of the velocities indicated also a longer period, presumably due to the orbital motion. To allow for this, different mean velocity constants were fitted to the observations on each of the two nights on which the observations extended over short intervals and two mean velocity constants were fitted to each of the two nights on which the observations extended over longer intervals. The single observation on the last night was ignored at this stage. The model fitted to the observations was:

$$v_{\lambda i} = A_\lambda \sin\left\{\frac{2\pi}{0{\cdot}2137015}\, t_i + \phi_\lambda\right\} + K_\lambda{}^j \qquad \mathrm{j} = 1, 2, \ldots, 6$$

where $v_{\lambda i}$ is the velocity of the line of wavelength λ at time t_i and each $K_\lambda{}^j$ refers to a group of observations extending over less than $0^{\mathrm{d}}{\cdot}13$.

There was a difference between the mean He I singlet ($\lambda\lambda$ 4009, 4143, 4387) and the mean He I triplet ($\lambda\lambda$ 4026, 4471) velocities; the mean value of this difference over the six groups of observations was $\sim$14 km s^{-1}. This is equivalent to a wavelength shift of $\sim$0·19 Å to the blue in both λ 4026 and λ 4471, which is about what is to be expected due to the presence of forbidden components in these two broad lines. Systematic differences were also found between the mean H I and the mean He I singlet velocities of up to $\sim$13 km s^{-1}. The relation between the two mean velocities for all six groups of data may be expressed as:

$$\bar{K}_{\mathrm{H}}{}^j / \bar{K}_{\mathrm{He}}{}^j \sim \tfrac{2}{3}.$$

This implies that the amplitude of the *orbital* variation for the H lines is less than those of the He lines due to blending and also that the γ-velocity of the system is $\sim$0 km s^{-1}.

It is thus evident that to obtain the plate velocities the H lines cannot be used. This leaves only a small number of lines, so the correction to the He triplet lines cannot be ignored. The final radial velocities were obtained using only the He lines,

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TABLE I

λ Sco: radial velocities in 1969–70

Helioc. JD	V (km s^{-1})	Helioc. JD	V (km s^{-1})
2440000+		2240000+	
317·1938	−27·6	366·2067	−16·9
317·2257	−20·0	366·2157	−17·8
317·2535	−20·7	366·2428	−23·0
365·2324	−41·1	366·2505	−28·2
365·2379	−42·8	366·2817	−24·0
365·2574	−39·9	366·2900	−20·7
365·2608	−41·5	366·3123	−14·9
365·2761	−35·4	366·3192	−14·7
365·2810	−36·7	765·0216	+21·6
365·2956	−33·5	765·0271	+17·6
365·3004	−35·8	765·0542	+25·0
365·3226	−26·0	765·0584	+28·1
365·3317	−25·7	765·0972	+35·8
365·9435	−12·1	765·1007	+39·5
366·0477	−33·8	765·1403	+45·0
366·0512	−32·4	765·1452	+45·2
366·0769	−22·1	765·1750	+45·8
366·0887	−26·2	765·1813	+50·7
366·1185	−19·5	765·2257	+31·0
366·1241	−21·3	765·2292	+33·9
366·1637	−19·7	765·2618	+32·8
366·1720	−14·1	765·2702	+35·7
366·1873	−16·1	766·2681	+92·1

with the rest wavelength of 4026·218 Å corrected to 4026·030 Å and of 4471·507 Å corrected to 4471·320 Å. When calculating the plate means the line velocities were weighted by the squares of the inverses of the rms residuals from the model given above. The mean velocities found are listed in Table I.

Before examining the short-period variation it was necessary to remove the orbital variation from the velocities. An orbital period of $5^d{\cdot}6$ has been given by Slipher (1903) but since this was based only on 11 observations and Slipher had no knowledge of the short period variation, this is unlikely to be correct. The present data are also, unfortunately, unsuitable for the determination of the orbital period. The frequency spectrum of the velocities calculated using the frequency analysis computer program described in Paper I contained many high peaks, especially at low frequencies. The highest peak had a period near 10 days and it was subtracted from the data, together with its first harmonic, to remove the effects of the orbital variation. Note that this is merely an artifice—the period used was not the same as the 10-day period discussed later in Section 2.2.

In the least squares frequency spectrum of the residual velocities there were many high peaks, but since there was one centred on $0^d{\cdot}213702$, the photometric period P_1, that was taken as the true period. Subtraction of a sine wave with this period (prewhitening) reduced the rms residual about the mean velocity from 7·8 to 3·9 km s^{-1}. Again, in the residual spectrum there were many peaks but one was centred on the harmonic $\frac{1}{2}P_1 = 0^d{\cdot}10685$. The ranges resulting from a least squares fit of both P_1 and $\frac{1}{2}P_1$ to the velocities were $17{\cdot}1 \pm 1{\cdot}2$ and $6{\cdot}0 \pm 1{\cdot}3$ km s^{-1}, respectively. These two periods reduced the rms residual to 3·2 km s^{-1} and there

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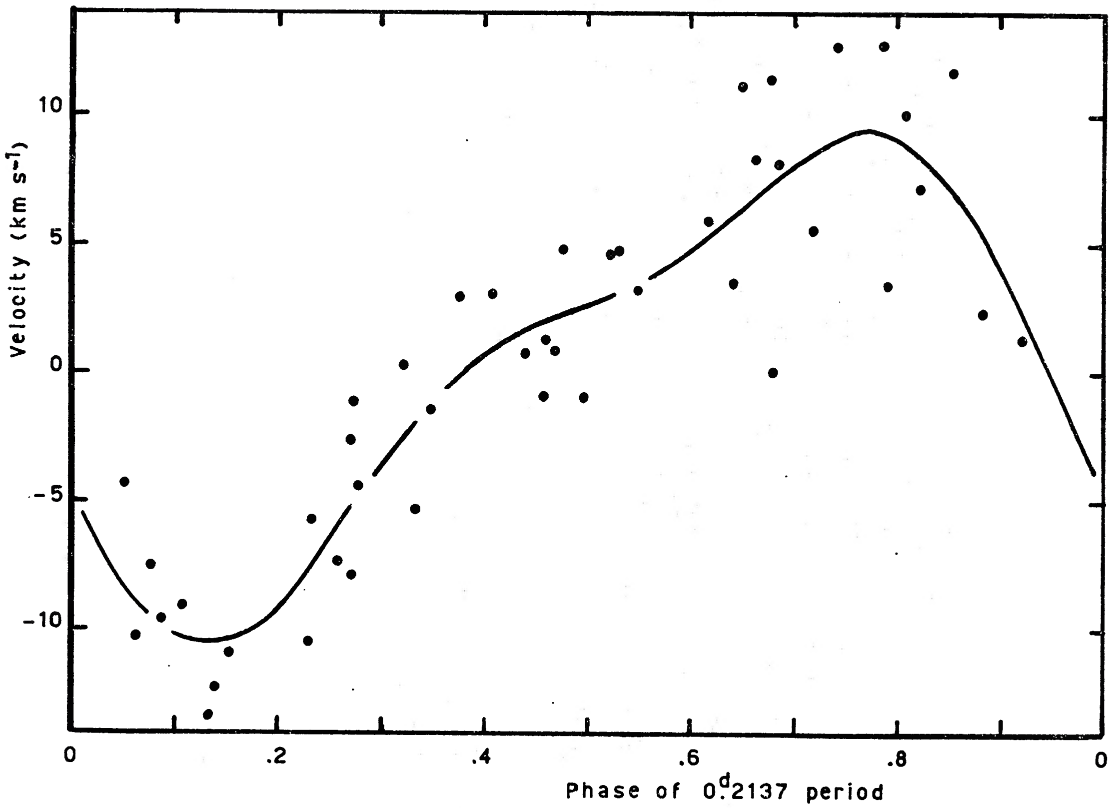

FIG. 1. *λ Sco: The* 1969–70 *radial velocities, with the orbital variation removed* (*Section* 2.1), *plotted against the phase of* P_1. *Phase zero corresponds to maximum light and the smooth curve represents the fit of* P_1 *and* $\frac{1}{2}P_1$ *to the data.*

was no significant periodicity left in the spectrum from $0^d.25$ to $0^d.05$. Fig. 1 shows the velocities, with the orbital variation removed, plotted against the phase of the P_1 period. The fitted curve is also shown. It is evident that the strongly asymmetric shape of the curve is the cause of the relatively large amplitude of the harmonic, the interval between maximum and minimum velocity being 0·63 P_1, instead of 0·5 P_1 as in a sine curve. The figure is drawn such that phase zero represents the phase of maximum light from Paper I. Although the phase of mean velocity on the decreasing branch of the fitted curve is −0·053, this phase difference from light maximum may not be significant as the curve is not well defined by the observations between phases −0·15 to +0·05.

2.2 *Light curves*

Fig. 2 shows the mean light curves for λ Sco in the 6 years from 1968 to 1973. The smooth curves are the P_1 and $\frac{1}{2}P_1$ waves for each year and the points are averages of an integral number of observations such that there are 40–50 points on each curve. In 1968 there were only 40 rather poor quality observations from two nights so that all are shown individually; the maximum was observed on one night and the decreasing branch on the other, two nights later. In 1969 four nights and 279 observations are represented, in 1970 10 nights and 228 observations, in 1971 seven nights and 146 observations and in 1972 seven nights and 220 observations. In 1973, 89 observations were obtained on three nights, on the two longest of which the mean magnitude was changing significantly during the night so that the true shape of the curve is not well defined. There are small but noticeable differences

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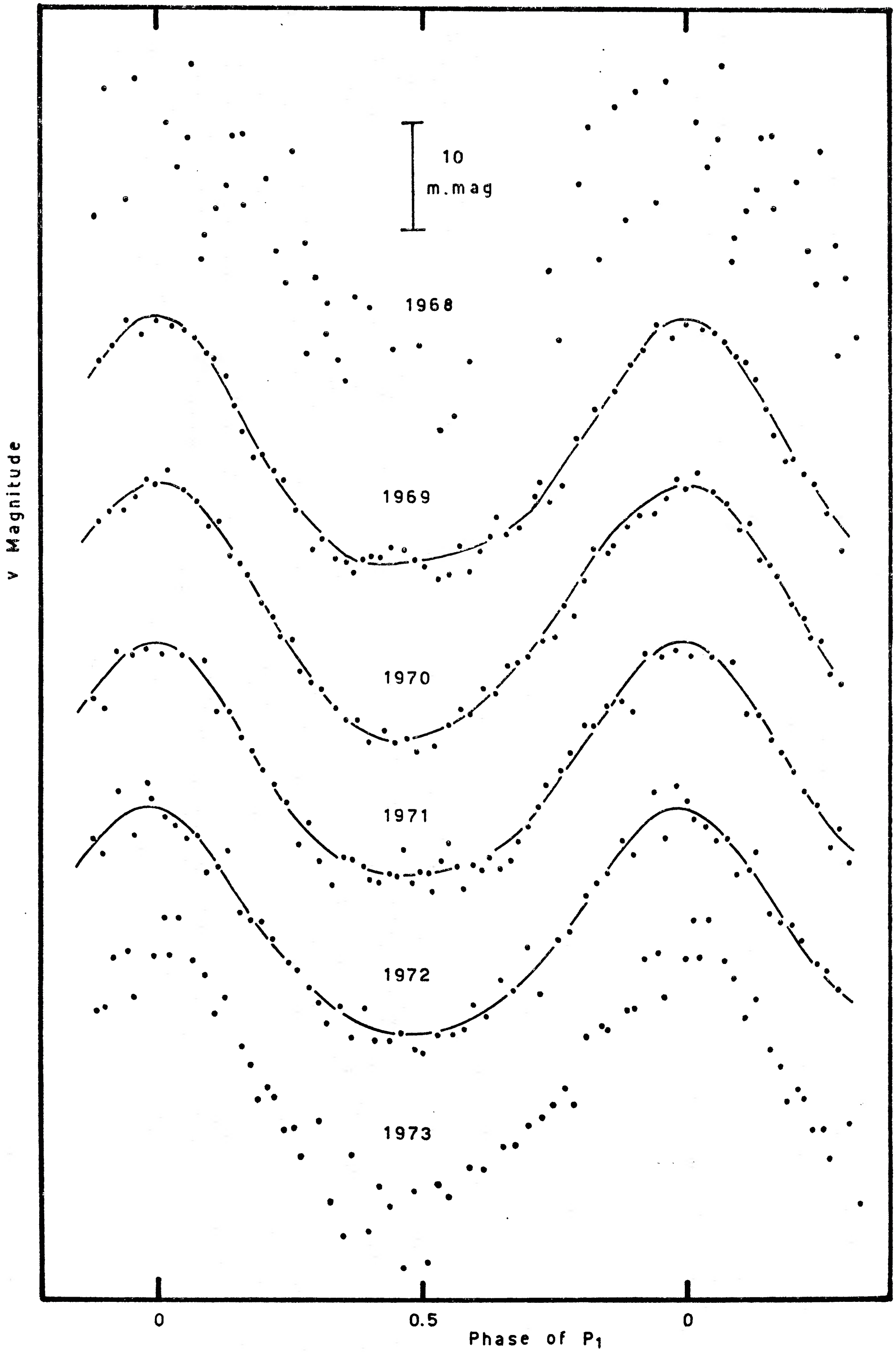

FIG. 2. *λ Sco: Mean light curves for each of the* 6 *years in which observations were obtained. The data plotted are described in Section* 2.2 *and the smooth curves represent the* P_1 *and* $\frac{1}{2}P_1$, *waves with the parameters listed in Table III.*

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TABLE II

λ Sco: nightly light ranges, phases and mean magnitudes

Hel. JD 2440000+	P_1 light range ± σ (m.mag)	P_1 phase ± σ (deg)*	$\frac{1}{2}P_1$ light range ± σ (m.mag)	$\frac{1}{2}P_1$ phase ± σ (deg)*	Mean v (λ Sco—HR 6628) ± σ (mag)
1969					
380·11	22·3±1·0	286±2	7·0±1·0	286±8	−3·2174±0·0003
381·09	23·9±0·8	285±2	6·0±0·9	297±9	−3·2162±0·0003
389·02	21·5±1·0	291±3	2·4±1·0	308±25	−3·2195±0·0003
1970					
690·19	20·6±2·4	278±7	4·3±2·5	—	−3·1829:±0·0007:
692·19	26·0±2·0	296±4	3·7±2·0	319±30	−3·2228±0·0005
731·15	25·9±1·7	284±3	1·7±1·7	—	−3·2259±0·0005
755·18	20·6±1·6	289±5	7·0±1·7	243±15	−3·2204±0·0005
774·14	22·6±0·9	289±2	2·5±1·1	316±22	−3·2233±0·0003
775·04	24·8±1·5	289±3	3·6±1·6	308±25	−3·2187±0·0004
776·99	24·0±1·4	296±3	3·2±1·4	232±25	−3·2152±0·0004
780·02	23·7±1·4	279±4	0·7±1·6	—	−3·2217±0·0004
1971					
1048·2	19·7±2·1	254±6	3·5±2·2	211±37	−3·2220±0·0006
1123·2	28·9±0·7	265±1	5·0±0·7	274±9	−3·2188±0·0003
1972					
1483·08	22·7±1·4	332±4	2·7±1·4	62±32	−3·2219±0·0004
1485·19	28·3±1·6	336±3	0·4±1·5	160±145	−3·2202±0·0004
1512·04	17·8±1·1	346±4	4·6±1·2	27±15	−3·2194±0·0003
1513·04	27·9±1·8	336±4	3·1±1·8	66±37	−3·2204±0·0005
1515·00	14·2±3·2	351±14	0·8±3·5	350±133	−3·2128±0·0009
1516·33	31·3±2·5	329±5	4·0±2·5	44±33	−3·2204±0·0006
1973					
1886·04	29·3±3·1	316±6	3·3±2·9	334:±65:	−3·2244±0·0008
1887·02	17·8±1·8	300:±10:	3·8±1·7	336:±28:	−3·2247±0·0005

* With respect to Hel JD 2440379·9195 and $P_1 = 0^{d}{\cdot}2137015$.

in the shapes of the curves—that for 1970 is the closest to a sinusoid, for instance, but all show a minimum wider than the maximum.

Table II lists the light ranges and phases of P_1 and $\frac{1}{2}P_1$ for all nights on which the observing time was long enough for them to be determined; in general it is necessary that the night's observations extend for longer than $\sim 0^{d}{\cdot}2$. A few nights were also excluded because clouds prevented the observations of a maximum or a minimum. Also listed are the mean values of v(λ Sco—HR 6628) for the nights.

It will be noted that the amplitudes of P_1 vary considerably from 1971 to 1973—far more than in 1969 and 1970. Removal of the P_1 and $\frac{1}{2}P_1$ variations from the 1972 data left an rms deviation of 4·8 m.mag (0·0048 mag) about a mean magnitude, which is to be compared with 2·4 m.mag for each of 1969 and 1970 separately (or 2·7 m.mag for both years combined (Paper I)). However, for the 1972 data, the next highest peak reduced the rms only to 4·4 m.mag, so that it appears there is no significant second period causing the amplitude variation. In addition to the change in amplitude, there are at least eight nights from 1969 to 1973 on which

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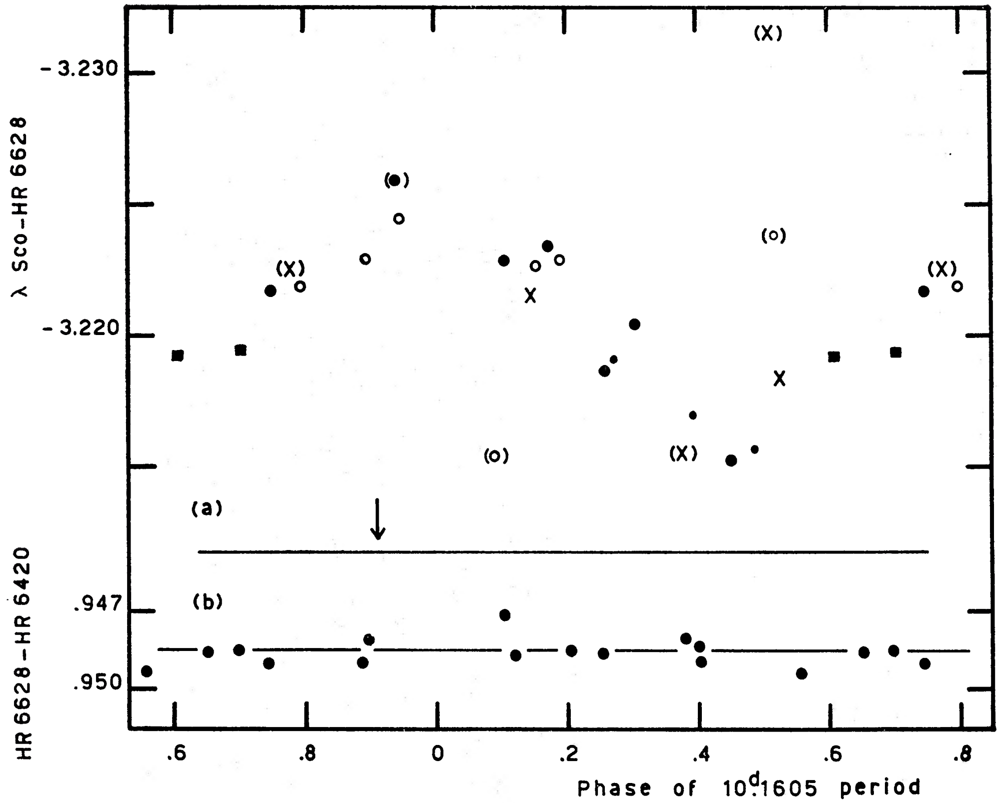

FIG. 3. (*a*) *λ Sco: Variation of the mean nightly values of v*(*λ Sco—HR* 6628) *with the* $10^{d}\cdot1605$ *period. Zero phase is at Hel. JD* 2440376·15. 1969 *nights are represented by small dots,* 1970 *nights by large dots,* 1971 *nights by crosses,* 1972 *nights by open circles and* 1973 *nights by squares. Symbols in parentheses are less well-determined values. The arrow is at the phase of JD* 2440690, *the magnitude of which is* 40 *m.mag below the curve.* (*b*) *v* (*HR* 6628–*HR* 6420) *plotted, for comparison with the above curve, against the phase of the* $10^{d}\cdot1605$ *period.*

the mean brightness was changing during the night. This can only be seen clearly when there are at least two maxima or two minima observed.

The $10^{d}\cdot15$ period mentioned in Paper I from the 1969 and 1970 observations was not evident in the frequency analysis of all the observations, although it was felt that the frequently observed nightly drifts in the mean magnitudes strongly suggested a long period. Upon plotting the mean magnitudes for the 5 years separately against the $10^{d}\cdot15$ phase, there seemed to be a maximum observed in 1972. Comparison of the phases of the 1970 and 1972 maxima indicated an improved value of the long period of $10^{d}\cdot1605 \pm 0^{d}\cdot0070$. Appropriate adjustments of the mean magnitude for each *year* yielded the curve shown in Fig. 3(a).

In order to verify the source and reality of this variation, differences were taken between the mean nightly magnitudes of the four comparison stars. Differences involving *υ* Sco and HR 6460 showed a range of 5–10 m.mag, but *v*(HR 6420–HR 6628) (Fig. 3(b)) showed a range of only 2·2 m.mag. In fact, when one of the 13 values available is removed, the rms deviation about the mean difference of 0·9485 mag is only 0·0006 mag (0·6 m.mag). This indicates a remarkable and hitherto unobserved constancy in brightness of two stars over a 3-yr period (from 1970 to 1973). HR 6420 is classified as B9 and HR 6628 as B8 V in the *Bright Star Catalogue*. In particular, the main comparison star for both λ Sco and κ Sco, HR 6628, is evidently not the cause of the $10^{d}\cdot1605$ variation in *v*(λ Sco—HR 6628).

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The yearly mean magnitude adjustments required to bring the nightly mean magnitudes for each year on to a common 10-day wave were small. The adjustments were +0·5, 0, +0·5, −2·5 and +5·5 m.mag for 1969, 1970, 1971, 1972 and 1973, respectively. It is not possible to ascertain if they are periodic.

Unfortunately, however, we have not yet discovered the cause of the drift in mean magnitude during some of the nights of observation. The largest drift, of about 12 m.mag over one short-period cycle, can be seen in the light curve for JD 2440690 in Fig. 1, Paper I. This night alone suggests that the slope is not due to the 10-day period since its mean magnitude is 40 m.mag below the curve of Fig. 3(a). Apart from this night, several other nights show up to ~5 m.mag drift in 5 hr, whereas the maximum rate of change during the 10-day cycle is only 2·5 m.mag per day. There are three other nights on which the mean magnitude deviated significantly from the $10^{d}\cdot1605$ curve; one value at phase ~0·1 falls below the curve near the maximum and two near phase 0·5 lie well above the region of the minimum. Consequently, the possible interpretation of the long period as being due to ellipsoidal distortion of the two stars (implying an orbital period of $20^{d}\cdot321$) does not agree with the interpretation of the two low mean magnitudes as being due to eclipses; they would occur at the minimum of an ellipsoidal variation. Moreover, the velocities available (Section 2.1) do not suggest either a $10^{d}\cdot1605$ or a $20^{d}\cdot321$ day orbital period. It is of course entirely possible that deviations could be due to variations in the secondary. Variations of a few per cent, not necessarily periodic, have been detected in many of the B stars observed during this programme.

The mean value for the ratio of the light range at $\frac{1}{2}P_1$ to that at P_1 is about 0·13. This ratio, a measure of the deviation from a sinusoid of the P_1 wave, does not increase with increasing light range of P_1.

2.3 *Colour and temperature variations*

Fig. 4 shows the v, $(b-v)$ and $(u-b)$ variations for the three nights of 1972 July 14, 16 and 17. The smooth curves on the three v graphs are the mean P_1 and $\frac{1}{2}P_1$ graphs for all 1972 nights. The parameters of the mean variation of v, $(b-v)$ and $(u-b)$ over the three nights are as follows:

v range	25·4 ± 1·8 m.mag
Hel. JD of max. light	2441515·063 ± 0·003
$(b-v)$ range	2·0 ± 1·0 m.mag
Hel JD of max. negative $(b-v)$	2441515·047 ± 0·017
$(u-b)$ range	9·8 ± 1·2 m.mag
Hel. JD of max. negative $(u-b)$	2441515·066 ± 0·005

Within the errors, maximum temperature occurs at maximum light and from Fig. 1 the velocity range is 20 ± 1 km s^{-1}, with the mean velocity on the decreasing branch (minimum radius on the radial pulsation hypothesis) also occurring close to maximum light.

If the variation is due to radial pulsation, we may estimate the temperature changes implied by the above light, colour and velocity variations. It is necessary to make a number of assumptions, which are listed below:

(1) λ Sco is composed of two stars of approximately equal brightness (Hanbury Brown *et al.* 1974) and the same colour. This means that the observed light and colour variations represent only one-half of the percentage changes in the variable component.

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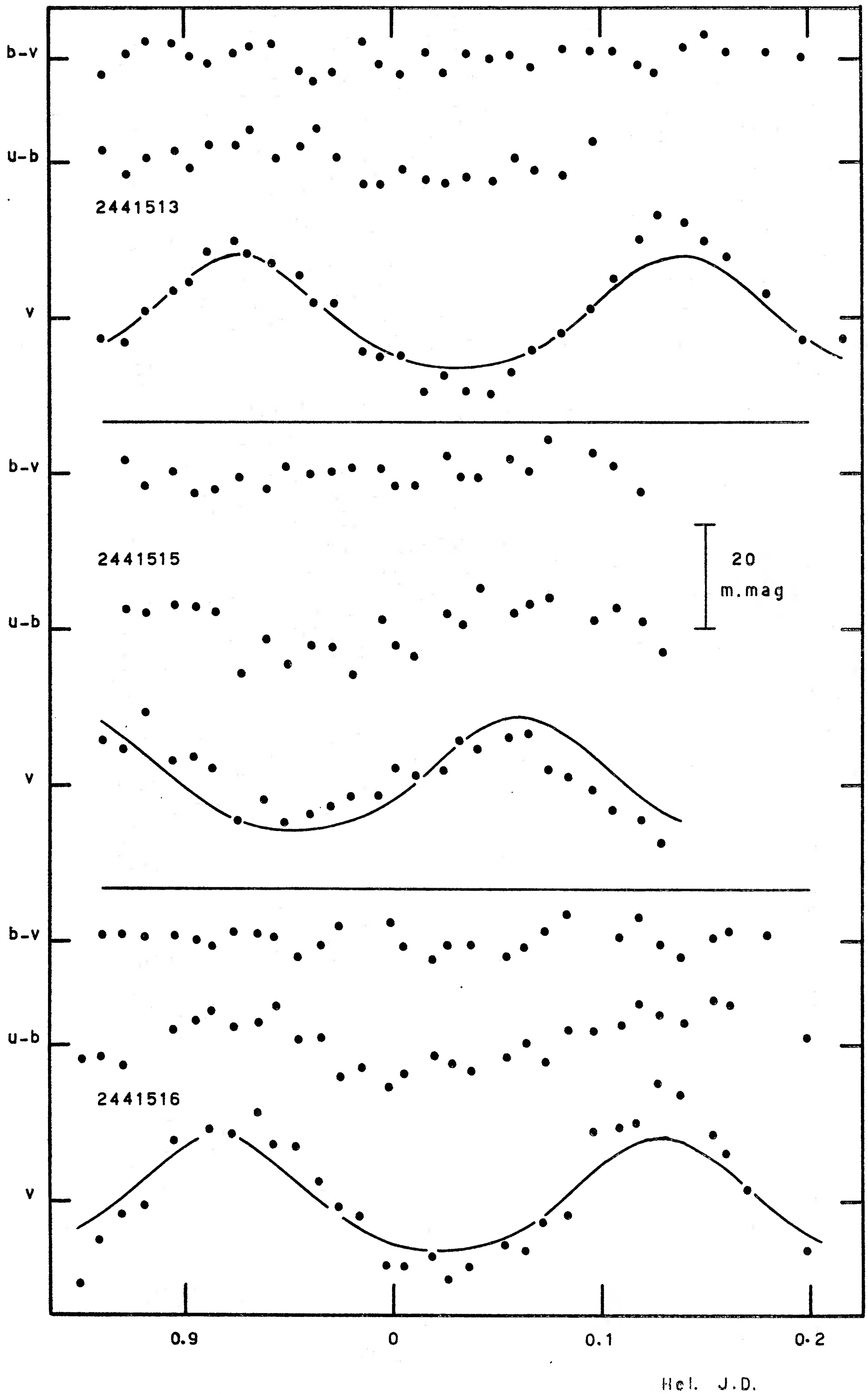

FIG. 4. *λ Sco: Three-colour observations in* 1972 *for* (*λ Sco—HR* 6628) *on the three nights shown. In each case the smooth curve is the mean curve for* 1972. *The deviations from the curves illustrate typical variations in the amplitude from night to night. The* (*b–v*) *variation is evident only when all observations are combined on to* P_1 (*Section* 2.3).

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(2) The velocity range measured from the blended and unresolved lines in the spectrum represents the true motion of the atmosphere of the variable. Without a fairly precise knowledge of the line profiles of each component, it is difficult to judge by how much the velocity range observed is an underestimate of the true value.

(3) For this B1·5 IV star, we assume that the radius is $9 \pm 1\ R_\odot$, its temperature T_e is 23 500 K and $\log g = 3 \cdot 5$.

The temperature changes indicated by the light, colour and velocity variations were found in the same manner as for α Vir (Shobbrook *et al.* 1972). The model atmospheres of van Citters & Morton (1970) and Bradley & Morton (1969) were used. The results are:

From Δv and the radial velocity range:	$\Delta T_e = 900 \pm 100$ K
From $\Delta(b\text{–}v)$:	$\Delta T_e = 700 \pm 400$ K
From $\Delta(u\text{–}b)$:	$\Delta T_e = 600 \pm 100$ K.

The errors are estimated from the errors in the original variations and the uncertainty of the interpolation between models. In addition, the ΔT_e determination from Δv is a minimum value because of the uncertainty of the true velocity range. Unfortunately, the errors are large because of the small and uncertain variations so that the results cannot be used to test the radial pulsation hypothesis.

2.4 *Period variations*

In 1970, 1971 and 1972, the observations covered a sufficiently long baseline during the observing season for the period to be determined to a fairly high accuracy

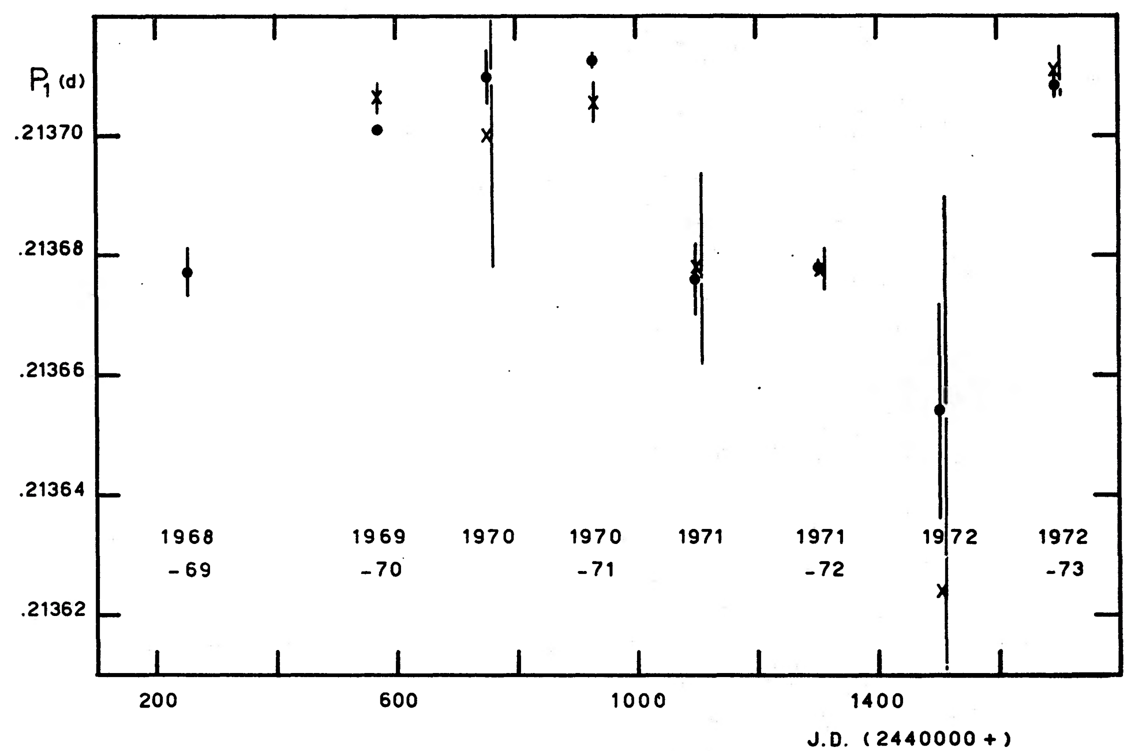

FIG. 5. *λ Sco: The dots represent the values of P_1 determined in, and between, the years shown, with their standard deviation error bars. The crosses, with slightly offset error bars in some cases, are the values of $\frac{1}{2}P_1$ multiplied by 2·0.*

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TABLE III

λ Sco: results of frequency analysis of the photometric observations

	Period ± σ (day)	Light range ± σ (m.mag)	Hel. JD of max. light ± σ (2440000 +)
1968*			
	0·21370:	25:	124·992
			±0·004
1969			
	0·21370:	23·0	383·5418
		±0·4	±0·0006
	0·10685:	5·0	383·5455
		±0·4	±0·0014
1970			
	0·2137099	24·0	752·1758
	±0·0000043	±0·5	±0·0006
	0·106850	2·6	752·1888
	±0·000011	±0·5	±0·0030
1971			
	0·213676	22·0	1099·2450
	±0·000006	±0·6	±0·0010
	0·106839	4·0	1099·2470
	±0·000008	±0·6	±0·0026
1972			
	0·213654	22·2	1503·5237
	±0·000018	±0·9	±0·0012
	0·106812	3·5	1503·5253
	±0·000033	±0·9	±0·0039
1973†			
	0·21370:	24·0	1886·0615
		±1·4	±0·0024
	0·10685:	3·4	1886·068:
		±1·2	±0·003:

* The 1968 curve is not well defined from two poor nights of observation.

† In 1973, one night shows only the minimum and rising branch and the other two show significant changes in the mean magnitude during the night. Consequently, although the rms deviations about smooth curves for each night are < 2 m.mag, no parameter can be accurately determined.

using the least squares frequency analysis program. These values have been listed in Table III. The mean period between consecutive observing seasons can be found from the times of maxima in each year, also given in Table III. Fig. 5 shows the different determinations of the period plotted against Julian date.

The period is evidently not constant, but it is not possible to determine unambiguously the form of the change. Unless a period change is linear between the dates considered, the period calculated from pairs of maxima has little meaning. Since within each observing season the period is sensibly constant, it is possible that there are sudden jumps in period from time to time; that is, the period is not continuously variable. This is strongly suggested by the fact that although the periods in 1970 and 1971 are markedly different, the mean period between 1970 and 1971 is close to that in 1970. Thus there may have been a sudden period decrease just before the 1971 observations.

The apparent rates of change of period are up to ± 200–300 s per century,

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which is much larger than is to be expected from evolutionary changes in the stellar structure. Eggleton & Percy (1973) have shown that changes of from about −15 to +20 s/century might be expected during the gravitational collapse and early shell burning phases. In λ Sco the period changes are of different signs from year to year, further indicating that they are not evolutionary. They may even be cyclic, with a period of about 3 yr, but many more years of observation are required to check this.

Fig. 5 also shows (crosses) that the variation of the harmonic $\frac{1}{2}P_1$ follows, within the errors, the same shaped curve as that of P_1, with the same percentage rate of change. This confirms that the non-sinusoidal P_1 wave maintains its shape from year to year, as illustrated in Fig. 2.

3. κ SCORPII

In Paper I we found a main variation of period $0^d{\cdot}19987$ in the light of κ Sco. This variation underwent amplitude and phase changes, which we concluded were probably due to another period of $0^d{\cdot}20544$. A longer period of $2^d{\cdot}951$ was also present and it was noted that the period of the beat between the two short periods was $2{\cdot}50 \pm 0{\cdot}02$ times longer than the $2^d{\cdot}951$ period.

3.1 *Radial velocities*

Although there are only 12 spectrograms of κ Sco available, they fully cover one short period cycle. They were reduced similarly to those of λ Sco and a sine curve with the $0^d{\cdot}19987$ (P_1) photometric period plus a mean velocity constant was fitted to the velocities of each line. The H I mean velocity was found to be $6{\cdot}4 \pm 0{\cdot}7$ km s^{-1} less than that of the mean of the He I singlet lines which indicates, by analogy with the results for λ Sco, that κ Sco is a spectroscopic binary. This is confirmed by the fact that the mean He I singlet velocity is 40 km s^{-1}, which when considered with the four plates taken by Buscombe & Morris (1960) gives an observed velocity range from +40 to −44 km s^{-1}. The final radial velocities were calculated using only the He lines, the rest wavelengths of the triplet lines being reduced by 0·20 Å to correct their mean velocity to that of the mean of the singlets. As for λ Sco, when calculating the plate velocities each line was weighted by the square of the inverse of the rms residual from the sine curve fitted to its velocities. The final mean radial velocities are listed in Table IV.

A sine curve with period P_1 fitted to the mean velocities has a range of $5{\cdot}8 \pm 1{\cdot}0$ km s^{-1}. As can be seen in Fig. 6, there is good agreement in amplitude and phase between the curve fitted to the mean velocities and that fitted to the velocities of the H line λ 4101. Since the latter set of velocities was not used in forming the mean velocities, the two sets of data are basically independent and their agreement indicates the correctness of the mean curve. The phase of the curve is such that the mean velocity of the decreasing branch lags behind the predicted time of maximum light (from Paper I) by $65^\circ \pm 20^\circ$. Such a relation between the light and velocity curves is unlikely, so possibly there was a phase shift of $\sim 65^\circ$ on that night. The phase shift is in the opposite direction to the 70° shift observed in the light on JD 2440777 (Paper I).

3.2 *Light curves*

Since Paper I we have obtained photometric observations in 1971 (10 nights and 258 observations), 1972 (eight nights and 227 observations) and 1973 (two

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TABLE IV

κ Sco: radial velocities in 1970

Helioc. JD 2440765 +	V (km s^{-1})
0·0327	+42·8
0·0875	+40·7
0·0722	+37·8
0·0771	+37·2
0·1077	+37·8
0·1146	+38·4
0·1507	+37·7
0·1576	+39·0
0·1861	+42·9
0·1931	+42·3
0·2340	+42·4
0·2389	+41·4

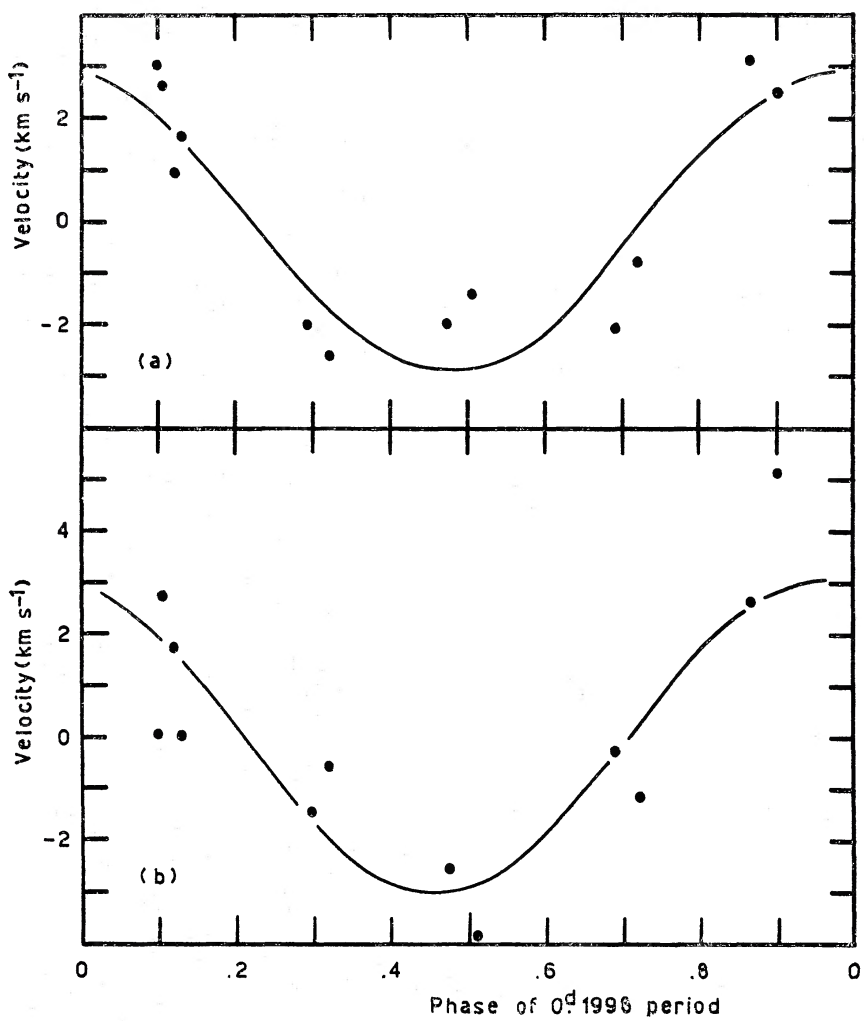

FIG. 6. *κ Sco: (a) The mean radial velocities plotted against the phase of* P_1. *The fitted sine curve is superimposed. (b) The radial velocities of the H line λ 4101 plotted against the phase of* P_1. *The fitted sine curve is superimposed.*

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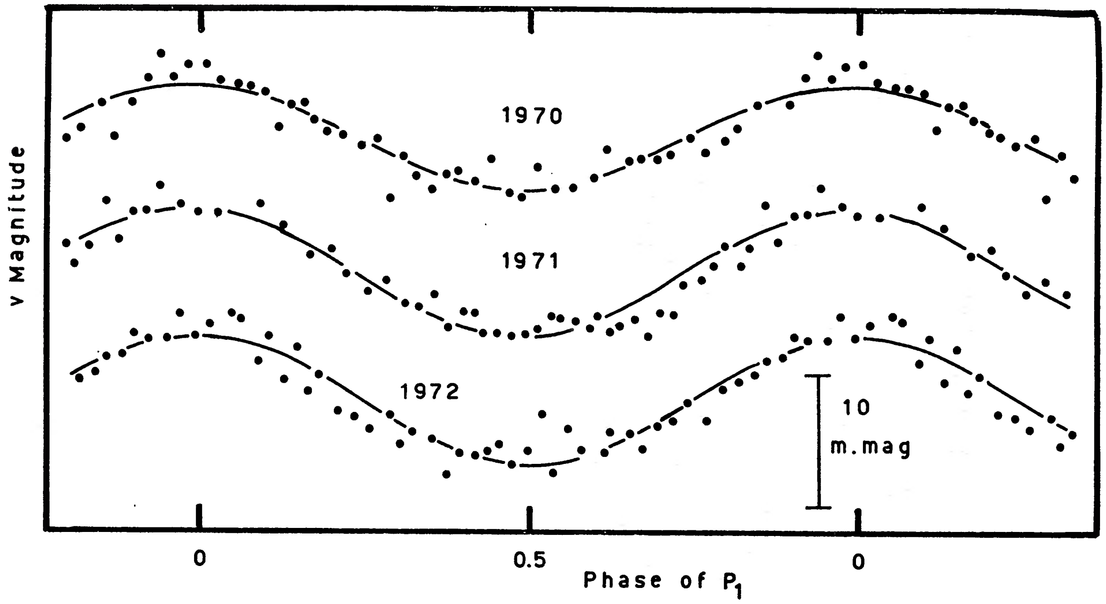

FIG. 7. *κ Sco: Mean light curves in* 1970, 1971 *and* 1972. *The data plotted are described in Section* 3.2 *and the smooth curves represent the* P_1 *sinusoids with the parameters for each year as listed in Table V.*

nights and 66 observations). With the exception of those for 1973, these data, together with those for 1970 (11 nights and 258 observations) were combined on to a P_1 sinusoid for each year and shown in Fig. 7 with 40–50 points per cycle. The amplitude variation is largely smoothed out for 1970, 1971 and 1972, but for 1973, when the two light ranges were 19 and 12 m.mag, a mean curve was not constructed. The three curves indicate a generally stable P_1 variation and there is a suggestion of them all having a slightly narrower maximum than minimum, as in λ Sco.

3.3 *Frequency analysis of the photometric observations*

The 1970 data have been re-analysed and a least squares solution made for the five periods listed in Table V. The harmonics $\frac{1}{2}P_1$ and $\frac{1}{2}P_2$ of course, merely express the non-sinusoidal nature of their respective fundamental waves. The parameters of P_1, P_2 and P_3 are changed a little from their Paper I values but the differences are within the standard deviations.

In the 1971 data, P_2 is not present. Instead, after subtraction of P_1 the highest peak in the frequency spectrum was at $P_4 = 0^{d}{\cdot}189512$; this period is not present in 1970 or 1972. $\frac{1}{2}P_1$ and $\frac{1}{2}P_4$ were present with rather low amplitudes. No long period peaks in the frequency spectrum were sufficiently distinct to be taken as real and in particular, P_3 is not present.

In the 1972 frequency spectrum, no significant peaks remained after subtraction of P_1 and $\frac{1}{2}P_1$. There is a peak at a period of $7^{d}{\cdot}44$, which is within the errors equal to the beat period of P_1 with P_2 in 1970, but the distribution of observing times (two groups of four nights, each in one week separated by one month) is not suitable for the determination of long periods. Consequently, it has a high probability of being a noise peak. There is also a peak at P_2, but it is too small to be taken as significant, especially as there are many higher peaks remaining in the spectrum.

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TABLE V

κ Sco: Results of frequency analysis of the photometric observations

	Period ± σ (day)	Light range ± σ (m.mag)	Hel. JD of max. light ± σ (2440000+)
1970			
P_1	0·199859	8·4	743·2277
	±0·000011	±0·5	±0·0018
P_2	0·205424	4·1	743·2438
	±0·000022	±0·5	±0·0038
$\frac{1}{2}P_1$	0·099939	2·3	743·2361
	±0·000009	±0·5	±0·0033
$\frac{1}{2}P_2$	0·102709	0·7	743·236
	±0·000032	±0·5	±0·011
P_3	2·9465	8·0	743·995
	±0·0024	±0·6	±0·025
1971			
P_1	0·199836	9·8	1110·1163
	±0·000010	±0·5	±0·0016
P_4	0·189512	5·3	1110·007
	±0·000018	±0·5	±0·003
$\frac{1}{2}P_1$	0·099911	1·7	1110·118
	±0·000016	±0·5	±0·005
$\frac{1}{2}P_4$	0·094733	1·4	1110·026
	±0·000018	±0·5	±0·006
1972			
P_1	0·200001	9·9	1502·583
	±0·000028	±0·6	±0·002
$\frac{1}{2}P_1$	0·099935	2·1	1502·587
	±0·000031	±0·6	±0·004

Table V lists the periods found in the 3 years, plus the light ranges and times of light maxima, all with standard deviations stated. The beat periods between P_1 and P_2 in 1970 and between P_1 and P_4 in 1971 differ by a factor 2·011 ± 0·007, so there is apparently a relation between P_2 and P_4. The relationships between the various frequencies (with $f = 1/P$) are as follows:

$$2{\cdot}5(f_1 - f_2) = f_3$$

$$2(f_1 - f_2) = -(f_1 - f_4).$$

As previously mentioned, the two nights of observation in 1973 show clearly the $0^{d}{\cdot}2$ wave with 19 and 12 m.mag light ranges on successive nights. Further information regarding the frequency spectrum could not be obtained because of the small amount of data.

Table VI lists the light ranges and phases for P_1 determined from a least squares fit of P_1 and $\frac{1}{2}P_1$ to the data on each night on which the observations extended over more than about $0^{d}{\cdot}2$. Also tabulated is the mean magnitude v(κ Sco—HR 6628) for each night.

Upon plotting the nightly light ranges for 1970, 1971 and 1972 separately against the phase of the $7^{d}{\cdot}37$ beat period found between P_1 and P_2 in 1970, an approximately sinusoidal wave was evident for all 3 years. With a small phase shift of the waves for each year corresponding to a period refinement to $7^{d}{\cdot}3316$, the three waves define a single curve which is shown in Fig. 8(a). The light ranges for

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TABLE VI

κ Sco: nightly light ranges, phases and mean magnitudes

Hel. JD 2440000+	P_1 light range ± σ (m.mag)	P_1 phase ± σ (deg)*	Mean v (κ Sco − HR 6628) ± σ (mag)
1970			
690·18	14·0±1·0	265±4	−2·4235±0·0003
692·19	10·1±1·6	260±10	−2·4209±0·0005
755·18	9·5±2·0	297±13	−2·4247±0·0005
774·14	5·7±1·5	251±16	−2·4248±0·0004
775·04	6·8±1·2	240±10	−2·4203±0·0003
770·0:	9·6±2·1	356:±14:	−2·4230±0·0006
780·02	12·0±1·6	256±8	−2·4258±0·0004
1971			
1048·19	8·1±1·6	197±13	−2·4255±0·0005
(1072·25	11:±2:	—	—)
(1096·28	14:±2:	—	—)
(1120·25	16:±2:	—	—)
(1122·21	19:±2:	—	—)
1123·19	11·9±0·6	269±3	−2·4258±0·0002
1125·05	7·0±1·7	214±14	−2·4226±0·0004
1151·12	10·3±1·1	220±6	−2·4187±0·0003
1152·09	11·6±1·5	244±7	−2·4221±0·0004
1972			
1483·08	12·1±1·0	272±5	−2·4233±0·0003
1485·18	5·2±1·5	11:±16:	−2·4238±0·0004
1488·10	9·8±1·0	271±6	−2·4282±0·0003
1512·04	12·2±1·0	225±5	−2·4259±0·0003
1513·04	19·4±1·0	239±3	−2·4214±0·0003
1515·00	5·7±2·6	220±26	−2·4197±0·0007
1516·02	5·0±2·2	248±27	−2·4244±0·0006
1973			
1886·02	19·4±0·8	247±2	−2·4295±0·0002
1887·03	11·8±1·4	259±7	−2·4234±0·0004

* With respect to Hel. JD 2440690·0595 and $P_1 = 0^{d}{\cdot}1998303$.

the 4 years of observations, including 1973, are shown with the symbols mentioned in the figure caption. Since the beat period between P_1 and P_4 in 1971 was one-half of that found in 1970, one would expect a double wave in the light range variation with the $7^{d}{\cdot}3316$ period. Unfortunately, there are no long series of observations in 1971 on nights between phases 0·22 and 0·73, so four other nights (in parentheses in Table VI) were chosen and the amplitudes fairly accurately estimated from visual inspection of the light curves. Two of the nights (JD 2441096 and 2441120) show light ranges which place them well above the minimum of the curve in Fig. 8(a); all four values are plotted in parentheses. It is probably these two nights which caused the beat period of $3^{d}{\cdot}7$ to be found in the 1971 data by the frequency analysis program.

It can be seen in Fig. 8(a) that there are five nights on which the nightly light ranges are considerably higher than the other values through which the curve passes. Besides the two values mentioned above from the 1971 season, there is one other in 1971 (JD 2441122), one in 1972 (JD 2441513) and one in 1973 (JD 2441886). As the main wave of Fig. 8(a) is clearly defined in each of the three years

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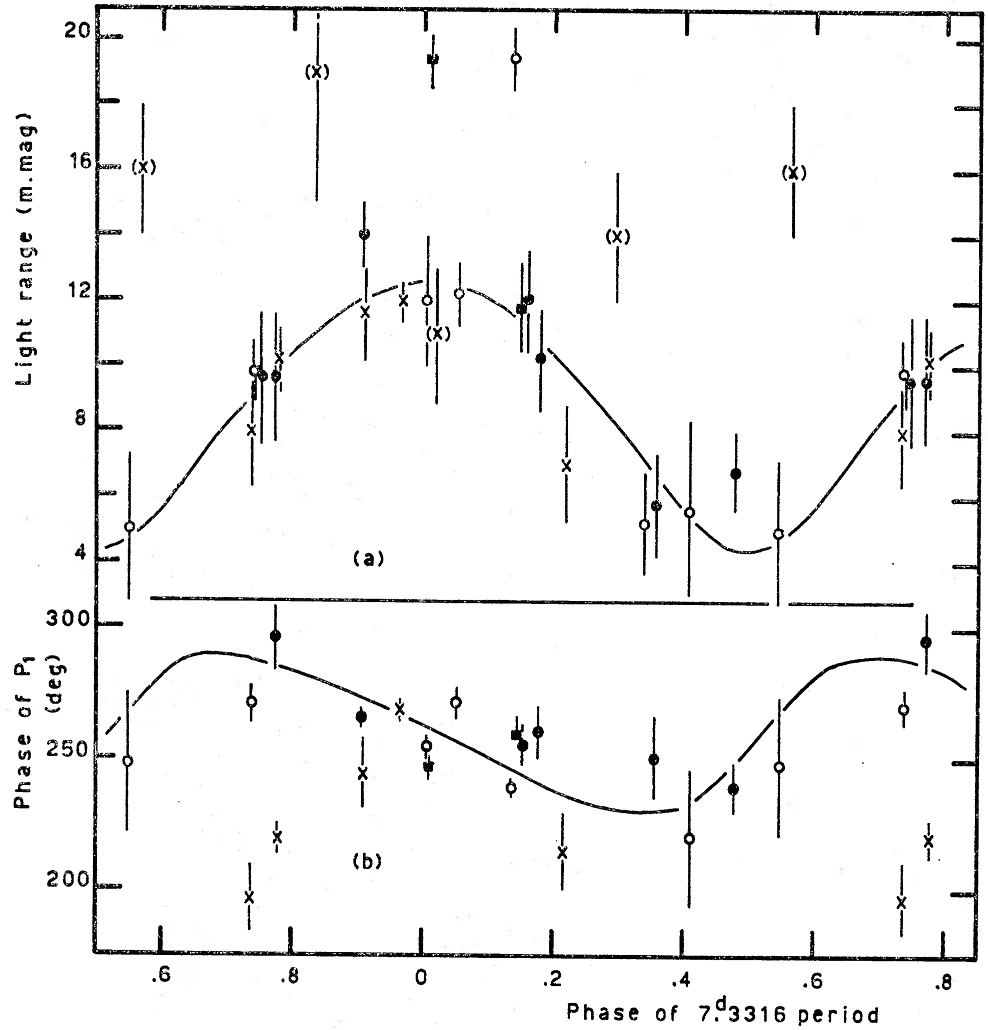

Fig. 8. *κ Sco: (a) Light ranges and (b) phases of the light curves for each night, as listed in Table VI, plotted against the phase of the* $7^d{\cdot}3316$ *beat period, zero phase of which is at Hel. JD* 2440690·88. *The symbols for each year are the same as described in the caption for Fig.* 3. *The smooth curves are the amplitude and phase variations to be expected from superposition of the* P_1 *and* P_2 *sinusoids, with the parameters for* 1970 *listed in Table V. The deviation of the* 1971 *phases (crosses) is discussed in Section* 3.3. *The two uncertain phases listed in Table VI are not plotted.*

1970, 1971 and 1972, it is statistically highly significant in spite of these five points. We consider that these five points represent a separate real phenomenon; no periodicity could be found in their occurrence.

Inspection of the phase variation of P_1 with the $7^d{\cdot}3316$ period reveals a common, moderately well-defined curve for 1970, 1972 and 1973, but a significant difference in 1971. The 1971 values (crosses in Fig. 8(b)) are rising in value during the phase of maximum defined by values from the other years; alternatively, the 1971 values lag behind the others by about 0·3 of the $7^d{\cdot}3316$ phase.

The smooth curves in Fig. 8(a) and (b) are calculated from the addition of two sine waves with periods P_1 and P_2, respectively. Since the P_2 variation was found only in the 1970 data, the parameters used are those given for P_1 and P_2 in 1970 in Table V. With the exception of the points previously referred to, both the light range and phase curves show a fairly good fit to the calculated curves. This fit

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indicates that P_2 is a real periodicity and not an artifact of a modulation of P_1 with the beat period (or a multiple of it) between P_1 and P_2. As has been pointed out by Shobbrook & Stobie (1974) it is improbable that amplitude and phase modulation curves would mimic the curves expected from simple superposition of sine waves. The fit also shows that P_2 was present in the few 1972 observations, notwithstanding the result of the fequency analysis.

3.4 *Colour variation*

Fig. 9 shows the v, $(b-v)$ and $(u-b)$ variations on three nights in 1972. They cannot be simply interpreted as the results of temperature and radius changes. On JD 2441515 the $(u-b)$ curve is 180° out of phase with the v variation and on the following night there appears to be a double wave in $(u-b)$ during one cycle of the v curve (although on the latter night the v curve is not well defined). There is no perceptible $(b-v)$ variation.

3.5 *Period of* κ *Sco*

Table V lists, in particular, the values and mean times of light maxima for P_1 in 1970, 1971 and 1972. From the times of maxima we can calculate the following values of P_1 between successive years, i.e.

$$\text{from 1970 to 1971,} \quad P_1 = 0^{\text{d}}{\cdot}1998303 \pm 0^{\text{d}}{\cdot}0000019 \text{ (sd)}$$

$$\text{from 1971 to 1972,} \quad P_1 = 0^{\text{d}}{\cdot}1998303 \pm 0^{\text{d}}{\cdot}0000018.$$

The night JD 2441886 in 1973 shows a light range of 19 m.mag, one of the highest observed. Since it lies very close to the maximum of Fig. 8(a) (albeit well above the curve) and also near the mean value of the P_1 phase (Fig. 8(b)), it is reasonable to assume that the time of maximum for this curve is also that of the P_1 variation. With this assumption, we have that:

$$\text{from 1972 to 1973,} \quad P_1 = 0^{\text{d}}{\cdot}199833 \pm 0^{\text{d}}{\cdot}000003{:}.$$

These 1-yr baseline values are all in close agreement. If we assume the period is constant the best value we can obtain is that from 1970 to 1972, which is:

$$P_1 = 0^{\text{d}}{\cdot}1998303 \pm 0^{\text{d}}{\cdot}0000010 \text{ (sd)}.$$

The values determined from the data within one observing season differ significantly from this value, but this is probably largely due to the at present unexplained departures from the simple beating period model. Given P_1 above, and the beat period of $7^{\text{d}}{\cdot}3316$ with an estimated uncertainty of $0^{\text{d}}{\cdot}004$, the value of P_2 is thus $0^{\text{d}}{\cdot}205430 \pm 0{\cdot}000004{:}$.

4. CONCLUSION

There are amplitude and phase variations from night to night in the light curves of both stars that are not accounted for by either the single short period in λ Sco or the beating periods in κ Sco. In some other β CMa stars which are also spectroscopic binaries, amplitude and/or phase variations have been found with the orbital periods and have been interpreted as being due to modulation, probably by the tidal effects of the secondary on the primary. Examples of these stars are σ Sco (Fitch 1967) in which phase modulation has been found and α Vir (Lomb

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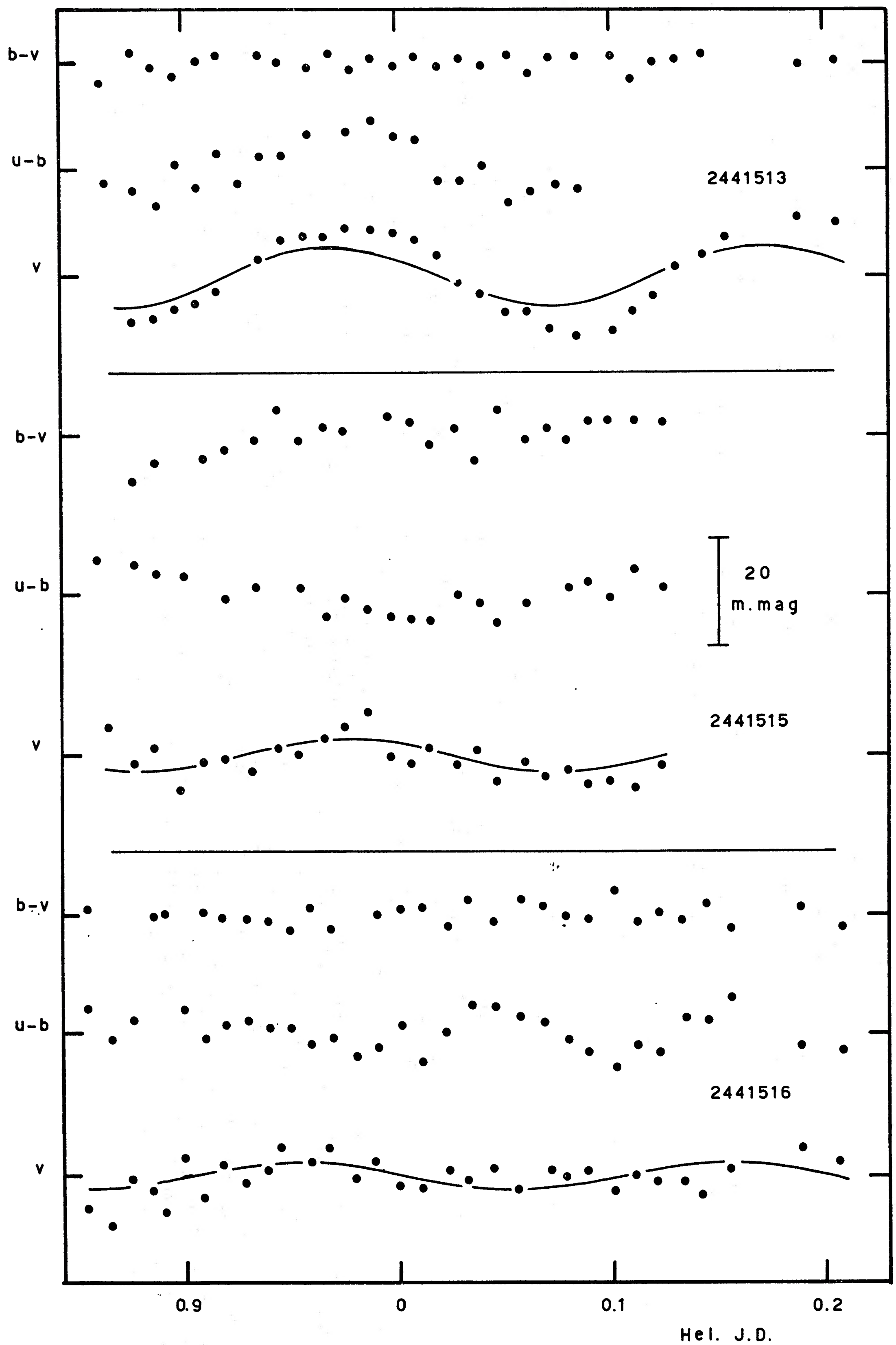

FIG. 9. *κ Sco: Three-colour observations in* 1972 *for* (*κ Sco—HR* 6628) *on the three nights shown. The smooth curves are the waves predicted for these nights from the amplitude and phase variation curves in Fig.* 8.

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1974) in which amplitude modulation has been found. In both these stars the variations are small and strongly non-sinusoidal, so that it was possible to find them only because the orbital periods were known. Unfortunately the orbital periods of neither λ Sco nor κ Sco are known, consequently such correlations cannot be investigated.

Not all the unexplained variation is likely to be due to the effects of the secondary. The significant increase in the range of amplitudes observed for λ Sco after 1970, the large changes in period from year to year for the same star and the daramatic change in the phase behaviour of the nightly waves for κ Sco in 1971 (Fig. 8(b)) are all unlikely to be explained in such a manner. Similar long-term changes in the behaviour of the pulsation have been observed in the broad-lined β CMa star, α Vir, in which there has been a progressive decrease in the mean light ranges from 1968 and 1969 through 1970 to 1971 (Shobbrook *et al.* 1972) and the amplitude modulation curve followed in 1968 and 1969 was no longer followed in 1970 (Lomb 1974). It is possible that this kind of instability in the pulsation is connected with high rotational velocity but further detailed observations of other broad-lined β CMa stars are necessary before this could be confirmed.

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Note. All *v* photometric observations made by R.R.S. on λ Sco and κ Sco, plus those on α Vir, β CMa, ξ^1 CMa and 15 CMa (total 4800) have been lodged with the Royal Astronomical Society under file number IAU(27)·RAS-38.

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