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ON THE PERIOD CHANGE OF THE CEPHEID SV VULPECULAE

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ABSTRACT

New *UBVRI* photometry and a small number of concurrent radial velocities are given for for the 45^d classical Cepheid, SV Vulpeculae. Reinvestigation of the star's period, previously considered to be erratic, shows in fact that the period is smoothly decreasing with time at a rate of 254 ± 10 s per year. This is interpreted as being due to evolution on the H-R diagram, and a comparison is made between the period rate derived from theoretical models and observation. Good agreement is found.

It is pointed out, however, that this good agreement is fortuitous, and that models with differing metallicity, l/H, etc., might give different predictions of the period rate. But, by the same token, the observed period rate offers a new hold on such theoretical parameters, and it is suggested that searches for similar period changes in other long-period Cepheids might be productive for stellar-evolution theory.

Subject headings: stars: Cepheids — stars: individual — stars: interiors — stars: pulsation

I. INTRODUCTION

SV Vulpeculae, with a period of 45^d, is one of the longest-period classical Cepheids known in the Galaxy. As such, its luminosity and color are of particular importance from the standpoint of the Cepheid period-luminosity law. Barnes, Evans, and Moffett (1978, and papers cited therein) have recently calibrated a new surface-brightness technique whereby a pulsating variable's distance may be derived geometrically once its V and $(V - R)$ light curves and its velocity curve are known. This would lead to an independent measure of SV Vul's luminosity, but previously no $V - R$ photometry was available for the star. The principal motivation for this work, then, was to provide these data in order to apply the Barnes *et al.* technique to this important star.

II. THE PHOTOMETRY

UBVRI photometry has been obtained with the standard photometer (Fernie 1974) attached to the David Dunlap Observatory's 0.6 m telescope in Richmond Hill, continuing between 1975 August and 1977 November. HD 187462, a G0 V star less than 1° away from SV Vul, was adopted as comparison star. Its magnitude and colors, as determined from tie-ins to the standard Johnson system on nine nights, are

TABLE 1
ADOPTED MAGNITUDE AND COLORS OF HD 187462

V	$U - V$	$B - V$	$V - R$	$V - I$
6.880	0.879	0.650	0.532	0.861

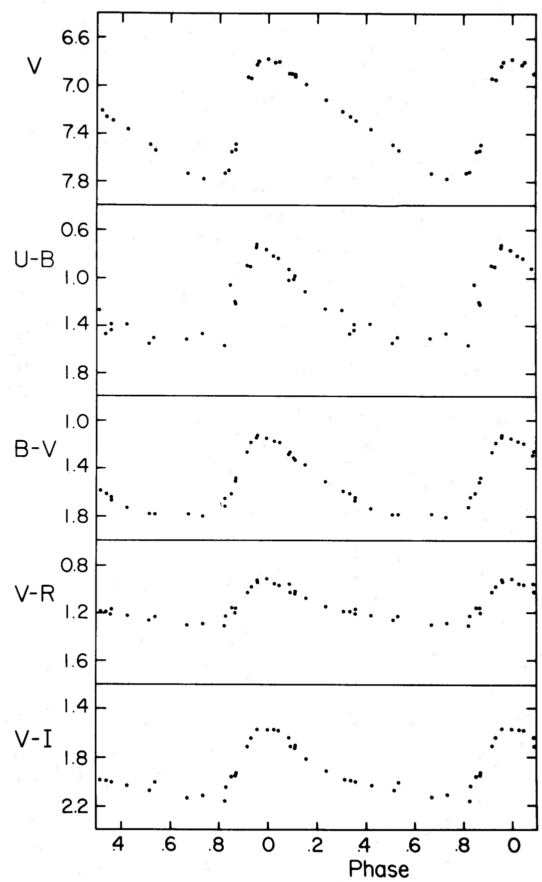

FIG. 1.—Light and color curves for SV Vul derived from the present photometry.

TABLE 2
PHOTOMETRY OF SV VUL

JD (2,440,000+)	Phase	V	$U-V$	$B-V$	$V-R$	$V-I$	$U-B$
2629.650	0.853	7.55	2.67	1.61	1.16	1.96	1.06
2632.654	0.920	6.93	2.17	1.27	1.03	1.71	0.90
2652.558	0.362	7.29	3.08	1.64	1.17	2.00	1.44
2981.673	0.673	7.73	3.29	1.78	1.30	2.13	1.51
3052.209	0.241	7.12	2.77	1.51	1.15	1.91	1.26
3078.515	0.825	7.73	3.29	1.72	1.31	2.16	1.57
3080.566	0.871	7.54	2.71	1.51	1.20	1.95	1.20
3083.480	0.936	6.95	2.00	1.19	0.98	1.64	0.81
3084.482	0.958	6.83	1.90	1.15	0.93	1.57	0.75
3086.457	0.002	6.78	1.92	1.15	0.92	1.57	0.77
3088.559	0.048	6.80	2.03	1.19	0.97	1.58	0.84
3090.453	0.090	6.91	2.30	1.28	0.96	1.64	1.02
3091.455	0.113	6.91	2.32	1.31	1.02	1.70	1.01
3303.695	0.828	7.73	...	1.65	1.23	2.04	...
3305.690	0.872	7.48	2.70	1.48	1.16	1.93	1.22
3309.690	0.961	6.80	1.87	1.14	0.94	1.57	0.73
3312.702	0.028	6.82	2.00	1.18	0.96	1.57	0.82
3315.694	0.094	6.91	2.20	1.27	1.03	1.71	0.93
3316.698	0.117	6.93	2.31	1.33	1.03	1.72	0.98
3318.664	0.160	6.99	2.48	1.37	1.08	1.81	1.11
3326.719	0.339	7.26	3.08	1.61	1.19	1.99	1.47
3327.683	0.361	7.29	3.06	1.67	1.21	2.00	1.39
3334.650	0.516	7.49	3.33	1.78	1.26	2.07	1.55
3335.659	0.538	7.54	3.28	1.78	1.23	2.00	1.50
3415.567	0.313	7.21	2.86	1.59	1.19	1.98	1.27
3420.573	0.424	7.36	3.12	1.73	1.22	2.03	1.39
3434.553	0.735	7.78	3.27	1.80	1.29	2.11	1.47

listed in Table 1, and were treated as exact for purposes of deriving magnitudes and colors for SV Vul. The results are listed in Table 2 and shown plotted in Figure 1.

The scatter in the $U-B$ curve is larger than desirable mainly because insufficient integration time was allowed to obtain good photon statistics in the U-filter. This was done deliberately because $U-B$ data already exist for SV Vul and it did not seem worthwhile to use additional observing time merely to repeat existing data. Despite this, however, it was noticed in the course of the program that the $U-B$ curve being measured differed in zero-point from the earlier one of Mitchell *et al.* (1964) by more than 0.1 mag. A considerable effort was then made to check the $U-B$ transformations as carefully as possible. Primary *UBV* standards were reobserved, and the transformation equations from these were comparable to ones obtained from supergiants alone. No differences were found, and it has not been possible to locate the source of the discrepancy in the present photometry. It may also be noted that the $(U-B)$ color of the comparison star, which is unreddened, could not be reconciled with a 0.1 mag shift in zero-point; it is as expected for the spectral type. More generally, it may be noted that SV Vul is so red that an extrapolation of the transformation equations is often required, so that photometric differences between observers is not unexpected. V and $B-V$, however, are in excellent agreement with the results of Mitchell *et al.* (1964). Intensity means of the magnitude and colors are given in Table 3.

It is potentially of interest to the theory of pulsation and stellar atmospheres to know how the epoch of peak flux through the atmosphere varies with wavelength. Usually, however, because of inadequate wavelength coverage and/or observational error, such data have not been available. Fortunately, good phase coverage near maximum light has made this possible for SV Vul, with results listed in Table 4 and shown in Figure 2. It seems that the epoch of maximum light increases linearly with effective wavelength, the I maximum coming 1.7 days (0.038 in phase) later than the U maximum.

III. RADIAL VELOCITIES

Because the surface-brightness technique (and also radius determination by Wesselink's method) needs accurate phase-linkage between radial velocity and photometric observations, a number of 16 Å mm^{-1} spectrograms were obtained at the DDO 1.9 m

TABLE 3
INTENSITY MEAN MAGNITUDE AND COLORS OF SV VUL

$\langle V\rangle$	$\langle U\rangle-\langle B\rangle$	$\langle B\rangle-\langle V\rangle$	$\langle V\rangle-\langle R\rangle$	$\langle V\rangle-\langle I\rangle$	$\langle R\rangle-\langle I\rangle$
7.22	1.15	1.46	1.09	1.85	0.76

TABLE 4

TIMES OF MAXIMUM LIGHT

Filter	λ_{eff} (μm)	$(JD)_{max}$ (2,443,000+)
U...........	0.36	86.05
B...........	0.44	86.25
V...........	0.55	86.55
R...........	0.70	87.55
I............	0.90	87.6

reflector during the course of the photometric program. Radial velocities from these are listed in Table 5. They serve only to phase the velocity curve with the light curves. The shape of the velocity curve can be established from the work of Sanford (1956) and Grenfell and Wallerstein (1969). This is not reported here; in fact, the original aim of the investigation is not pursued further, because it became clear that the surface-brightness technique will require recalibration for long-period Cepheids (Barnes 1978). Until this is done, it seems best not to present any analyses of the data connected with the method.

IV. THE PERIOD CHANGE

SV Vul has long been known to have a variable period. It was one of the stars in a major study on Cepheid period variations undertaken by Parenago (1956), in which he concluded that Cepheids do not show smooth secular period variations, but instead behave erratically, maintaining one period for a while and then jumping suddenly to another. This, Parenago concluded, applied also to SV Vul.

Since the current observations showed that the period had again changed from previously determined values, a new analysis of the star's period was carried out. Using the observed epochs of maximum light listed by Parenago (back to the discovery date in

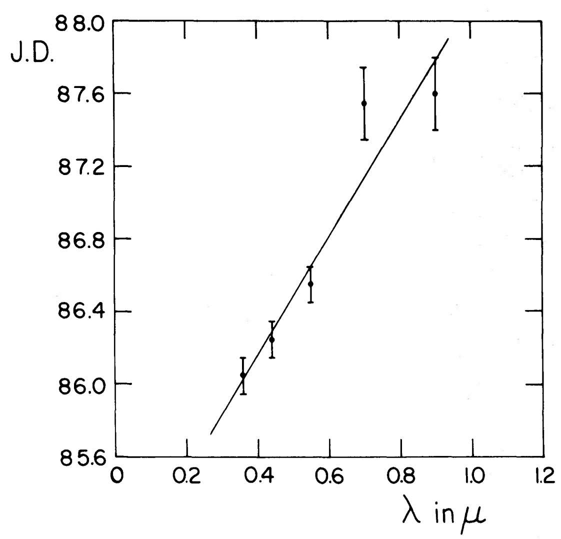

FIG. 2.—Epoch of maximum light as a function of effective wavelength of filter. The ordinate scale should have 2,443,000 added to it.

TABLE 5

RADIAL VELOCITIES OF SV VUL

JD (2,443,000+)	Radial Velocity (km s^{-1})
283.814..........	-5.85 ± 0.20
289.819..........	$+4.99 \pm 0.29$
317.764..........	-22.22 ± 0.39
352.681..........	$+8.87 \pm 0.59$
436.576..........	$+20.16 \pm 0.73$

1913), plus three more-recent epochs listed in Table 6, the usual $O - C$ diagram was constructed. This is shown in Figure 3. The systematics of such diagrams are well known, in particular that a period changing linearly with time will produce a parabola on the diagram. This, it seems clear from Figure 3, is the case for SV Vul; the curve in the diagram is a parabola fitted to the points by least-squares. Thus we conclude rather firmly that SV Vul does *not* show erratic period changes, but instead has a linearly decreasing period. The decrease is $(8.06 \pm 0.31) \times 10^{-6}$ days per day, or 254 ± 10 s y^{-1}.

The revised elements for the epochs of maximum (visual) light, derived from the least-squares fit, are

$$\begin{aligned} JD_{\max V} = {} & 2443086.89\ (\pm 0.37) \\ & + 45.0121\ E\ (\pm 0.0034) \\ & - 0.0001814\ E^2\ (\pm (0.0000069)\ . \end{aligned}$$

Close examination of Figure 3 suggests that a second-order effect may exist. Over intervals of a decade or so, the points tend to fall systematically below the curve, then above the curve, etc. If normal points are formed from these residuals, they can be assembled into a rough sinusoid of amplitude about 1^{d}6 and period about 27 years. An obvious interpretation would be a light-time effect in a binary orbit, but this proves to need a total minimum mass for the system of several thousand solar masses, and so is ruled out (as it also is by the radial-velocity data). If the effect is real, and it is emphasized that the evidence is not strong, it presumably reflects a long-term modulation in the pulsation itself.

The most likely explanation of the main 254 s yr^{-1} variation is that it is caused by the evolution of this very luminous star across the H-R diagram, its changing radius producing through the $P\sqrt{\rho}$ relation a changing period. Theory suggests that most Cepheids are in the second crossing (right to left) of the instability strip, and this is in accord with the present

TABLE 6

RECENT EPOCHS OF MAXIMUM LIGHT

JD	Reference
2437187.9..........	Mitchell *et al.* 1964
2438268.9..........	Fernie *et al.* 1965
2443086.55.........	This paper

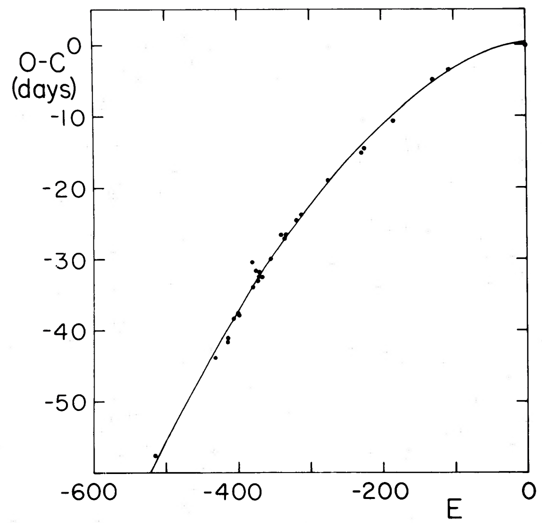

FIG. 3.—The $O - C$ diagram for SV Vul. The curve is a least-squares parabola fitted to the points, and shows the star to have a linearly decreasing period.

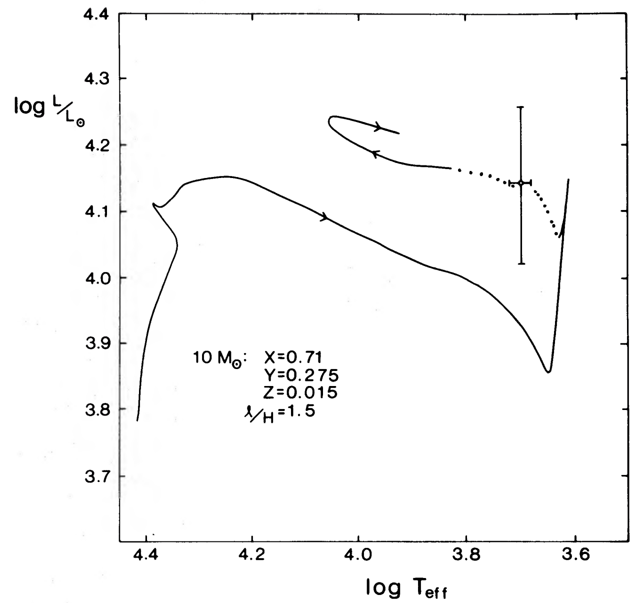

FIG. 4.—Theoretical H-R diagram, showing the location of SV Vul and the evolutionary track of a 10 $M_{\odot}$ star by Flower. Individual points in the neighborhood of SV Vul represent individual models from which the theoretical rate of period change was derived.

observations of a decreasing period. For comparison between theory and observation, therefore, it is assumed that SV Vul is on this second crossing. Before the comparison can be made, however, it is necessary to establish the position of SV Vul on the theoretical H-R diagram.

The color-excess scale of Cepheids is not yet in a satisfactory state (Canavaggia, Mianes, and Rousseau 1975), and in the case of SV Vul more than a dozen values of E_{B-V} are to be found (or can be derived from various formulae) in the literature. They vary from 0.39 to 0.66; many are related in the sense that they depend on the same observational data and/or are variations of the same basic method. Rather than attempt any exhaustive discussion here, we will be content simply to take $E_{B-V} = 0.5 \pm 0.1$ for SV Vul. Then, $(\langle B \rangle - \langle V \rangle)_0 = 0.96 \pm 0.1$.

The conversion of intrinsic color to effective temperature for supergiants is another difficult question. Flower (1977) reviews a number of scales, and from the discussion there we may adopt $T_{\rm eff} = 5000 \pm 200$ K, the uncertainty reflecting mainly the uncertainty in color excess.

At present the best estimate of the star's luminosity is to be had from the period-luminosity relation (Sandage and Tammann 1969), which gives $M_V = -5.7$. With a bolometric correction of $+0.1$ mag (Flower 1977), we have $M_{\rm bol} = -5.6 \pm 0.3$, the uncertainty being merely an educated guess.

We are now in a position to compare the star with theoretical models. Although models for stars in this part of the H-R diagram have been published, for example, by Harris and Deupree (1976), they are not suited to present purposes. Generally only the details of models at the extrema of the loops are published, from which only an average rate of period change along a branch of the loop can be derived. But the actual rate can be expected to vary considerably along the branch, so that an average rate is of little use.

By good fortune unpublished details of models for a 10 $M_{\odot}$ star passing almost directly through the position of SV Vul on the H-R diagram were available

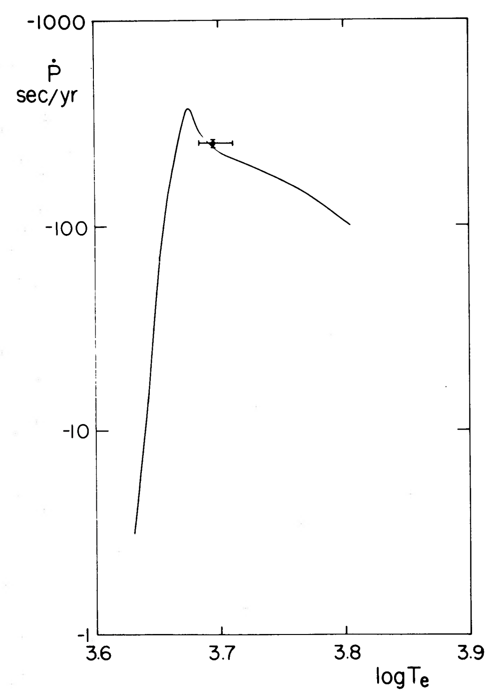

FIG. 5.—Rate of period change as a function of effective temperatures of models along the track shown in Fig. 4. The point represents the observed position of SV Vul.

from Flower (private communication). These are plotted in Figure 4, and the theoretical rate of period change derived from the models by use of the $P\sqrt{\rho}$ relation is shown in Figure 5. It is clear from the latter diagram why an average rate of period change along the track will not suffice: it can easily be an order of magnitude lower than the peak rate.

Figure 5 shows good agreement between theory and observation; sufficient, it would seem, to make the interpretation of SV Vul's period change as due to secular evolution almost certain. However, although that conclusion seems safe, the particularly good agreement is undoubtedly fortuitous. Reference to Figure 2 of Harris and Deupree (1976) shows how sensitive the positions and shapes of the tracks are to chemical composition. Higher values of metallicity lower the tracks in the H-R diagram, as, of course, does lower mass. Indeed, it would have been preferable to have had models of higher mass and higher metallicity than the 10 $M_{\odot}$ and $z = 0.015$ used by Flower. Furthermore, the value of mixing-length to scale-height ratio that is used also affects the positions of the tracks.

These difficulties are well illustrated by appealing to theoretical relations derived by other authors. For instance, the values of period, mass, luminosity, and effective temperature used above are inconsistent with equation (4) of Iben and Tuggle (1975). Taking these period, luminosity, and temperature values, that equation yields a mass of only 6.3 $M_{\odot}$. On the other hand, equation (18) of Becker, Iben, and Tuggle (1977) suggests that the luminosity of SV Vul must be significantly higher ($M_{\text{bol}} = -6.7$), and equation (13) of that paper then requires a mass of some 12 or 13 $M_{\odot}$, depending on chemical composition choices, and a predicted period rate probably an order of magnitude higher than observed.

Obviously, then, the excellent agreement between theory and observation in Figure 5 is largely due to good luck. The point, however, is that the period change may well offer a further observational hold on the choice of theoretical parameters for modeling Cepheids. Now, not only must the models satisfy the period and position of the star on the H-R diagram, they must also satisfy the rate of period change.

On the observational side, since the period change of SV Vul was discovered almost accidentally, it may well be worth reexamining the period behavior of other long-period Cepheids. Very rough calculations suggest that the rate of period change falls by about an order of magnitude for each magnitude decrease in M_{bol}, so the effect would be undetectable in the shorter-period Cepheids. Attention should first be concentrated on stars with periods over, say, 20 days.

I am much indebted to Philip Flower for making available the details of his theoretical models, as well as for informal discussions. My thanks also to Nancy Evans for obtaining and measuring the spectrograms of SV Vul.

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