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ON THE NATURE OF THE LIGHT VARIATIONS OF V564 OPHIUCHI

V564 Ophiuchi was discovered by Tsesevich (1952), who published a finding chart of its field and described it as an RV Tauri variable with a period of 70.6 days. Preston, Krzeminski, Smak and Williams (1963; hereafter, PKSW) obtained UBV photometry and low-dispersion spectrograms of the variable, finding V = 9.72 - 10.42 and B-V = 1.55 - 1.72 and a G8p - K2(M2) spectral range. DuPuy (1973) commented upon the poor repeatability of the light curves and found similar ranges in brightness and color. Erleksova (1975) reclassified V564 Oph as an SRd variable because of its erratic light curve and red color and derived elements of minimum light using published photometry. Dawson (1979) estimated [Fe/H] between -0.7 and -1.4 from DDO photometry and compared reddening estimates from PKSW, DuPuy, and Burstein and McDonald (1975) to obtain E(B-V) = 0.21 mag. This agrees well with the color excess (0.1 - 0.2 mag) found by FitzGerald (1968) from stars of types O through F. DuPuy, Allwright, Dawson and Africano (1983; hereafter, DADA) obtained Stromgren b, y photometry over roughly a 200-night span. Wahlgren (1985,1986) estimated a spectral type of K3-4 IIb and derived [Fe/H] = -1.05 (using synthetic spectra) from a spectrogram of 2.5 A resolution taken at the Perkin Observatory (Ohio State) on 22 June 1985 (J.D. 2,446,238). Part of the red color of V564 Oph comes from material between us and the star's photosphere; removing the effects of this material gives an intrinsic (B-V) around 1.4 - 1.5, which well matches the late G to early K spectral type range. Gehrz (1972) found only mild infrared excesses for V564 Oph in observations over several nights, which suggests that most of the star's reddening is interstellar and not circumstellar.

We decided to obtain and examine photometry of V564 Oph over many pulsation cycles, to redetermine its period, to study cycle-to-cycle variations, and to attempt to improve its classification.

Most of the data were obtained by two of us (Lines and Lines) at our observatory in Mayer, Arizona, during 1983, 1984 and 1987. We used a 50-cm Cassegrain telescope and an uncooled RCA 1P21 detector with calibrated UBV filters. Because V564 Oph is so red, the U signal was too weak for accurate photometry with our equipment; therefore, we restricted our work to V magnitudes and B-V colors. All measurements were made differentially with respect to SAO 122871 [= BD+07°3496], then corrected for extinction and transformed to the standard system. Sets of three individual comparisons were averaged to form nightly means; the standard deviations are no larger than 0.02 mag in V and B-V. On two nights in 1983, two nights in 1984 and one night in 1987, the magnitude and color of SAO 122871 was determined from comparisons with the secondary UBV standard SAO 122686 [= BD+05°3469 = HD 161242]; these observations show SAO 122871 to be constant within observational errors and to have V = 8.33, B-V = 1.13.

Two of us (Baird and Dawson) obtained UBV and Kron-Cousins RI observations of V564 Oph in 1985 at the Cerro Tololo Inter-American Observatory, as part of a larger survey of southern RV Tauri variables. The general results of this survey will be published elsewhere. We used the 41-cm Lowell reflector and UBVRI filter set #2 with a gallium arsenide (RCA C31034A) detector cooled with dry ice. The all-sky photometry has average nightly standard deviations of 0.013 mag in V and 0.006 mag in B-V.

One of us (AAVSO observer, Horowitz) observed V564 Oph visually on 97 nights from June, 1985 to November, 1986, using six nearby comparison stars to estimate brightness. The visual estimates are useful for maintenance of the cycle count and for monitoring the form of the pulsation over long times but are much less accurate than the photoelectric measurements because of the small amplitude of the variable.

The time intervals covered by the observations are listed in Table 1, and the photoelectric light curves are shown in Figures 1 through 6.

Table 1
Observations of V564 Oph

Observers	J.D. Range	Dates	Photometry
Preston et.al. (1963)	2,437,488 - 2,437,581	7/61 - 10/61	UBV
DuPuy et.al. (1983)	2,444,337 - 2,444,518	4/80 - 10/80	b,y
Lines and Lines (*)	2,445,440 - 2,445,560	4/83 - 8/83	BV
Lines and Lines (*)	2,445,831 - 2,445,950	5/84 - 9/84	BV
Dawson and Baird (*)	2,446,197 - 2,446,259	5/85 - 7/85	UBVRI
Lines and Lines (*)	2,446,965 - 2,447,079	6/87 - 10/87	BV
Horowitz (*)	2,446,237 - 2,446,741	6/85 - 11/86	visual

* = this paper

The first two figures reproduce the observations of PKSW and DADA. As noted by others, the light curves of V564 Oph show considerable variation from cycle to cycle. Minima can be symmetric (e.g., J.D. 2,447,067) or markedly asymmetric (e.g., J.D. 2,446,983). If the width of a deep minimum is measured from the average magnitude of the decline to the time when the same magnitude occurs on the subsequent rise, the widths of minima range from about 12 - 30 days. The depths of deep minima range from about 0.4 - 0.7 mag below average maximum brightness.

Julian dates of minimum light were estimated from the photoelectric light curves and are given in Table 2. DADA used the y and b filters of the four-color (Stromgren) system.

Using times estimated from photoelectric measurements of the four most symmetric and best-observed minima (J.D. 2,437,524, 2,445,509, 2,445,867 and 2,447,067) yields the linear ephemeris

$$J.D.(min) = 2{,}437{,}453.16 + 70^{d}.688 * E.$$

Using all the times of minima determined from photoelectric photometry except for the minimum at J.D. 2,444,503 gives the linear ephemeris

$$J.D.(min) = 2{,}437{,}452.85 + 70^{d}.666 * E.$$

The column labeled "E" in Table 2 contains the numbers used with our linear ephemerides, and O-C values [in days] computed with them are listed, respectively, as O-C(1) and O-C(2). We also computed O-C values [in days] from Erleksova's quadratic ephemeris:

$$J.D.(min) = 2{,}437{,}520 + 70^{d}.325 * E' + 0^{d}.0073 * (E' + 10)^{2}$$

Those values are listed in the table as O-C(3).

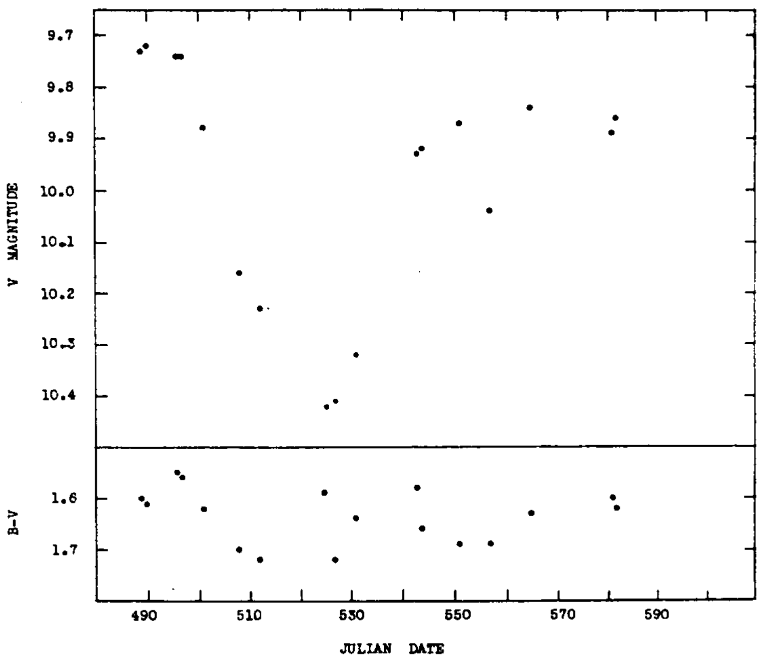

Figure 1. Johnson V magnitude and B-V color index. Add 2,437,000 to the abscissa values to obtain Julian dates. Data are from PKSW (1963).

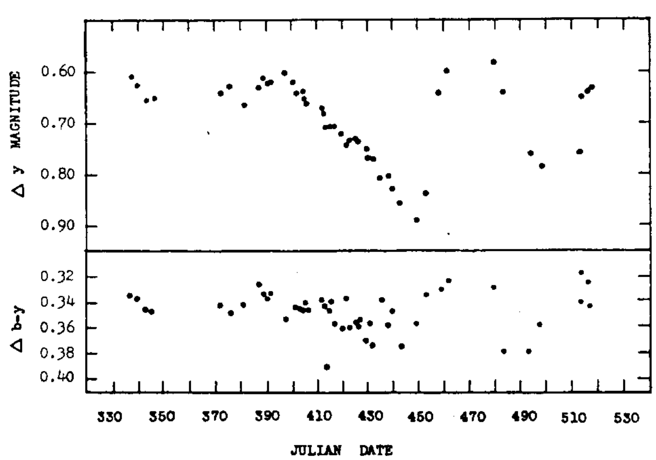

Figure 2. Differential Stromgren y magnitude and b-y color index. The comparison star was BD+07°3496. Add 2,444,000 to the abscissa values to obtain Julian dates. Data are from DADA (1983).

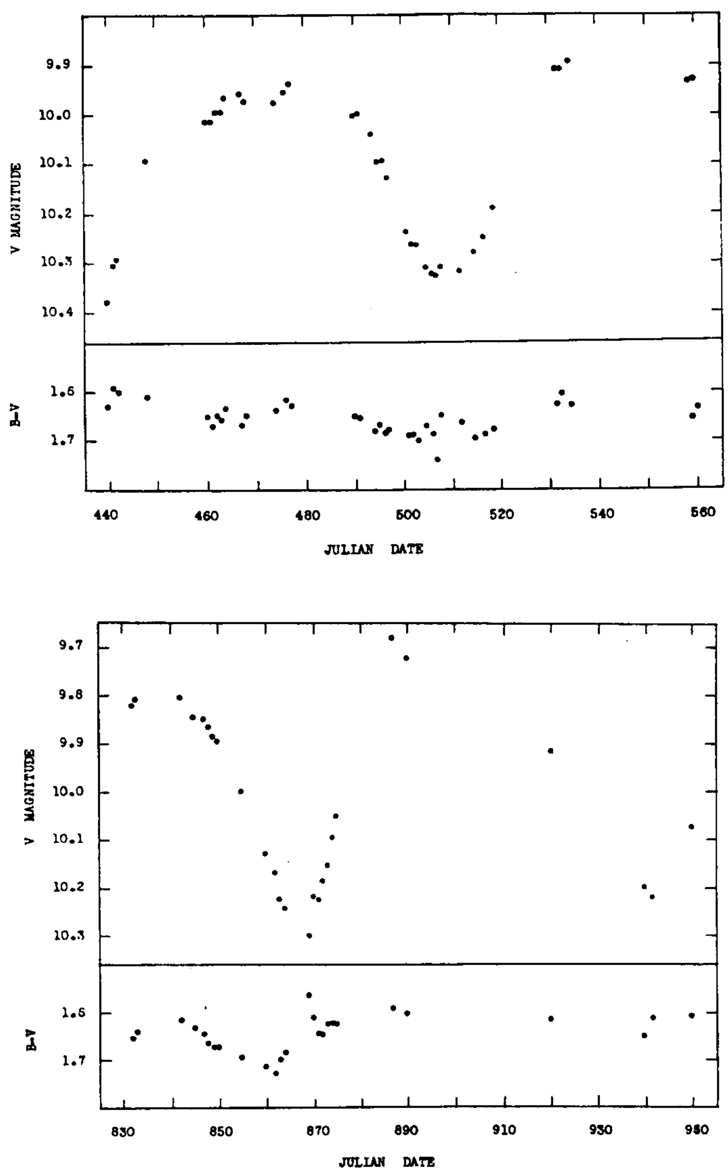

Figure 3. AND Figure 4. V magnitude and B-V color index. Add 2,445,000 to the abscissa values to obtain Julian dates. Data are from Lines and Lines (this paper).

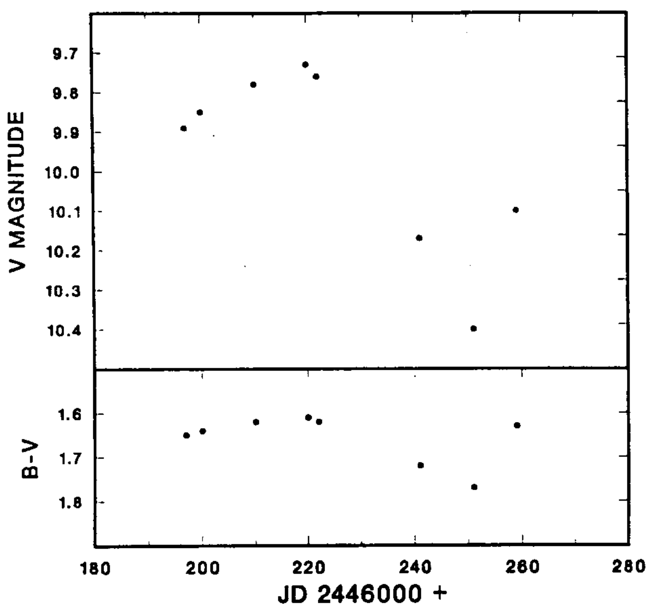

Figure 5. V magnitude and B-V color index. Add 2,446,000 to the abscissa values to obtain Julian dates. Data are from Dawson and Baird (this paper).

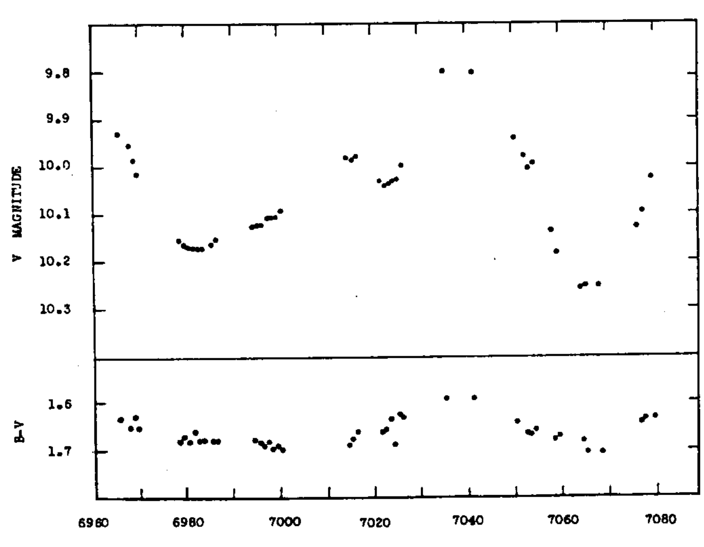

Figure 6. V magnitude and B-V color index. Add 2,440,000 to the abscissa values to obtain Julian dates. Data are from Lines and Lines (this paper).

Table 2
Observed and Calculated Times of Minima

J.D. (min)	E	E′	O-C(1)	O-C(2)	O-C(3)	Comments	Reference
2,437,524	1	0	+0.2	+0.5	+4.0		PKSW (1963)
2,437,557	1.5	0.5	-2.2	-1.8	+1.0	1 data point	PKSW
2,444,449	99	97.5	-2.3	+0.2	-12.0	v. asymmetric	DADA (1983)
2,444,503	99.5	98	+16.4	+18.9	+6.0		DADA
2,445,471	113.5	111.5	-5.2	-2.4	-2.0	v. shallow	This paper
2,445,509	114	112	-2.6	+0.2	+3.9		This paper
2,445,867	119	117	+2.0	+4.9	+1.2		This paper
2,445,942	120	118	+6.3	+9.2	+4.0	few points	This paper
2,446,251	124.5	122.5	-2.8	+0.2	-12.0	few points	This paper
2,446,983	135	132.5	-13.0	-9.8	-3.3	asymmetric	This paper
2,447,023	135.5	133	-8.4	-5.1	+0.5	shallow	This paper
2,447,067	136	133.5	+0.2	+3.6	+8.3		This paper

It is clear from an inspection of Table 2 that neither a linear nor a quadratic ephemeris completely describes the light variations of V564 Oph. Many of the O-C values are much larger than the uncertainty (typically ~2 days) in estimating times of minimum. The minimum of J.D. 2,444,503, which follows a very asymmetric one (see Figure 2), comes nearly 1/4 period late if we assign it E = 99.5, and the asymmetric minimum of J.D. 2,446,983 comes about 1/5 period early for E = 135. A deep minimum is seen for E = 124.5, and a moderately deep one was observed visually for E = 128.5, as though an interchange of minima had occurred earlier. Thereafter, the light curve shows lower amplitudes and a more sinusoidal character.

The behavior of B-V around times of V minimum light is interesting. For RV Tauri and some SRd variables, the star reaches its largest (reddest) B-V before deep V minimum light and its bluest color during the rise in brightness that follows. This behavior is seen for the minima in Figures 1 and 2, and for at least the first minimum shown in Figure 4, but it is not obvious for other minima. The variations in B-V are approximately in phase with the brightness changes for the other symmetric minima. B-V "spikes" toward bluer color seem to be present near the times of the well-observed minima in Figures 3 and 4, and possibly for the minimum of Figure 1; if they do not arise from observational errors, their physical significance is unclear. B-V is not reddest preceding the asymmetric minimum at J.D. 2,446,983, nor does it become bluer following that minimum, but it does become bluer following the minimum at J.D. 2,447,023.

Is V564 Oph an RV Tauri star? Its estimated [Fe/H] value is typical of that found for other RV Tauri variables but is somewhat metal-rich for those SRd variables which have had abundance analyses; [Fe/H] = -1.5 to -2 is a more typical range for them, and SRd variables are considered members of a Halo population. Alternating deep and shallow minima are not as strongly evident in V564 Oph as they are in well-known RV Tauri variables, and its maximum-to-minimum V amplitude (0.6 mag) and B-V amplitude (0.1 mag) are also low, but its minima display more symmetry than is usually found for SRd variables. The possible interchange of minima before J.D. 2,446,200 may be support for RV Tauri variation, but the presence of very asymmetric minima suggests that more than one process may be affecting the pulsation amplitudes.

V564 Oph sometimes shows RV Tauri characteristics, but it can also show Cepheid-like intervals or sudden brightness dips reminiscent of R Coronae Borealis stars. Its light variations resemble those of AR Puppis (a carbon-rich RVb) and AR Sagittarii (a variable which also shows some deep and shallow minima); see Figures 7 and 9 of Payne-Gaposchkin, Brenton and Gaposchkin (1943). Simultaneous UBV and infrared photometry for this variable could be very revealing.

Perhaps it is better, following Eggen (1986), to refer to V564 Oph as a 'pseudocepheid,' one of many late-type stars for which underlying stable pulsation is occasionally disturbed in different ways, until the nature of the disturbance can be better defined.

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