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SPECTRAL VARIATIONS IN ζ OPHIUCHI RELATED TO ROTATION?

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ABSTRACT

Two $2\frac{1}{2}$ hour series of high-resolution spectra of the rapidly rotating O9.5 V star ζ Ophiuchi show several distinct features at the 1% level which move through the broad λ6678 He I absorption line. The nature of the velocity variation is consistent with nonuniformities in stellar surface brightness being carried across the line of sight by rotation. If a narrow absorption feature, which is seen on both nights, corresponds to the same region of the star, the rotation period is 21.7 hours. If this period is correct, then the observed acceleration of the feature leads to 560 km s^{-1} for $v \sin i$ and 7×10^6 km or 10 $R_\odot$ for $r_* \sin i$. These correspond well with published values except that they imply $i \sim 90°$. Alternatively, if values of $i = 55°$ and $r_* = 10\ R_\odot$ are assumed, the rotation period is 19.7 hours and $v \sin i$ is 508 km s^{-1}. The profiles of the velocity variable features have been recovered by a Fourier deconvolution technique for each night. They both show a broad emission with a sharp reversal. The latter doubled in strength by the second night. The associated "spot" appears to be confined to about 1% of the visible stellar disk. Some indication of the degree of gravity darkening is given in Figure 1 based on a value of $v \sin i$ = 560 km s^{-1}.

Subject headings: line profiles — stars: early-type — stars: individual — stars: rotation

I. INTRODUCTION

Moderate stellar rotation distorts an absorption line by convolving the intrinsic line shape with a semi-ellipse whose width is proportional to $v \sin i$ moderated by limb darkening (see, for example, Slettebak *et al.* 1975). Some O and B stars appear to be rotating so rapidly that they must be close to break-up velocity. For these, gravity darkening in the equatorial region must significantly restrict the half-widths of lines. The effect is probably sensitive both to wavelength and to i, the inclination of the rotation axis to the line of sight (Hutchings 1976).

In deriving rotational velocities, observed line profiles are generally compared with theoretical model predictions, and it is assumed that the stars are stable, except for irregular mass loss from some of the rapid rotators which is indicated by variable Hα emission (see, for example, Slettebak and Reynolds 1978 for a recent summary). We are currently acquiring high signal-to-noise spectra for a selection of rapid rotators to determine better line profiles and to see whether variability contributes to the line broadening.

Low-dispersion spectra of ζ Ophiuchi (HD 149757, $V = 2.56$, O9.5 V) showed night-to-night variations in the profiles of the He I λ5876 and λ6678 lines. As a result, we observed the star at higher resolution to determine the nature of the variations. It is the purpose of this paper to report that these observations indicate that the surface of the star is of nonuniform brightness and that, by "tracking" these nonuniformities in motion across the line of sight, values of the rotation period, projected radius, rotational velocity, and the degree of gravity darkening can be derived. A technique has also been developed to recover the spectral profile of the moving features.

II. THE OBSERVATIONS

The observations were made at the Dominion Astrophysical Observatory with the coudé spectrograph of the 1.22 m telescope (see Richardson, Brealey, and Dancey 1971). The detector was a Reticon RL 1024C/17 linear array of silicon diodes refrigerated with liquid nitrogen and used directly in the spectrum without intensification. The detection system has been described in detail by Walker (1977). The spectral resolution was 0.12 Å per diode.

Details of the observations of ζ Oph are given in Table 1. The low altitude of the star at Victoria limited the time series to approximately $2\frac{1}{2}$ hours each. The rotational broadening in ζ Oph is so great ($\sim$15 Å full width) that weak absorption lines are "washed out" or become blended with neighboring lines. Consequently, we have confined our attention to the He I λ6678 line, which has a central depth of about 10% of the continuum.

The averaged λ6678 line profiles from 1978 May 8, July 28, and July 29 are shown in Figure 1. The time series of spectra from 1978 July 28 and 29 are plotted in Figures 2 and 3, respectively, together with their mean spectra. Mean exposure times are approximately 20 minutes and 8 minutes for July 28 and 29, respectively. In all cases the original spectra have been normalized by the continuous spectrum of an incandescent lamp to eliminate diode-to-diode variations in sensitivity and instrumental spectral curvature. All of the spectra have been filtered to 20% of the Nyquist

TABLE 1

OBSERVATIONS OF ζ OPHIUCHI AND VELOCITIES OF FEATURES A AND B

JD	Mid-exposure (UT)	Wavelength (A)	Velocity (km/s)*	Time (mins) in Fig. 6
2443636+	1978 May 8			
0.88692	9:17:10			
0.89271	9:25:30			
2443717+	1978 July 28		FEATURE A	
0.68774	4:30:20.5	6670.5	-328	0.0
0.70113	4:49:37.5	6671.5	-274	19.3
0.71503	5:09:38.5	6672.3	-247	39.3
0.73543	5:39:01	6673.9	-175	68.7
0.74933	5:59:02	6674.4	-153	88.7
0.76322	6:19:02	6675.7	-94	108.7
0.77711	6:29:02	6677.2	-27	128.7
0.79100	6:59:02	6678.6	+36	148.7
2443718+	1978 July 29		FEATURE B	
0.68206	4:22:10	6677.1	-31	124.0
0.68959	4:33:01	6677.8	0	134.8
0.69562	4:41:42	6678.2	18	143.4
0.70142	4:50:03	6678.5	31	151.8
0.70727	4:58:28	6679.3	67	160.3
0.71424	5:08:30.5	6679.4	76	170.2
0.71876	5:15:01	6680.1	103	176.8
0.72456	5:23:22	6680.3	112	185.2
0.73841	5:43:19	6681.7	175	205.0
0.74421	5:51:40	6682.4	207	213.4
0.75007	6:00:06	6682.9	229	221.9
0.75587	6:08:27	6683.1	238	230.2
0.76167	6:16:48	6683.6	260	238.6

* Velocities relative to a line centre of 6677.8 Å.

frequency (which is equivalent to a resolution of about 0.6 Å). The wavelength scale was established from comparison spectra, and correction for the Earth's motion has been applied in the usual way.

III. THE VARIATIONS

A disturbance can be distinctively seen moving from short to long wavelength in the spectral series of 1978 July 28 in Figure 2 with a similar effect in the series of 1978 July 29 in Figure 3. Further, the mean line profiles are asymmetric, with the center of gravity of the line being displaced to longer wavelengths.

The asymmetry is probably due, at least in part, to the λ6683.2 line of He II appearing to the long-wavelength side of the λ6678.1 He I line. The star ζ Oph shows the λ6527 He II line in absorption, and the λ6683 and λ6527 He II lines are normally of comparable strength. This blend probably also accounts for the depression in the continuum at wavelengths greater than λ6686. We have noted from low-dispersion spectra that the He II absorption appears to be variable from night to night.

There are several sharp, persistent features in the line profiles, notably that at λ6671.8 on 1978 July 29, which do not coincide with any known telluric lines. The possibility of their being instrumental cannot be ruled out.

In order to isolate the variations in the λ6678 He I line profile, difference spectra have been formed by subtracting the mean spectrum for each night from the individual normalized spectra for that night. The difference spectra are shown in Figures 4 and 5. The limits of the absorption-line profile are indicated and a mean level has been drawn for each, using the regions of the difference spectrum outside the line profile.

The motion of features through the line profiles can be clearly seen, particularly on 1978 July 29. The wavelengths of two absorption features, one from each series, identified as A and B, are tabulated in Table 1. Adopting a mean wavelength of λ6677.8 for the absorption line on both nights, the wavelengths of A and B have been converted to velocities relative to the line center. The velocities of features A and B are plotted against time in Figure 6, where the variation has been made continuous by a sliding fit of the curve

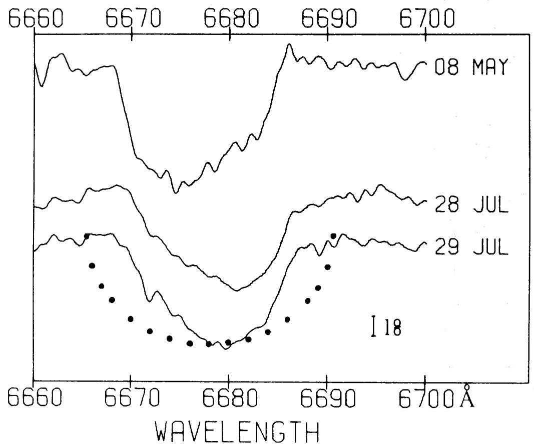

FIG. 1.—Mean spectra of ζ Oph in the region of λ6678 He I from the nights of 1978 May 8, July 28, and July 29. The spectra have been smoothed to 20% of the Nyquist frequency for a resolution of approximately 0.6 Å. The dotted line indicates the expected line profile in the absence of gravity and limb darkening if $v \sin i$ = 560 km s^{-1}.

for B to that of A. This sliding fit assumes that the accelerations of features A and B are due to the same mechanism and differ only in phase.

IV. INTERPRETATION

In our view the most logical explanation for the strikingly similar behavior of features A and B is that they represent regions of lower than average temperature being carried across the surface of the star by rotation, probably near the equatorial region. If θ is the longitude of the spot relative to the line of sight and δ is its latitude relative to the stellar equator, then $(v \sin i) \cos \theta \cos \delta = (aT/2\pi)$ and $(r_* \sin i) = (T/2\pi)$ $(v \sin i)$, where a is the observed acceleration of the

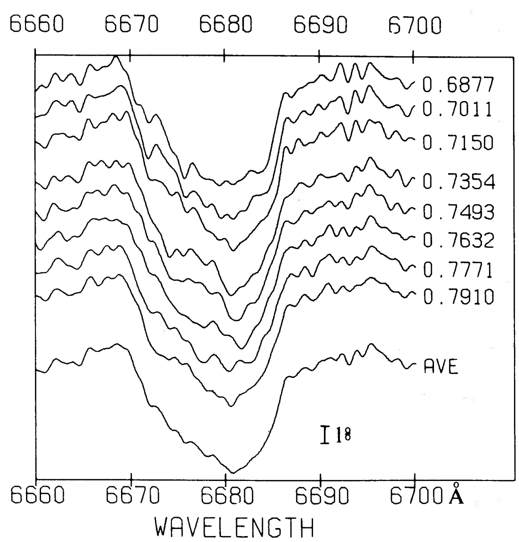

FIG. 2.—Individual spectra at λ6678 He I of ζ Oph taken at approximately 20 minute intervals, together with a mean spectrum, 1978 July 28.

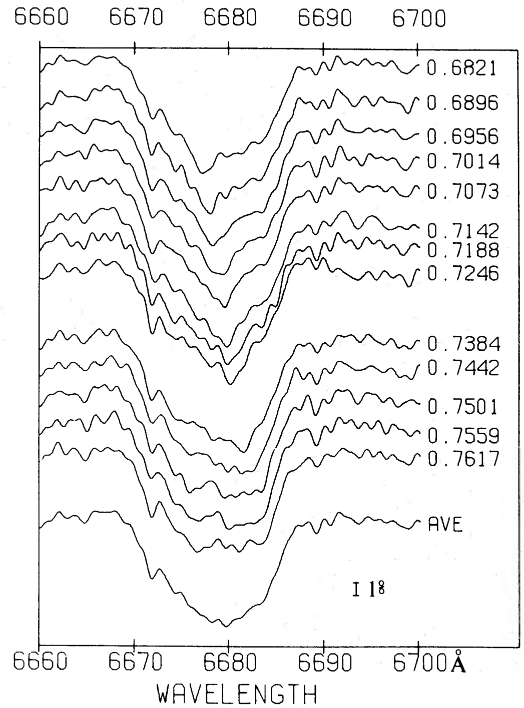

FIG. 3.—Individual spectra at λ6678 He I of ζ Oph taken at approximately 8 minute intervals, together with a mean spectrum, on 1978 July 29.

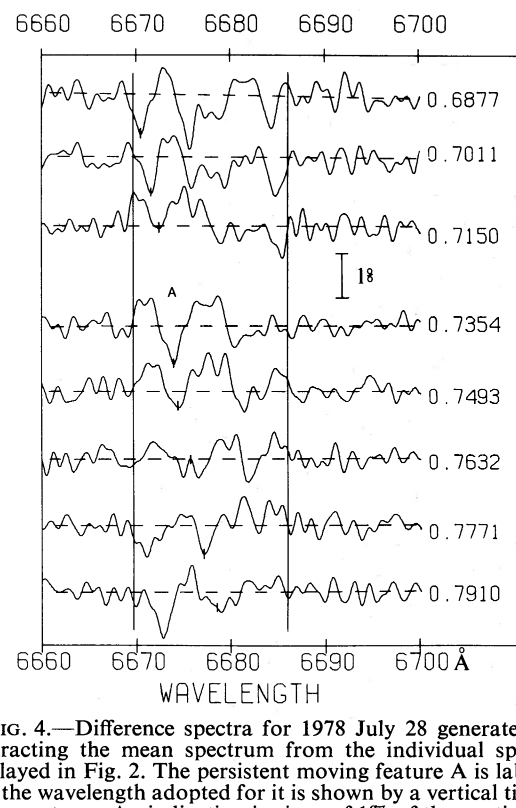

FIG. 4.—Difference spectra for 1978 July 28 generated by subtracting the mean spectrum from the individual spectra displayed in Fig. 2. The persistent moving feature A is labeled and the wavelength adopted for it is shown by a vertical tick in each spectrum. An indication is given of 1% of the continuum height in the original spectra.

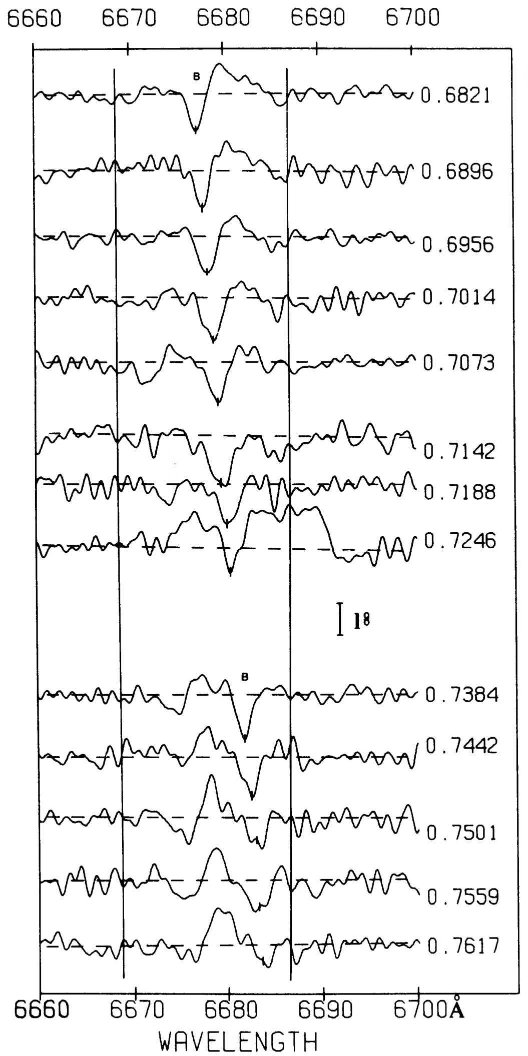

FIG. 5.—Difference spectra for 1978 July 29 generated by subtracting the mean spectrum from the individual spectra displayed in Fig. 3. The persistent, moving feature B is labeled and the wavelength adopted for it in each spectrum is shown by a vertical tick. The 1% indicated corresponds to 1% of the continuum height in the original spectra.

feature, T the period of rotation, and r_* the stellar radius.

The period T can be determined if either (*a*) the same spectral feature is detected on different revolutions, or (*b*) the acceleration of the feature is observed over a large enough fraction of the period to permit a sine curve to be fitted with confidence. From Figure 4 it is clear that the variation of velocity is largely linear and does not allow a sine curve to be fitted with confidence.

The period could be accurately estimated if one of the absorption features on 1978 July 28 could be identified with feature B on 1978 July 29. According to Hutchings and Stoeckley (1977), $v \sin i$ and i for ζ Oph are 390 km s^{-1} and 55°, respectively. These figures suggest that one might expect a period of about 22 hours if $r_* = 10\ R_\odot$. From our observations, if features

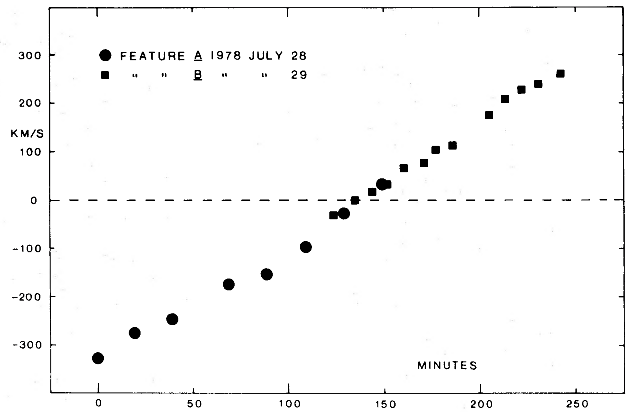

FIG. 6.—Variation with time of the velocities of feature A (*large dots*) and Feature B (*squares*) relative to the adopted line center of λ6677.8. A sliding fit has been made by eye to show the variation for A and for B as continuous.

A and B are caused by the same region on the surface seen one revolution apart, one derives $T = 21.7$ hours. These two periods are sufficiently close to justify considering that A and B are indeed due to the same region. From Figure 4, $a = 0.045$ km s^{-2} at the zero velocity crossing where $\cos \theta = 1$. If $\delta = 0°$ one derives the values $v \sin i = 560$ km s^{-1}, and $r_* \sin i = 10\ R_\odot$. It is interesting that these values correspond exactly to the break-up velocity suggested by Hutchings and Stoeckley (1977) and to the radius derived from photometric data (Underhill *et al.* 1978), provided $i \sim 90°$.

V. GRAVITY DARKENING AND $v \sin i$

Features A and B may well not be due to the same surface irregularity. In this case one must adopt values for r_* and i. Taking $r_* = 10\ R_\odot$ from Underhill *et al.* (1978) and $i = 55°$ from Hutchings and Stoeckley (1977) gives $v \sin i = 508$ km s^{-1}. This is still much larger than the values of 390 km s^{-1} and 320 km s^{-1} derived by Hutchings and Stoeckley (1977) and Slettebak *et al.* (1975), respectively, from the comparison of theoretical and observed line profiles. Balona (1975) gives a value of 367 km s^{-1}, using Slettebak's system for calibration. Part of the uncertainty in these determinations lies in estimating the magnitude of gravity darkening (see also Hutchings 1976).

The estimates of $v \sin i$ in this paper are independent of gravity darkening except to the extent that it limits the range of accelerations which can be measured and does not allow the fitting of a sine curve to the velocities. Taking our value of $v \sin i = 560$ km s^{-1} as correct, we indicate in Figure 1 by dots the line profile to be expected in the absence of gravity and limb darkening.

In view of the extensive ultraviolet observations of ζ Oph now available and the severe equatorial darkening present in the UV (Hutchings 1976), it would be interesting to examine such UV data for evidence of circumpolar irregularities in disk brightness by a technique similar to that used in this paper.

VI. PROFILE OF THE VARIABLE FEATURE

The difference spectra of Figures 4 and 5 do not accurately show the true profile of the feature moving through the broad He I λ6678 line, because each spectrum contributes to the mean. In consequence the different profiles tend to change gradually through the sequence. It is, however, possible to recover the true profile of the moving feature.

At any particular time t the observed data, $D(\lambda, t)$ can be expressed as the sum

$$D(\lambda, t) = A(\lambda) + B(\lambda, t)\,, \quad (1)$$

where $A(\lambda)$ is the broad constant profile and $B(\lambda, t)$ represents the variable component. If we assume that the variation is simply a translation of a constant profile, $P(\lambda)$, along the λ axis, then $B(\lambda, t)$ can be represented as the convolution integral,

$$B(\lambda, t) = P(\lambda) * \delta(\lambda - \lambda_t)\,, \quad (2)$$

where λ_t is the central wavelength at time t. It is evident from the difference spectra that values for λ_t relative to an arbitrarily specified origin can be obtained without difficulty even though the profile $P(\lambda)$ is not unambiguously determined. However, given values of λ_t, both $A(\lambda)$ and $P(\lambda)$ can in fact be recovered as follows:

The Fourier transform of equation (1) is

$$D(k, t) = A(k) + P(k) \exp(-jk\lambda)t \quad (3)$$

where equation (2) has been used, and, e.g.,

$$D(k, t) = \int_{-\infty}^{\infty} D(\lambda, t) \exp(-jk\lambda) d\lambda \quad (4)$$

with analogous expressions for $A(k)$ and $P(k)$. The mean spectrum is defined as

$$\langle D(k) \rangle = \frac{1}{N} \sum_{t=1}^{N} D(k, t)$$
$$= A(k) + P(k) \sum_{t=1}^{N} \frac{\exp(-jk\lambda)t}{N}\,, \quad (5)$$

where we have taken t to be an integral index parameter and N is the number of spectra in the series. If the rth spectrum is subtracted from the mean, we find

$$P(k) = \frac{\langle D(k) \rangle - D(k, r)}{\sum_{t=1}^{N} \exp(-jk\lambda)t/N - \exp(-jk\lambda)r}\,. \quad (6)$$

All of the quantities appearing on the right-hand side of equation (6) are observable. Hence $P(k)$ can be calculated and $P(\lambda)$ is obtained by an inverse Fourier transform. In practice, each spectrum is subtracted in turn from the mean and the corresponding estimates of $P(k)$ are then averaged in the k domain to give the final result, and $A(\lambda)$ is easily obtained through equation (5).

Figure 7 shows the averaged values of $P(\lambda)$ for features A and B from 1978 July 28 and July 29. The absorption feature in the profiles has been aligned with a wavelength of λ6678.2. There is a remarkable similarity between the features for both nights. A broad emission is accompanied by a sharp reversal or self-absorption which is in many ways reminiscent of the Hα profiles for certain mass-loss stars in which a broad emission is seen with a nearly centered self-absorption. Indeed, ζ Oph was seen to go through such an Hα emission phase between 1971 and 1973 (see Irvine 1974; and Niemela and Méndez 1974). While the form of the emission is little changed between the two nights with a broad long-wavelength wing and a sharp, short-wavelength cutoff, the absorption is twice as great on July 29. This might argue against features A and B arising from the same surface region, but, on the other hand, if the feature is caused in some way by mass loss, an increasing self-absorption would naturally explain the change.

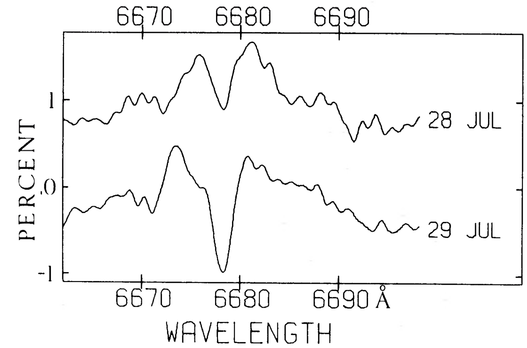

FIG. 7.—The profiles, $P(\lambda)$, of the velocity variable components of the 1978 July 28 and July 29 He I λ6678 line of ζ Oph derived by a Fourier deconvolution technique described in the text. The spectral intensity is in percentage of the stellar continuum height.

There is an ambiguity of interpretation for the profiles in Figure 7. If the emitting material is widely spread over the stellar disk the emission will appear broad because of different projected velocities. However, if the emission and absorption arise in the same region, it suggests a high-velocity dispersion or electron temperature associated with the region. The unsymmetric emission profile implies that the former interpretation is more likely.

One feature of the deconvolution procedure for $P(\lambda)$ which should be remarked on is the apparent extension in Figure 7 of $P(\lambda)$ beyond the limits of the λ6678 He I line. The effect of the time series is to sample the surface over more than the hemisphere visible for a single exposure and hence to display features over a wider wavelength range.

In our view the sharp absorption component of features A and B is probably caused by cooler material confined to one region or spot of the surface. Since this feature accounts for some 10% of the line width, it suggests that the cooler material covers approximately 1% of the visible stellar disk. This is admittedly a very rough estimate and could only be improved with more extensive observations.

As far as we know the only other early-type star for which spots rotating with the surface have been suggested as the source of variability is EW Lacertae.

Walker (1953) pointed out that the photometric variability of this rapidly rotating shell star might be commensurate with its period of rotation. In this case the continuum variations are of the order of 20% and dependent on wavelength. Lester (1975) considers that a model involving a large star spot is not consistent with his extensive multicolor photometry and that some kind of damped oscillation is more likely.

It is not clear that the photometric variations of EW Lac and the line profile variations we are reporting for ζ Oph have anything in common. They are of quite different magnitudes and by their nature the variations in ζ Oph must be inhomogeneous over the stellar disk. Unfortunately, we are not aware of any extensive multicolor photometry of ζ Oph which could be compared with that for EW Lac.

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