

PULSATIONS OF THE Oe STAR ζ OPHIUCHI FROM *MOST* SATELLITE¹
PHOTOMETRY AND GROUND-BASED SPECTROSCOPY

G. A. H. WALKER,² R. KUSCHNIG,² J. M. MATTHEWS,² P. REEGEN,³ T. KALLINGER,³ E. KAMBE,⁴ H. SAIO,⁵ P. HARMANEC,^{6,7}
D. B. GUENTHER,⁸ A. F. J. MOFFAT,⁹ S. M. RUCINSKI,¹⁰ D. SASSELOV,¹¹ W. W. WEISS,³ D. A. BOHLENDER,¹² H. BOŽIĆ,¹³
O. HASHIMOTO,¹⁴ P. KOUBSKÝ,⁷ R. MANN,¹⁵ D. RUŽDŽAK,¹³ P. ŠKODA,⁷ M. ŠLECHTA,⁷ D. SUDAR,¹³ M. WOLF,⁶ AND S. YANG¹⁵

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ABSTRACT

Twenty-four days of highly precise *Microvariability and Oscillations of Stars (MOST)* satellite photometry obtained in mid-2004 of the rapidly rotating O9.5 V star ζ Oph have yielded at least a dozen significant oscillation frequencies between 1 and 10 cycles day⁻¹, clearly indicating its relationship to β Cephei variables. Eight periods were found in He I λ 4922 and H β line profile variations (LPV) of which six coincide with those from the *MOST* photometry. This unique photometric and spectroscopic detection of radial and nonradial pulsations leads to a plausible model in which high l -modes are excited when their frequencies in the corotating frame are similar to those of low-order radial modes. We propose that the dominant photometric 4.6 hr period (f_1) corresponds to a radial first overtone excited by the κ -mechanism associated with the Fe opacity bump. No unambiguous rotational period can be identified in either the light curve or the LPV.

Subject headings: line: profiles — stars: early-type — stars: emission-line, Be —
stars: individual (ζ Ophiuchi) — stars: oscillations — stars: rotation

1. INTRODUCTION

ζ Oph (HD 149757, HIP 81377, HR 6175; $V = 2.58$, $B - V = 0.01$) is one of the most rapidly rotating ($v \sin i \sim 400$ km s⁻¹) Be stars known. It undergoes episodic mass loss (seen as emission at H α) lasting a few months roughly every decade (Kambe et al. 1993; Harmanec 1989). Blaauw (1961) identified ζ Oph as a runaway star, and Hoogerwerf et al. (2001) claim that the pulsar PSR J1932+1059 is its former primary. While formally classified O9.5 V, Herrero et al. (1992) find the ζ Oph line profiles more compatible with O9 III, but Repolust et al. (2004) prefer O9 V. It has been recognized for some time that

ζ Oph lies close to the blue edge of the β Cephei instability strip.

The profiles of stellar lines broadened by rotation offer a one-dimensional view of the stellar surface. In the case of ζ Oph, the profiles are distorted by ripples at $\sim 1\%$ level traveling from blue to red in a few hours (Walker et al. 1979), which Vogt & Penrod (1983) modeled by nonradial pulsations (NRP) and the star's rotation. They concluded that shadowing could also generate the ripples, but there was no matching photometric modulation. They also pointed out that NRP pulsation energy is large enough to drive mass loss through shock waves (see also Kambe et al. 1993; Reid et al. 1993).

Several campaigns have been organized to monitor the line profile variations (LPV) of ζ Oph (e.g., Kambe et al. 1993, 1997; Reid et al. 1993). In all cases the LPV proved to be multiperiodic and could be reconciled with traveling sectorial modes of high degree. One frequency, 7.1868 cycles day⁻¹ (3.339 hr), was detected in all campaigns; the others are listed in Table 1. Balona & Kambe (1999) went further and fitted model profiles to a spectral time series of He I λ 6678, which yielded a full set of pulsation parameters.

Being bright, ζ Oph is awkward photometrically, and although obviously variable, no consistent period has ever been found from the ground. Balona & Kambe (1999) summarized the extensive photometric observations up to 1993. The only convincing periodicities were several close to 5.18 cycles day⁻¹ seen in 1985 but not subsequently.

Harmanec (1989, 1999) pointed out that shadowing is still a viable option for the LPV. He also drew attention to the presence of a super, or commensurable, period of ~ 0.64 days associated with the various LPV periods that could be either the revolution rate of spokes or the rotation rate of the star and for which he found evidence in all of Balona's photometry and *Hipparcos* satellite observations.

While periodicities for high-degree modes can be derived from LPV, it is relatively difficult to detect LPV caused by low-degree and radial modes in rotationally broadened lines. Photometric observations of sufficient precision can comple-

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² Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada; gordonwa@uvic.ca, matthews@astro.ubc.ca.

³ Institut für Astronomie, Universität Wien Türkenschanzstrasse 17, A-1180 Vienna, Austria.

⁴ Department of Earth and Ocean Sciences, National Defense Academy, Yokosuka, Kanagawa 239-8686, Japan.

⁵ Graduate School of Science, Astronomical Institute, Tohoku University, Sendai 980-8578, Japan.

⁶ Astronomical Institute of the Charles University, V Holešovičkách 2, CZ-180 00 Prague 8, Czech Republic; hec@pleione.asu.cas.cz.

⁷ Astronomical Institute, Academy of Sciences, CZ-251 65 Ondřejov, Czech Republic.

⁸ Department of Astronomy and Physics, St. Mary's University, Halifax, NS B3H 3C3, Canada.

⁹ Mont Mégantic Observatory, Département de Physique, Université de Montréal CP 6128, Succursale Centreville, Montréal, QC H3C 3J7, Canada.

¹⁰ Department of Astronomy and Astrophysics, David Dunlap Observatory, University of Toronto, P.O. Box 360, Richmond Hill, ON L4C 4Y6, Canada.

¹¹ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

¹² National Research Council of Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada.

¹³ Hvar Observatory, Faculty of Geodesy, Zagreb University, 10000 Zagreb, Croatia.

¹⁴ Gunma Astronomical Observatory, 6860-86 Nakayama, Takayama, Gunma 377-0702, Japan.

¹⁵ Department of Physics and Astronomy, University of Victoria, P.O. Box 3055 Station CSC, Victoria, BC V8W 3P6, Canada.

TABLE 1
 ζ OPHIUCHI PERIODICITIES

f	MOST PHOTOMETRY				LINE PROFILE VARIATIONS		
	hr	cycles day ⁻¹	mmag	S/N	Line	Amplitude	S/N
1 ^a	4.633	5.1806	7.279	33.8	H β	0.0027	14.5
.....	...	...	...	...	He I	0.0017	9.7
2	8.968	2.6761	2.229	15.1	...	...	...
3	3.571	6.7209	1.331	8.9	H β	0.0016	6.9
.....	...	...	...	...	He I	0.0012	3.3
4	7.880	3.0458	1.693	8.4	...	...	...
5 ^{b,c}	3.337	7.1921	1.197	7.7	H β	0.0030	13.6
.....	...	...	...	...	He I	0.0022	10.6
6 ^b	5.344	4.4910	1.072	7.4	H β	0.0009	4.2
7	11.777	2.0379	0.784	5.7	...	...	...
8 ^d	15.625	1.5360	0.727	5.8	...	...	...
9	8.127	2.9532	0.771	5.7	...	...	...
10 ^e	4.468	5.3717	0.697	5.8	...	...	...
11	6.610	3.6310	0.634	5.7	...	...	...
12	16.775	1.4307	0.615	5.7	...	...	...
13 ^c	2.434	9.8614	0.638	5.4	H β	0.0032	19.0
.....	...	...	...	...	He I	0.0026	15.7
14	9.770	2.4566	0.587	5.4	...	...	...
15	19.898	1.2061	0.537	5.1	...	...	...
16	2.256	10.6385	0.563	5.2	H β	0.0008	4.9
.....	...	...	...	...	He I	0.0007	3.6
17 ^c	1.390	17.27	...	...	He I	0.0009	5.7
18	1.243	19.31	...	...	He I	0.0008	4.2
19 ^f	2.018	11.89	...	...	...	...	...

^a Balona & Kambe (1999) detected a series of photometric peaks in 1985 centered on 5.18 cycles day⁻¹, with an amplitude of ~ 6 mmag, but not in subsequent years.

^b Also detected by Kambe et al. (1997) in 1993.

^c Also detected by Reid et al. (1993) in 1989.

^d Detected photometrically by Harmanec (1999).

^e f_1 structure flagged by SigSpec (see text).

^f Only detected by Kambe et al. (1997) in 1993 but not in 2004.

ment spectroscopic results by revealing low-order, and radial, modes, hence the motive for this campaign.

2. THE OBSERVATIONS

2.1. MOST Photometry

The *Microvariability and Oscillations of Stars (MOST)* photometric satellite was launched into a 101.4 minute polar Sun-synchronous orbit (altitude 820 km) in 2003 June. It can stare for weeks at a target within a zodiacal band some 54° wide. The instrument is fully described by Walker et al. (2003), and the first scientific results have been published by Matthews et al. (2004) and Rucinski et al. (2004). A 15/17.3 cm Rumak-Maksutov telescope feeds a Fabry image of the bright target star onto a CCD through a single custom broadband filter (350–700 nm). The experiment was designed to detect photometric variations with periods of minutes at micromagnitude precision and does not rely on comparison stars or flat-fielding for stability. Tracking jitter was dramatically reduced early in 2004 to $\sim 1''$ (unprecedented for a microsatellite of such low inertia), obviating second-order errors from image wander.

ζ Oph was observed from 2004 May 19 to June 11, inclusive. Individual 1 s exposures were taken every 10 s. For this Letter, the data were condensed into 2 minute means. *MOST* suffers from parasitic light at certain orbital phases, with the amount and phase depending on the stellar coordinates. ζ Oph was observed closer to the Earth's bright limb than any other target to date, and the parasitic light rose as high as 3.7 times the signal from ζ Oph. In consequence, data around this phase

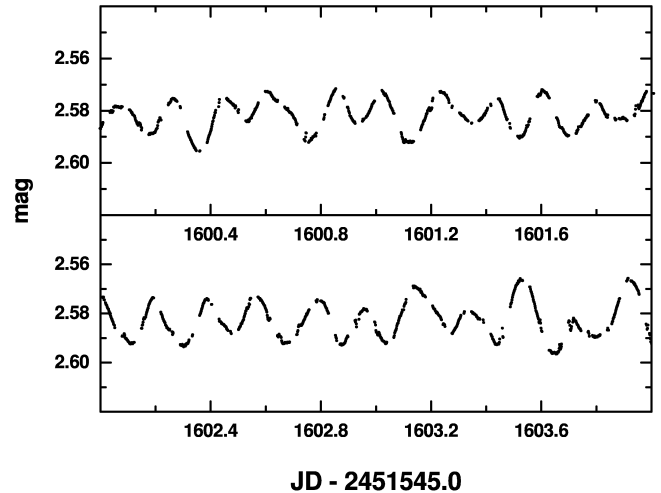


FIG. 1.—Four day portion of the ζ Oph 24 day light curve observed with *MOST* in 2004. It is dominated by the 4.633 hr period (f_1). For 40% of each satellite orbit the background skylight was too high for proper correction, which explains the gaps. Individual exposures were 1 s taken every 10 s, and the points in the light curve are 2 minute means. The signal level was calibrated in V from ground-based photometry.

were excluded. Despite this, a 60% duty cycle of entirely usable data was possible, causing the regular gaps in the portion of the light curve seen in Figure 1.¹⁶

The basic data received from the satellite were reduced independently by R. K. (technique 1) and P. R. (technique 2). In technique 1, a running, averaged sky background phased to the orbital period was subtracted from the data (Rucinski et al. 2004). In technique 2, correction for background included a detailed mapping of the light distribution within the whole frame including the target Fabry image and the sky Fabry images. Both techniques yield the same amplitude spectrum within the resolution of the observations (0.0276 cycles day⁻¹) with a noise of 0.027 mmag (technique 1) and 12 parts per million (technique 2), between 86 and 98 cycles day⁻¹ (where no signal or orbit peaks disturb the statistics). Full details of techniques 1 and 2 will be given in papers now in preparation.

The amplitude spectrum of the observations reduced according to technique 1 in units of millimagnitude is shown in Figure 2 with aliases of the satellite orbital frequency removed. Of the 379 detected peaks, the 16 of most significance are listed in order of signal-to-noise ratio (S/N) in Table 1 ($f_{17,18,19}$ were only detected in LPV). The possibility of long-term drifts in the *MOST* photometry cannot be ruled out but is under review; consequently, frequencies less than 1 cycle day⁻¹ were considered sufficiently doubtful to be omitted. In conjunction with the technique 2 reduction, stringent significance criteria were established using SigSpec (Reegen 2005). Peaks that are aliases of the highest amplitude periodicities within the resolution of the data (0.03 cycles day⁻¹) or peaks seen as substructures of a stronger peak within the resolution are normally rejected. Five peaks flagged as aliases by SigSpec are retained in Table 1 in part because they have been detected spectroscopically (viz., $f_7 = f_5 - f_1$, $f_8 = f_3 - f_1$, $f_{11} = 2f_1 - f_3$, $f_{12} = f_6 - f_4$, $f_{13} = f_2 + f_5$). The 5.1806 cycles day⁻¹ of f_1 (period 4.633 hr, 7.279 mmag amplitude) dominates the light curve in Figure 1.

¹⁶ The complete light curve can be downloaded from <http://www.astro.ubc.ca/MOST>.

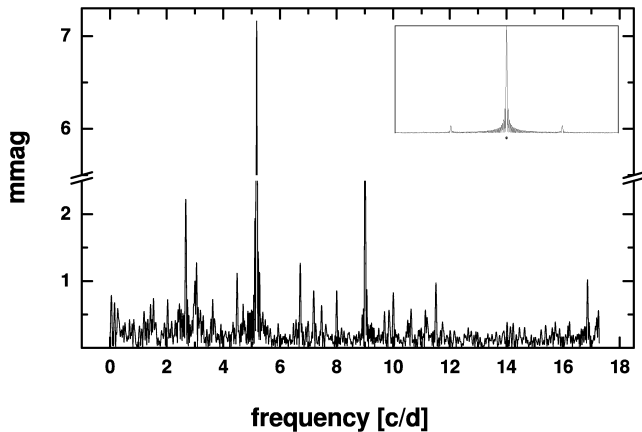


FIG. 2.—Amplitude spectrum derived from the full 24 day *MOST* light curve of ζ Oph of which a portion is shown in Fig. 1. Artifacts and aliases associated with the satellite orbital period (101.4 minutes) have been removed. The window function, on the same scale, is shown at top right.

2.2. Ground-based Photometry

During the *MOST* observations, P. H., H. B., D. R., and D. S. made 83 individual *UBV* observations of ζ Oph from the Hvar Observatory. On the basis of their reduction to the Johnson *V* system, the average signal level of the *MOST* observations corresponds to $V = 2.582$ mag.

While the Hvar photometry has good phase coherence with f_1 and a similar semi-amplitude of 9 mmag, the best-fitting sinusoid to the Hvar photometry actually has a frequency of 1.536 cycles day^{-1} , which coincides with f_8 and earlier photometric analyses by Harmanec (1999).

3. LINE PROFILE VARIATIONS

Useful spectral series were acquired on 17 of the days that *MOST* was on target at the DAO (D. A. B., R. M., S. Y.), Gunma (E. K., O. H.), and Ondřejov (P. K., P. H., M. W., P. Š., M. Š.) Observatories. The spectra were all reduced to a common resolution of 10 km s^{-1} . Data reduction and extraction of periodicities by E. K. were restricted to the $\text{H}\beta$ and $\text{He I } \lambda 4922$ lines and closely followed the procedures in Kambe et al. (1997). From spectra at $\text{H}\alpha$ and $\text{H}\beta$ there was no evidence of any emission-line episodes.

Temporal sinusoids were fitted by least-squares to the residuals at each point across the profile and the significance of the fit based on the Akaike information criterion (Kambe et al. 1997). Amplitudes and phases for the f_1 , f_5 , and f_{13} peaks are plotted against wavelength for $\text{He I } \lambda 4922$ in Figure 3. The diagonal march of points with phase through the line is characteristic of NRP, with the diagonal “lines” being more crowded at the higher frequencies. Although $\text{H}\beta$ is a stronger line than the $\text{He I } \lambda 4922$ line, it suffers much greater intrinsic Stark and collisional broadening, thereby blurring resolution of the stellar surface. As a result, $\text{He I } \lambda 4922$ is the better line with which to detect the modes of highest degree.

The seven LPV periodicities considered significant are listed in Table 1 together with amplitudes and signal-to-noise ratios. No frequencies less than 1 cycle day^{-1} were considered sufficiently reliable to be included.

Following Telting & Schrijvers (1997), we have estimated l -values of the detected LPV peaks from differences in phase for sinusoids at the extreme line wings. The l -values of the

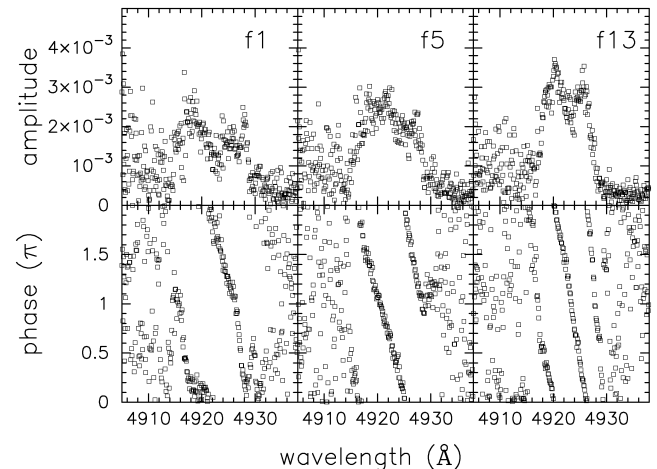


FIG. 3.—Amplitudes and phases for the three most significant frequencies detected in the profile variations of the $\text{He I } \lambda 4922$ line (see text).

known strong peaks, f_5 ($l = 3-4$) and f_{13} ($l \sim 7$), are consistent with previous observations. Here f_1 has $l = 3-4$, but its m -value may be small (e.g., $|m| = 1$) because its phase changes less smoothly. The higher frequency peaks (f_{16} , f_{17} , f_{18}) have larger and smooth ($l \sim |m|$ -like) phase changes with wavelength, so that they are likely to have frequencies similar to that of f_1 in the rotating frame. Although the full analysis of our spectroscopic data will be presented in a future paper, the l -values estimated here from LPV are roughly consistent with the simple theoretical model (β Cephei-type pulsation) discussed below.

4. MODELING THE OSCILLATIONS

The frequencies in Table 1 may not be stable over long timescales. The large amplitude of f_1 should always be visible in ground-based photometry, but it was only reported in 1985 (Balona & Kambe 1999) and confirmed by the 2004 Hvar photometry reported here. Further, in 1993 Kambe et al. (1997) found that f_{19} was the strongest LPV signal but it was not seen in 2004, whereas f_{17} has the larger LPV amplitude in 2004 but was considered an alias of f_{19} in 1993. This emphasizes the importance of simultaneous spectroscopic and photometric observations.

4.1. Rotation

The rotational frequency of ζ Oph is expected to be in the range of $1-1.5 \text{ cycles day}^{-1}$, making f_8 , f_{12} , and f_{15} candidates. Balona & Kambe (1999) favor something in the region of 1 cycle day^{-1} . Here f_8 corresponds to an equatorial speed of $\sim 600 \text{ km s}^{-1}$, which Balona & Kambe (1999) claim is still less than breakup for such a massive star; f_8 also corresponds to the “super” period found by Harmanec (1989, 1999). Each of f_8 , f_{12} , and f_{15} is only seen photometrically, and two might also be combinations of other frequencies ($f_8 = f_3 - f_1$, $f_{12} = f_6 - f_4$), making it difficult to single out one of them as the rotational period in the absence of other evidence.

Four frequency pairs from Table 1 differ by $2.02 \text{ cycles day}^{-1}$ (viz., $f_5 - f_1$, $f_6 - f_{14}$, $f_{18} - f_{17}$, and $f_{19} - f_{13}$) and $f_5 - f_2$ by $4.04 \text{ cycles day}^{-1}$. This $2.02 \text{ cycles day}^{-1}$ difference is unlikely to be an integer of the rotational frequency corresponding to even $l - m$ (i.e., symmetric) modes, because rotation effects (e.g.,

the Coriolis force, deformation) do not predict equidistant rotationally split frequencies (Saio 1981).

Howarth et al. (1993) from discrete absorptions in UV spectra, and Oskinova et al. (2001) from a 20% modulation of the X-ray flux from ζ Oph, detected recurrence frequencies of 1.2–1.3 cycles day⁻¹ that could correspond to Ω_{rot} , but these need confirmation by longer observations. On the basis of the above, we cannot provide a definite value for the rate of rotation.

4.2. The Model

H. S. undertook a preliminary nonadiabatic pulsation analysis for evolutionary models of $23 M_{\odot}$ with an initial chemical composition of $(X, Z) = (0.69, 0.03)$. The evolutionary track passes through the error box of $[\log(L/L_{\odot}), T_{\text{eff}}] = [4.87 \pm 0.13, (32.0 \pm 1.0) \times 10^3 \text{ K}]$ for ζ Oph (Repolust et al. 2004). For a simplified illustrative analysis, the effect of rotation on the stability is disregarded, but the pulsation frequencies are corrected for rotational shifts including first and (nonspherical) second-order effects by using the results of Saio (1981), where a rotation frequency of 1 cycle day⁻¹ is assumed. Radial and nonradial modes are excited by the κ -mechanism associated with the Fe-bump in the opacity near $T = 2 \times 10^5 \text{ K}$ (Dziembowski & Pamyatnykh 1993; Saio et al. 2000). ζ Oph lies close to the blue edge of the instability strip, and the number of unstable modes can change considerably within the error box.

Since the photometric amplitude of f_1 is by far the largest of the detected photometric modes, we have chosen it to be radial. At the position of ζ Oph in the H-R diagram, the fundamental mode and the first and second overtones are unstable. If f_1 is the fundamental mode, the model must lie to the blue of the blue edge of the instability strip, which means that it would not be excited. On the other hand, if f_1 is the radial second overtone, T_{eff} has to be $\sim 30,000 \text{ K}$, which is outside the error box for ζ Oph. Here f_1 can be identified with the radial first overtone for a model at

$[\log(L/L_{\odot}), \log T_{\text{eff}}] = (4.99, 4.49)$ that lies within the error box.

In the model, the frequency of the radial first overtone is similar to those of nonradial $(l, m) = (1, -1)$ and $(3, 1)$ modes, of which the latter may be responsible for the LPV associated with f_1 . The frequencies of unstable modes of $l \leq 3$ with even $(l - |m|)$ (whose eigenfunctions are symmetric with respect to the equator) range from 1.2 to 8 cycles day⁻¹, which covers the range observed. Finally, we note that all modes less than 1.8 cycles day⁻¹ correspond to retrograde modes in the corotating frame. The simultaneous presence of prograde and retrograde modes has been suggested as the cause of episodic mass loss (Ando 1986; Kambe et al. 1993) with the amplitudes of NRP modes changing on the timescale of the mass loss. Our first detection of f_1 in LPV and the disappearance of f_{19} may indicate such a long-term amplitude modulation.

The coincidences of the theoretical (rotationally shifted) and observed frequencies are sufficiently close that we believe that the assumption of β Cephei-type pulsations driven by the κ -mechanism associated with the Fe bump in the opacity can plausibly explain most of the variations that we see.

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