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# *MOST* DETECTS *g*-MODES IN THE Be STAR HD 163868[1]

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## ABSTRACT

We have extracted a 37 day light curve with a precision of 0.0012 mag per point for the *Microvariability and Oscillations of Stars* (*MOST*) guide star, HD 163868 (B5 Ve). Its rich frequency spectrum resembles that of a slowly pulsating B (SPB) star but, being a rapid rotator, we designate it SPBe. The 60 most significant periods lie in three distinct groups centered on 8 days and 14 and 7 hr. We demonstrate that the 14 and 7 hr periods can be modeled by two swarms of high-order, prograde sectorial *g*-modes ($m = -1, -2$), which are destabilized by the iron opacity bump. Our model also predicts a group of *r*-modes with periods near 2.3 days, which correspond to frequencies observed in the tail of the 8 day group. The remaining periodicities, between 7 and 11 days, cannot be explained by unstable modes in our model.

*Subject headings:* stars: early-type — stars: emission-line, Be — stars: individual (HD 163868) — stars: oscillations — stars: rotation

*Online material*: color figure

## 1. INTRODUCTION

Waelkens (1991) first coined the term “slowly pulsating B star” (SPB) for a group of B8–B3 stars of 3–7 $M_\odot$ with multiperiodic light and color variations. Their periods were much too long for radial pulsations. Many more SPBs were mined from *Hipparcos* photometry (Waelkens et al. 1998). SPB variations can be explained by *g*-mode pulsations of low spherical harmonic degree ($\ell$) and high radial order ($n$) excited by the $\kappa$-mechanism in the Fe opacity bump (e.g., de Cat et al. 2004; Dziembowski et al. 1993; Gautschy & Saio 1993). Although generally considered slow rotators, Aerts et al. (1999) found several rapidly rotating SPBs with more complex line profile variations.

HD 163868 ($V = 7.4$, B5 Ve, $v \sin i \sim 250$ km s$^{-1}$) was found to be variable (Sterken et al. 1998) when used as a comparison star for WR 103 (HD 164270). Woodward (1975) had in fact already announced its variability even on a timescale of hours, but Massey et al. (1984) found it constant to a few hundredths of a magnitude. Sterken et al. (1998), after consideration of all available photometry, suggested that HD 163868 might be a 850 day binary with a compact secondary, but pointed out that its on-off variability might be due to positive interference of nonradial pulsations (NRP). Percy et al. (2004) found a possible periodicity of ∼0.3 day. No one seems to have suggested that HD 163868 might be an SPB star.

HD 163868 was one of 20 guide stars for the photometry of WR 103 by the *MOST* satellite. One of us (R. K.) recognized the SPB character of the star’s variations. The results presented here are the first demonstration of the potential of *MOST* guide-star photometry for variable star studies.

## 2. THE *MOST* PHOTOMETRY

The *MOST* photometric satellite was launched in 2003 June and is fully described by Walker et al. (2003). The first scientific results were published by Matthews et al. (2004). A 15/17.3 cm Rumak-Maksutov telescope feeds two CCDs, one for tracking, the other for science, through a single, custom broadband filter (350–700 nm). Tracking jitter was dramatically reduced early in 2004 to ∼1″, thereby making quality, in-focus photometry possible with both CCDs.

Since launch, satellite operations have been upgraded to allow photometry with the *MOST* Startracker. In the case of WR 103, the data sampling interval was 10 s, during which five separate 1.5 s exposures were taken of each guide star. The signals of individual guide stars were combined on board to a single value after first-order sky subtraction. For this paper, the data are binned in intervals of 2 minutes. Observations were made from 2005 June 14 to July 21, for a total of 36.6 days, with >137,000 values recorded for HD 163868. The WR 103 field was the first one observed outside the *MOST* Continuous Viewing Zone. Consequently, the duty cycle was limited to about 50% of the 101 minute orbit.

*MOST* suffers from parasitic light, which depends on orbital phase. Data points contaminated by very high background levels and extreme outliers were omitted. Stray light was suppressed by subtracting a smoothed light curve phased to the orbit, based on a running mean of 3 orbits. This correction removes any modulation at the 101.413 minute *MOST* orbital

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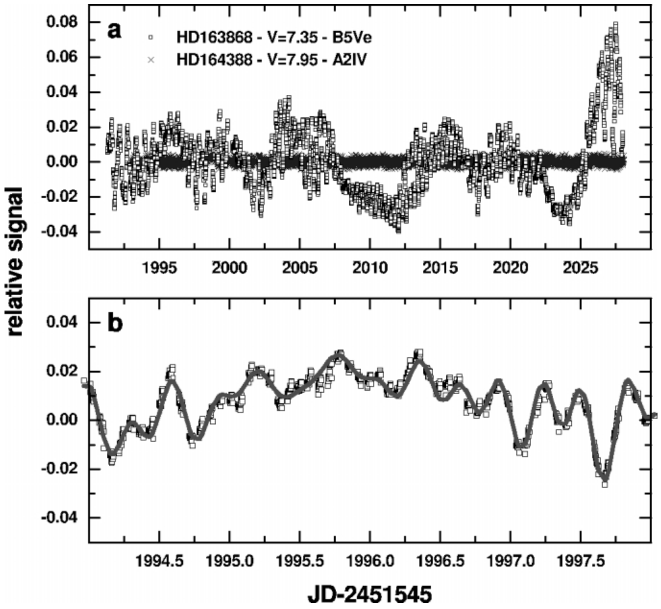

FIG. 1.—(*a*) 2005 *MOST* 37 day light curve of the guide star HD 163868 and the simultaneously observed guide star HD 164388. (*b*) 5 day portion of the HD 163868 light curve with the data binned every 2 minutes. The 2 $\sigma$ error bars are ∼0.0012 and are similar to the data points in size. The duty cycle was ∼50% because HD 16386 lay outside the continuous viewing zone, accounting for the gaps. The solid line is the fit of the 60 frequencies found in the light curve. The 7 and 14 hr periodicities dominate in (*b*), while the full light curve in (*a*) highlights longer period variations of 7–11 days. [*See the electronic edition of the Journal for a color version of this figure*.]

period and its harmonics. A long-term instrumental trend, also seen in the other guide stars, was removed with a second-order polynomial.

Figure 1 displays the full light curve of HD 163868 and of another guide star, HD 164388 (A2 IV, $V = 8.0$), which appears to be constant. Many features in the HD 163868 light curve resemble those already seen in the composite ground-based light curve of Sterken et al. (1998). An expanded 5 day portion of the *MOST* light curve is included to better display the higher frequency variations. Complete light curves for both stars and the 60 frequencies detected in HD 163868 (discussed in § 3) can be downloaded from the *MOST* public archive.[12]

## 3. THE FOURIER SPECTRUM

The time series was analyzed with a combined Fourier and nonlinear least-squares technique, CAPER, developed by one of us (C. C.). CAPER calculates a discrete Fourier amplitude spectrum based on Matthews & Wehlau (1985) modified version of the algorithm produced by Deeming (1975). The largest amplitude is identified and its phase estimated from the real and imaginary parts of the Fourier transform. The S/N is the amplitude of the peak divided by the noise averaged over a 0.23 mHz segment of the amplitude spectrum centered at that frequency.

The parameters are refined by a nonlinear least-squares fit using the Levenberg-Marquardt method (Press et al. 1992),

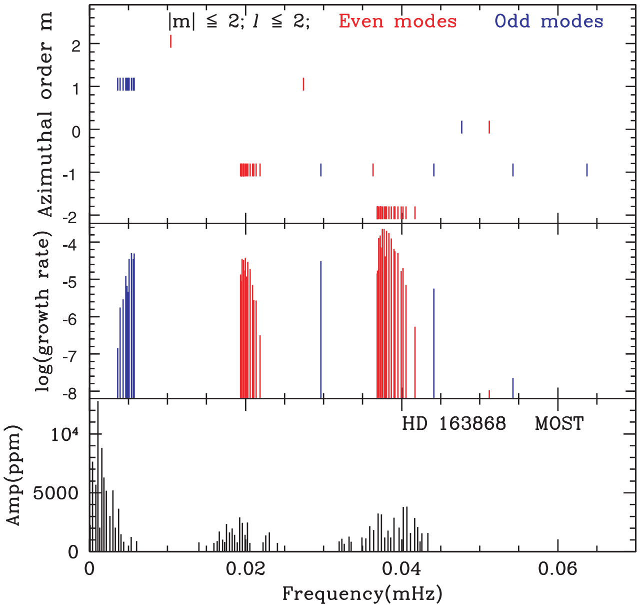

FIG. 2.—*Top and middle panels*: Frequencies and growth rates of excited pulsations in a 6 $M_\odot$ main-sequence model with a rotational frequency of 0.016 mHz ($v_e = 305$ km s$^{-1}$, $\log L = 3.136$, $\log T_e = 4.226$, $\log R = 0.639$). Only low latitudinal degree ($\ell \leq 2$) and low azimuthal order ($|m| \leq 2$) modes are shown. Red and blue lines show even and odd modes, respectively. For even (odd) modes, pulsational perturbations are symmetric (antisymmetric) to the equator. Positive (negative) azimuthal orders, *m*, refer to retrograde (prograde) modes in the corotating frame of the star. Odd modes at ∼0.005 mHz are high-order *r*-modes, while most of the others are high-order *g*-modes. *Bottom panel*: HD 163868 amplitude spectrum from *MOST*.

which minimizes $\chi^2$ between a fitting function and the data. A sinusoidal fitting function of the form

$$F_{\rm fit}(t) = \sum_{i=1}^{N} A_i \sin\,(2\pi\nu_i t + \phi_i)$$

was chosen, where $A_i$, $\nu_i$, and $\phi_i$ are the *i*th amplitude, frequency, and phase of the *N* parameter sets, respectively.

The $F_{\rm fit}$ is subtracted from the original data set. A Fourier spectrum of the residuals is calculated, and a new parameter set identified. These new parameters, in conjunction with the previous set(s), is refitted to the original time series and the process iterated to a predefined stopping criterion.

Sixty periodicities ($\nu_i$) were detected with a $S/N > 3.4$ at a frequency resolution of 0.0005 mHz. All 60 peaks are plotted in the third panel of Figure 2, where they clearly group into three clusters near 0.0015, 0.02, and 0.04 mHz, corresponding to periods of about 8 days and 14 and 7 hr, respectively. The solid line in Figure 1*b* shows how well the periodicities fit the data.

## 4. MODELING THE OSCILLATIONS

H. S. and U. L. have chosen a best-fitting evolutionary model for HD 163868 from a series with 6 $M_\odot$. The rotation frequency is assumed constant throughout the stellar interior and evolution. An initial chemical composition of $(X, Z) = (0.7, 0.02)$ is adopted. The opacity was obtained from OPAL tables (Iglesias & Rogers 1996). Although spherically symmetric stellar structure is assumed, the centrifugal force is included in the hydrostatic equilibrium by adding the term $\frac{2}{3}r\Omega^2$, where *r* is

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[12] Available at http://www.astro.ubc.ca/MOST.

the distance from the center and $\Omega$ is the rotation frequency. Rotational mixing is ignored.

A nonadiabatic, nonradial pulsation analysis was performed, including the effects of rotation with a method similar to that of Lee & Baraffe (1995). The latitudinal dependence of a nonradial pulsation of a rotating star with an azimuthal order $m$ cannot be represented by a single spherical harmonic. We expanded the eigenfunction into a series of terms proportional to spherical harmonics with a given azimuthal order $m$. The latitudinal dependence of pulsations is divided into even and odd with respect to the equator; we call these modes even modes and odd modes, respectively. An even (odd) mode temperature perturbation, for example, is represented by terms proportional to spherical harmonics with even (odd) $\ell - m$. No odd mode is expected to be detected for a star seen nearly equator-on.

Although a single $\ell$ value is no longer a good parameter, we use the $\ell$ value of the component with the largest amplitude at the stellar surface to represent the property of a pulsation mode. The effect of rotational deformation of the equilibrium state on pulsations is included, although the effect is small for low-frequency pulsations.

Figure 2 shows the frequencies and growth rates of nonradial modes of low azimuthal orders excited in a model rotating at a frequency of 0.016 mHz (period ~17.4 hr). The assumed rotation rate corresponds to an equatorial rotational velocity of 305 km $\mathrm{s}^{-1}$, for a stellar radius of 4.3 $R_{\odot}$. All the pulsation modes excited in these models are due to the $\kappa$-mechanism driving the Fe bump of opacity at $T \approx 2 \times 10^5$ K. Negative $m$ corresponds to prograde modes in the corotating frame of the star. Red and blue lines in the figure show even and odd modes, respectively. The horizontal axis is the pulsation frequency in the inertial frame, $\nu$, which is related to the frequency in the corotating frame, $\bar{\nu}$, by

$$\nu = |\bar{\nu} - m\Omega|.$$

The two groups of even modes excited around 0.02 and 0.04 mHz are high-order *g*-modes. Because the frequencies in the corotating frame are much smaller than the rotation, the frequencies of these modes in the inertial frame are close to $|m|\Omega$.

The excitation of high-order *g*-modes by the Fe bump in the opacity in B-type stars generates pulsations in SPB stars (Gautschy & Saio 1993; Dziembowski et al. 1993). Our analysis suggests that among high-order *g*-modes, prograde sectoral modes are excited in rapidly rotating stars as in nonrotating stars, but retrograde and prograde tesseral modes are hardly excited at all. This is in contrast to the conclusions of Townsend (2005a), who investigated the stability of *g*-modes in rapidly rotating stars using the traditional approximation. The difference seems to come from the stabilizing effect of mode couplings (Lee 2001). The traditional approximation suppresses mode couplings.

The swarm of odd modes at very low frequencies around 0.005 mHz corresponds to *r*-modes with $m = 1$. Since these modes have frequencies of ~$\Omega$ in the corotating frame, the frequencies become very small in the inertial frame. The frequency of a high-order *r*-mode deviates from the canonical frequency $2\Omega/(m + 1)$ for a pure toroidal motion. The deviation is caused by the buoyancy force, which acts on a nonzero compression and expansion generated by the *r*-mode, for which the $\kappa$-mechanism works in the same way as for *g*-modes. These *r*-modes are called "mixed modes" by Townsend (2005b) and "quasi *g*-modes" by Savonije (2005).

No even *r*-mode is excited, because the corotating frame frequency of an even *r*-mode is too small for the $\kappa$-mechanism to be effective. The excitation of *r*-modes in rapidly rotating B stars has been predicted recently by Savonije (2005), Townsend (2005b), and Lee (2005). Since the amplitude of *r*-modes is large at midlatitudes (Lee & Saio 1997), they can only be detected when the inclination angle of the rotation axis to the line of sight is moderate. The equatorial velocity of our model is 305 km $\mathrm{s}^{-1}$, while we estimated $v \sin i \sim 250$ km $\mathrm{s}^{-1}$ from spectra taken by one of us (S. M.) at Okayama Astrophysical Observatory. This would lead to an inclination angle of 55°, appropriate for the detection of odd *r*-modes.

## 5. CONCLUSIONS

The continuous, quality photometry with *MOST* has already led to a plausible model for the excitation of high-$\ell$ *p*-modes in the Be star $\zeta$ Oph (Walker et al. 2005). In the case of HD 163868, the two clusters of frequencies we predict for *g*-modes agree remarkably well with those actually detected by *MOST* (Fig. 2, *bottom*). This implies that HD 163868 is a rapidly rotating "SPBe" star, in which a swarm of high-order, prograde *g*-modes are excited.

HD 163868 can also be identified as a $\lambda$ Eri star, Be stars with light and radial-velocity variations with periods comparable to their rotation (e.g., Balona 1995). Variations comparable to the rotation period can be explained by high-order *g*-modes with $|m| = 1$, while double-wave light curves often seen in $\lambda$ Eri stars can be explained if high-order *g*-modes of $|m| = 2$ are excited simultaneously, as the theory predicts.

If we interpret our model correctly, the low-frequency periods ~0.005 mHz in HD 163868 are *r*-modes—the first to be detected in a rapidly rotating star. Our results also indicate the importance of *g*- and *r*-modes for angular momentum transport in the Be phenomenon.

While the model satisfactorily accounts for peaks with frequencies ≥0.005 mHz, it cannot explain the three strong peaks at 0.00108, 0.00159, and 0.00186 mHz, corresponding to periods of 10.8, 7.3, and 6.2 days, respectively. There are no such low-frequency peaks for the comparison star HD 164388, strongly suggesting that they are not instrumental. According to our models, these periods are too long for NRP, and while one can speculate that they might be associated with the disk, they remain a challenge to be unravelled by more extensive photometry.

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