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THE RADIAL VELOCITY VARIABILITY OF THE K GIANT β OPHIUCHI. I. THE DETECTION OF LOW-AMPLITUDE, SHORT-PERIOD PULSATIONS

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ABSTRACT

We present precise radial velocity measurements ($\sigma \sim 20$ m s^{-1}) of the K giant β Oph taken over 8 consecutive nights in 1992 June and 2 nights in 1989 July. An analysis of the 1992 June data revealed the presence of a 0.255 ± 0.005 day period. The 1989 July data also show short-term variability; however, aliasing is more severe for these data, making it difficult to determine a period reliably. A Scargle-type periodogram yields a period of 0.813 ± 0.007 days, whereas a CLEAN analysis results in a period of 0.455 ± 0.007 days for the 1989 July data. Subtracting the nightly means from the 1989 July data results in a period of 0.237 ± 0.007 days. These short-period radial velocity variations can only result from stellar pulsations. Use of the empirical Q equation of Cox, King, & Stellingwerf indicates that a second-overtone mode can account for the 0.255 day period if β Oph has a mass of 7 $M_\odot$ and a radius of 10 $R_\odot$. These values result, however, in a log g much higher than published values. If β Oph possesses a lower mass, then higher ($n \geq 4$–6) overtone radial or nonradial modes are needed to account for such a short period. Theoretical work by Ando on nonradial acoustic modes in the envelope of late-type stars yields periods of about 2 hr for high-order acoustic modes ($\ell > 10$) in stars having a mass and luminosity near that of β Oph. Extrapolating these results to low-order ($\ell = 1, 2$) modes (that can be detected by radial velocity measurements) yields oscillation periods of 2–16 hr. A detailed pulsational analysis using a stellar model appropriate for β Oph is needed to identify the pulsation mode of the 0.255 day period. There is some evidence that a period different from 0.255 days was present in the 1989 July data. If so, then β Oph may be another K giant, like α Boo, that is switching pulsation modes, although more observations are needed to confirm this.

Subject headings: stars: giants — stars: individual (β Ophiuchi) — stars: oscillations — techniques: radial velocities

1. INTRODUCTION

Recently it has been discovered that K giants exhibit radial velocity variations (Smith, McMillan, & Merline 1987; Walker et al. 1989), some of which are quite complex. The radial velocity variability of α Boo was first detected by Smith et al. (1987), who reported the presence of a 1.84 day period. Later Hatzes & Cochran (1993) demonstrated that α Boo, α Tau, and β Gem showed radial velocity variations with periods ranging from 233 to 643 days. These long periods may well be the signatures of rotational modulation by surface features, although theoretical work and more observations are needed before one can exclude nonradial pulsations or the presence of low-mass companions as the cause of these variations. Two of these stars (α Boo and α Tau) showed significant night-to night variations as high as 100 m s^{-1}, but no periods could be determined for this short-term variability. Subsequently the radial velocity of α Boo was monitored during 8 nights in 1992, and these new data revealed the presence of at least two sinusoidal components with periods of 2.46 and 4.03 days (Hatzes & Cochran 1994). There was also marginal evidence for the presence of a 8.5 day component. Whereas the long-period variations can arise from a number of phenomena, these short-period variations can only be due to stellar pulsations. These data did not show the presence of the 1.84 day period found by Smith et al. (1987). Depending on the choice of mass and radius for α Boo, the 1.84 day period can be identified with the first or second harmonic radial mode, and the 2.46 day period represents the next lower harmonic. If these periods are indeed due to radial pulsations, then this strongly suggests that α Boo is switching pulsation modes.

So far, α Boo is the only K giant for which short-term periods have been derived. It is important to determine how ubiquitous such short-term variability is among K giants and the periods involved, for this is the first step in understanding the nature of these variations. Since this variability results from stellar oscillations, K giants may represent a new class of objects to which stellar pulsation theory may be applied. Such analyses can reliably determine various stellar parameters such as mass and radius as well as probe the internal structure of these stars. Here we report on the short-period variability of a second K giant, the K2 III star β Oph.

2. DATA ACQUISITION

The radial velocity of β Oph was monitored for 8 consecutive nights in 1992 June. These data were collected using the coudé spectrograph at the McDonald Observatory 2.1 m telescope. A 1200 groove mm^{-1} grating used with a Tektronics 512 × 512 CCD provided a resolution of 0.10 Å (2.5 pixels) and a wavelength coverage of 23 Å centered on 5520 Å. The wavelength reference for measuring the relative stellar radial velocities was provided by a molecular iodine gas absorption cell placed before the entrance slit to the spectrograph during a stellar observation. All velocity shifts of the stellar spectrum were measured with respect to the iodine absorption lines. Since the stellar spectrum and wavelength reference have identical optical paths and are recorded simultaneously on the

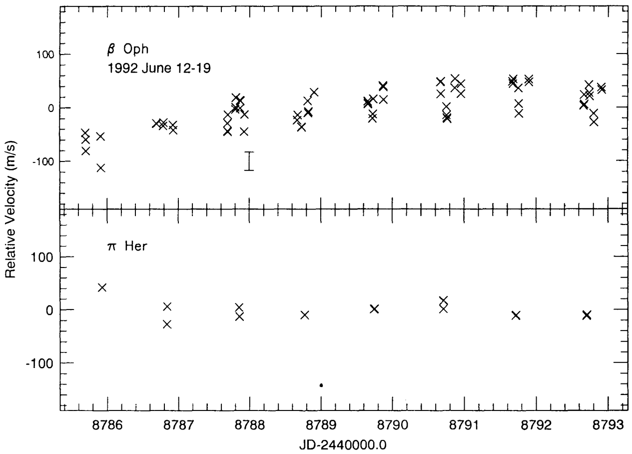

FIG. 1.—*Top:* Relative radial velocity variations of β Oph during 1992 June 12–19 measured using an iodine absorption cell. A typical error of a single measurement is about 17 m s^{-1} (indicated by the bar). *Bottom:* Radial velocity variations of π Her during the same time span.

same location of the detector velocity shifts due to instrumental effects are minimized. Our experience using this cell with the coudé spectrograph of the 2.1 m telescope indicate that a precision of 10–20 ms s^{-1} is possible (Hatzes & Cochran 1993, 1994).

Observations of β Oph were made on each of the 8 nights in three or four sets separated by 1.5–2 hr. The total time span of the nightly observations ranged from 4 to 5.5 hr. The top panel of Figure 1 shows the relative radial velocity variations for β Oph during 1992 June 12–19, and Table 1 lists the actual measurements. On a given night the radial velocity for this star changed by up to 50 m s^{-1}. There also appears to be a long-term trend of increasing nightly average in the radial velocity. This peaks around JD 2,448,792 and is followed by a slight decline on the last night. The lower panel of Figure 1 shows the radial variations during these same 8 nights for the K2 II star π Her. The standard deviation of the π Her radial velocities is about 13 m s^{-1}. During this run observations were also made on a standard spot on the lunar surface, and these resulted in radial velocity measurements with a standard deviation of about 17 m s^{-1}. The radial velocity variations of β Oph are therefore real and not instrumental in origin.

Radial velocity data on β Oph were also obtained for 4 continuous hours on the night of 1989 July 15 and for 3 continuous hours on 1989 July 17. These data were taken using the coudé spectrograph of the 2.7 m telescope and a different measurement technique. An echelle grating was used in single pass along with a Tektronics 512 × 512 CCD. This provided a wavelength coverage of 12.8Å centered on 6300 Å at a spectral resolution of 0.05 Å (230 μm slit which subtended 2 pixels on the CCD). An interference filter was used to isolate order 36 from the echelle grating. For these data the telluric O_2 lines provided the velocity metric. Griffin & Griffin (1973) first proposed that these features could be used to provide a stable wavelength reference for measuring precise radial velocities. This technique was employed for the McDonald Observatory Planetary Search program from 1987 to 1990, and radial velocity data taken during this time had a typical long-term error of about 15 m s^{-1} (Cochran & Hatzes 1994). The short-term error on a given night or during one observing run can be better than 10 m s^{-1} using this method.

Figure 2 shows the radial velocity variations for β Oph on the nights of 1989 July 15 and 17, and Table 2 lists the measurements. These data confirm the presence of short-term variability in the radial velocity of β Oph. The radial velocities determined using the O_2 technique are internally self-consistent, but they have a different velocity zero point because both this and the I_2 technique measure relative, not absolute, velocities. On 1989 July 15 the radial velocity of β Oph steadily increased by about 50 m s^{-1} over the course of the 4 hr observing interval. A line fitted to this first night's data yielded a standard deviation of 7.3 m s^{-1}. On 1989 July 17 the radial velocity decreased by about 70 m s^{-1} during the observing interval and had a mean level that was 50 m s^{-1} higher than on July 15. The standard deviation about this slope was 8.4 m s^{-1}. A value of 10 m s^{-1} was adopted as the typical error for the individual measurements using the telluric technique, and this is indicated as a bar in Figure 2. These data have a higher

TABLE 1

β OPH RELATIVE RADIAL VELOCITIES: 1992 JUNE 12–19

Date[a]	V (m s^{-1})	Date[a]	V (m s^{-1})	Date[a]	V (m s^{-1})	Date[a]	V (m s^{-1})
8785.697......	−46.8	8787.867......	13.9	8789.730......	16.1	8791.752......	36.7
8785.700......	−59.5	8787.870......	−0.7	8789.868......	40.9	8791.756......	7.7
8785.703......	−80.8	8787.874......	12.6	8789.870......	38.4	8791.760......	−10.7
8785.910......	−53.2	8787.929......	−44.8	8789.873......	14.8	8791.897......	53.0
8785.915......	−112.2	8787.933......	−12.8	8790.667......	47.9	8791.901......	47.7
8786.691......	−29.1	8788.669......	−23.3	8790.671......	25.6	8792.662......	3.6
8786.697......	−29.9	8788.676......	−13.5	8790.674......	48.5	8792.666......	23.9
8786.790......	−33.8	8788.730......	−35.6	8790.752......	1.8	8792.670......	6.2
8786.795......	−27.7	8788.735......	−36.5	8790.755......	−14.0	8792.735......	42.4
8786.928......	−32.0	8788.813......	12.9	8790.760......	−18.7	8792.739......	27.7
8786.933......	−41.7	8788.820......	−9.5	8790.765......	−20.9	8792.743......	21.6
8787.692......	−28.8	8788.827......	−7.0	8790.867......	36.6	8792.802......	−11.0
8787.694......	−43.4	8788.902......	28.7	8790.871......	53.9	8792.808......	−27.3
8787.697......	−12.7	8789.653......	11.7	8790.952......	25.8	8792.907......	37.9
8787.699......	−44.7	8789.656......	6.4	8790.955......	44.3	8792.912......	33.2
8787.803......	−3.1	8789.659......	8.3	8791.669......	48.9		
8787.806......	0.8	8789.724......	−20.2	8791.675......	44.5		
8787.808......	18.6	8789.728......	−12.0	8791.681......	53.7		

[a] Date = Julian Day − 2,440,000.0.

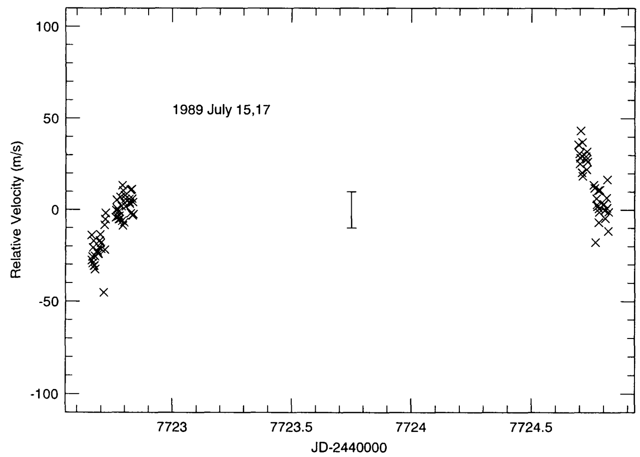

FIG. 2.—Relative radial velocity variations of β Oph on 1989 July 15 and 17. These measurements were made using the telluric O_2 lines as a wavelength reference. The typical error for the individual measurements is about 10 m s^{-1} (indicated by the bar).

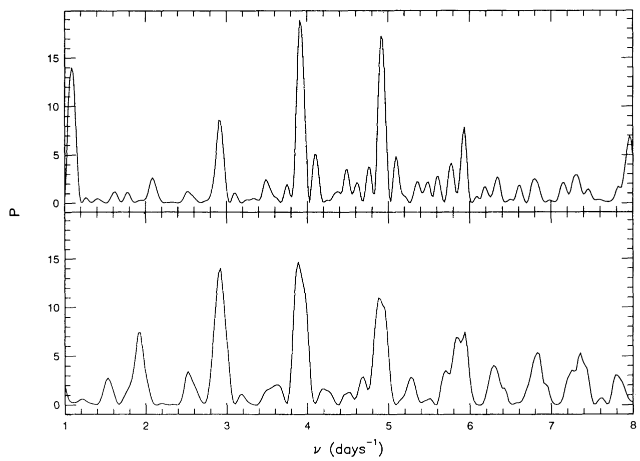

FIG. 3.—Scargle-type periodogram of the radial velocity data for β Oph from 1992 June 12–19. *Bottom:* Periodogram for the 1992 June data after subtracting a second-order polynomial fit to the nightly means.

precision because of the higher resolving power and the more stable spectrograph of the 2.7 m coudé setup.

3. RESULTS

3.1. *Period Analysis*

A period analysis was performed on the data using the technique of Scargle (1982). The top panel of Figure 3 shows the periodogram of the radial velocity data for β Oph during 1992 June 12–19 (Fig. 1). The primary peak occurs at a frequency of 3.92 days^{-1} (0.255 day period), and the secondary peak has a frequency of 4.90 days^{-1} (0.204 day period). The false-alarm probability can be calculated from the amplitude of the peak if one knows the number of independent frequencies (Scargle 1982). Using either the number of data points or the expression of Horne & Baliunas (1986) for the number of independent frequencies results in a false-alarm probability of $\approx 10^{-5}$.

The periodogram shown in Figure 3 was computed without removing the long-term trend in the nightly averages evident in Figure 1. One should, of course, be wary of performing such a procedure, as this removes signal from the data. However, for K giants subtracting long-term trends may be desirable. At least two K giants exhibit both long- and short-period radial velocity variations (Hatzes & Cochran 1993), so the change in the nightly averages seen in β Oph over the course of the 8 night run may just be a manifestation of such long-term behavior. There is evidence that β Oph exhibits long-term radial

TABLE 2

β OPH RELATIVE RADIAL VELOCITIES: 1989 JULY 15, 17

Date[a]	V (m s^{-1})	Date[a]	V (m s^{-1})	Date[a]	V (m s^{-1})	Date[a]	V (m s^{-1})
7722.661......	−14.0	7722.720......	−1.8	7722.824......	10.8	7724.767......	−17.7
7722.662......	−27.7	7722.762......	−4.3	7722.826......	−2.0	7724.771......	6.3
7722.664......	−25.8	7722.765......	−0.4	7722.830......	11.2	7724.773......	3.0
7722.666......	−29.3	7722.767......	5.3	7722.832......	6.0	7724.775......	2.0
7722.667......	−20.8	7722.769......	0.5	7722.833......	−3.2	7724.776......	2.1
7722.669......	−17.1	7722.770......	−3.8	7722.835......	4.1	7724.778......	10.8
7722.671......	−30.7	7722.774......	−5.3	7722.837......	−2.5	7724.780......	−6.8
7722.673......	−30.7	7722.776......	−0.9	7724.695......	35.8	7724.781......	0.7
7722.675......	−25.5	7722.778......	−3.4	7724.697......	35.5	7724.783......	−1.2
7722.676......	−32.6	7722.780......	−5.2	7724.699......	30.9	7724.784......	11.0
7722.683......	−23.1	7722.782......	6.8	7724.701......	25.4	7724.799......	2.8
7722.684......	−22.6	7722.787......	1.8	7724.703......	28.4	7724.801......	3.4
7722.686......	−22.8	7722.789......	−6.2	7724.705......	43.4	7724.805......	−0.2
7722.688......	−24.3	7722.791......	13.3	7724.708......	29.7	7724.807......	−4.6
7722.689......	−24.0	7722.792......	−8.8	7724.709......	20.5	7724.808......	0.0
7722.693......	−20.5	7722.794......	10.4	7724.711......	37.1	7724.812......	6.7
7722.695......	−16.9	7722.797......	−7.0	7724.713......	18.6	7724.814......	1.1
7722.697......	−13.6	7722.799......	3.7	7724.726......	29.4	7724·815......	16.7
7722.699......	−18.3	7722.801......	7.8	7724.727......	27.7	7724.819......	−11.6
7722.701......	−21.5	7722.803......	5.8	7724.729......	22.2	7724.821......	−1.1
7722.713......	−45.2	7722.804......	1.7	7724.730......	32.0		
7722.715......	−8.4	7722.819......	5.8	7724.732......	26.4		
7722.717......	−21.9	7722.821......	3.9	7724.759......	13.7		
7722.718......	−5.2	7722.822......	3.1	7724.763......	12.0		

[a] Date = Julian Day − 2,440,000.0.

velocity variations and a paper examining this is currently in preparation. Since we are searching for periods shorter than the length of the observing run and the data spans sufficient time so that long-term trends can be discerned (at least over 8 days), such rectification should have a minimal effect on the derived periods. The lower panel of Figure 3 shows the Scargle-type periodogram after subtracting a second-order polynomial fit to the nightly means. Although the dominant peak still occurred at 3.92 day^{-1}, its amplitude was reduced and more power appeared in the secondary peak at $\nu = 2.92$ days^{-1}.

The CLEAN algorithm of Roberts, Lehár, & Dreher (1987), which is designed to remove the effects of the sampling window from the period transform, was also applied to both the rectified and the unrectified data, and in both instances the secondary peak structure in the transforms was greatly minimized, leaving only a single peak at 0.255 days.

The top panel of Figure 4 shows the unrectified radial velocity data phased to the 0.255 day period, while the lower panel shows the rectified data phased to the same period. Sinusoidal variations are evident in the phase diagrams of both data sets, although the peak-to-peak amplitude of the raw data is higher (100 m s^{-1}) than the rectified data (40 m s^{-1}). The rms scatter about the mean curves in these figures is 17 m s^{-1}, consistent with the standard deviation of the lunar observations. Kovacs (1981) derived an expression for the error in the frequency of a peak in a periodogram. Although his expression is valid for equally spaced data, Baliunas et al. (1985) found that uneven sampling of data does not alter the results to a noticeable degree. This expression results in an uncertainty of ± 0.005 days for the period.

An obvious concern is that the 0.255 day period might be merely an artifact of the sampling pathology. After all, the window size on each night ranges from 4 to 5.5 hr, and this is uncomfortably close to the period found by the period analysis. We are convinced that this is not the case. The mean width of the data window over the 8 night run is 0.240 days, and this differs significantly from the 0.255 day period found in the periodogram. Furthermore, numerical simulations in § 3.2 indicate that such large peaks in the periodogram at a period of 0.255 days cannot arise from random noise sampled in the same manner as the data.

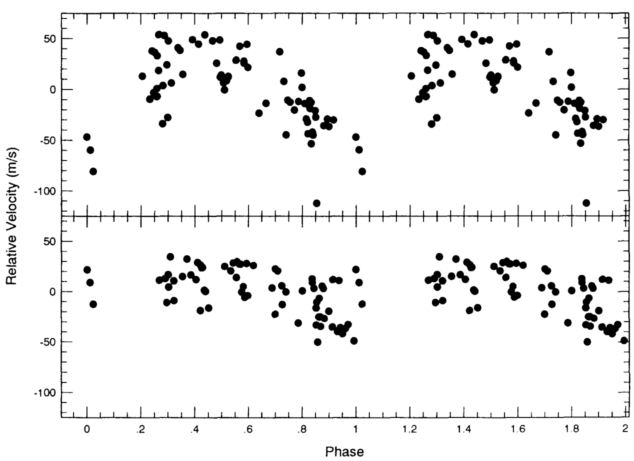

FIG. 4.—*Top:* Unrectified radial velocity data from 1992 June 12–19 phased to a period of 0.255 days. *Bottom:* Radial velocity after subtracting a second-order polynomial fit to the nightly averages and phased to a period of 0.255 days.

The top panel of Figure 5 shows the periodogram for the 1989 July data. As expected, the aliasing of these data is much more severe, and this results in a forest of false peaks. The highest peak occurs at 1.23 days^{-1} ($P = 0.813 \pm 0.007$ days) with a false-alarm probability $\approx 10^{-11}$, and secondary peaks occur at a spacing of about 0.5 days^{-1}. The CLEAN algorithm, on the other hand, produces a periodogram with a peak amplitude at 2.20 days^{-1} ($P = 0.455 \pm 0.007$ days). (This underscores the severe alias problems of the 1989 July data set. There are clearly short-period variations present (as attested by the low value of the false-alarm probability), but it is difficult to discern the period that is actually present.

The lower panel of Figure 5 shows the periodogram of the rectified 1989 July data set. Subtraction of the nightly averages removes power from the low-frequency end of the periodogram, and this causes the peak amplitude to occur at a much higher frequency, in this case 4.22 days^{-1} ($P = 0.237 \pm 0.007$). (A CLEAN analysis of the rectified data also yields a peak amplitude at 4.22 days^{-1}.) Thus the true period present in the 1989 July data depends on whether there is an underlying long-term component to the variations and our ability to remove it from the data. Clearly it is more difficult to discern long-term trends with only 2 nights of data. The difference in the average radial velocity between these 2 nights amounts to 50 m s^{-1}, which is about the difference in the binightly means of the 1992 June data. This suggests that there is a long-period (>8 days) component to the radial velocity variations in the 1989 July data, so that the periods derived from the rectified data may represent the true periods that are present.

The top panel of Figure 6 shows the unrectified 1989 July data phased to the 0.455 day period (from the CLEAN analysis), while the lower panel shows the rectified data phased to the 0.237 day period. Both phase diagrams show sinusoidal (or sawtooth) variations, although phasing the rectified data using the 0.237 day period results in a smaller amplitude (40 m s^{-1} as opposed to 60 m s^{-1}) as well as a smoother sawtooth shape than the data phased to the 0.455 day period. Although the shorter period is more consistent with the 0.255 day period found in the 1992 June data set, we cannot distinguish with any certainty which of these two periods is actually present in the 1989 July data set. It is difficult to infer long-term trends for the nightly averages from just 2 nights of data, and the unrectified

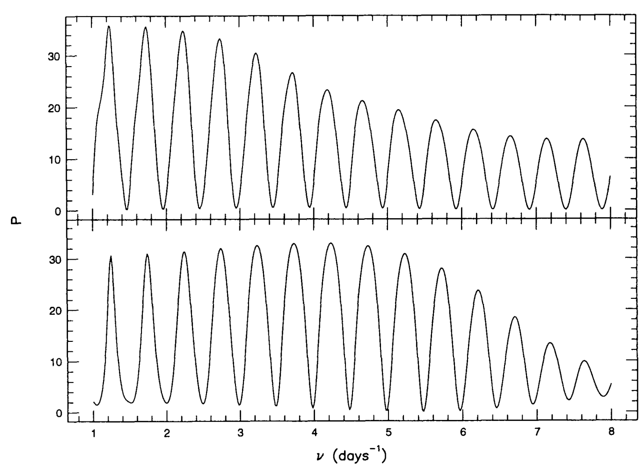

FIG. 5.—Periodogram of the radial velocity data for β Oph from 1989 July 15 and 17. *Bottom:* Periodogram for the 1989 July data after subtracting the nightly means.

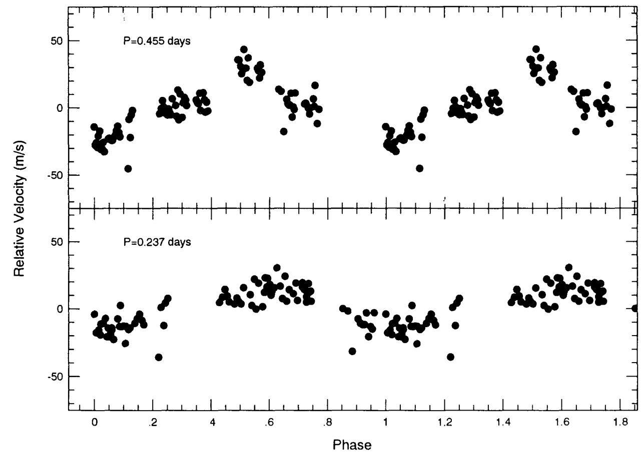

FIG. 6.—Unrectified radial velocity data from 1989 July phased to a period of 0.455 days. *Bottom:* Radial velocity after subtracting a linear fit to the nightly averages and phased to a period of 0.237 days.

data may indeed be sampling a waveform with a period of 0.455 days.

3.2. *Numerical Simulations*

Although the false-alarm probabilities calculated from the periodograms are rather small, the true statistical significance of a peak is best established through numerical simulations (A. W. Irwin 1993, private communication). This was investigated using 200 periodograms of randomized data sampled in the same manner as the 1989 and 1992 data sets. The standard deviation of the random data was taken to be 10 m s^{-1} for the 1989 set simulation and 17 m s^{-1} for the 1992 set simulation. Figure 7 shows the histogram of amplitudes for the highest peak for each of the 200 numerical simulations. The top panel is the simulation appropriate for the 1992 data set, while the lower panel is for the 1989 data set. In all 200 noise periodograms the largest amplitude peak is considerably lower than that of the highest peak in the data periodograms. This is consistent with the low value of the false-alarm probabilities and confirms that the peaks in the data periodograms are indeed significant. (Also, the frequency of the highest peak in the noise periodograms was randomly distributed throughout the spectral range and with only about 2% of these peaks near the 0.255 day period of the real data.)

The effects of the data window for both periodograms make it difficult to determine which frequency is real and which are aliases. Application of the CLEAN algorithm offers little assistance in finding the true period. Although this technique does an excellent job of removing alias peaks, the dominant peak in the CLEANed spectrum usually coincides with the highest peak of the input periodogram. The major peaks in the periodograms (Figs. 3 and 6) are of comparable height, and the presence of noise may cause an alias frequency to have a higher amplitude than the signal peak.

To quantify the effects of aliasing, simulations were performed on model data consisting of a pure sine wave sampled in the same manner as the data. Gaussian noise with a standard deviation appropriate for each of the data sets ($\sigma = 10$ m s^{-1} for the 1989 set and $\sigma = 17$ m s^{-1} for the 1992 set) was also added. The frequency of the model data was taken from the major peaks in the data periodograms. The semiamplitude and phase of the input sine wave were the last-squares values from the Scargle periodogram. Two hundred periodograms were calculated, and the frequency of the highest amplitude peak was noted (the highest peak in all 200 periodograms was statistically significant). Tables 3–5 summarize the results of these simulations. The first column lists the frequency of the model sine wave. The other column headings give the frequencies of the various peaks found in the model periodograms. Beneath each of these is the percentage of the simulations for which the highest peak appears at that frequency. These tables can be used to get an approximate probability that the highest peak in the data periodogram actually coincides with the true period.

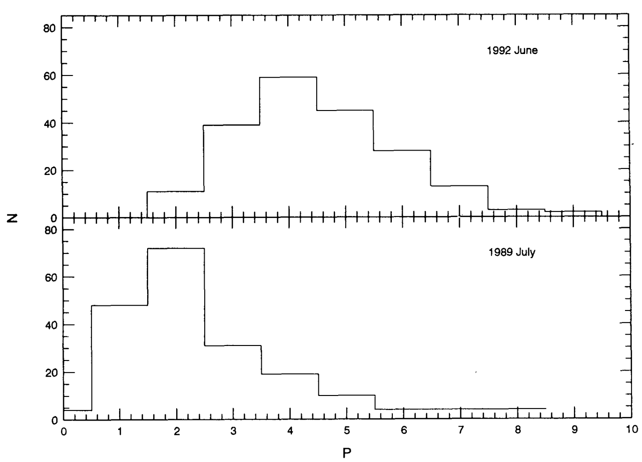

FIG. 7.—Results of numerical simulations using 200 periodograms on randomized data. *Top:* Histogram of amplitudes for the highest peak in the periodogram for the random data. In this case the random data have a standard deviation of 17 m s^{-1} and are sampled in the same manner as the 1992 June data set. *Bottom:* Histogram of peak amplitudes from periodograms of noise ($\sigma = 10$ m s^{-1}) sampled in the same manner as the 1989 July data set.

TABLE 3

ALIAS FREQUENCIES NEAR $\nu = 3.9$ days^{-1} FOR 1992 JUNE DATA: PERCENTAGE OF PERIODOGRAMS WITH PEAK AT ν_{max}

	ν_{max}				
MODEL ν	1.9	2.9	3.9	4.9	5.9
2.9	1.0	98.0	1.0	0.0	1.0
3.9	0.0	3.5	89.5	7.0	0.0
4.9	0.0	0.5	8.5	81.5	9.0

TABLE 4

ALIAS FREQUENCIES NEAR $\nu = 2.2$ days^{-1} FOR 1988 JULY DATA: PERCENTAGE OF PERIODOGRAMS WITH PEAK AT ν_{max}

	ν_{max}							
MODEL ν	0.2	0.7	1.2	1.7	2.2	2.7	3.2	3.7
1.2	46.5	32.0	1.5	2.5	17.5	0.0	0.0	0.0
1.7	0.0	23.5	1.5	13.5	37.5	24.0	0.0	0.0
2.2	0.0	0.0	8.0	38.0	15.5	14.5	16.0	8.0
2.7	11.5	9.0	0.0	2.0	35.0	29.5	12.0	1.0
3.2	0.0	0.0	0.0	0.0	1.0	35.0	59.5	4.5

TABLE 5

ALIAS FREQUENCIES NEAR $\nu = 4.2$ days^{-1} FOR 1988 JULY DATA: PERCENTAGE OF PERIODOGRAMS WITH PEAK AT ν_{max}

	ν_{max}					
MODEL ν	3.2	3.7	4.2	4.7	5.2	5.7
3.7...........	24.0	66.5	9.5	0.0	0.0	0.0
4.2...........	1.5	21.0	55.0	20.5	2.0	0.0
4.7...........	0.0	6.0	23.5	44.0	26.5	0.0
5.2...........	0.0	0.0	3.5	26.0	50.5	20.0

Table 3 is the simulation for the 1992 data, and it shows that the highest peak in the periodogram is indicating the true frequency about 80%–90% of the time. The maximum of the data periodogram occurs at a period near 0.25 days or $\nu = 3.9$ days^{-1} (Fig. 3), and even though this is the most likely frequency that is present, there is about a 10% chance that the true signal has either a 0.34 ($\nu = 2.9$ days^{-1}) or 0.20 day ($\nu = 4.9$ days^{-1}) component.

As expected, the alias effects are more severe for the 1989 data set. Table 4 lists alias frequencies near $\nu = 2.2$ days^{-1} or a period of 0.45 days (peak in the CLEANed periodogram) using the 1989 unrectified July data as a model. This simulation shows that, due to the sampling window, the peak of the data periodogram more than likely does not indicate the true period. For instance, if the peak of the data periodogram is near a period of 0.45 days ($\nu = 2.2$ days^{-1}), then the true period can be 0.83, 0.59, 0.45, or 0.37 days ($\nu = 1.2$, 1.7, 2.2, or 2.7 days^{-1}).

Table 5 lists the aliases near 4.2 days^{-1} ($P = 0.24$ days), which is appropriate for the rectified 1989 July data. The aliasing seems to be a little less severe than the simulation for the unrectified data. The peak of the data periodogram ocurs near 0.237 days or $\nu = 4.22$ days^{-1} (lower panel of Fig. 5), and Table 5 indicates that there is about a 55% probability that this is the true period and a 24% probability that the actual period is near 0.21 days ($\nu = 4.7$ days^{-1}). Periods of 0.27 and 0.19 days ($\nu = 3.7$ and 5.2 days^{-1}) are also possible but are less likely.

4. DISCUSSION

The short-period radial velocity variations found in β Oph can only result from stellar oscillations. The presence of a low-mass companion can immediately be dismissed, since the semi-major axis of the orbit would be less than 2 solar radii, considerably less than the expected radius for a K giant. Likewise, these variations cannot be due to rotational modulation, since the expected rotation period for a K giant should be ~100 days or more. To test whether radial pulsations are a plausible explanation for the radial velocity variations, simple calculations of the expected period for the fundamental and the first two harmonic radial modes were made using the empirical Q relationship derived by Cox, King, & Stellingwerf (1972). Although this equation is valid for stars covering a wide range of masses and radii, it was derived using stellar models inappropriate for K giants. Their "Q" algorithm refers to stars having more convection and a higher abundance of helium in the envelope, so the actual periods for the radial modes may differ slightly from the derived periods.

There are no angular diameter measurements for β Oph, so its radius must be inferred from its luminosity and effective temperature. Ianna & Culver (1985) list the parallax of β Oph as 0\".033 with an error of 10%. This results in $M_V =$ 0.133–0.57. McWilliam (1990) determined an effective temperature of 4550 K and a suface gravity of $\log g = 2.63 \pm 0.2$ for this star. These values are consistent with a $\log g = 2.5$ and a temperature of 4683 K determined by Kjærgaard et al. (1982). These parameters result in a bolometric magnitude of -0.41 to 0.02, a radius in the range 11–17 $R_\odot$, and a stellar mass of 1.2–7.4 $M_\odot$.

The actual errors in $\log g$, however, may be considerably larger than the formal errors for McWilliam's $\log g$ determination due to the difficulty of measuring this quantity in yellow giants. For instance, in the case for α Boo, McWilliam's $\log g$ was 0.7 larger than the results of Peterson, Dalle Ore, & Kurucz (1993) and 1.2 larger than a value determined by Mäckle et al. (1975). However, it is unlikely that β Oph has a $\log g$ as low as α Boo ($\log g = 1.0$), since this would result in a mass range of 0.1–0.2 $M_\odot$. To bring the mass to reasonable values ($M \sim 1\ M_\odot$) with such a low $\log g$ requires a larger radius by a factor of 2–3, and this is only possible if the parallax for β Oph is grossly in error. It also seems unlikely that the $\log g$ is much higher than McWilliam's value, since that would imply an unreasonably large mass for a K giant ($>10\ M_\odot$). Although the $\log g$ measured by McWilliam is consistent with the inferred radius and reasonable assumptions about the mass of β Oph, the true error of this measurement may be larger.

Figure 8 summarizes the results of the calculations of the periods for radial pulsations. The radius of β Oph in solar radii is plotted along the abscissa, while the stellar mass in solar units is plotted along the ordinate. Regions restricted by the range of mass and radius estimated for β Oph are indicated by horizontal and vertical dashed lines. The nominal $\log g$ value eliminates mass and radius values in the regions covered by the diagonal dashed lines. The allowable values of mass and radius for β Oph thus lie in the clear region between the heavy lines. Also shown are three lines of constant pulsation periods. The three numbers in parentheses near the lines are the periods (in days) of the fundamental, first harmonic, and second harmonic

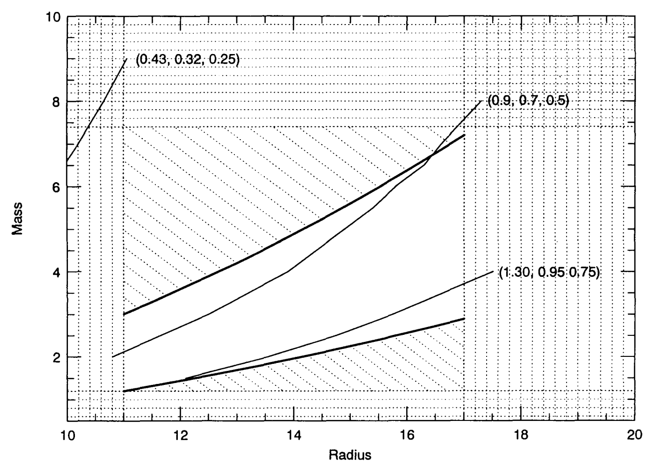

FIG. 8.—Mass-radius diagram for β Oph. Regions that are outside the estimated values for the mass and radius are indicated by horizontal and vertical dashed lines. The $\log g$ measurements of McWilliam (1990) limit β Oph to a region bounded by the heavy curves and exclude M and R-values covered by the diagonal dashed lines. The other three lines give the locus of constant-period radial pulsation modes. The numbers in parentheses give the period (in days) of the fundamental, first harmonic, and second harmonic of radial modes.

radial modes, respectively. A stellar mass of 7.4 $M_\odot$ and a radius of 10.4 $R_\odot$ result in periods of 0.43 days for the fundamental and 0.25 days for the second harmonic (line in upper left-hand corner). Although this is consistent with the observed periods, these values lie well outside the nominal range of allowable parameters. These stellar parameters result in log $g = 3.4$, considerably larger than the published values, but, considering the difficulty of the log g determination, possibly not an unreasonable value. More log g measurements are required to confirm such a large value of the surface gravity. Assuming McWilliam's measurement of log g to be correct, it is not possible to match the observed 0.255 day to any of the first radial pulsation modes using reasonable values of the mass and radius. It is possible to match the 0.455 day period (if it is indeed present) to a second overtone radial mode using a radius of $R = 11\ R_\odot$ and a mass of 3 $M_\odot$; otherwise periods for the fundamental radial mode range are ~ 1 day, and those for the second harmonic radial mode range from 0.5 to 0.75 days. Extrapolating the pulsation periods to higher overtones suggests that if the 0.255 day period arises from radial pulsations, then it comes from an overtone mode with $n \geq 4$–6.

Alternatively, the short-period pulsations in β Oph may be nonradial in nature. Ando (1976) investigated the stability against linear, nonadiabatic nonradial oscillations for acoustic modes in the envelopes of late-type stars covering a wide range of stellar models. We have performed numerical calculations that indicate that nonradial pulsations would have to have $\ell \leq 4$ [where ℓ is the index of spherical harmonics $Y_{\ell,m}(\theta, \phi)$] in order to be detected by our radial velocity measurements. Higher order modes cannot be detected, since there is a cancellation of local velocities on the stellar surface in the integrated radial velocity for these modes. Ando only examined $\ell \geq 10$, but an extrapolation to lower ℓ can be made using the asymptotic theory of p-mode oscillations. This predicts that the frequency of even and odd ℓ p-mode oscillations alternate by $\nu_0/2$, where ν_0 is a characteristic frequency (Tassoul 1980). The stellar model considered by Ando with the stellar parameters closest to those of β Oph had log $g = 2.97$, $M = 3.0\ M_\odot$, and log $(L/L_\odot) = 1.7$. This results in periods for the $\ell = 1$, 2 p-mode oscillations in the range 2–16 hr, which is of the order of the observed periods. Although this suggests that we are seeing acoustic pulsation modes in this star, a pulsation analysis using the stellar parameters appropriate for β Oph as well as a treatment of lower order ℓ-modes is needed to confirm this.

The 1989 July data are too sparse to determine which of the periods is correct: the 0.455 days (from the CLEAN analysis), 0.813 days (from the Scargle-type periodogram), or the 0.237 day period resulting after subtracting the nightly means, or any of the aliases of these periods. Although the periods from the rectified 1989 July data are near the 0.255 day period found in the 1992 data, there is some evidence that the short-term periods present in each data set are in fact different. None of the major peaks in the 1989 data periodogram have frequencies corresponding to the 0.255 day period found in the 1992 data set. Synthetic data consisting of a 0.255 day period sine function sampled in the same manner as the 1989 data set produce a periodogram whose major peaks are significantly shifted from those found in the 1989 data. Furthermore, phasing the 1989 July data to the 0.255 day period or any of the other periods found in the 1992 set periodogram produces a phase diagram that looks significantly worse than the one derived using those periods found in the 1989 data set. It may be that β Oph has switched pulsation modes between the time of the 1989 and 1992 observations. Such mode-switching may have also been seen in the radial velocity variations of α Boo (Hatzes & Cochran 1994). Several periods were observed in α Boo during the same time span as the β Oph observations, but the dominant one was a 2.56 day period, considerably longer than the 1.86 day period found by Smith et al. (1987). More observational monitoring of β Oph is needed to establish whether the 0.255 day period is stable or whether β Oph switches pulsation modes.

5. SUMMARY

An analysis of radial velocity data for β Oph taken during 8 nights in 1992 reveals the presence of a 0.255 day period. Data taken over 2 nights in 1989 July also show the presence of short-term variability. It is possible that the 1989 data have a different period from the 1992 data, but this cannot be confirmed, since aliasing as well as the effects of long-term velocity trends on the sparse 1989 data set make it virtually impossible to determine the actual period that is present. These short periods are tentatively consistent with either high-order ($n \geq 4$–6) overtone radial modes ($\ell = 0$) or nonradial ($\ell \leq 4$) acoustic modes. Theoretical work in the pulsation stability of K giants is needed before the exact pulsation mode in β Oph can be identified. This analysis on late-type stars has been sparse, primarily because observational data were not available for confirming theoretical results. The use of precise radial velocity measurements is changing this situation. As more and better radial velocity measurements of K giants become available (as well as period determinations), it is hoped that these inspire additional and more rigorous theoretical investigations. It is also encouraged that such future theoretical investigations utilize stellar models with parameters taken from actual (and observable!) stars.

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REFERENCES

Ando, H. 1976, PASJ, 28, 517
Baliunas, S. L., et al. 1985, ApJ, 294, 310
Cochran, W. D., & Hatzes, A. P. 1994, Ap&SS, in press
Cox, J. P., King, D., & Stellingwerf, R. 1972, ApJ, 171, 93
Griffin, R. & Griffin, R. 1973, MNRAS, 162, 243
Hatzes, A. P., & Cochran, W. D. 1993, ApJ, 413, 339
———. 1994, ApJ, 422, 369
Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Ianna, P. A., & Culver, R. B. 1985, AJ, 90, 1870
Kjærgaard, P., Gustafson, B., Walker, G. A. H., & Hultqvist, L. 1982, A&A, 115, 145
Kovacs, G. 1981, Ap&SS, 78, 175
Mäckle, R., Holweger, H., Griffin, R., & Griffin, R. 1975, A&A, 38, 239
McWilliam, A. 1990, ApJS, 74, 1075
Peterson, R. C., Dalle Ore, C. M., & Kurucz, R. L. 1993, ApJ, 404, 333
Roberts, D. H., Lehár, & Dreher, J. W. 1987, AJ, 93, 968
Scargle, J. D. 1982, ApJ, 263, 835
Smith, P. H., McMillan, R. S., & Merline, W. J. 1987, ApJ, 317, L79
Tassoul, M. 1980, ApJS, 43, 469
Walker, G. A. H., Yang, S., Campbell, B., & Irwin, A. W. 1989, ApJ, 343, L21