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# SHORT-PERIOD RADIAL VELOCITY VARIATIONS OF α BOOTIS: EVIDENCE FOR RADIAL PULSATIONS

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## ABSTRACT

Precise radial velocity measurements ($\sigma \sim 20$ m s$^{-1}$) of α Boo taken over eight consecutive nights in 1992 June are presented. A periodogram of the data shows significant power at periods of 2.46 days and 3.8 days. A separate analysis, using nonlinear least-squares fitting, reveals an additional period at 8.5 days, but at a very low amplitude ($\sim 14$ m s$^{-1}$), in addition to 2.46 day and 4.03 day periods. However, the 1.84 day period found by Smith et al. is not found in these data. The expected periods of the fundamental and first harmonic modes of radial pulsations were estimated using the radius determination of Di Benedetto & Rabbia, published log $g$ values, and the empirical $Q(M, R)$ relationship of Cox, King & Stellingwerf. The 2.46 day period is near that expected for the fundamental or first harmonic radial mode, depending on the choice of stellar mass which is uncertain due to the wide range of surface gravity determinations. For a given mass and radius the 1.84 day period found by Smith et al. coincides with that of the next harmonic. These periods indicate that the short-term variability of α Boo may be explained by radial pulsations. Furthermore, it seems that this star has switched pulsation modes to a lower overtone from the time of the Smith et al. measurements. A recent investigation into the excitation of acoustic oscillations in α Boo by Balmforth, Gough, & Tout reveals peaks in the growth rates of modes having periods very near those observed in α Boo for a stellar model of 0.23 $M_\odot$. This low value of the mass, however, is inconsistent with stellar evolution theory and a recent determination of the surface gravity of this star. It is clear that α Boo is multiperiodic and may be changing modes on timescales of a few years. This star may thus be an ideal candidate for the application of pulsation theory to late-type, evolved stars and may provide important tests of stellar evolution theory.

*Subject headings:* stars: individual (α Bootis) — stars: oscillations — techniques: radial velocities

## 1. INTRODUCTION

In a recent paper we reported the presence of a 233 day period with an amplitude of 500 m s$^{-1}$ and a possible 46 day period with an amplitude of 50 m s$^{-1}$ in the radial velocity of the K2 III star α Boo (Hatzes & Cochran 1993). That work also showed that this star exhibited night-to-night radial velocity variations as large as 100 m s$^{-1}$. Unfortunately, the sampling of these data was insufficient to determine the period of the short-term variations. Short-term variability ($\sim$days) in the radial velocity of α Boo has been reported by other investigators. Smith, McMillan, & Merline (1987) claimed the presence of a 1.84 day period (or an alias at 2.18 days) with an amplitude of 200 m s$^{-1}$. Cochran (1988) confirmed that α Boo exhibited changes in the radial velocity on a 2 day timescale, but could not determine a precise period. Later Belmonte et al. (1990a, b) reported the presence of a 2.7 and an 8.3 day period in the radial velocity variations of α Boo.

We have been obtaining radial velocities of a modest sample of K giants in an effort to understand the nature of the variability in these stars. In 1992 June we were able to monitor the radial velocity of α Boo for eight consecutive nights. A period analysis of these data indicates the presence of 2.46 and 3.8 day (or 4.03 day) components, as well as a possible 8.5 day period with a very low amplitude. We suggest that these periods may result from radial pulsations.

## 2. DATA ACQUISITION

Radial velocity data for α Boo were taken using an iodine absorption cell at the coudé focus of the McDonald Observatory 2.1 m telescope. A 1200 gr mm$^{-1}$ grating in second order along with a Tektronics 512 × 512 CCD yielded a dispersion of 0.046 Å pixel$^{-1}$ at a central wavelength of 5520 Å. An 85 μm slit provided a spectral resolution of 0.11 Å.

Use of the iodine absorption cell greatly improves the precision of the radial velocity measurements. The cell containing gaseous molecular iodine is placed in the optical path of the telescope just before the entrance slit to the spectrograph, and the resulting iodine absorption spectrum that is superposed on top of the stellar spectrum provides a stable wavelength reference against which radial velocity shifts of the star are measured. Since any instrumental shifts affect both the stellar and wavelength reference equally, radial velocity precisions to better than 10 m s$^{-1}$ are possible. The quartz cell containing the gaseous iodine is permanently sealed and regulated at a temperature of 50 °C. A description of the cell and its use is given by Cochran & Hatzes (1990).

The radial velocity of α Boo was monitored each night during Universal Dates 1992 12–19 June. The observing program was tailored to search for periods greater than several hours and consequently α Boo was not observed continuously. Rather, observations of this star were made several times each hour in between those of other program stars.

Figure 1 shows the radial velocities for π Her (K3 II) on each of the eight nights and μ Her (G5 IV) on the last five nights of the observing run. The standard deviation of the μ Her data is about 11 m s$^{-1}$, whereas the π Her data has a standard deviation of about 17 m s$^{-1}$. If the radial velocity measure from the first night of the π Her data is excluded from the standard deviation calculation (since it is significantly higher than the measurements from the other seven nights), a value of 13 m s$^{-1}$ is obtained. On each night a standard spot on the lunar surface

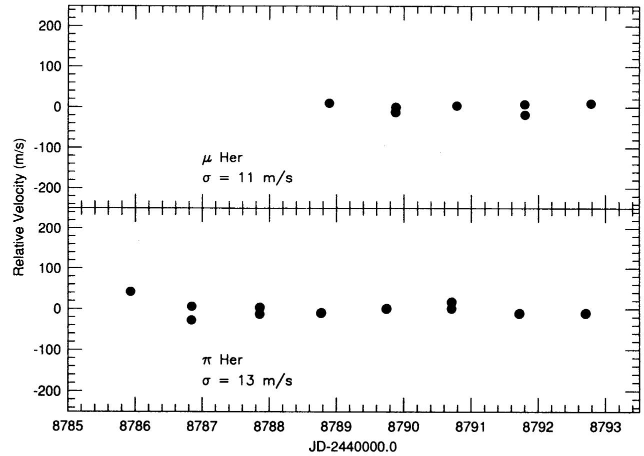


FIG. 1.—The radial velocity variations of $\pi$ Her (*top*) during 1992 June 12–19 and $\mu$ Her (*bottom*) during 1992 June 15–19.

was also observed, and these lunar velocities were reduced to heliocentric velocities using the JPL DE200 Planetary Ephemeris. The resulting standard deviation of the lunar radial velocities was about 11 m $s^{-1}$.

The rms scatter in the radial velocity measurements on a given night can actually be significantly smaller than the month-to-month scatter. This is because slight changes in the instrumental profile from run-to-run (or night-to-night) can introduce errors in the radial velocity measure (Hatzes & Cochran 1992) and, since no attempt has been made to model the instrumental profile in the radial velocity calculations, these errors could be significant. The month-to-month radial velocity measurements of the Moon yielded a standard deviation of about 17 m $s^{-1}$. This value is more consistent with the standard deviation for radial velocity for several (4–5) observations of $\alpha$ Boo taken within a few minutes of each other. The mean value of this standard deviation is 15 m $s^{-1}$ throughout the observing run. Therefore the conservative value of 20 m $s^{-1}$ shall be adopted as the typical error for the radial velocity measurements.

The relative radial velocity of $\alpha$ Boo during the eight nights is shown in Figure 2, and the values are listed in Table 1. The typical error is shown as a bar in the figure. The nightly variations as well as the night-to-night variations can be as large as 100 m $s^{-1}$, and this is significantly larger than the standard deviation in the velocities of $\pi$ Her, $\mu$ Her, or the Moon. Clearly $\alpha$ Boo is undergoing large changes in the radial velocity within several days.

## 3. PERIOD ANALYSIS

### 3.1. *Periodogram Analysis*

A period analysis was performed on the data using the technique outlined in Scargle (1982) and Horne & Baliunas (1986). The resulting periodogram in the frequency range $0.1 < \nu < 1.5$ $\text{days}^{-1}$ is shown in Figure 3. The periods of the major peaks in this frequency range are indicated in the figure. The dominant peak occurs at a period of 2.46 days. However, phasing the data according to the other major periods (1.67, 2.46, and 4.36 days) also produce reasonable-looking phase diagrams with readily evident sinusoidal variations (Fig. 4), so it is difficult to distinguish true periods from aliases.

In order to understand the structure seen in the periodogram, period analyses were conducted on synthetic data generated using pure sine waves sampled at the same intervals as the data. The amplitude of each sine was taken to be 50 m $s^{-1}$, and random noise with a standard deviation of 20 m $s^{-1}$ was also added to the synthetic data. The periodograms of these synthetic data with periods of 1.67, 2.46, and 4.26 days are shown in Figure 5. Note that the periodogram of a single sinusoid is incapable of reproducing all the peaks in the data periodogram. However, a combination of the periodograms for the 4.3 and 2.46 day sinusoid comes closest to matching the data periodogram. From these simulations we also conclude that the 1.67 day peak is an alias of the 2.46 day peak.

A simple model of the data periodogram was generated using the sum of two sine waves with periods of 2.46 and 4.36 days and amplitudes of 50 m $s^{-1}$. Once again random noise with a standard deviation of 20 m $s^{-1}$ was added, and the function was sampled in the same way as the actual data set. The periodogram of this function is shown in Figure 6. The phase diagrams of the synthetic data using the periods of 1.67, 2.46, and 4.3 days are also shown in Figure 7. Note the striking similarities between these figures and the actual periodogram and phase diagrams. We conclude that at least two periods,

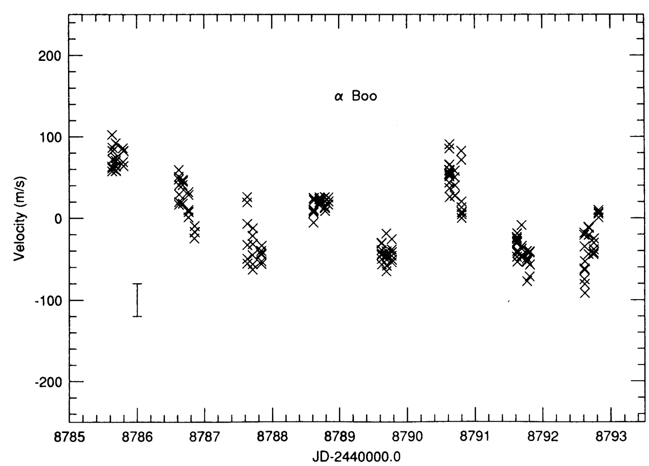


FIG. 2.—The relative radial velocities of $\alpha$ Boo during 1992 June 12–19. The bar indicates the typical error of 20 m $s^{-1}$.

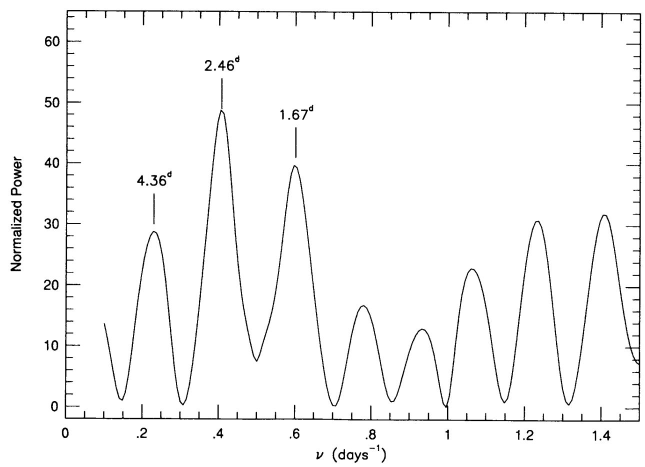


FIG. 3.—The periodogram of the radial velocities of $\alpha$ Boo shown in Fig. 2. The periods in days of the dominant peaks are indicated.

TABLE 1

α BOOTIS RELATIVE RADIAL VELOCITIES

| Date[a] | V (m s$^{-1}$) | Date[a] | V (m s$^{-1}$) | Date[a] | V (m s$^{-1}$) | Date[a] | V (m s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 785.630 | 102.2 | 787.633 | −49.8 | 789.630 | −43.7 | 791.621 | −40.6 |
| 785.630 | 57.4 | 787.634 | −55.5 | 789.692 | −19.1 | 791.622 | −43.1 |
| 785.632 | 63.2 | 787.708 | −21.8 | 789.693 | −65.6 | 791.623 | −19.3 |
| 785.633 | 61.0 | 787.709 | −45.2 | 789.695 | −44.2 | 791.624 | −53.6 |
| 785.636 | 71.8 | 787.710 | −63.1 | 789.696 | −40.9 | 791.625 | −40.3 |
| 785.637 | 82.4 | 787.711 | −56.5 | 789.697 | −47.3 | 791.688 | −9.2 |
| 785.638 | 86.4 | 787.712 | −31.8 | 789.698 | −58.7 | 791.689 | −37.8 |
| 785.684 | 91.9 | 787.713 | −12.6 | 789.772 | −46.3 | 791.690 | −46.1 |
| 785.685 | 57.8 | 787.836 | −40.0 | 789.773 | −25.9 | 791.691 | −48.6 |
| 785.686 | 70.2 | 787.837 | −43.2 | 789.773 | −38.7 | 791.692 | −34.5 |
| 785.687 | 58.5 | 787.838 | −56.0 | 789.774 | −54.5 | 791.766 | −41.0 |
| 785.688 | 73.9 | 787.839 | −44.5 | 789.775 | −51.4 | 791.767 | −54.0 |
| 785.690 | 63.5 | 787.841 | −52.9 | 789.775 | −41.8 | 791.768 | −49.7 |
| 785.790 | 85.9 | 787.843 | −33.7 | 789.699 | −51.2 | 791.769 | −52.5 |
| 785.792 | 68.8 | 788.614 | −5.7 | 790.616 | 64.9 | 791.770 | −77.4 |
| 785.798 | 82.5 | 788.615 | 6.8 | 790.617 | 53.3 | 791.807 | −71.8 |
| 785.799 | 82.5 | 788.616 | 8.8 | 790.618 | 58.9 | 791.808 | −42.5 |
| 785.801 | 63.8 | 788.618 | 24.2 | 790.619 | 85.1 | 791.810 | −41.1 |
| 785.802 | 82.2 | 788.618 | 10.3 | 790.619 | 43.1 | 791.811 | −41.3 |
| 786.619 | 59.1 | 788.620 | 24.6 | 790.620 | 51.0 | 791.812 | −57.2 |
| 786.620 | 50.7 | 788.621 | 21.8 | 790.621 | 36.5 | 792.613 | −21.1 |
| 786.621 | 47.5 | 788.702 | 16.0 | 790.622 | 90.4 | 792.614 | −18.5 |
| 786.622 | 16.4 | 788.703 | 19.7 | 790.622 | 55.0 | 792.615 | −18.6 |
| 786.623 | 40.4 | 788.704 | 23.4 | 790.623 | 65.6 | 792.616 | −75.2 |
| 786.624 | 19.6 | 788.705 | 23.0 | 790.624 | 25.6 | 792.617 | −35.2 |
| 786.625 | 29.0 | 788.706 | 25.5 | 790.625 | 57.8 | 792.617 | −62.2 |
| 786.678 | 40.7 | 788.707 | 18.2 | 790.697 | 49.9 | 792.618 | −63.8 |
| 786.679 | 44.7 | 788.709 | 22.9 | 790.698 | 57.8 | 792.619 | −81.0 |
| 786.680 | 17.7 | 788.782 | 13.8 | 790.699 | 27.3 | 792.620 | −92.0 |
| 786.681 | 46.9 | 788.784 | 25.8 | 790.700 | 39.9 | 792.622 | −53.4 |
| 786.682 | 45.9 | 788.785 | 12.3 | 790.701 | 27.0 | 792.676 | −11.8 |
| 786.762 | 31.8 | 788.786 | 12.9 | 790.795 | 82.3 | 792.677 | −11.3 |
| 786.764 | 10.0 | 788.788 | 8.6 | 790.797 | 71.0 | 792.678 | −44.5 |
| 786.765 | 0.8 | 788.790 | 20.8 | 790.798 | 20.1 | 792.679 | −21.2 |
| 786.766 | 28.5 | 788.835 | 16.6 | 790.799 | 12.9 | 792.680 | −12.6 |
| 786.767 | 7.5 | 788.837 | 25.2 | 790.800 | −0.3 | 792.750 | −44.7 |
| 786.851 | −25.1 | 788.839 | 20.4 | 790.801 | 4.3 | 792.752 | −42.5 |
| 786.854 | −16.9 | 789.621 | −39.4 | 790.802 | 7.3 | 792.753 | −30.7 |
| 786.855 | −10.0 | 789.621 | −31.2 | 790.803 | 6.8 | 792.754 | −38.6 |
| 786.857 | −17.4 | 789.622 | −45.6 | 791.617 | −23.8 | 792.756 | −25.4 |
| 787.630 | 19.1 | 789.623 | −30.3 | 791.618 | −47.6 | 792.821 | 9.5 |
| 787.631 | 25.9 | 789.624 | −44.8 | 791.619 | −28.7 | 792.822 | 4.9 |
| 787.632 | −32.9 | 789.625 | −50.6 | 791.620 | −31.0 | 792.823 | 6.8 |
| 787.632 | −7.2 | 789.626 | −57.3 | 791.620 | −26.0 | 792.824 | 0.3 |

[a] Date = Julian Day −2,448,000.0.

one near 2.46 days and the other near 4.36 days, are present in radial velocity variations for α Boo during 1992 12–19 June.

### 3.2. *CLEAN Analysis*

To confirm the presence of both periods, the data were also analyzed using the CLEAN algorithm of Roberts, Lehár, & Dreher (1987). This algorithm is designed to remove artifacts introduced into the power spectrum by missing data (i.e., the sampling window). Thus CLEAN should remove any false peaks in the power spectrum due to aliasing. The top panel of Figure 8 shows the "dirty" power spectrum of the α Boo data in the frequency range $0 < \nu < 5$ days$^{-1}$ with true and false peaks present. This was calculated using a standard fast Fourier transform algorithm and not the period search algorithm used for Figure 3. The lower panel shows the resulting Fourier transform after application of the CLEAN technique. It is characterized by strong peak at 2.46 days and a weaker one at 3.8 days. The slight shift of the latter peak to longer periods in the raw periodogram is probably the effect of the data window. There are also smaller residual peaks at 1.23, 0.61, 0.21 days, but these are most likely artifacts. These occur at $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{12}$ of the period of the dominant peak, and they can easily be due to the shape of the 2.46 day variation departing from a pure sinusoid. Also the sampling pathology of our data (typically a set of observations every hour in a span of 5 hr each night) is probably not suited to detecting such short periods.

### 3.3. *Component Analysis Using Nonlinear Least Squares*

The periods present in the radial velocity data were also derived using the nonlinear least-squares fitting program GaussFit (Jefferys, McArthur, & McCartney 1991) and the functional form

$$V_r = V_0 + A_0 \sin\left(\frac{2\pi}{P} + \phi\right).$$

A bootstrap technique was employed in the analysis: a sine fit was made to the dominant component to the velocity varia-

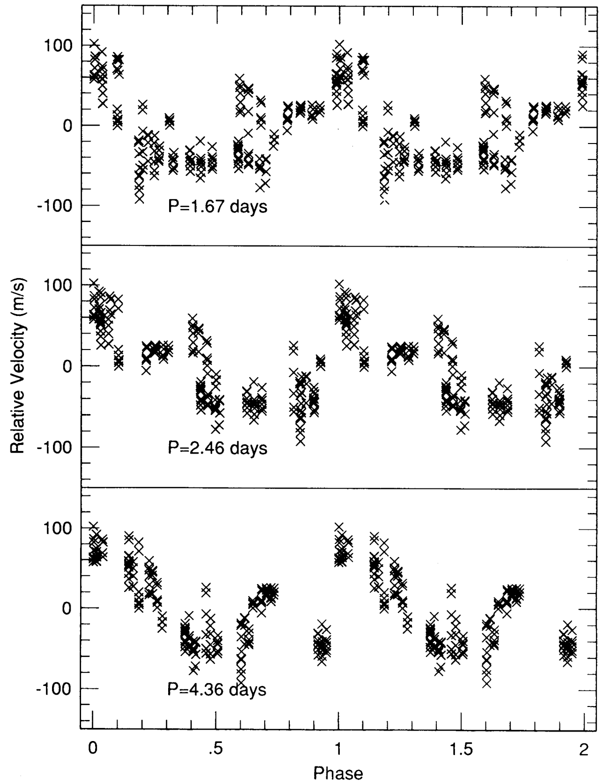


FIG. 4.—The radial velocity data of α Boo phased to a period of 1.67 days (*top*), 2.46 days (*middle*), and 4.36 days (*bottom*).

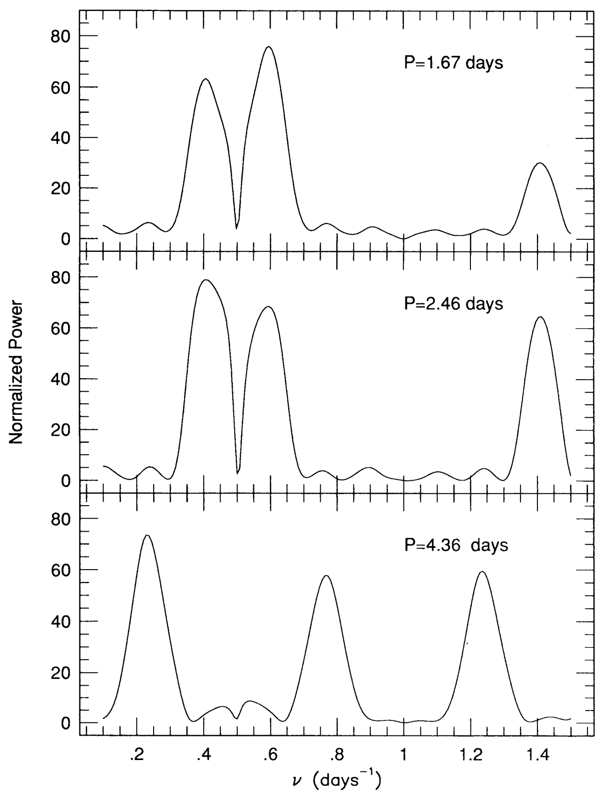


FIG. 5.—Periodograms of sine functions having periods 1.67 days (*top*), 2.46 days (*middle*), and 4.36 days (*bottom*). The sampling of these synthetic data is the same as in Fig. 2. Random noise with a standard deviation of 20 m $s^{-1}$ has also been added to the fake data.

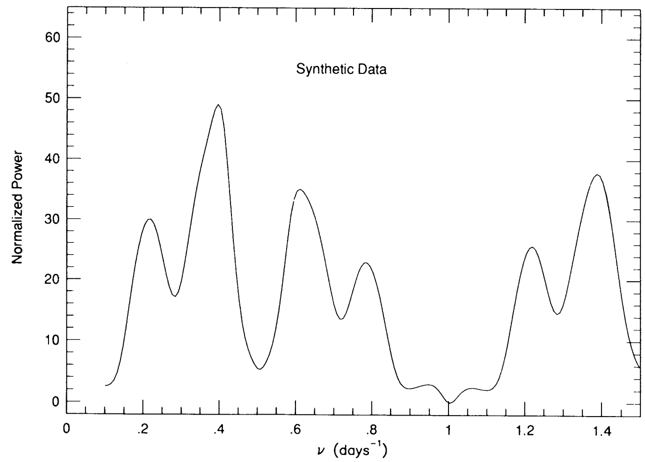


FIG. 6.—Periodogram of synthetic data consisting of the sum of 2 sine functions having periods of 2.46 and 4.3 days and amplitudes of 50 m $s^{-1}$. The sampling of this fake data is the same as in Fig. 2 and random noise at a level of 20 m $s^{-1}$ has also been added.

tions. This component was then subtracted from the data and a subsequent fit was made on the velocity residuals. The initial guess to the period and amplitude of the sine functions required by GaussFit was provided by Fourier analysis. Successive sine components were found and subtracted from the data until the standard deviation of the final residuals was equal to the error of the individual measurements, about 20 m $s^{-1}$.

Figure 9 shows the results of this analysis and the periods and respective amplitudes of the sine waves are summarized in Table 2. The top panel in the figure shows the fit to the raw

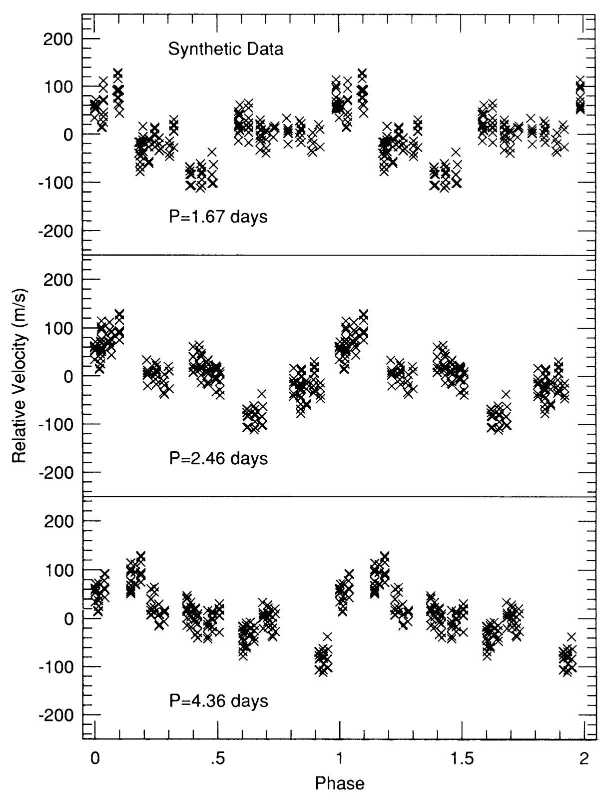


FIG. 7.—Phase diagrams of the 2 sine fake data set (Fig. 6) phased to a period of 1.67 days (*top*), 2.46 days (*middle*), and 4.36 days (*bottom*).

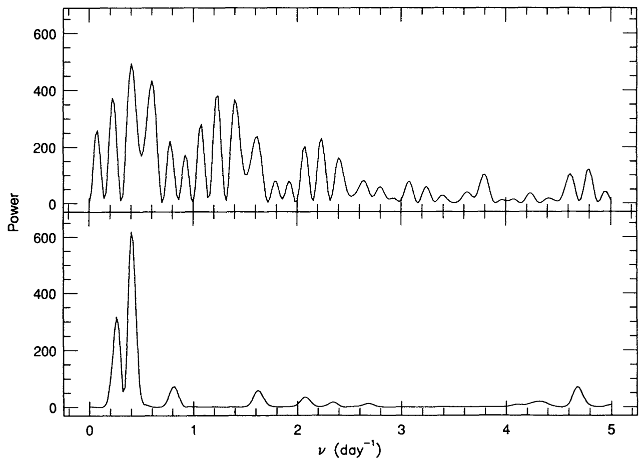


FIG. 8.—*Top*: The "dirty" Fourier transform of the radial velocity data for α Boo; *bottom*: the resulting Fourier transform after application of the CLEAN algorithm.

data with a sine wave having a period of 2.46 days and an amplitude of 54 m $s^{-1}$. The second panel shows a fit to the residuals using a sine wave with a period of 4.03 days and an amplitude of 30 m $s^{-1}$. This confirms the two periods found by the periodogram and CLEAN analyses. All three techniques

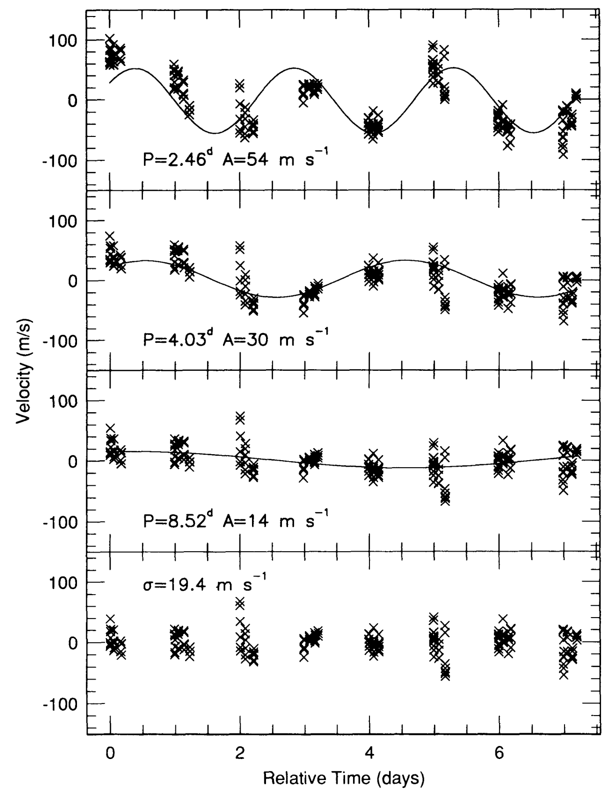


FIG. 9.—Results of nonlinear least-squares fitting. *Top panel*: Radial velocity data for α Boo and the fit (line) using a 2.46 day period sine wave with an amplitude of 54 m $s^{-1}$; *second panel*: velocity residuals after subtracting the dominant 2.46 day component. The line represents a fit with a 4.03 day period sine wave having an amplitude of 30 m $s^{-1}$; *third panel*: velocity residuals after subtracting the 2.46 and 4.03 day components. The line represents a fit with an 8.5 day period sine wave with an amplitude of 14 m $s^{-1}$; *bottom panel*: velocity residuals after subtracting all three sine components. The standard deviation of the final residuals is 19.5 m $s^{-1}$.

TABLE 2

PERIODS DETERMINED THROUGH NONLINEAR LEAST-SQUARES FITTING

| Period (days) | Amplitude (m $s^{-1}$) | $\sigma_P$ | $\sigma_{amp}$ |
|---|---|---|---|
| 2.46 .......................... | 54 | 0.02 | 3.7 |
| 4.03 .......................... | 30 | 0.08 | 2.3 |
| 8.52 .......................... | 14 | 1.15 | 2.0 |

yield identical periods for the dominant component and consistent periods of about 4 days for the secondary component. There are slight differences in the period for the secondary component but this is not surprising due to the rather short data window for the observations.

A Fourier analysis of the data residuals after subtracting the 2.46 and 4.03 day components yielded significant power around 8 days. A sine fit to these residuals yielded a period of 8.52 days with an amplitude of 14 m $s^{-1}$ The fit to these residuals is shown in the third panel of Figure 9. The reality of this component is very uncertain because the data window is comparable to this period (8 days) and the amplitude is near the error of the individual radial velocity measurements. This long period component could easily result from the 4 day component not having a pure sinusoidal shape, and the resulting residuals may thus exhibit variations with an alias of the 4 day period.

The bottom panel of Figure 9 shows the residuals of the data after subtracting all three components. Including the 8.5 day component in the fitting results in residuals having a standard deviation of 19.4 m $s^{-1}$, very near the expected errors. Omitting the 8.5 day component results in residuals of 22 m $s^{-1}$, slightly higher than the measurement error. This difference is slight and cannot be used to confirm the presence of the 8.5 day period. A Fourier analysis of the residuals shown in the bottom panel of Figure 9 yields no additional periods.

The standard deviation in the residuals of the radial velocity for night 3 and night 6 of the observing run were slightly higher than for the other nights (30 m $s^{-1}$ as opposed to 15 m $s^{-1}$). It is possible that these larger errors may be due to a less stable instrumental profile during those nights. However, we cannot exclude the possibility that there are even shorter timescale variations in the radial velocity of α Boo (less than a day). If this is so, the fact that these variations appear intermittently (in this case twice in 8 days) suggests that, if present, they are not long-lived.

## 4. DISCUSSION

The 2.7 day period found by Belmonte et al. (1990b) is most likely related to the 2.46 day period found in this work. However, our data show no evidence of the 1.84 day period found by Smith et al. (1987), and it is unlikely that one of the periods is in error. The uncertainty in the radial velocity measurements of Smith et al. and this work are comparable (~20 m $s^{-1}$). Also contemporaneous monitoring of "constant" stars by both techniques eliminates instrumental effects as the source of the periodic variations. The alias period of the Smith et al. measurements is 2.18 days, significantly different than the periods found here. The only remaining conclusion is that the radial velocity of α Boo changed from a dominant period of 1.84 days at the time of the Smith et al. observations to a 2.46 day period at the time of our observations.

Smith et al. noted that the 1.84 day period was near the period for the second harmonic of radial pulsations. We have also estimated the expected period for the fundamental mode ($F$) as well as the first two harmonics ($1H$ and $2H$) for radial pulsations using the empirical $Q(M, R)$ relationship determined by Cox, King, & Stellingwerf (1972). Since α Boo is not a member of a binary system, its mass must be inferred from estimates of its radius and surface gravity. Di Benedetto & Rabbia (1987), using Michelson interferometry, measured a radius for α Boo of $24.4 \pm 1.2\ R_\odot$. This value was used in all the period calculations. The surface gravity of α Boo is considerably more uncertain with published values of log $g$ ranging from 0.9 (Mäckle et al. 1975) to 2.19 (McWilliam 1990). These yield mass values in the range of 0.1–3.7 $M_\odot$. These calculated radial pulsation periods are summarized in Table 3.

A stellar mass of 2.1 $M_\odot$ results in $F = 3^{d}41$, $1H = 2^{d}46$, and $2H = 1^{d}86$. A mass of 3.43 $M_\odot$, calculated with the higher log $g$ of McWilliam, results in $F = 2^{d}46$, $1H = 1^{d}83$, and $2H = 1^{d}44$. So, by choosing a mass and radius for α Boo within the uncertainties of these quantities, one can match the 2.46 day period to either the $F$ or $1H$ mode. For these given masses and radii the 1.84 day period then coincides with the next harmonic ($1H$ or $2H$), respectively. It seems that radial pulsations is a viable explanation for the short-term radial velocity variability of α Boo. If this is the case, then it also appears that α Boo has switched pulsation mode to a lower overtone. One should note, however, that the "$Q$" equation of Cox et al. is appropriate for stars with higher helium envelope abundance and less convection than α Boo is expected to have. More problematical is the fact that, though these masses are consistent with the published values of log $g$, they are considerably higher than the 0.7–1.0 $M_\odot$ predicted by stellar evolution theory for α Boo's location in the H-R diagram.

The most recent determination of log $g$ was made by Peterson, Dalle Ore, and Kuruz (1993) who found a value of log $g = 1.5 \pm 0.15$ which corresponds to a mass in the range of 0.7–1 $M_\odot$. The dominant 2.46 day period coincides to the second harmonic when using a log $g = 1.68$ and $R = 23.8\ R_\odot$. The period of the fundamental and first harmonic mode is 5.82 days and 3.64 days, respectively. The $Q$ relationship of Cox et al. does not extend past the second harmonic, but extrapolating the values for the first two overtones results in a period for the third harmonic of around 1.7 days. Although the match of these periods to the observed periods are not as good as those produced by the higher mass values, they are probably consistent considering that these are empirically derived $Q$ values calculated using models inappropriate for α Boo. This simple analysis indicates that the periods we observed for α Boo are near those of the first three harmonic radial modes. The 1.84 day period observed by Smith et al. would represent the next higher harmonic from the shortest period we detected. A radial pulsation analysis on the appropriate stellar model may put the theoretical values more in line with the observed ones.

So, if the observed periods in the radial velocity variations of α Boo are due to radial pulsations, and this star has switched modes from a higher to a lower overtone (or fundamental), then the short-period variability in K giants may be related to the semiregular (SR) variables, three of which have shown evidence of mode switching from the fundamental to an overtone radial mode (Cadmus et al. 1991). Continued monitoring of α Boo should reveal how often and over what timescales this switching occurs. In the SR variables the possible mode switching occurs over a few pulsation cycles, and such rapid changes in the pulsation characteristics of α Boo, if present, would require a small stellar envelope mass.

Recently, Balmforth, Gough, & Tout (1991) studied whether acoustic pulsations might be excited in α Boo. The growth rates for acoustic modes were examined using two classes of models, one where the stellar mass was taken to be 0.8–1.0 $M_\odot$, and another where the mass was taken to be 0.23 $M_\odot$ (appropriate for the lower log $g$ values). The high-mass models yielded growth rates that peaked around periods of 2 days, slightly less than the dominant period found by our study and close to the value found by Smith et al. (1987).

The behavior of the growth rates as a function of pulsation frequency for the low-mass model was more complicated. The peaks in the growth rates were approximately uniformly spaced and centered around 1.5, 2.9, and 4.4 μHz. This corresponds to periods of 7.7, 4.0, and 2.6 days, which are tantalizingly close to the periods found in this radial velocity study. If the observed periods are due to acoustic pulsations, the observed period spacing seems to be consistent with α Boo having a mass around 0.2 $M_\odot$. Although this is inconsistent with the results predicted by stellar evolution theory, there is evidence for some K giants having subsolar masses. For the visual binary γ Leo (K0 III), Wilson (1967) found a mass less than 0.3 $M_\odot$. Helfer & Wallerstein (1968) derived mass estimates for a sample of 27 early K giants and found half the stars to be very much less massive than Hyades K giants. One star, $\phi^2$ Ori, which is very similar to α Boo in that it is a high-velocity, weak-CN star, had a derived mass of 0.22 $M_\odot$. Further theoretical analysis is needed before one can conclusively say that the radial velocity variations are due to acoustic

TABLE 3

Theoretical Radial Pulsation Periods

| Period (days) | Mode | log $g$ | Radius ($R_\odot$) | Remarks |
|---|---|---|---|---|
| 3.41 | $F$ | 2.00 | 24.4 | Match $2^{d}46$ period to $2H$ with nominal literature log $g$ |
| 2.46 | $1H$ | 2.00 | 24.4 | |
| 1.86 | $2H$ | 2.00 | 24.4 | |
| 2.46 | $F$ | 2.19 | 24.4 | log $g$ of McWilliam 1990 |
| 1.83 | $1H$ | 2.19 | 24.4 | |
| 1.44 | $2H$ | 2.19 | 24.4 | |
| 5.82 | $F$ | 1.68 | 23.8 | log $g$ near Peterson et al. 1993 |
| 3.64 | $1H$ | 1.68 | 23.8 | Value and match $2^{d}46$ period to $2H$ |
| 2.46 | $2H$ | 1.68 | 23.8 | |
| 8.33 | $F$ | 1.50 | 24.4 | log $g$ of Peterson et al. 1993 and match Belmonte et al. 1990a, b |
| 4.51 | $1H$ | 1.50 | 24.4 | |
| 2.95 | $2H$ | 1.50 | 24.4 | $8^{d}3$ period to $F$ |

oscillations that indicate a low mass for α Boo. Mäckle et al. (1975) discussed the consequences of such a low mass for a K giant. In order for a star to become a red giant in a reasonable length of time, stellar evolution theory requires that it have $M > 1\ M_{\odot}$. If the main-sequence mass for α Boo was more than this, one is confronted with the problem of considerable and *early* mass loss. If α Boo is on the ascending red giant branch, it currently has insufficient mass to ignite helium burning.

The low-amplitude 8.5 day period found by the nonlinear least-squares fitting would normally be dismissed as inconclusive if it were not for the fact that Belmonte et al. (1990a, b) found an 8.3 day component in the radial velocity of α Boo, but with a much larger amplitude (50 m $s^{-1}$). We cannot claim with any certainty that a period near 8 days is also present in our data; the data window is too short and the amplitude of the 8.5 day component is small and comparable to the error of our measurements. If the 8.5 day component is indeed present in our data, it has a much smaller amplitude than was observed by Belmonte et al. If this period actually represents that of the fundamental mode, a mass of 0.7 $M_{\odot}$ is required ($F = 8^{d}.3$, $1H = 4^{d}.5$, $2H = 2^{d}.7$). However, the match to the shorter periods found in this study is not as good. This could be reconciled if nonradial pulsations were responsible for the shorter periods.

If the short-term variability of α Boo results from radial pulsations, the expected photometric variations would be quite small and almost undetectable. Integrating the radial velocity curve results in a change in radius of only 0.001% (using an amplitude of 100 m $s^{-1}$). Assuming that the effective temperature of the star remains constant, this amounts only to a few hundredths of a millimagnitude variation. Applying the velocity-amplitude relationship of classical Cepheids (Allen 1973) to α Boo results in $\Delta m_v = 2$ mmag. Interestingly, Belmonte et al. (1990a) found a period of 2.5 days in the photometry with an amplitude of 2.5 mmag. However, this low photometric amplitude needs confirmation.

It is interesting that the combined amplitudes of the two sine waves found by this work and Belmonte et al. (1990b) is approximately the same, about 100 m $s^{-1}$ and this is close to the amplitude of the variations observed by Smith et al. (∼160 m $s^{-1}$). Furthermore, in both our data sets the amplitudes were equally divided between the two "modes." If the variations are due to pulsations, it seems that the energy of the pulsations is distributed equally among the modes that are present.

The radial velocity variations of α Boo seem to be complex and so far at least six periods have been detected in the radial velocity variations: 233, 46, 8.3, 4.0, 2.5, and 1.8 days. Although the 233 day period may well be due to rotational modulation (Hatzes & Cochran 1993), the numerous others that cover a wide range of values suggest that nonradial and radial pulsations may be present in α Boo and that the modes change on timescales of several years. Although difficult to perform, continuous observations over a week or more made every few months may be needed to completely understand the radial velocity behavior of α Boo.

It is also clear that not all K giants exhibit short-term variability. One of our program stars, π Her, is a K3 II star and it showed no significant variations above the 10 m $s^{-1}$ level during the 8 day observing run. McWilliam (1990) lists the parameters of π Her as $\log g = 1.68$, $T_{\rm eff} = 4100$ K, and $M_V = -1.60$. This yields a stellar radius of about 37 $R_{\odot}$ and a mass of 2.4 $M_{\odot}$. The period of the fundamental radial mode is therefore on the order of a week. Such a radial velocity variation could have been easily detected in the course of the eight night run. Beta Gem, a K0 III star, also does not show significant night-to-night variations indicating the absence of any short-term variability (Hatzes & Cochran 1993). That work also showed that α Tau can exhibit changes in the radial velocity as much as 100 m $s^{-1}$ between successive nights, although these changes are not as frequent for α Boo. Using a radius of 41.9 $R_{\odot}$ (Mozurkewich et al. 1991) and a mass of 2.5 $M_{\odot}$ (derived using the log $g$ of McWilliam) for α Tau results in periods for the fundamental and harmonic modes of radial pulsations in the range 4–8 days. Since most of the radial velocity data for α Tau were accumulated in runs no longer than about 3 days, this may explain why the observed night-to-night radial velocity variations in α Tau are not as frequent or as large as those seen for α Boo. Clearly long (∼1 week) observing runs are needed for a larger sample of K giants to see what short-term periods are present and whether these periods coincide with those expected for radial pulsations. This should help establish if radial pulsations are indeed present in these stars.

## 5. SUMMARY

We have monitored the radial velocity variations of α Boo for eight consecutive nights and found the presence of two periods, 2.46 and 4 days, as well as a possible component at 8.5 days. There is some uncertainty in the mass of α Boo, but it is possible to explain one or more of these periods as due to radial pulsations. If so, then the 1.84 day period found by Smith et al. (1987) represents the next higher harmonic to the 2.46 day period found in this study and it would seem that α Boo has "mode switched." The only analysis, to date, on the pulsational stability of acoustic oscillations in α Boo yields peaks in the growth rates of the modes with the same period spacing as those found in this study for a stellar mass of 0.23 $M_{\odot}$. Further theoretical work on pulsations in α Boo is needed to derive the periods of radial and nonradial pulsations in α Boo as well as determine which modes are excited.

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## REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Athlone),
Balmforth, N., Gough, D., & Tout, C. 1991, in Lecture Notes in Physics, 388, ed. D. Gough & J. Toomre (Berlin: Springer), 381
Belmonte, J. A., Jones, A. R., Pallé, P. L., & Cortes, T. R. 1990a, Ap&SS, 168, 77
———. 1990b, A&A, 358, 595
Cadmus, R. R., Jr., Willson, L. A., Sneden, C., & Mattei, J. A. 1991, AJ, 101, 1043
Cochran, W. D. 1988, ApJ, 334, 349
Cochran, W. D., & Hatzes, A. P. 1990, in Optical Spectroscopic Instrumentation and Techniques for the 1990s: Applications in Astronomy, Chemistry, and Physics, ed. B. J. McNamara & J. M. Lerner (Proc. SPIE, 1318), 148
Cox, J. P., King, D., & Stellingwerf, R. 1972, ApJ, 171, 93
Di Benedetto, G. P., & Rabbia, Y. 1987, A&A, 188, 114
Hatzes, A. P., & Cochran, W. D. 1992, in High Resolution Spectroscopy with the VLT, ed. M.-H. Ulrich (Garching: ESO), 275
———. 1993, ApJ, 413, 339
Helfer, H. L., & Wallerstein, G. 1968, ApJS, 16, 1

Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Jefferys, W., McArthur, B., & McCartney, J. 1991, BAAS, 23, 997
Mäckle, R., Holweger, H., Griffin, R., & Griffin, R. 1975, A&A, 38, 239
McWilliam, A. 1990, ApJS, 74, 1075
Mozurkewich, D., Johnston, K. J., Simon, R. S., Bowers, P. F., & Gaume, R. 1991, AJ, 101, 2207
Peterson, R. C., Dalle Ore, C. M., & Kurucz, R. L. 1993, ApJ, 404, 333
Roberts, D. H., Lehár, J., & 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,
Wilson, O. C. 1967, in Modern Astrophysics: A Memorial to Otto Struve, ed. M. Hack (Paris: Gauthier-Villars), 241