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LONG-PERIOD RADIAL VELOCITY VARIATIONS IN THREE K GIANTS

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ABSTRACT

Precise relative radial velocities ($\sigma \sim 20$ m s^{-1}) are presented for three K giants: α Tau, α Boo, and β Gem. The data reveal periods of 233 days for α Boo, 643 days for α Tau, and 558 days for β Gem. These periods are much too long to be due to radial pulsations. Currently, the only plausible explanations for these radial velocity variations are that they are due to rotational modulation by surface features (the expected rotation periods for these stars are of order the observed periods), nonradial pulsations, or planetary companions. Orbital solutions to the radial velocity variations yield companion masses in the range of 3 to 12 Jovian masses. However, the fact that all three stars exhibit similar periods and give comparable companion masses suggests that the variability is intrinsic to the star (either rotational modulation or pulsations). Phasing the radial velocity measurements of α Boo and α Tau by Walker et al. to our ephemeris results in a good agreement in both phase and amplitude with our radial velocity data. These long-term variations seem to have been present and coherent for at least the last 10 yr. The period of the relative radial velocity variations for α Boo is identical to the period of He I 10830 Å variations found by Lambert. This indicates that the observed radial velocity variations may be related to the chromospheric heating in these stars. α Boo and α Tau show significant night-to-night changes in the radial velocity of up to 100 m s^{-1}. This indicates the presence of short-term periods. However, the sampling pathology of our data is such that these periods cannot be well determined. β Gem shows no significant night-to-night variations.

Subject headings: binaries: spectroscopic — stars: giant — stars: oscillations

1. INTRODUCTION

Techniques for the measurement of precise relative stellar radial velocities are revealing variability in stars at a level below the detection threshold of more traditional radial velocity and photometric measurement techniques. A recent example of this is the radial velocity variations found in the K giants, many of which are IAU radial velocity standards. The variability of Arcturus was discovered by Smith, McMillan & Merline (1987) using a Fabry-Perot etalon in transmission as a means of providing a precise wavelength reference. Their result was subsequently confirmed by Cochran (1988) who measured stellar radial velocity shifts with respect to telluric O_2 absorption lines. Both investigations revealed variability with about a 2 day period and having a semiamplitude of 200 m s^{-1}. Cochran's data also showed the presence of possible long-term variations on time scales of several hundred days and amplitudes around 400 m s^{-1}. A later study by Irwin et al. (1989) reported long-term variability in the radial velocity variations of α Boo with a possible 600 day period.

Walker et al. (1989; hereafter WYCI) showed that radial velocity variability may be a common phenomenon among K giants. Using an HF absorption cell they obtained precise radial velocities of several K giants over a 6 yr interval and found all of them to be radial velocity variables with amplitudes ranging from 30 to 300 m s^{-1}. The nature of these radial velocity variations is not yet known. The K giants are situated in a region of the H-R diagram separating two classes of known variables: the cooler Mira variables having periods of several hundred days and the warmer Cepheids having periods no longer than tens of days. Both of these classes of objects have rather large (~km s^{-1}) radial velocity variations that are always accompanied by significant photometric variations. It is tempting to speculate that the K giants are merely an extension of these known classes of variable stars. However, before any such comparisons can be made one must establish the extent of variability among K giants and more importantly the amplitudes and periods involved.

In 1987 September we began a program at McDonald Observatory to measure precise relative radial velocities of stars in an effort to detect planetary companions. As an adjunct to this program we have been monitoring a modest sample of K giants. Here we present strong evidence for long-term periodic behavior in the radial velocities of three K giants: α Boo, α Tau, and β Gem.

2. DATA ACQUISITION

Radial velocity data were obtained at McDonald Observatory using two different measurement techniques and two telescopes. The key to making precise radial velocity measurements of stars is to superpose the wavelength standard on the stellar spectrum so that instrumental shifts affect both equally. Initially the McDonald Observatory Planetary Search (MOPS) program utilized the telluric O_2 lines at 6300 Å as a wavelength reference. This technique was originally proposed by the Griffins (1973) with the claim that precisions of about 10 m s^{-1} were possible.

The "telluric" data for the K giants were acquired at McDonald Observatory using the coudé focus of the 2.7 m telescope. An echelle grating was used in single pass along with a Texas Instruments 800 × 800 3-phase CCD. This provided a wavelength coverage of 11.6 Å centered on 6300 Å at a spectral resolution of 0.036 Å (130 μm slit which subtends 2 pixels on the CCD). An interference filter was used to isolate order 36 from the echelle grating. Our experience with this radial velocity technique indicated that for bright stars a nightly precision as high as 10 m s^{-1} was possible and a month-to-month precision of about 20 m s^{-1} was typical. These data have the longest time base of all the data sets.

The main disadvantage of the telluric line technique is that one has no control over the absorbing medium providing the wavelength reference, i.e., the Earth's atmosphere. Pressure and temperature changes in the atmosphere as well as winds ultimately limit the precision of the technique. For these reasons use of an iodine absorption cell began in 1989 October. Steller radial velocities now measured with respect to the iodine spectrum which is superimposed on the stellar spectrum. Molecular iodine was chosen primarily because it is a relatively benign gas with a dense spectrum and it has a high enough vapor pressure so that a relatively short (15 cm long) cell produces sufficient absorption. Also, gaseous iodine has often been employed as a means of providing a stable wavelength reference. Beckers (1973) used an I_2 absorption cell to study motions in sunspot umbrae. More recently the cell has been applied to obtaining stellar radial velocities by several investigators (Libbrecht 1988; Cochran & Hatzes 1990; Marcy & Butler 1992).

The iodine cell used for this work consists of a quartz tube 5 cm in diameter and 15 cm long and sealed at both ends with optical quartz windows. A more detailed description of the cell's construction is given elsewhere (Cochran & Hatzes 1990). The temperature of the cell was controlled to $50° \pm 0.1°$ C.

A limited quantity of "iodine" data was acquired at the coudé foci of the 2.7 m and 2.1 m telescopes. At the 2.7 m telescope the same grating and detector as the O_2 setup were used; however, order 44 of the echelle was utilized so as to provide a central wavelength of 5190 Å and a bandpass of 9.3 Å. The fact that I_2 has only weak absorption features shortward of 5000 Å and longward of 6000 Å necessitated using a bluer spectrograph setting. The spectral resolution was 0.029 Å for a 130 μm slit.

Spectral data were also obtained at the coudé focus of the 2.1 m telescope using a 1200 grooves mm^{-1} grating in second order along with a Tektronix 512 × 512 CCD. This resulted in a dispersion of 0.046 Å pixel^{-1} at the central wavelength of 5520 Å and a spectral bandpass of 23 Å. An 85 μm slit provided a spectral resolution of 0.11 Å.

Data were reduced to radial velocities by using a modified version of the Fahlman & Glaspey (1973) shift-detection algorithm. In this method a "model" spectrum is calculated by shifting and combining a spectrum of a continuum source taken through the I_2 cell with the spectrum of the star taken without the I_2 cell. The rms difference of this model spectrum and the observed spectrum is minimized while varying the shift and linear dispersion of both the pure I_2 and pure stellar spectrum.

It is desirable to have good spectrograph stability when making precise radial velocity measurements. Even though use of an iodine cell compensates for instrumental shifts between separate exposures, instrumental shifts *during* an exposure can produce changes in the instrumental profile and these can introduce significant errors in the radial velocity measurements, particularly at low resolving powers (Marcy & Butler 1992; Hatzes & Cochran 1992). These errors can be minimized by measuring the point spread function (PSF) from the iodine spectrum to take into account any changes in its shape when computing the radial velocity (Marcy & Butler 1992).

As part of the radial velocity survey we observe a fixed region on the lunar surface as a "standard" observation to monitor any systematic errors in the radial velocity measurements. These data show that the month-to-month precision for the telluric radial velocity measurements is about 15–20 m s^{-1}. Radial velocity measurements using the I_2 cell at the 2.7 m coudé show a monthly rms scatter of about 7 m s^{-1}, a significant improvement over the telluric technique. Use of the I_2 cell at the 2.1 m coudé gives lunar radial velocities with a monthly rms scatter of about 20 m s^{-1}. The larger errors for the 2.1 m data is a direct consequence of the lower spectral resolution of the data as well as the poorer mechanical and thermal stability of the older 2.1 m spectrograph. These measurements indicate that the PSF is rather stable from run-to-run so that an accurate modeling of the instrumental profile would result in a marginal improvement in the radial velocity measure. To simplify the data reduction we did not include the PSF modeling in determining the radial velocity shifts.

3. RESULTS

3.1. *Period Analysis*

The radial velocity variations for α Tau, β Gem, and α Boo are shown in Figure 1. The nightly averages of the relative radial velocities are listed in Tables 1A–C. Circles represent data obtained using the telluric O_2 lines as a velocity reference, measurements made with the I_2 absorption cell at the 2.7 m telescope are shown as crosses, and triangles indicate I_2 data obtained at the 2.1 m telescope. These three measurement techniques are each self-consistent, but have different velocity zero points because they are able to measure only relative, not absolute, radial velocities. Therefore, an offset has been applied

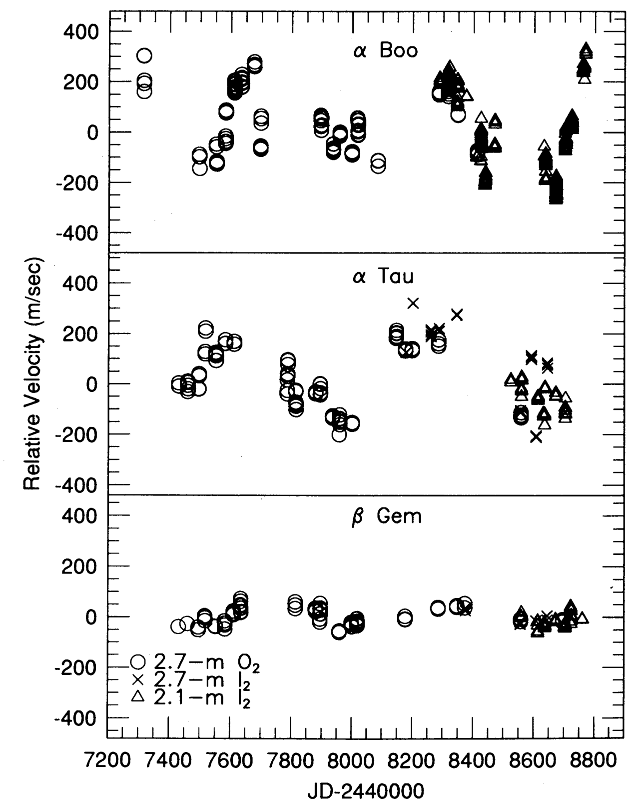

FIG. 1.—The radial velocity variations of α Boo (*top*), α Tau (*middle*), and β Gem (*bottom*). Circles represent measurements using the telluric O_2 lines at 6300 Å as a velocity reference and data taken at the 2.7 m telescope. Velocity measurements made using an iodine absorption cell are shown as crosses for data taken at the 2.7 m telescope and triangles for data taken at the 2.1 m telescope.

TABLE 1A

α BOOTIS RELATIVE RADIAL VELOCITIES
(nightly averages)

Date[a]	V ($m\ s^{-1}$)	Date[a]	V ($m\ s^{-1}$)
313.763	302.5	1318.971	23.5
314.754	185.0	1320.966	201.5
496.028	−93.5	1321.872	196.5
497.022	−144.5	1345.963	117.5
552.020	−52.5	1346.874	188.5
552.989	−122.5	1347.928	70.5
581.947	−30.0	1375.812	140.5
582.946	81.5	1409.734	−98.5
610.757	178.5	1411.728	−79.1
611.762	165.5	1422.786	−107.2
633.840	217.0	1423.669	18.3
634.866	188.5	1424.708	−40.9
675.656	263.5	1436.745	−204.5
696.734	−60.5	1437.665	−186.5
697.818	51.5	1438.660	−150.5
895.009	67.5	1468.702	−57.4
895.011	46.5	1469.686	43.5
895.013	23.5	1631.986	−75.8
895.015	302.5	1636.991	−117.2
895.974	185.0	1638.014	−183.5
897.003	−93.5	1670.924	−254.2
935.880	−144.5	1671.957	−207.1
957.927	−52.5	1672.919	−251.3
958.007	−122.5	1701.868	−46.1
998.868	−30.0	1702.005	−61.3
1016.863	81.5	1703.924	14.0
1017.802	178.5	1704.835	−36.1
1018.809	165.5	1722.787	0.0
1084.758	217.0	1723.885	32.2
1286.033	188.5	1724.000	45.0
1288.021	263.5	1724.671	37.0
1315.997	−60.5	1759.897	247.9
1316.937	51.5	1760.714	245.3
1317.005	67.5	1764.604	250.9
1318.939	46.5	1768.796	318.4

[a] Date = Julian Day − 2,447,000.0.

TABLE 1B

α TAURI RELATIVE RADIAL VELOCITIES
(nightly averages)

Date[a]	V ($m\ s^{-1}$)	Date[a]	V ($m\ s^{-1}$)
429.978	−15.2	1145.993	184.0
430.823	−4.8	1146.996	205.4
459.891	−31.1	1147.000	202.5
459.892	−5.3	1176.963	136.4
460.779	−20.0	1178.941	90.8
495.850	−20.1	1198.995	139.8
496.815	36.3	1200.989	290.4
516.788	124.0	1260.735	171.5
517.811	215.7	1285.768	162.6
551.707	119.5	1287.795	184.3
552.600	101.4	1345.621	242.3
582.659	166.7	1523.903	−29.7
611.609	165.6	1555.973	−151.9
785.980	−15.2	1557.892	−126.9
786.943	−4.8	1558.790	−70.1
787.855	−31.1	1559.893	−18.2
813.936	−5.3	1591.675	70.6
814.898	−20.0	1607.730	−254.9
879.830	−20.1	1613.855	−98.3
894.780	36.3	1631.817	−164.1
895.737	124.0	1635.793	−177.8
935.700	215.7	1636.812	−56.8
957.577	119.5	1644.767	36.9
958.690	101.4	1672.720	−86.3
959.628	166.7	1703.627	−156.9
1000.622	165.6	1704.605	−140.6

[a] Date = Julian Day − 2,447,000.0.

to each data set to remove the different velocity zero points. The agreement between the three data sets is quite good in spite of the fact that they were taken with different spectrograph setups, telescopes, and measurement techniques. All three stars show what appears to be periodic behavior on time scales of several hundred days. The amplitude of these variations are 100 $m\ s^{-1}$ for β Gem, 400 $m\ s^{-1}$ for α Tau, and 500 $m\ s^{-1}$ for α Boo. This is consistent with the results of WYCI who found that the radial velocity variations for β Gem were significantly smaller than those of α Boo and α Tau.

A periodogram analysis using the technique of Scargle (1982) was performed on the data after averaging measurements taken on the same night (Tables 1A–C). Periodograms for the three stars in the frequency range $0 < \nu < 0.01$ $days^{-1}$ are shown in Figure 2. The periodogram from α Boo (Fig. 2 *top*), shows three strong peaks, but with the most power occurring at a period of 233 days. The other peaks lie at periods of 555 days and 313 days. The major peak at 233 days is statistically significant (false alarm probability = 2.9×10^{-6}) using the criteria outlined by Scargle (1982) and Horne & Baliunas (1986). The secondary peaks at 555 and 313 days, however, most likely result from the sampling pathology of the data. Simulations were conducted using sine functions with periods of 555, 233, and 313 days and sampled at the same intervals as the observed data. The

TABLE 1C

β GEMINORUM RELATIVE RADIAL VELOCITIES
(nightly averages)

Date[a]	V ($m\ s^{-1}$)	Date[a]	V ($m\ s^{-1}$)
430.953	−45.9	1285.855	25.4
549.939	−33.7	1287.836	43.6
495.985	−52.5	1345.673	39.1
516.863	−4.5	1347.654	35.0
517.863	−16.5	1373.623	40.5
551.767	−44.3	1375.668	16.5
581.770	−22.7	1555.988	−41.0
582.725	−41.8	1557.966	−19.0
610.701	9.0	1558.916	20.3
611.683	7.4	1559.911	12.8
633.676	36.0	1608.044	−30.9
634.629	60.2	1613.920	−28.1
635.641	17.4	1635.906	−17.6
813.981	−45.9	1636.956	−25.1
879.913	−33.7	1637.932	−26.4
880.882	−52.5	1644.830	−12.3
894.880	−4.5	1644.835	−16.6
895.934	−16.5	1672.760	−4.2
896.926	−44.3	1696.738	−22.8
958.705	−22.7	1701.797	−30.6
998.672	−41.8	1703.739	−29.7
1000.679	9.0	1704.813	−27.2
1016.650	7.4	1722.714	44.9
1017.620	36.0	1723.678	11.2
1018.603	60.2	1724.694	18.9
1176.991	17.4		

[a] Date = Julian Day − 2,447,000.0.

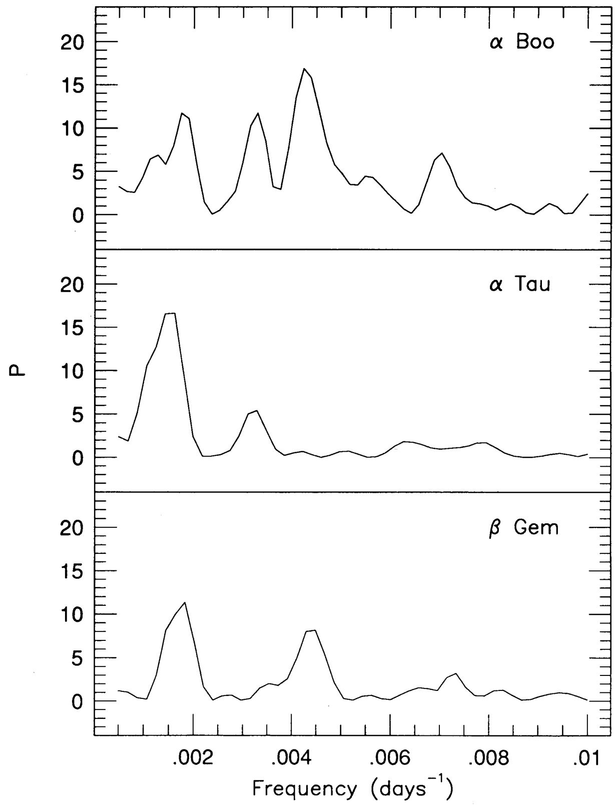

FIG. 2.—Periodograms in the frequency range $0 < \nu < 0.01$ days^{-1} for α Boo (*top*), α Tau (*middle*), and β Gem (*bottom*).

resulting periodogram of the pure sine wave with a 233 day period was the only one able to reproduce all the observed peaks in the periodogram of α Boo. The periodogram of the simulated data, however, had a more dominant peak at $P = 233$ days than the data for α Boo. We therefore conclude that the long-term radial velocity variations of α Boo are consistent with a single period at 233 days.

The power spectrum of α Tau (Fig. 2, *center*) is dominated by a single peak at 654 days (false alarm probability = 3.2×10^{-6}). Simulations using sine functions with a period of 654 and sampled in the same way as the data indicate that the secondary peak at 310 days results from the data window. Most of the power in the periodogram of β Gem (Fig. 2, *bottom*) is concentrated in a strong peak at 562 days (false alarm probability = 6.2×10^{-4}) and a slightly weaker peak at 222 days. Once again simulations using a pure sine wave with a 562 day period indicate that the weaker peak results from the sampling window.

A period search on the unaveraged data was also conducted using the phase dispersion minimization (PDM) algorithm of Stellingwerf (1978). This algorithm is better suited to finding periodicities in data having nonsinusoidal variation. Figure 3 shows the θ (phase dispersion) versus period plot resulting from the PDM analysis for the three stars in this study. Possible periods in the data manifest themselves as small values of θ. The θ-plot for α Tau is characterized by a single deep, broad minimum around 630 days, whereas the one for β Gem shows a very broad minimum centered around 554 days. There is also a narrow, shallower minimum near 225 days which may just be a harmonic of the longer period.

The θ-plot for α Boo appears to be more complicated than for the other stars. The deepest, narrowest minimum is at 230 days and another broader minimum near 460 days. Again, one of these periods may also be a harmonic of the other. Also there is another local minimum near 585 days and a shallower minimum around 135 days.

The complex structure seen in the θ-plots for α Boo and β Gem makes it difficult to determine which periods are actually present in the data. This complexity may be due to a combination of effects: there is a large amount of scatter in the radial velocity measurements (up to 100 m s^{-1}) that is intrinsic to the star, a finite data window that extends for less than 2 periods for β Gem and α Tau, as well as the sampling pathology of the measurements. The deepest minima in the θ-plots are consistent with periods determined from the periodograms.

3.2. *Comparison to Other Measurements*

Radial velocity measurements have been made for α Boo by WYCI and Cochran (1988). The radial velocity data for α Boo from the top panel of Figure 1 have been phased according to the ephemeris 2,447,298.619 + 233*E* and are shown as crosses in Figure 4. The WYCI data phased to the same ephemeris are shown as circles and the Cochran data are represented by triangles. There is good agreement in phase and amplitude between all data sets. Keep in mind that the "effective" error bar for the individual points is about 100 m s^{-1} since α Boo exhibits night-to-night variations of this magnitude. The WYCI data covers the time span 1981–1986, the Cochran data the period 1986–1987, and the data of this work 1988–1991. Thus the 233 day period in the radial velocity variations seems

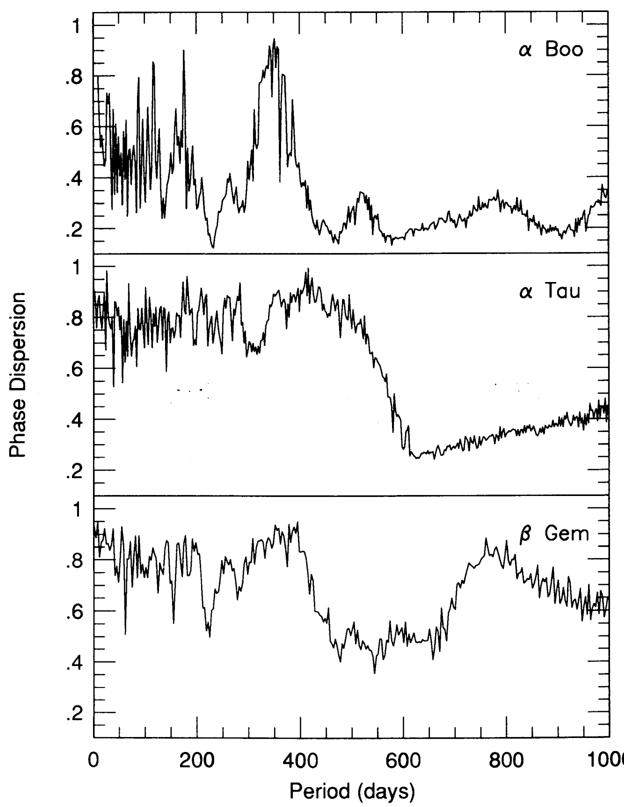

FIG. 3.—The phase dispersion minimization θ-diagram for α Boo (*top*), α Tau (*middle*), and β Gem (*bottom*). Minima represent possible periods in the data sets.

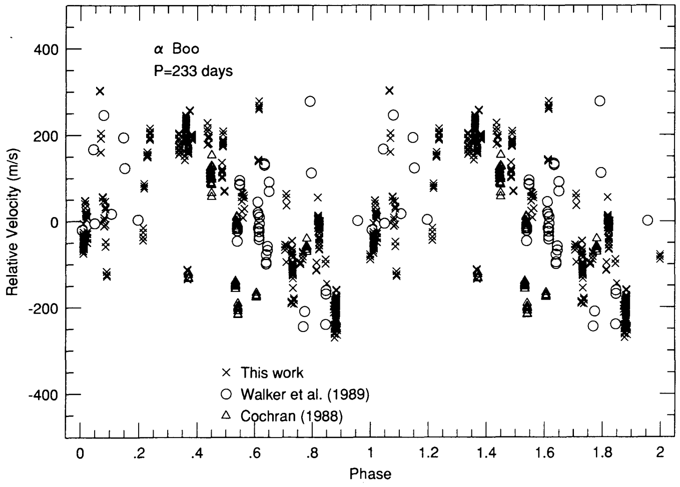

FIG. 4.—The radial velocity data of α Boo phased to a period of 233 days. Crosses represent the measurements of this work, circles the data of WYCI, and triangles the measurements of Cochran (1988).

to have been present for at least 10 yr and with the same amplitude and phase.

Irwin et al. (1989) reported a 640 day or longer period in the radial velocity variations of α Boo which is close to the 585 day period resulting from the PDM analysis. However, phasing the data to this period results in a phase-velocity diagram with considerably more scatter. Also the WYCI data appear to be almost 180° out of phase with our data when using the longer period. Although we cannot firmly establish that the 585 day period is not present (there is a pseudosinusoidal variation evident in the phase diagram calculated with this period), the fact that the 233 day period provides the best phasing of the two data sets makes us more confident that it is the only long-term period (> 100 days) present in the data.

WYCI also obtained radial velocity measurements for α Tau and β Gem during 1981–1986. The α Tau measurements phased to the ephemeris 2,447,498.643 + 643E are shown as solid circles in Figure 5. The revised period results from a periodogram analysis on the combined data sets. The phased radial velocity measurements of our study are indicated by the crosses. Again, the agreement in phase and amplitude between the two measurements is quite good. As in α Boo the long period in the radial velocity variations of α Tau is long-lived and coherent.

The WYCI data for β Gem are shown as circles and our data are shown as crosses in Figure 6. Both data sets have been phased to the ephemeris 2,447,613.381 + 558E. Once again the revised period results from a periodogram analysis on all the data. The agreement with the McDonald data, although not as good as for α Boo and α Tau, is still good. The WYCI data for β Gem are more sparse than for the other two stars so it is difficult to tell if the 558 day period is also present in their data. Note that the amplitude of the variations have not changed significantly over the last 10 yr. More recently, Larson et al. (1983) found a 585 day period in the radial velocity variations of β Gem.

3.3. *Nature of the Long-Period Variations*

3.3.1. *Hypothetical Stellar Companions*

The period analysis for the three stars indicate the presence of 200–600 day periodic variations in the relative radial velocities. Such long-term variations can arise from a number of phenomena: (1) the presence of low-mass companions, (2) radial or nonradial pulsations, or (3) the rotational modulation by surface features (e.g., spots, plage). To test whether the gravitational influence of a companion is a viable explanation of the radial velocity variations, orbital solutions were made on the data sets (not including the WYCI and Cochran sets) near the periods indicated by periodograms. The orbital solutions for the three stars are shown as lines in Figure 7. The individual data points (*crosses*) are also shown phased to the period of 231 days for α Boo, 654 days for α Tau, and 554 days for β Gem. Orbital solutions were also found for α Boo near 585 days and for β Gem near 225 days, but these resulted in higher residuals in the $O-C$. The solutions presented are thus the "best" solutions.

Table 2 shows the final orbital parameters for the three K giants. Note the rather small mass function for each system. The stellar masses range from 2.5 to 4 $M_\odot$ (see Table 3). If one assumes that the companion mass is negligible compared to the primary mass, then one derives secondary masses in the

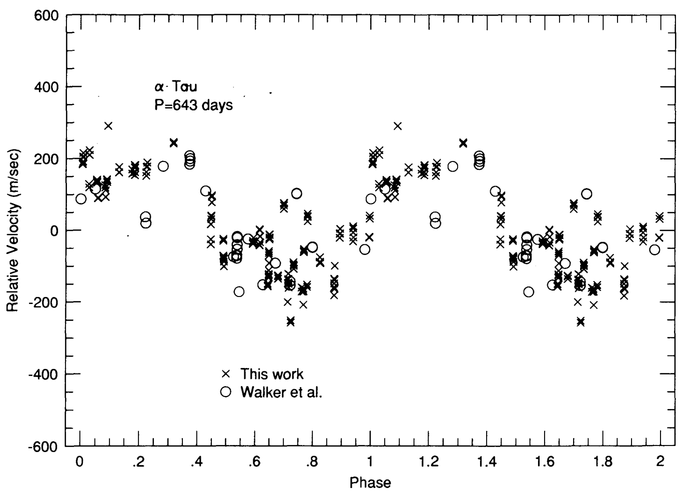

FIG. 5.—The radial velocity data of α Tau phased to a period of 643 days. Crosses represent the measurements of Fig. 1 and circles the measurements of WYCI.

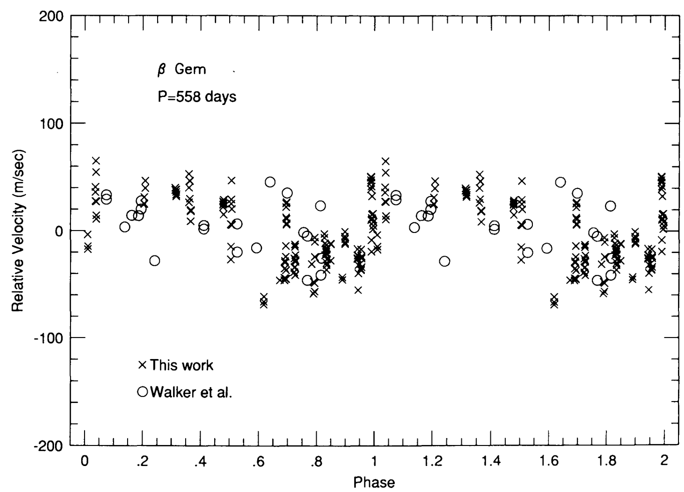

FIG. 6.—The radial velocity data of β Gem phased to a period of 558 days. Crosses are from this work and circles are the measurements of WYCI.

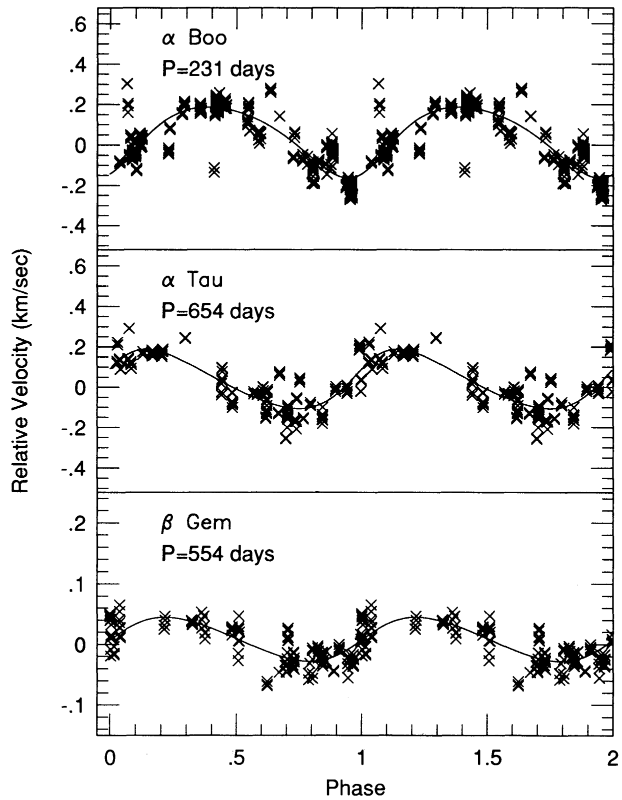

FIG. 7.—Orbital solutions (*lines*) to the radial velocity data (*crosses*) for α Boo (*top*), α Tau (*middle*), and β Gem (*bottom*).

range of 3 to 12 Jupiter masses. If true, then it would seem that planetary companions around K giants have been detected. Although this hypothesis cannot be excluded, it seem improbable that all three stars would have planets with similar masses and periods unless planet formation around the progenitors to K giants was an ubiquitous phenomenon.

3.3.2. *Radial Pulsations*

Radial velocity variations may also arise from radial pulsations. Cox, King, & Stellingwerf (1972) gave a fitting formula for the period of the fundamental and first two harmonics for radial pulsations as a function of stellar mass and radius. The radii and masses for these stars as well as the periods (in days) for the fundamental and first two harmonics of radial pulsation are listed in Table 3. The radii for β Gem and α Tau come from lunar occultation measurements (Mozurkewich et al. 1991) while the radius determined by Di Bendetto & Rabia (1987) was used for α Boo. These radii, along with log g values determined by McWilliam (1990), were used to derive a mass for each star. The fundamental radial modes for these stars have periods ranging from 0.6 to 8.6 days and those of the harmonic modes are even less. Since these are at least two orders of magnitude smaller than the observed period, radial pulsations can be eliminated as a cause for the long-period radial velocity variations. If pulsations are responsible for the observed variations, then they must be nonradial in nature. Note, however, that the 1.84 day period in the radial velocity variations of α Boo claimed by Smith et al. (1987) is near the calculated period for the first harmonic radial mode.

One can also exclude radial pulsations as the mechanism for the radial velocity variations after integrating the radial velocity curve to determine the change in radius for the three stars and consequently the expected photometric variations. The percent change in the stellar radius is 8% for α Boo, 11% for α Tau, and 14% for β Gem. If one assumes a constant effective temperature during the pulsation cycle, then the concomitant photometric variations should thus be large (several tenths of a magnitude) and easily detectable. So far, no such brightness variations have been reported for these stars although there is one unconfirmed report of α Tau changing its brightness by almost 0.06 magnitudes over a 20 day time span (Blanco & Catalano 1970).

TABLE 2

IMPLIED ORBITAL PARAMETERS

Star	Period (days)	e	$f(m)$ ($M_\odot$)	$a \sin i$ (AU)	Companion Mass (Jovian masses)
α Boo	231 ± 1	0.147	1.19×10^{-7}	1.1	11.7
α Tau	654 ± 10	0.147	2.05×10^{-7}	2.0	11.4
β Gem	554 ± 8	0.124	2.68×10^{-9}	1.9	2.9

TABLE 3

EXPECTED RADIAL PULSATION PERIODS

Star	R(km)	$M(M_\odot)$	P_f(days)	P_{1h}(days)	P_{2h}(days)
α Boo	1.70×10^7	3.4	2.4	1.8	1.4
α Tau	2.93×10^7	2.5	8.56	5.30	3.8
β Gem	6.53×10^6	2.8	0.57	0.42	0.34

3.3.3. *Rotational Modulation*

Surface features such as spots or plage can create asymmetries in the spectral line profiles that change as the star rotates. This would be detected as a radial velocity variation with the rotation period of the star. One can test this hypothesis by obtaining an upper limit on this rotation period determined from the star's projected rotational velocity and radius. If the periods of the radial velocity variations are much larger than this maximum rotation period, then rotational modulation by surface features can be excluded as an explanation for the radial velocity variations.

The projected rotational velocity, V, was measured for each star using the Fe I 6302.5 Å line. Model atmospheres from Bell et al. (1976) were used along with Kurucz's WIDTH5 routines to generate a set of specific intensity profiles. These were integrated over a grid of 1600 elements representing the stellar disk. The standard radial-tangential prescription for the macroturbulent velocity, M, was employed. The integrated synthetic profile was then compared to the observed profile in wavelength space. A precise measurement of V and M would entail a multiline approach including both strong and weak lines in the analysis as well as the use of Fourier techniques (e.g., Gray 1982). In this work, however, we are mainly interested in a range of possible values for V to see if these are consistent with rotational modulation by surface features as a cause for the radial velocity measurements.

The "best" values for the projected rotational velocities and macroturbulent velocities (in km s^{-1}) are α Boo: $V = 2.75$, $M = 4.3$, α Tau: $V = 2.3$, $M = 3$, β Gem: $V = 1.5$, $M = 3$. At such low rotational velocities macroturbulence and rotation contribute equally to the spectral line broadening. A slight decrease in one parameter can be compensated by an increase in the other such that a good fit to the observed spectral line is

TABLE 4

ROTATIONAL PERIODS

Star	V (km s^{-1})	M (km s^{-1})	Maximum P_{rot}(days)
α Boo	$1.5 < V < 3.7$	$3.3 < M < 5.3$	600 ± 300
α Tau	$2.5 < V < 4.0$	$1.5 < M < 3.3$	1000 ± 400
β Gem	$0.7 < V < 2.5$	$2.5 < M < 3.5$	400 ± 220

still obtained. Table 4 shows the range of possible values for V and M that still provide an adequate fit to the observed profiles. Keep in mind that a low value of V accompanies a high value of M. The projected rotational velocities for two of the stars in our sample were also determined by Gray (1982) who found $V = 2.4$ km s^{-1}, $M = 4.8$ km s^{-1} for α Boo and $V = 2.5$, $M = 4.2$ km s^{-1} for β Gem. Smith & Dominy (1979) found values of $V = 2.7 \pm 0.5$, $M = 3.2 \pm 0.4$ km s^{-1} for α Boo, $V = 2.7 \pm 0.2$, $M = 3.3 \pm 0.5$ km s^{-1} for α Tau, and $V = 0.8 \pm 1$, $M = 3.3 \pm 1$ km s^{-1} for β Gem. All of these values are consistent with the values determined in this study.

Also listed are the maximum values of the rotation periods and their uncertainties resulting from the range of V values. Since the true rotational velocity can be larger by a factor of $(\sin i)^{-1}$, where i is the unknown inclination of the star, the actual rotation periods can be considerably less than this. The derived periods from the radial velocity variations are all comfortably less than maximum rotational period for the respective star, with the marginal exception of β Gem. The best value of V for this star yields a rotation period of 316 days, far below the radial velocity period of 558 days. However, only a slight decrease in V to 0.8 km s^{-1} (within the errors of the measurement) makes both periods consistent. Therefore, we conclude that the projected rotational velocities of these stars cannot be used to eliminate the rotational modulation hypothesis as a viable explanation for the radial velocity variations.

3.4. *Other Long-Period Variations*

A search was made for the presence of other long-term variations ($P > 10$ days) in the data set by searching for periods in the residuals of the data produced after subtracting the dominant component to the variations. No significant periods were found in the residuals for either α Tau or β Gem. A possible period of 46 days with an amplitude of 50 m s^{-1} was found in α Boo. The residuals phased to this period are shown in Figure 8. The reader is cautioned that the presence of this period is uncertain. Even though the amplitude is at least a factor of 2 greater than the typical errors in the individual points, it is still less than the scatter (due to intrinsic short term variability) of the measurements.

3.5. *Short-Term Variations*

The scatter of the data points about the mean phase-velocity curve for α Boo and α Tau is significantly greater than the typical errors of the individual points (about 20 m s^{-1}). The scatter is clearly intrinsic to the stars. Both α Boo and α Tau show night-to-night variations as large as 100 m s^{-1}. Such large, short-term variations with a period of 1.84 days have been seen in α Boo by Smith et al. (1987) and Cochran (1988). Beta Gem, on the other hand, has an rms scatter of about 20 m s^{-1} about the mean phase-velocity curve which is comparable to the size of the measurement errors.

These short-term variations are best seen as a histogram of the observed changes in the radial velocities (ΔV_r) for consecutive night observations. If there are no short-term variations, then most of the histogram entries would cluster near the value of $\Delta V_r = \pm 20$ m s^{-1}. These histograms are shown in Figure 9 for α Boo (*top*), α Tau (*middle*), and β Gem (*bottom*). Both α Tau and α Boo show consecutive night changes in the radial velocity up to 100 m s^{-1}. Although β Gem can show night-to-night changes in the radial velocity of as much as 50 m s^{-1}, most values are peaked near $\Delta V_r = \pm 20$ m s^{-1}. We therefore conclude that our data for β Gem show no significant short-term variations on time scales of a few days.

A period search in the range $0.1 < P < 10$ days was also performed on the residual velocity measurements after removal of the long-period trends. No significant periods were found in this range for either of the stars. In the case of α Boo no significant power was found at either the 1.84 day period

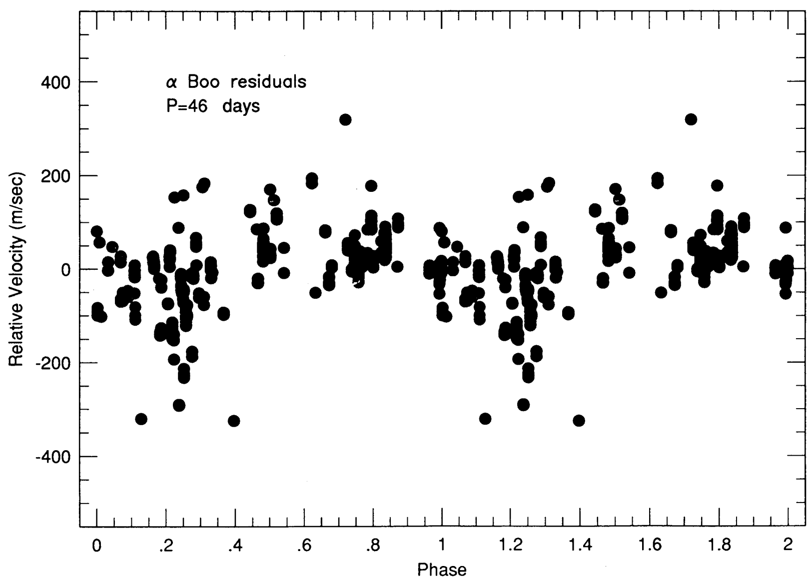

FIG. 8.—The α Boo radial velocity residuals (after removal of the 233 day period) phased to the period of 46 days

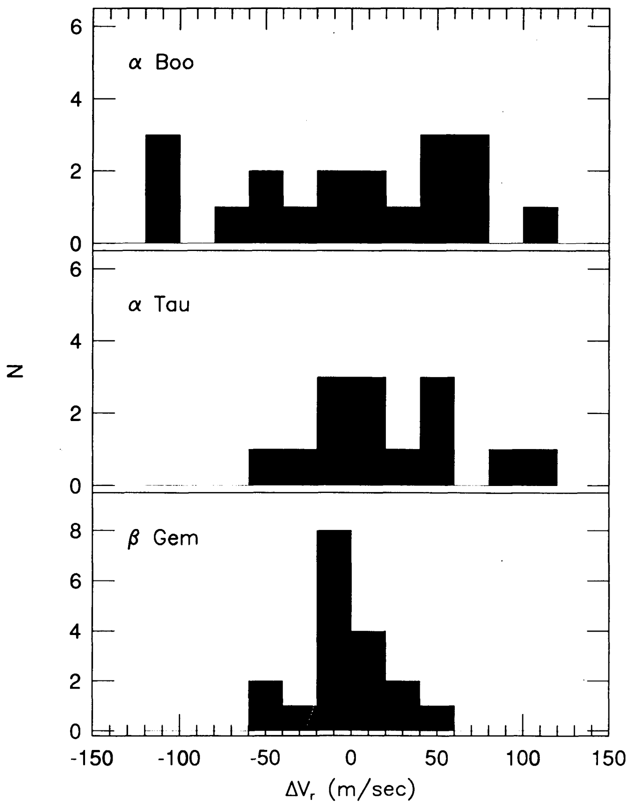

FIG. 9.—Histogram of the night-to-night ($\Delta t \sim 1$ day) changes in the radial velocity (ΔV_r) for α Boo (*top*), α Tau (*middle*), and β Gem (*bottom*).

reported by Smith et al. (1987) or the 2.7 day period found by Belmonte et al. (1990). This suggests that these periods may not be stationary. Perhaps this is why Belmonte et al. did not detect a 1.8 day component to the radial velocity variations of α Boo in spite of 10 consecutive nights of observations. If these short-period components are indeed transient, then they would not have been detected with our sampling window.

4. DISCUSSION

At the present time only radial pulsation can be eliminated as an explanation for the radial velocity variations for these three K giants. The exciting possibility that the variations are due to the presence of planetary companions should be treated cautiously. Campbell, Walker, & Yang (1988) in their radial velocity survey of solar-type F–K stars found that Jovian-sized companions were not common around these stars. This result has also been confirmed by the McDonald Observatory planetary program (Cochran & Hatzes 1993). It therefore seems suspicious that in small sample of K giants, all were found to have Jovian-sized companions. The progenitors to the K giants, however, are A-type stars, objects excluded from most planetary search programs. It is possible that planetary companions are common around A stars; however, a radial velocity survey of these stars is truly needed to confirm this. Unfortunately, A stars are poorly suited for radial velocity surveys. Their spectra have a paucity of stellar lines which are often shallow and broadened due to stellar rotation. Also other variable phenomena such as pulsations (δ Scuti stars) as well as magnetic and spectral variables can be found among the A stars, and these could mask any radial velocity variations due to low-mass companions. The low-mass companion hypothesis does provide a natural explanation for the apparent long-lived variations (in phase and amplitude) found in α Boo and α Tau.

Rotational modulation is also a viable hypothesis since the derived periods fall within the expected rotational periods for these stars (Table 4). Further evidence for this is offered by the He I 10830 Å variations. This line is formed in the chromosphere of the star and thus can be an indicator of magnetic active regions. A survey of the He I line in a sample of K giants by Lambert (1987) revealed strong variability of this feature in α Boo with a period of 233 days, the same period as the radial velocity variations. Lambert assumed that the He I variations were due to the presence of active regions and that the 233 day period reflected the rotation period of the star. If this is the case then the long-term radial velocity variations may well be due to rotational modulation by a surface feature, possibly even due to the stellar active regions responsible for the He I variability. If, in fact, the radial velocity variations were due to the presence of a companion, then the orbital period would have to be the same as the rotational period. Rotational modulation as a cause of radial velocity variations has been suspected for another K giant. Walker et al. (1992) reported radial velocity variations with a period of 2.7 yr in the K0 III star γ Cep, which is comparable to the periods found in the giants of this work. These variations were accompanied by equivalent width variations in the Ca I 8662 Å line. They concluded that this long period represented the rotation period of the star.

There are arguments, however, against rotational modulation being the cause of the radial velocity variations in the three stars of this work. First, β Gem shows radial velocity variations, and yet Lambert found that the He I emission in this star was constant. Conceivably the constant He I emission may be due to a uniform distribution of active regions across the star. These, however, would produce very small radial velocity variations (although the amplitude of the variations for β Gem are the smallest of the three stars). However, Larson et al. (1983) recently found evidence for periodic chromospheric emission in β Gem with the same period as the radial velocity variations. This would lend support to the rotational modulation hypothesis.

The radial velocity measurements of WYCI and Cochran (1988) along with the ones of this work indicate that the mechanism responsible for the radial velocity variations in α Tau and α Boo have been present for the past 10 yr. This suggests that any surface features responsible for the radial velocity variations are long-lived and have not migrated from their initial location on the stellar surface. Such long-lived features in the form of starspots have been encountered in RS CVn stars, but one would expect changes in both the amplitude and possibly the phase of the variations as active regions decay and new ones emerge, presumably at different locations on the star.

It is also unlikely that surface features in the form of plage are responsible for the radial velocity variations in these stars. On the Sun, plage are visible only in chromospheric lines such as (Hα, Ca II H and K) and they are virtually invisible in photospheric lines. The radial velocity variations are present in roughly the same amplitudes in three different wavelength regions so we can presume that all photospheric lines are equally affected. It seems unlikely, therefore, that the radial velocity variations can be due to plage. The presence of dark spots, however, can affect most photospheric lines and if they cover enough of the stellar surface, then they would create line asymmetries which would manifest themselves as radial velocity variations. The expected photometric variations on these stars depend on the size of the spots and their temperature. The amplitude of the radial velocity variations, however, suggests that these spots would be large enough to produce photometric variations detectable by conventional differential photometry. Photometric studies on these stars are sparse, but all are believed to be photometrically constant. Long-term photometric monitoring of these stars should establish if spots are responsible for the radial velocity variations.

If surface features related to stellar activity were responsible for the radial velocity variations in α Boo, then one would also expect to see equivalent width variations, particularly in temperature-sensitive lines. Irwin et al. (1989) measured the equivalent width of Ca II, Si I, Ti I, and Fe I spectral lines in α Boo and found that the changes were less than a few percent. They concluded that the temperature change of the star over the visible hemisphere was less than 25 K. It is difficult to reconcile these measurements with the hypothesis that cool/hot spots on the surface are causing the radial velocity measurements.

Alternatively, the hypothetical surface features responsible for the radial velocity variations may not be the classical spot/plage regions but an unknown phenomena. For example, Toner & Gray (1988) have reported finding a "starpatch" on ξ Boo A. This patch represents a velocity rather than a brightness inhomogeneity caused by the macroturbulent velocity in the patch being different than in the surrounding photosphere. This creates measurable line asymmetries and radial velocity variations. If the radial velocity variations are due to such patches (or cool spots), we should expect to also see changes in the spectral line shapes. The resolution of our data is high enough so that a detailed analysis of the spectral line shapes may establish such variability. Such an analysis is currently in progress and will be presented at a later date.

If, on the other hand, the radial velocity variations are due to pulsations, then the fact that the He I 10830 Å emission varies with the same period suggests that the chromospheric heating in α Boo may not be due entirely to magnetic activity. Cuntz & Luttermoser (1990) argued that stochastic shocks produced by short-period acoustic waves could provide a mechanism for forming the He I 10830 Å line. However, this mechanism requires rather short period waves ($\sim$4 hr). If the He I line strength is to modulated with the 233 day period seen in radial velocities of α Boo, then the long-period pulsations must somehow influence the shorter period acoustic waves responsible for the He I 10830 Å formation. Cuntz (1990) also proposed that long-period waves could drive the mass loss in the K giants. The periods required, however, are of order days which is at least two orders of magnitude less than the observed long-term periods. These periods, on the other hand, are near the observed short-term variations seen in α Boo and α Tau.

The star with the lowest radial velocity amplitude, β Gem, also has virtually no night-to-night variations. Intriguingly, this star shows constant He I 10830 Å (Lambert 1987). By contrast, α Boo has the largest amplitude radial velocity variations, the largest and most frequent night-to-night changes, as well as the presence of multiperiods (e.g., the 46 and 1.8 day periods). Lambert (1987) found that α Boo had large and rapid He I variations. This along with the 233 day period in both the radial velocity and He I equivalent width variations would seem to indicate that the variations of both these quantities are intimately related. If the radial velocity variations are due to pulsation phenomena, then these stars may represent an ideal laboratory for studying nonmagnetic heating of chromospheres. A detailed study of the correlation of the He I variations with the radial velocity variations should help establish what role, if any, the observed radial velocity variations have in heating the chromospheres in giant stars.

The detection of a possible 46 day period in α Boo may also be important. Kemp et al. (1986) reported intrinsic variable polarization with an amplitude of 0.005% and a possible period of 45 days. The amplitude of the radial velocity and polarization variations phased to this period are sufficiently small as to cast some doubt on their reality. But the fact that both measurements may be detecting the same period makes it more difficult to dismiss these variations as instrumental in origin. Further, high-precision polarimetric data on these stars would confirm if variable polarization is common in these stars and their relationship to the radial velocity variations.

In a recent study of the duplicity in late-type stars Duquennoy & Mayor (1991) found evidence for long-period variations in five K and M giants. Interestingly, two M giants and one K giant had derived periods of about 500 days and with amplitudes ranging from 0.7 to 1.5 km s^{-1} These periods are comparable to those of the K giants in our investigation. It may well be that long-term radial velocity variations are an ubiquitous phenomenon in K giants, and, if so, one should be cautious about attributing them to the presence of low-mass companions, as did Duquennoy & Mayor.

If the radial velocity variations are due to stellar pulsations, then the long periods observed in the K giants suggest that they are more closely related to the Miras and M supergiant variables than the classical Cepheids. In a study of radial velocity variations in three M supergiants, Smith, Patten, & Goldberg (1989) found periods of $\sim$400 days for α Ori and $\sim$260 days for α Sco. These periods are comparable to the periods seen in the K giants. Maeder (1980) found that supergiants across the H-R diagram have periods systematically longer than the theoretical Q value for the fundamental mode of radial pulsations. He suggested that the variations are due to the excitation of g^{-1} modes by rotation (Ledoux 1967, 1969). These modes, which are associated with convective instability, correspond to dynamical instability and should not produce periodic motions. However, rotation provides an extra restoring force and a periodic motion may result. An interesting consequence of this hypothesis is that the pulsation period is proportional to the rotation period.

In a discussion on the excitation of g^{-1} modes in M giants, Smith et al. (1989) pointed out that horizontal displacements in M supergiants should be small. The ratio of vertical to horizontal displacements is proportional to the square of the dimensionless frequency (Cox 1980). For M supergiants as well as K giants this value is small. Since horizontal motions dominate, the expected photometric variations should be small and difficult to measure. The photometic variations of these stars would thus be small or undetectable if nonradial pulsations are indeed present.

5. SUMMARY AND CONCLUSIONS

We have demonstrated the presence of long-period variations in the relative radial velocity of three K giants. These periods are much too long to be due to radial pulsations. In two of these stars, α Boo and α Tau, these variations seem to have been present at the same amplitude and phase for at least

10 yr. Orbital solutions to the radial velocity variations of the three stars yield companion masses in the range of 3 to 12 Jovian masses. Alternatively, these variations may be due to nonradial pulsations, but theoretical work on pulsating K giants is needed to confirm this. Rotational modulation by some form of surface feature can also explain the radial velocity variations since the rotation period for these stars is expected to several hundred days. If this is the case then these may also be accompanied by photometric variations. A long-term photometric study of these stars to search for such variability may prove useful.

The K giants show variability in Ca I H and K emission (Gray 1980), He I 10830 Å emission (Lambert 1987), and polarization (Kemp et al. 1986). The precise relationship between these forms of variability and the radial velocity variations is unknown. In the case of α Boo the long-period radial velocity variations is identical to that found in the He I emission. The possible 46 day period in α Boo is near the period of reported polarization variability in this star. It seems that the radial velocity variability is indeed related to the other forms of variability.

Two of the stars in this work show significant night-to-night variations. The expected period of radial pulsations in these stars is on the order of days so this short-term variability may be due to radial pulsations. In particular, the 1.84 day period reported by Smith et al. (1987) is near the period of the first harmonic radial mode. Clearly a detailed study of the short-term variability is needed to determine the actual periods present.

It may be that radial velocity variability is an ubiquitous phenomena in K giants although the number of such known variables is small. We are conducting a survey on a larger sample of K giants to see to what extent such variability is present in such objects and if other K giants show such long period variations.

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