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The Puzzling K and Early-M Giants: A Summary of Precise Radial Velocity Results for 15 Stars

Ana M. Larson

Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195

Stephenson L. S. Yang

Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, B.C. V8W 3P6, Canada

Gordon A. H. Walker

Department of Geophysics and Astronomy, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada

Abstract. Nearly a decade ago, "yellow giants" were introduced as a new class of low-amplitude radial-velocity variable stars. In this report we discuss new results for 12 spectral type K and early-M giants based on long-term monitoring using both the hydrogen-fluoride and iodine-cell techniques. We compare these results with those of published data for 3 additional stars (γ Cephei, β Geminorum, and β Ophiuchi), and discuss possible implications for the underlying physical mechanism(s).

1. Introduction

Yellow giants were first introduced as a new class of low-amplitude radial-velocity variable stars by Walker et al. (1989). Since then, observational evidence for low-amplitude ($30 \leq K \leq 600$ m s^{-1}) variability in the differential velocities of K giants has continued to grow. In 1991, as the observations at the Canada-France-Hawaii telescope (CFHT) were concluding (see Walker et al. 1995), the hydrogen-fluoride (HF) program was installed at the Dominion Astrophysical Observatory (DAO). The observations of K and M giants and supergiants at the DAO expanded upon the CFHT observations. In this report, we summarize our results for the evolved stars from CFHT observations (see also Irwin, VandenBerg, & Larson 1999) and our results for some of the evolved stars observed at the DAO (see also Yang, Walker, & Larson 1999). Table 1 lists the stars discussed in this report and includes both new and previously published results. The stars are listed in order of increasing standard deviations of the radial velocities (Col. 4).

2. The HF technique and $\Delta EW_{866.2}$ index

Campbell and Walker (1979), Campbell et al. (1986), and Walker et al. (1995) describe the HF absorption-cell technique and the associated reduction procedure for obtaining precise radial velocities. Larson et al. (1993a) give the derivation of the chromospheric emission index, $\Delta EW_{866.2}$, and the method used to determine its internal errors. The $\Delta EW_{866.2}$ index is used only in the analyses of the CFHT stars. The DAO spectra contain low-level fringing and fixed-pattern noise which make this index unreliable for these data. The CFHT data have had run corrections applied; the DAO data have not. The run corrections are described in Larson et al. (1993b). The method we use to determine the presence of significant (> 99% confidence level) periods is given in Irwin et al. (1989), Larson et al. (1993b), and Walker et al. (1995).

Table 1. Summary of the K and early-M Giants

HR*	Star	SpT	σ_{RV} m s^{-1}	P$_1$ dy	K$_1$ m s^{-1}	P$_2$ dy	K$_2$ m s^{-1}
7948	γ^2 Del	K1 IV	15	526.0	12.0		
6603	β Oph	K2 III	20	142.0	30.0	13.0	75.0
8974	γ Cep	K0 III	27	923.0	27.0		
0617	α Ari	K2 IIIab	31				
2990	β Gem	K0 IIIb	33	585.0	46.0		
4301	α UMa	K0 IIIa	40	138.0	33.0		
0168	α Cas	K0 III	45				
6859	δ Sgr	K2.5 IIIa	47			5.4	51.0
6705	γ Dra	K5 III	70				
5563	β UMi	K4 III	78	548.0	104.0		
1457	α Tau	K5 III	115	651.0	124.0	1.8	32.0
3748	α Hya	K3 II-III	115	848.0	128.0		
5340	α Boo	K1.5 III	152	294.0	134.0	33.0	116.0
0152	HR 152	K5-M0 III	170				
0337	β And	M0 IIIa	201	715.0	323.0		

* HR 152: I_2 data from Lick Observatory; HR 6859: includes I_2 data from McDonald Observatory; HR 2990: Larson et al. 1993b; HR 6603: Hatzes and Cochran 1996; HR 8974: Walker et al. 1992; HR 5340: the two periods are aliases.

3. Notes on individual stars

HR 7948: One component of a K1 IV – F8 V binary, γ^2 Delphini has a marginally significant signal in its radial velocities corresponding to a 526-dy period (see Fig. 1 and Table 1). Irwin et al. (1999) discuss this binary in detail.

HR 617: Significant long-term variability for α Arietis was first noted in Walker et al. (1989). However, the current analysis (see Fig. 1) shows that the variability is not periodic. In his search for short-term (≈ 2-dy) Arcturus-like

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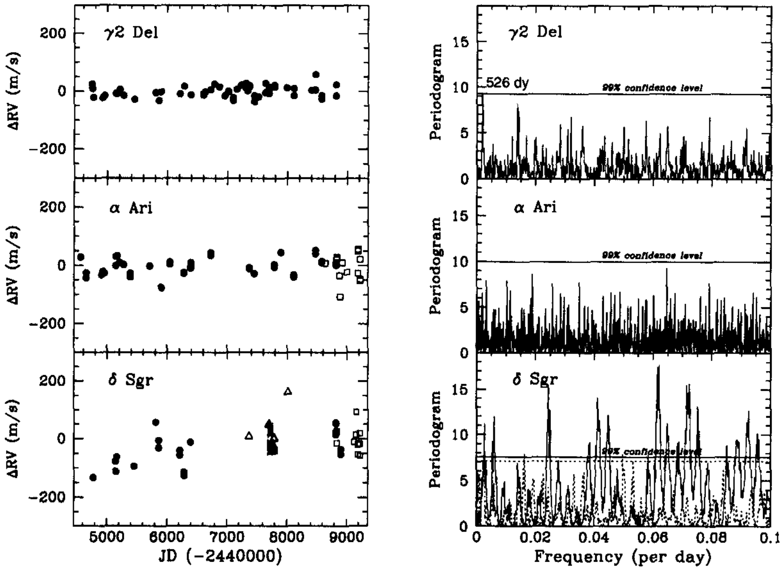

Figure 1. Results for γ^2 Del, α Ari, and δ Sgr. Solid points are CFHT data; open squares, DAO data; open triangles and 5-pt stars, McDonald Observatory data for δ Sgr (51 observations between JD 2 447 600 and JD 2 447 850). The dotted line for δ Sgr is the periodogram having the period given in Table 1 as part of the parent function (see text).

pulsation, Horner (1996) sampled this star extensively over a 10-dy period; no periods of 10 days or less were found.

HR 6859: Fig. 1 shows the CFHT and DAO data for δ Sagittarii obtained using the HF technique, and the McDonald Observatory data obtained using the I_2 technique. The star was observed intensively between JD 2 447 600 and JD 2 447 850 at the McDonald Observatory. Because we had adequate sampling to constrain short-term aliasing, we searched for periods as short as one day for this star. The most significant frequency corresponds to a period of 5.3581 ± 0.0008 days. Because of limited space here, however, we show only those frequencies corresponding to periods greater than 10 days.

The solid line in Fig. 1 for δ Sgr is the periodogram with a linear parent function; the dotted line, the linear parent function and the 5.36-dy sinusoidal solution. One notes that all of the significant frequencies are aliases of the 5.36-dy period – the significance of the peaks is dramatically reduced when the periodic solution is included. Similar results were found for frequencies greater than 0.1 dy^{-1}.

Does the 5.36-dy period represent radial pulsation? Using rather uncertain values for parallax, luminosity, mass, and radius, and the empirical relationships given in Cox, King, & Stellingwerf (1972), formulae which are applicable to stars with radiative envelopes, we derive a fundamental period of $\Pi_0 \approx 7$ days.

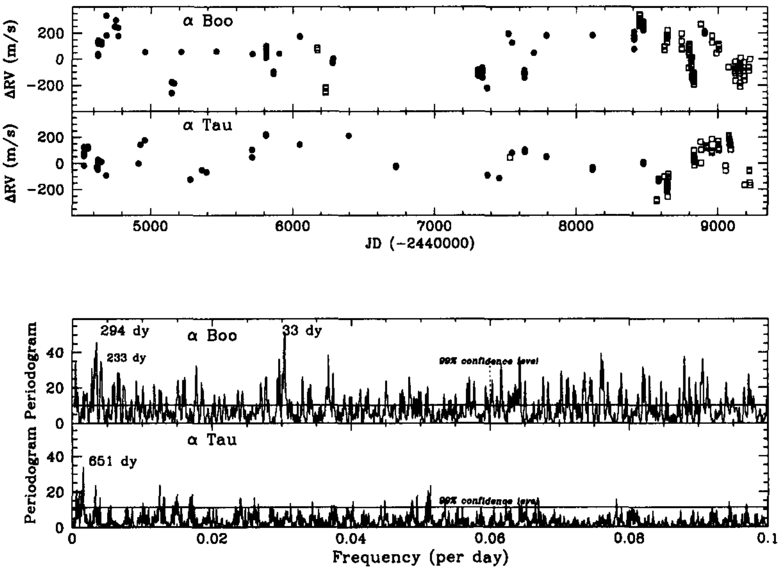

Figure 2. Results for α Boo and α Tau. The solid points represent CFHT data; the open squares, DAO data. The 294- and 33-dy periods for α Boo are aliases. The 233-dy period corresponds to that noted by HC93.

The 5.36-dy period could conceivably be the fundamental mode, or a modest overtone.

In addition to the periodic variability found in the differential radial velocities of δ Sgr, the CFHT data also show a significant (false alarm probability of 0.0001), $>$ 12-yr linear trend. For comparison purposes, we have arbitrarily shifted the DAO and McDonald Observatory data to match this trend.

HR 5340: The discovery of short- and long-term periods in the radial velocities of α Bootis established the foundation for the study of K giant variables. Since the short-term ($<$ 10 dy) periods are discussed in detail elsewhere (Merline, 1999), we will limit our discussion here to periods greater than 10 days.

The top panel of Fig. 2 shows the data for the CFHT observations (solid circles) and DAO observations (open squares). The periodogram shows that the two most significant frequencies correspond to periods of 33 and 294 days. These two periods are aliases: the 294-dy peak "disappeared" when the 33-dy sinusoidal solution was included in the parent function. (Note: Most of the other significant peaks are also aliases of the 33-dy period.) Hatzes and Cochran (1993, hereafter HC93) found 233 days as the most significant period in their data. A similar period is also present in our data; the corresponding frequency is indicated in Fig. 2. This peak is *not* an alias of the 33-dy period.

Unlike γ Cephei and, to a lesser extent, β Geminorum, the periodogram for the $\Delta EW_{866.2}$ index for α Boo shows no significant peaks corresponding to either the 294- or 33-dy aliased periods.

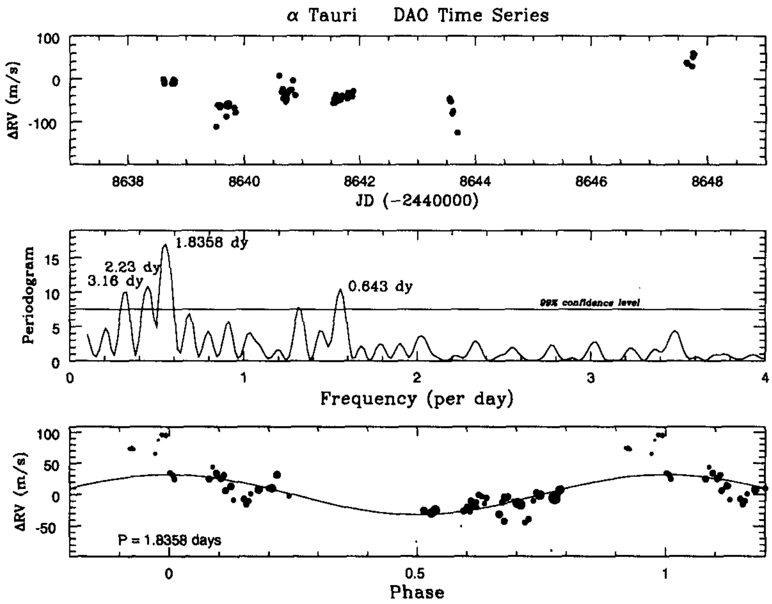

Figure 3. Results for α Tau time series, 1992 January (JD 2 448 638–48). The mean internal error for this observing run was 15.6 m s^{-1}. The area of each data point shown in the phase plot is inversely proportional to the square of the internal error estimate for that point.

HR 1457: The current status of the RV research for α Tauri is given in HC98. They (HC93) found an RV period of 643 ± 10 days, leading to an orbital solution of 654 days (HC98). Our analysis of the combined CFHT and DAO data shows a period of 651 days, consistent with the HC98 results. The other significant peaks seen in the periodogram are aliases of this 651-dy period. As emphasized in HC98, we found *no* coincident period at 651 days in our $\Delta EW_{866.2}$ index. Although the 651-dy period could be due to rotation modulation of some surface feature(s), the lack of any chromospheric emission and line-bisector variability (HC98) weakens any rotation-based hypothesis.

It appears that α Tau joins β Ophiuchi and α Boo as multi-periodic K giants. Short-term radial-velocity variations have been suspected for α Tau since the discussion in Walker et al. (1989); however, until the time-series observations at the DAO in 1992, there was not sufficient monitoring to determine if this variability was periodic. Fig. 3 shows the observations from the six nights of observing in 1992 January. For two of the nights the observations spanned approximately 8 hours. This type of time coverage is ideal for finding periods of order 2-3 days, and as the weighted periodogram (Fig. 3) shows, a significant period of ≈ 1.84 days was detected, the only real period present in the data. The other periods are all aliases of the 1.84-dy period. Fig. 3 shows the data phased on the short-term period given in Table 1. The high data points at zero-phase reflect sporadic, short-term variability not at all unusual for this star.

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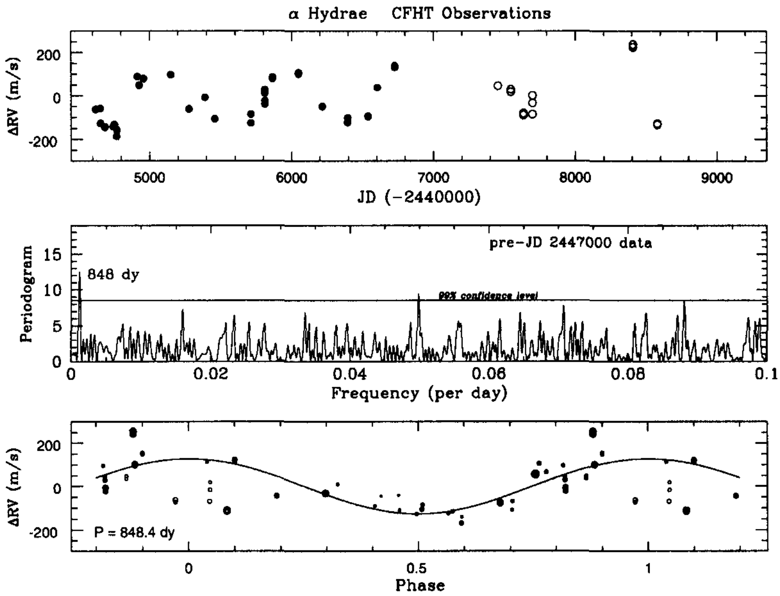

Figure 4. Results for α Hya. Different symbols are used to delineate the two time frames: pre- and post-JD 2 447 000 (see text). The bottom figure shows the data phased on the 848-dy period (see Table 1). The area of each data point shown in the phase plot is inversely proportional to the square of the internal error estimate for that point.

The 1.84-dy RV period may reflect radial pulsation in α Tau. We can crudely estimate the periods for the fundamental and first and second harmonics from the mass-radius relationships given in Cox et al. (1972). Our calculations show the fundamental mode should be of order 10 days. The presence of convection will increase this period; thus, if the 1.84-dy period is radial pulsation, it must be one of the higher harmonics ($n \approx 4$).

HR 3748: Even a casual glance at pre-JD 2 447 000 data shown in Fig. 4 for α Hydrae reveals cyclical behavior. The remaining CFHT observations (which, as luck would have it, were not nearly as extensive as pre-JD 2 447 000), shown as open circles in Fig. 4, reveal a change in the cycles. The periodogram for pre-JD 2 447 000 data shows a significant 848-dy period. This period is not distinguishable from other significant peaks and aliasing when all the data are considered. The bottom panel of Fig. 4 shows the data phased on the 848-dy period. The change in the amplitude of post-JD 2 447 000 data around zero phase clearly shows that this star is shifting period and/or phase.

The $\Delta EW_{866.2}$ index for α Hya shows intrinsic variability, albeit of very low amplitude – α Hya is one of the most chromospherically quiet stars in our giant sample (Larson et al. 1993a). The periodogram of the $\Delta EW_{866.2}$ data shows no significant peaks corresponding to the RV period.

HR 152: The top-left panel of Fig. 5 shows the data obtained using the I_2 technique at Lick Observatory (Butler et al. 1996). Previous work (see Noyes

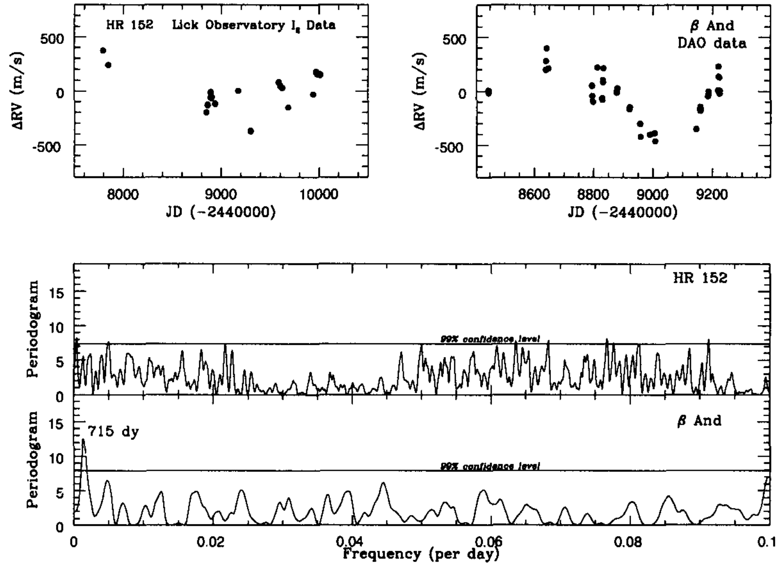

Figure 5. Results for HR 152 and β And. For HR 152, there are no significant peaks coinciding with the $\sim$ 600-dy period detected by other groups (see text). β And has a single period at 715 days.

et al. 1996) detected a period of $\sim$ 650 days and an amplitude of $\sim$ 500 m s^{-1}. As the periodogram for HR 152 shows, there are marginally significant peaks of order two weeks, 200 days, and > 2 500 days, but none corresponding to the $\sim$ 600-dy period detected by the other groups. From the sparse sampling of these data, and perhaps from the use of an oversimplified parent function, we are unable to add any definitive statements about periodicity in the radial velocities of this star.

HR 337: Radial-velocity variability becomes more common and of larger amplitude for M giants. Fig. 5 shows the DAO data for the M0 IIIa star, β Andromedae. The periodogram shown in the bottom panel of Fig. 5 indicates that this star has a single period of 715 days. This star also shows substantial changes in its chromospheric emission.

HR 168, HR 4301, HR 5563, HR 6705: Fig. 6 shows the data for four of the giants observed at the DAO. These data have larger external errors than the CFHT data, typically 30-40 m s^{-1}. For periods greater than 100 days, the binary α Ursae Majoris shows a marginally significant period at 138 days. β Ursae Minoris has a marginally significant period at 588 days. More precise data and additional monitoring are needed to confirm these periods. The other two stars shown in Fig. 6, α Cassiopeiae and γ Draconis, are low-amplitude RV variables, but this variability was not periodic over the span of our observations. Note, however, that short- and long-term periods have been detected in γ Dra using the more precise I_2 absorption cell technique (Hatzes, personal communication). Rao et al. (1993) found a possible 326-dy period in the Ca II H and K emission

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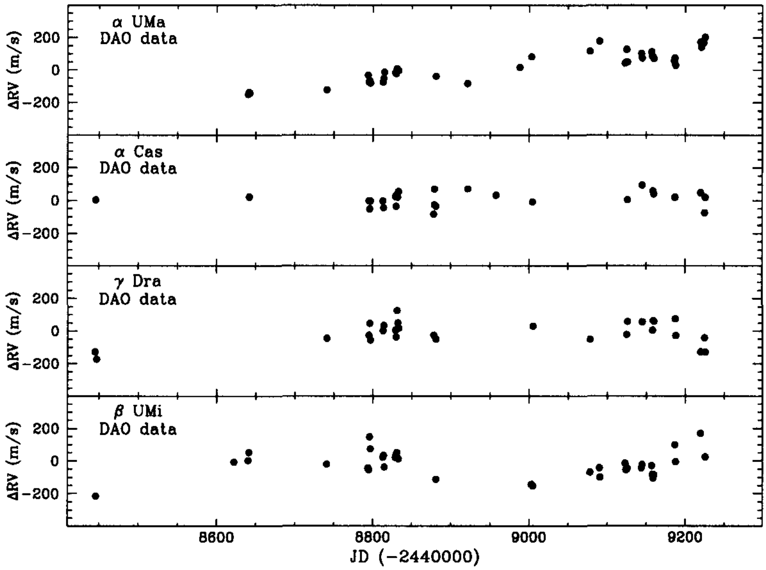

Figure 6. The data for four DAO stars with marginally significant or no detected periods in their radial velocities: α UMa, α Cas, γ Dra, and β UMi.

data for α Cas. Thus our null detections may be due to the lower precision and the unreliability of our $\Delta EW_{866.2}$ index for the DAO data.

4. Discussion

This work adds five additional K and early-M giants to the list of stars having long-term, low-amplitude RV periods: γ^2 Del, α UMa, β UMi, α Hya, and β And; and one star with a short-term period: δ Sgr. With a period of 1.84 days, α Tau joins α Boo and β Oph as multi-periodic stars. We find a medium-term periodicity of 33 days in α Boo.

Are we getting any closer to understanding the physical source for these RV periods? The most comprehensive discussions of possible mechanisms are given in HC93, HC96, and HC98 (see also Larson et al. 1993b; Larson 1996). Although we are probably detecting radial pulsation for the short-term periods, we may not be dealing with a single mechanism for the medium- and long-term periods.

Surface phenomena? We have shown that our $\Delta EW_{866.2}$ index is a sensitive indicator of chromospheric emission (Larson et al. 1993a). Because of similar RV and $\Delta EW_{866.2}$ periods in the data of γ Cep and β Gem, the simplest explanation for the long-term periods is rotation modulation of surface features. Unfortunately, simultaneous monitoring of chromospheric emission is not available for the DAO observations, nor those obtained using an I_2 absorption cell. For three of the CFHT stars – α Tau, α Boo, and α Hya – we *do* have simultaneous mon-

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itoring of chromospheric emission and find *no* periods in the $\Delta EW_{866.2}$ index corresponding to the long-term RV periods. The development, structure, and evolution of active regions and associated plages are complicated even for the Sun. The possibility of our viewing different aspects or kinds of active regions on these giants presents an interesting field of study.

Low-mass companions? Unless A - F dwarfs (the progenitors of K giants) have an overwhelming proclivity for producing planets, it is unlikely that the long-term periods represent low-mass companions. However, because it is so difficult to monitor the radial velocities of A - F dwarfs, we cannot summarily dismiss this possibility, at least for some of the stars. Additional photometric and spectral observations, preferably concurrent, such as those discussed in HC98 for α Tau, are needed. Photometric observations are being obtained for β Gem, β Oph, α Tau, γ Dra, and HR 152 (Fekel, personal communication).

Pulsation? From Table 1, it appears that there is no correlation between the spectral type of a star or the standard deviation of its differential radial velocities and the length of the period found or the multiplicity of periods. To help us fit pieces of the puzzle together, we need updated calculations for radial and non-radial pulsation for K giants, including the possibility of g-modes and r-modes in the presence of convection and H-burning shells.

The varying results for the stars in this report, based upon the precision of the measurements and the intensity of the monitoring, raises the question: Given a precision of 3 m s^{-1} (or better) and extensive time coverage, will we find that *all* K and early-M giants have multiple periods?

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Discussion

Hatzes: With regard to the variability of γ Dra and α Tau, our short-period detection of γ Dra (3.5 and 5.5 days, I think) was based on 8 consecutive nights of data, was well-suited for the detection of short-period variability. Our α Tau data had a monthly sampling, so we should not have seen a 1.8-day period. But we did see significant night-to-night changes indicative of short-period variability. Also, could you comment on the long-period variations in K giants? I used to think they were due to another phenomenon besides pulsation, but we are now finding periods in the 30–180 day range. Maybe the long periods just represent the low-frequency end of an oscillation spectrum. If so, then the equivalent-width variations associated with the long-period radial-velocity variations may be due to acoustic heating of some type.

Larson: We have not yet given much attention to the period range 30–180 days, primarily because (for most stars) our sampling was not optimal for finding or confirming these periods. We should address the possibility you suggest of some kind of acoustic heating.

Hummel: The Navy Prototype Optical Interferometer is being used to measure the diameters of K giants, e.g. α Ari, γ Dra, α UMa, α Cas, β Gem, with a precision of better than 1%. We also detect the limb darkening in those stars.

Larson: Thank you. Those measurements will be essential in learning more about such stars.

Udry: Among the giants of the CORAVEL standard stars the same trend in σ_{V_r} vs. M_v or $B-V$ is observed. The CORAVEL precision is not good enough safely to recognize small-amplitude or short-period variations, but its 20-yr time coverage allows a good detection of 100–200 m s^{-1} variations with periods of a few hundred days which, in our data, keep their coherence for several cycles, typically 10 to 20.

Larson: None of this is really surprising any more. They appear variable at all levels. Maybe we can use the variations to learn about evolutionary states once we have studied enough stars.

Mazeh: I would like to suggest another algorithm to analyse your data, instead of using the power spectrum. I have in mind autocorrelation which is very effective for modulation that does not retain the phase.

Larson: We will take a look at your suggestion for those stars for which the periodograms give weak results.

Hatzes: Because there are so many periods and timescales involved, I think the best way to study these stars is with an automated spectroscopic survey telescope. Is anyone here a personal friend of Bill Gates?

Larson: I note no response from the audience. I know someone who *works* at Microsoft, but that is not unusual for a Seattle-ite. Seriously, I think efforts should continue to find a telescope *and* observers.

Batten: A brief comment from the chair - α Ceti is called an IAU standard but probably shouldn't be, since it sometimes varies by even more than was shown here.