Precise Stellar Radial Velocities
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Radial Velocity Observations of Non-radially Pulsating Stars

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Abstract. The rapidly oscillating Ap stars (roAp) are a class of nonradially pulsating stars oscillating in low-degree modes with periods of 4–15 minutes. We have started a program to study the oscillations on several roAp stars using precise radial velocity (RV) measurements. The typical mean RV amplitude for the roAp stars we have observed is 50–400 $\mathrm{m\,s^{-1}}$, but this amplitude depends on the spectral region used for the measurement of the RV amplitude. A detailed line-by-line analysis reveals that the pulsational amplitude depends not only on atomic species, but on the line strength as well. For a given atomic species weak spectral lines exhibit a pulsational amplitude 10–100 times higher than for strong lines. The elemental effect can be understood in the context of the inhomogeneous distribution of elements known to occur on these stars and that is believed to result from the global dipole magnetic fields that are present. For instance, if an element is concentrated near the magnetic pole then it may have a higher RV amplitude than one that is distributed about the magnetic equator. The line strength effect is interpreted as arising from vertical structure to the pulsations since weaker lines are formed, on average, deeper in the atmosphere than stronger lines. Precise RV measurements may prove to be a powerful tool for probing both the vertical and horizontal structure of the pulsations in roAp stars.

1. Introduction

Precise stellar radial velocity (PRV) measurements have already had considerable success at finding the first planets around other stars. These types of measurements can also provide valuable knowledge of stellar oscillations by discovering new classes of low-amplitude pulsating stars and revealing new knowledge about known pulsating stars. PRVs have already shown that K giants are a new class of pulsating stars. The radial velocity (RV) variations for these stars are of low amplitude ($\sim$ 50–400 $\mathrm{m\,s^{-1}}$) and multi-periodic with periods

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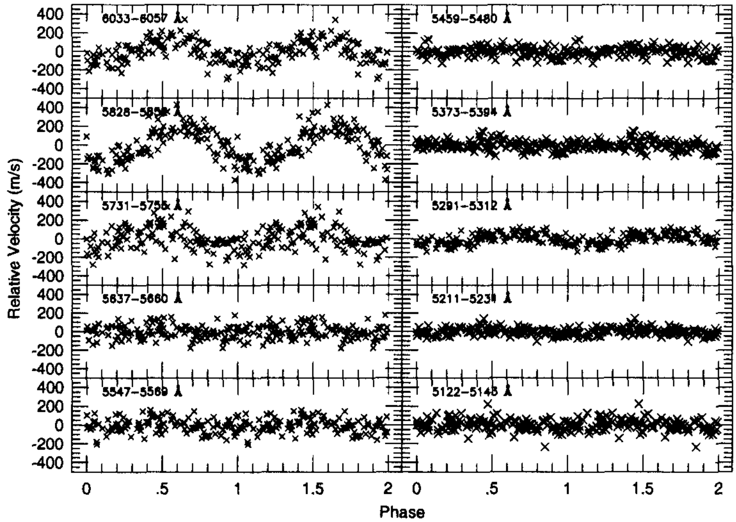

Figure 1. The RV variations of γ Equ in 10 spectral orders phased to the pulsational period found by a Fourier analysis.

ranging from a few days to several hundreds of days. These RV variations almost certainly arise from radial and non-radial pulsations. It was our intention also to discuss RV measurements of K giant stars, but there are several papers presented at this conference dealing with the RV variations of K giants (see contributions by Larson and Merline). Since this subject is adequately covered in these proceedings we chose to examine how PRVs can shed new insights on stars that are known to be pulsating. In particular we will present some new and exciting results on rapidly oscillating Ap stars.

2. The roAp stars

The rapidly oscillating Ap (roAp) stars are a class of pulsating stars oscillating in high overtone, low-degree, nonradial p-modes with periods ranging from 4 to 15 minutes (see Kurtz 1990 for an excellent review of these stars). These stars, like most Ap stars, have global dipole fields of a few hundred to several thousand gauss whose axis is inclined with respect to the rotation axis (oblique rotator). The roAp stars were discovered via photometry and much of our knowledge about the stellar pulsations have come from these measurements, including the fact that the photometric amplitude is modulated with the rotation of the star. This can be explained by the oblique rotator model of Kurtz (1982) which has the axis of pulsations aligned with the magnetic axis rather than the rotation axis. Photometric measurements have also established that these stars are multiperiodic and pulsating in $\ell = 1$–3, $m = 0$ modes (zonal modes).

Unlike photometric studies, there have been few RV studies of roAp stars, because of the difficulty of making these measurements. Measuring the expected small RV shifts requires high resolution spectral data. Unfortunately, the pul-

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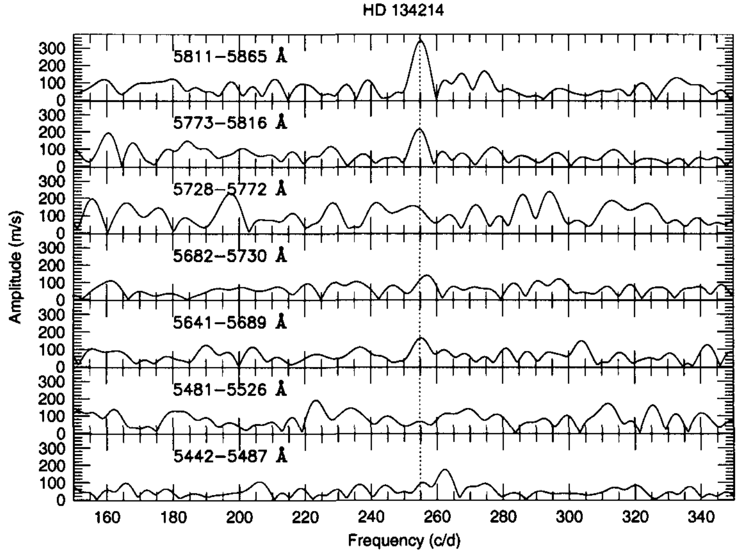

Figure 2. Fourier transform of the RV variations of HD 134214 in 7 spectral orders.

sation periods are short requiring exposure times of $\approx$ 1 min., which severely limits the signal-to-noise ratio one can achieve without phase smearing. A pioneering attempt to measure RV variations in the roAp star HR 1217 was made by Matthews et al. (1988) using a mercury lamp for a wavelength reference. In the 4350–4500 Å wavelength region they detected an RV peak-to-peak amplitude of 400 $\mathrm{m\,s^{-1}}$ on one night, but were unable to detect any significant variations on another second night. They found that the radial-velocity amplitude to photometric amplitude for this star, $2K/\Delta m$, was about 60 $\mathrm{km\,s^{-1}}$ $\mathrm{mag^{-1}}$, a value comparable to Cepheid variables. Libbrecht (1989) used an iodine absorption cell in the spectral region 5322–5377 Å to detect RV variations in the roAp star γ Equ with a $2K$ amplitude of 42 $\mathrm{m\,s^{-1}}$, resulting in a $2K/\Delta m = 30$ $\mathrm{km\,s^{-1}}$ $\mathrm{mag^{-1}}$. Hatzes & Kürster (1993) searched for RV variations in the wavelength interval 5365–5410 Å in α Cir and found none above a level of 23 $\mathrm{m\,s^{-1}}$ which placed an upper limit of $2K/\Delta m < 10$ $\mathrm{km\,s^{-1}}$ $\mathrm{mag^{-1}}$.

At McDonald Observatory and the Special Astrophysical Observatory we have begun a program to study roAp stars using precise radial-velocity measurements. The initial goal of this study was to measure the $2K/\Delta m$ ratio for these stars which could be compared to values for other pulsating stars, possibly shedding some light as to the nature of the excitation mechanism for the pulsations. Also, we hoped to resolve the discrepant $2K/\Delta m$ measurements for roAp stars found by various investigators.

3. Observations

Most of the observations presented here were taken with the 2-d coudé spectrograph of the McDonald Observatory 2.7-m telescope. This instrument along

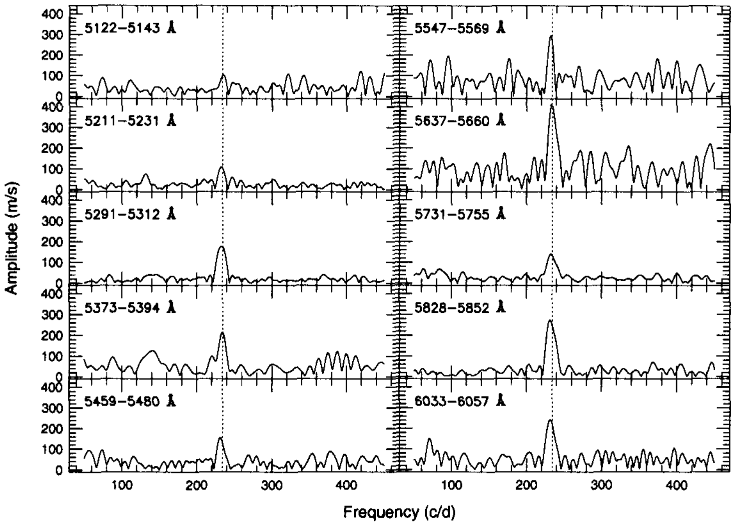

Figure 3. The Fourier transform of the RV variations for HR 1217 in 10 spectral orders. The dashed lines marks the dominant mode.

with a Tektronix 2048×2048 CCD detector provides a wavelength coverage of 3500 Å – 1μm at a resolving power of $R = (\lambda/\Delta\lambda) = 60\,000$. Some early observations were made using a Texas Instruments 800×800 CCD detector which did not cover the full spectral format. Consequently, there were large gaps in the wavelength coverage. The wavelength reference for all RV measurements was provided by an iodine gas absorption cell.

For observations of roAp stars it is important to minimize the dead time between exposures which is taken up mostly by the CCD readout time. To minimize this the CCD was binned a factor of two perpendicular to the dispersion and only a sub-frame of 1000 rows spanning the wavelength interval 4500–7000 Å (coverage of I_2 absorption lines) was read. This resulted in a readout + write time of about 30 seconds.

4. Detection of Broad-band RV Variations in roAp Stars

Although our program is rather young, we have already detected RV variations in 5 roAp stars. The analysis for many of these stars is incomplete and here we present preliminary results for only a few stars. (Our results for 33 Lib are presented in a paper elsewhere in these proceedings.)

The spectral format of the échelle spectrograph naturally divides the stellar spectrum into wavelength intervals. To improve the RV precision, measurements were first made using the full ("broad-band") interval covered by each spectral order. In §5 we present RV measurements for individual spectral lines.

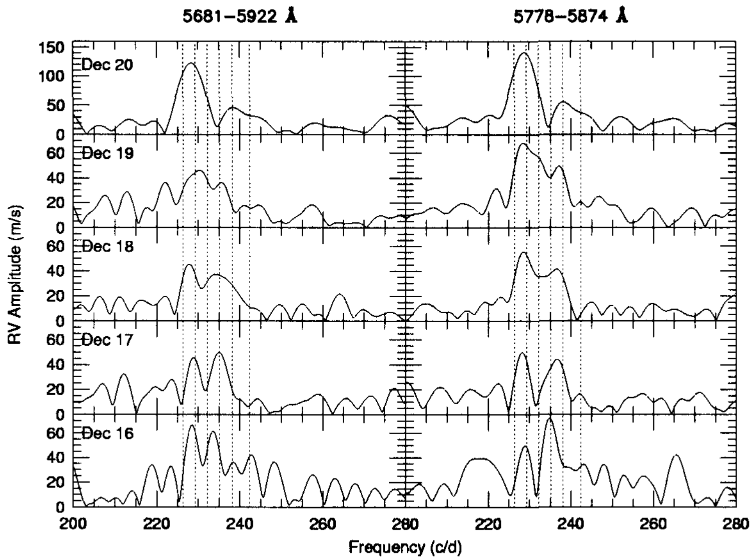

Figure 4. The Fourier transform of RV measurements in two spectral orders, 5681–5922 Å (left) and 5778–5874 Å (right) for HR 1217 on six nights in 1997 December.

4.1. γ Equ

The photometric variability of this star is dominated by 4 pulsation modes with a mean period of about 12 minutes and an amplitude of $\Delta B \approx 1.6$ mmag. The primary pulsation mode was evident in a Fourier analysis of our RV data and Fig. 1 shows these measurements for 10 spectral orders phased to the pulsational period. (These data were taken with the TI 800×800 CCD.) RV variations are readily apparent, but the amplitude varies significantly in the different spectral regions being as high as 400 m s^{-1} in the spectral range 6033–6057 Å and almost nondetectable blueward of about 5500 Å.

4.2. HD 134214

HD 134214 oscillates in a single mode with a period of 5.65 min. and a photometric amplitude of $\Delta B = 4.8$ mmag. Observations were made for four consecutive hours using the Sandiford cassegrain échelle spectrograph of the 2.1-m telescope at McDonald Observatory. Exposure times were 50 s resulting in a typical signal-to-noise ratio of 20. Fig. 2 shows the Fourier transform of radial-velocity measurements in 7 spectral orders. The dashed vertical line indicates the frequency of the dominant mode found by photometry. RV variations are present in two, possibly 3 spectral orders with the amplitudes ranging from less than 100 m s^{-1} to as high as 400 m s^{-1}.

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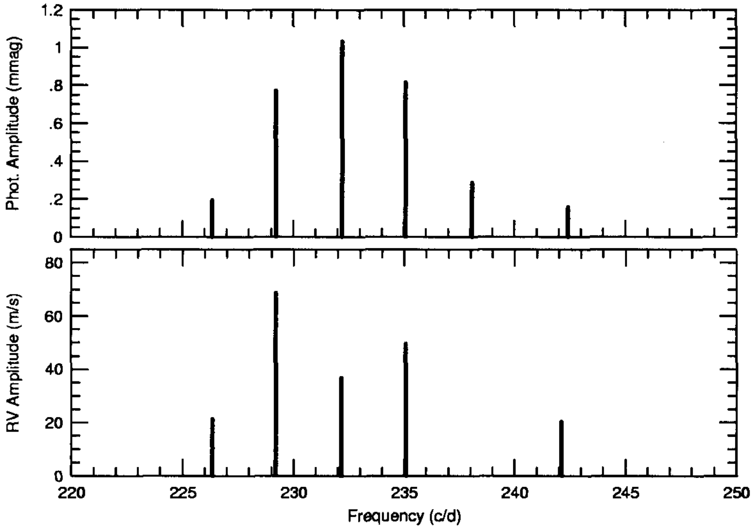

Figure 5. (Top) Schematic of the photometric amplitude spectrum for HR 1217. (Bottom) Schematic of the RV amplitude spectrum for HR 1217 based on an analysis of one spectral order spanning six nights in 1997 December.

4.3. HR 1217

This star shows 6 pulsation modes with a mean period of 6.15 min. Fig. 3 shows the Fourier transform of our RV measurements taken over a 4-hr continuous time span. (Again, the smaller TI CCD was used for these observations.) The dominant pulsational period (frequency location indicated by the dashed vertical line) is evident in all spectral orders, but again the amplitude varies significantly from 100 $\mathrm{m\,s^{-1}}$ to 400 $\mathrm{m\,s^{-1}}$.

Matthews et al. (1988) found that the RV amplitude for this star changes significantly from one night to the next, possibly an indication of rotational modulation, or the interaction or decay of the various oscillation modes. We obtained a long time series of data spanning 11 nights in 1997 December and 1998 January in order to study the pulsational behavior of this star throughout a rotation period ($P_{\mathrm{rot}} \approx$ 12 days). We are still in the process of analyzing the data, but Figs. 4 and 5 show preliminary results of our analysis. Fig. 4 shows the Fourier transform of RV measurements from two spectral orders of data taken on 6 nights in 1997 December. The vertical dashed lines mark the location of known pulsation modes. There are several features to note about this figure. 1) The Fourier transform of the two spectral orders are remarkably consistent indicating that much of the structure seen in the transform is real; we are detecting more than one mode on a given night. 2) The Fourier amplitudes of corresponding peaks in the two spectral orders can change significantly from night to night. For instance, the region 5681–5922 Å has a higher RV amplitude than the 5778–5874 Å region on 22 December which was not the case on 20

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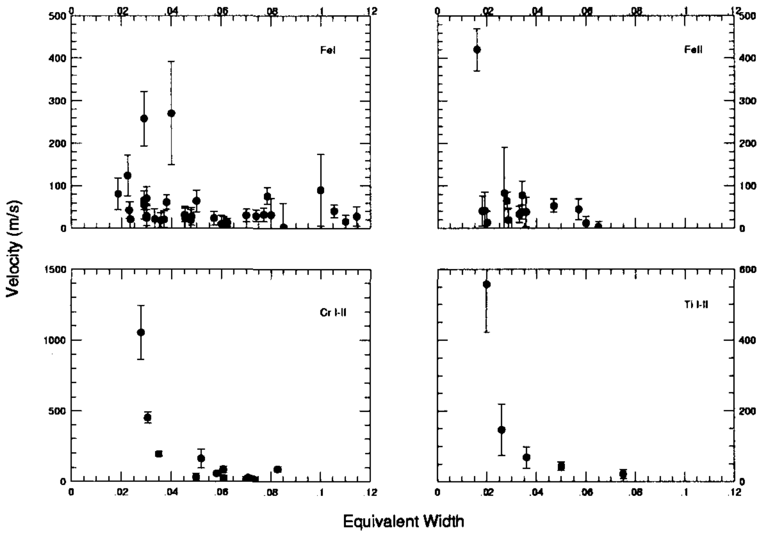

Figure 6. The RV amplitude as a function of equivalent width for Cr I and II, Ti I and II, and Fe I and II in γ Equ.

December. 3) The dominant modes that are present can change significantly from night-to-night.

We have also performed a Fourier analysis on the full data set spanning the six night shown in Fig. 4. The analysis was made in a bootstrap manner: the contribution of the dominant period was removed and a Fourier analysis was made on the pre-whitened data. This continued until there were no significant peaks above the noise level. The bottom panel of Fig. 5 shows the resulting schematic RV amplitude spectrum for the order spanning 5681–5922 Å. The top panel shows the photometric schematic amplitude spectrum (from Kurtz 1990). Our limited data were able to recover 5 of the 6 known oscillation modes.

5. RV Variations of Individual Spectral Lines

In order to understand fully the large differences in the RV amplitude derived from different spectral regions it was necessary to determine the RV variations for individual lines. A detailed analysis for γ Equ is currently in press (Kanaan & Hatzes 1998) the main results which are shown in Fig. 6. It shows the least squares RV amplitude as a function of line equivalent width for iron, chromium, and titanium. Two effects are evident. First, for a given equivalent width the mean RV amplitude for chromium and titanium is significantly higher than for iron. Secondly, for a given atomic species the RV amplitude is an increasing function of decreasing line strength, i.e. weaker lines tend to have a higher amplitude than stronger lines.

We were surprised to find that some spectral features in γ Equ could exhibit RV variations with amplitudes $\approx 1\ \mathrm{km\,s^{-1}}$. Our initial observations were

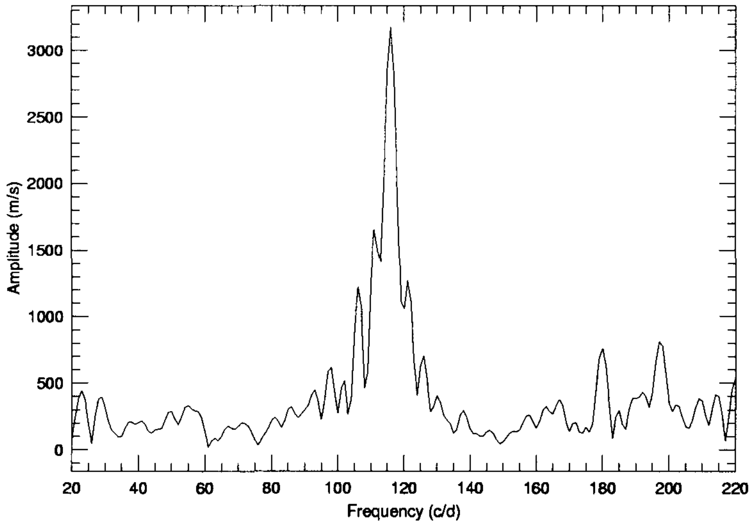

Figure 7. Fourier amplitude spectrum of the RV variations for one spectral line in γ Equ.

made with the smaller TI CCD which had large wavelength gaps. Since then we have taken more observations of γ Equ using the larger Textonix CCD and have found that some spectral lines exhibit even higher RV amplitude than those shown in Fig. 6. Fig. 7 shows the Fourier transform for one (as yet unidentified) spectral line in γ Equ. The frequency of the large peak corresponds to that of the dominant pulsation mode, but the amplitude is nearly 3 $\mathrm{km\,s^{-1}}$, a factor of 100 times greater than the RV amplitude of many spectral lines in γ Equ. Fig. 8 shows the RV variations phased to the pulsational period. Note the slow rise on the ascending part of the RV curve followed by the rapid decline. This is characteristic of the RV curve for many pulsating stars (e.g. δ Scuti, RR Lyrae) and is possibly an indication of non-linear effects. We believe that the large scatter about the mean curve is an indication of the presence of another frequency not related to any known ones for this star. The presence of an additional frequency is also evident in the Fourier transform of the RV measurements. For a single frequency the window function should produce a set of alias peaks that are symmetrical about the main lobe which is not the case (Fig. 7).

6. Discussion

We have detected pulsational RV variations in several roAp star and all show a similar behavior in that the RV amplitude is strongly dependent on the spectral region used for computing the radial velocity. This amplitude can differ by a factor of 10–100. The RV behavior can also be complicated. In some stars, like γ Equ, the RV variations are large in a relatively small spectral range. In other stars, like HR 1217, the RV variations are detectable over a broad spectral region, albeit with grossly different amplitudes. Also, the wavelength region where the

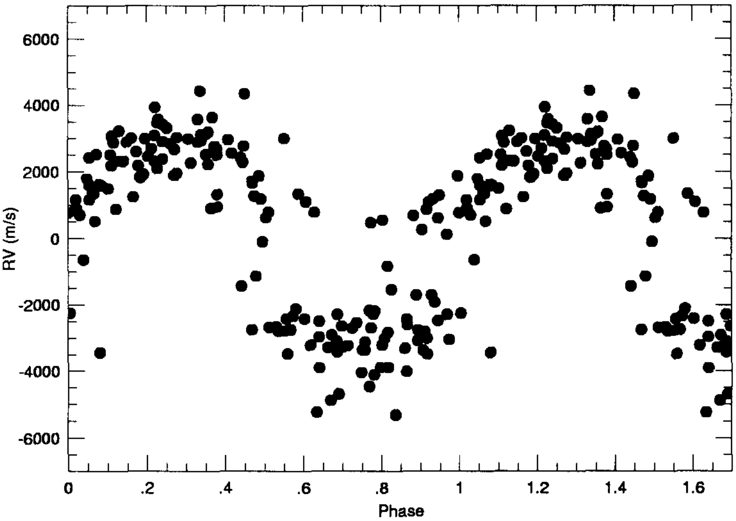

Figure 8. The RV variations for the spectral line used in Fig. 7 phased to the pulsational period

RV amplitude is a maximum can differ from star to star. For example, this RV maximum occurs in the region 5800–5900 Å in γ Equ, but near 5600 Å in HR 1217.

An analysis of the RV variations for individual lines shows that the RV amplitude depends on both the atomic species of the line as well as the line strength. Some atomic lines, like chromium and titanium in γ Equ have a higher mean RV amplitude than lines of iron. For a given atomic species the RV amplitude increases with decreasing line strength. This line strength effect has also been confirmed for the roAp star α Cir (Baldry et al. 1998). Thus the discrepant RV amplitudes found in the various spectral regions are due primarily to 1) the atomic species that dominates that wavelength region and 2) the relative number density of weak spectral lines.

Our interpretation of the increasing RV amplitude as a function of line strength is that it is due to an atmospheric height effect. Weaker spectral lines are formed, on average, deeper in the stellar atmosphere than stronger lines. The oscillations in roAp stars have a large radial order, so one expects a short vertical wavelength to the oscillations. Possibly the weaker lines are formed closer to the excitation mechanism or, alternatively, further away from a node. The drop in photometric amplitude as a function of wavelength from blue to red is also interpreted as arising from this vertical structure (Kurtz 1998).

The variations with atomic species is best understood in terms of the abundance distribution on Ap stars. It is well known that the distributions of elements on the surface of magnetic Ap stars is non-uniform, with some elements concentrated near the magnetic poles and others near the magnetic equator. If an element, say chromium, is concentrated more towards the magnetic pole, then RV measurements would be weighted towards those regions of the star where the pulsational amplitude for zonal modes is higher and where the atmospheric motion is parallel to the field lines and is thus unrestrained in its motion. An element that is concentrated around the magnetic equator could have a lower RV amplitude because zonal modes have a lower pulsational amplitude at the equator (and can be exactly zero for odd-numbered ℓ-modes). Also the atmospheric motion is now perpendicular to the magnetic field lines which can restrain any vertical motion.

The large RV amplitude for the one line in γ Equ (Fig. 7) borders on the unbelievable. There are two possibilities for the high RV amplitude for this line. Either it represents a true RV amplitude for this line, or it is due to blending of a nearby, temperature sensitive line. There are temperature variations associated with the pulsations and if there is a nearby weak blend whose strength is very temperature sensitive, then this could skew the centroid of the strong line making it appear to have a much higher RV amplitude than it really has. If the large RV variations for this line are indeed real, then this implies that this line is either formed very close to the excitation region of the star, or in between two vertical nodes of the pulsations where the RV amplitude should be maximized.

The large variations in the RV amplitude derived from different spectral regions sheds some light on the discrepant $2K/\Delta m$ values found by various investigators. It is clear from our measurements that pulsational RV amplitude for a given star can differ by a factor of up to 100, depending on which spectral region is examined. A $2K/\Delta m$ determination for an roAp star is thus largely a meaningless measurement. Furthermore, it is clear that in making RV measurements of the pulsations in roAp stars it is essential to have as broad a wavelength coverage as possible. Measurements concentrating on a narrow wavelength interval may miss many of the important details of the RV variability in these stars.

The rapid increase in RV amplitude with decreasing line strength and thus increasing depth in the stellar atmosphere suggests that the excitation region lies in a very thin layer very close to the stellar photosphere. One may speculate that the oscillations in these stars are due to an opacity effect (κ mechanism), possibly related to the peculiar abundances in these stars thought to occur in a relatively thin layer of the atmosphere. If true, then the RV amplitude should change quickly as a function of height in the stellar atmosphere. Future RV studies may well uncover some of the mysteries behind the oscillations in the Ap stars.

Acknowledgments. This work was supported by CRDF grant UP2-317. We wish to thank David Gray for useful discussions during this conference.

Discussion

Brown: Is it possible that the diffusion processes that cause the element abundance anomalies might cause velocity variations with height as well as with horizontal position on the surface?

Hatzes: Certainly. There has not been a whole lot of work on this, but it has been suggested in the literature.

Griffin: You have clearly demonstrated a depth dependence of radial velocity. Since the wings of strong lines are formed deeper down (where fainter lines also form) one would expect to see asymmetries in those wings. Such asymmetries could also affect measurements of line centroids.

Lampens: Your work is based on data where the complete frequency pattern may not be recovered, so isn't it 'premature' or 'difficult' to try to analyse amplitude modulations (even though it was done on simultaneously measured sets of lines of different elements)?

Hatzes: It is premature, since I have analyzed (frequency analysis) only half the data set. The frequency spectrum may change after the full analysis.

Vinko: How do you measure the radial velocities of individual lines? Do you use bisector velocities or do you measure the displacement of the line core?

Hatzes: I use the whole spectral line as a template, appropriately masked so as to exclude all other spectral features.

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