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# On the roAp star status of $\beta$ Coronae Borealis

D. W. Kurtz[1] and F. Leone[2]

[1] Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE, UK
e-mail: dwkurtz@uclan.ac.uk
[2] INAF - Osservatorio Astrofisico di Catania, via S. Sofia 78, 95123 Catania, Italy
e-mail: fleone@ct.astro.it

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**ABSTRACT**

$\beta$ CrB is one of the best-studied of the magnetic Ap stars. Three independent investigations have suggested that this star is pulsating with a period of either 6.1 min, 11.5 min or 16.2 min, making this a rapidly oscillating Ap star. The presence of pulsations in $\beta$ CrB has important implications for the understanding of pulsation driving and damping in roAp stars, and each study has called for additional observations to confirm the suggested pulsations. New high time resolution, high spectral resolution, high signal-to-noise spectra of $\beta$ CrB obtained with the high resolution spectrograph SARG on the 3.55-m Telescopio Nazionale Galileo are unable to confirm any of the suggested periods. There is no indication of any variability with a period near 6.1 min. Studies of Fe I lines suggest that the 11.5-min period is spurious. Studies of Ce II lines do not find the 16.2-min period suggested for one Ce II line, but are not precise enough to test the finding of 16.2-min oscillations for a large section of spectrum, hence the case for the 16.2-min period is still good. An extensive investigation of $\beta$ CrB is needed to resolve the issue.

**Key words.** stars: magnetic fields – stars: chemically peculiar – stars: oscillations – stars: individual: HD 137909

## 1. Introduction

The rapidly oscillating Ap (roAp) stars occupy a restricted area of instability in the HR Diagram, ranging in temperature from about 6600 K to 8500 K and having luminosities between the zero age main sequence and the terminal age main sequence (TAMS). Hubrig et al. (2000) discussed known roAp stars and non-oscillating Ap (noAp) stars in this area of the HR diagram and found that the roAp stars seem to be less evolved than the noAp stars. However, Cunha (2002) predicted that more luminous stars within the above area should have longer periods than have previous been detected in roAp stars. Photometric searches for these stars show a period range of 5.65−15 min, with the exception of HD 60435 which may have longer periods (Matthews et al. 1987). Following Cunha's prediction, Elkin et al. (2005b) discovered low amplitude pulsations in the radial velocity variations in HD 116114 with a period of 21 min, close to the value predicted by Cunha for a star near the TAMS. This has extended the range of periods known for roAp stars, and led to some question about whether there is a luminosity difference between roAp and noAp stars.

There have been many suggestions over the last two decades for driving mechanisms for the roAp stars. Two recent discussions are those of Balmforth et al. (2001) and Saio (2005), who find driving from the $\kappa$-mechanism operating in the H ionisation zone. In both cases, the magnetic field plays an important role in mode driving and selection. However, Ap stars with strong magnetic fields in the range of temperature and luminosity of roAp stars may still be either roAp or noAp stars.

Ryabchikova et al. (2004) made a strong case that ionisation disequilibria between Nd II and Nd III and between Pr II and Pr III is a signature of roAp stars. That is, the doubly ionised ions show much stronger lines than the singly ionised ions in roAp stars, whereas several noAp stars investigated did not show this anomaly, which is explained by strong stratification of Rare Earth elements high in the atmospheres of the roAp stars (Ryabchikova et al. 2002; Mashonkina et al. 2005). Ryabchikova et al. (2004) suggested that possibly all magnetic Ap and Fp stars up to $T_{\rm eff}$ = 8100 K are roAp stars, with the stars classified as noAp stars in this temperature range simply having pulsation amplitudes so small that they have not been detected yet. They cite as important evidence for this the discovery of pulsations in radial velocity variations in the cool Ap star $\beta$ CrB (Ando et al. 1988; Kochukhov et al. 2002; Hatzes & Mkrtichian 2004), suggesting that this may be a key element in understanding roAp stars and calling for more high quality spectroscopic observations. Neither HD 116114, nor $\beta$ CrB shows the Pr-Nd anomalies, so that this is clearly not a requirement for an Ap star to be an roAp star, although it is a very strong indicator amongst the roAp stars currently known.

Figure 3 of Hubrig et al. (2000) and Fig. 2 of Hubrig et al. (2005) show an astrometric HR Diagram for roAp and noAp stars where $\beta$ CrB at $\log T_{\rm eff} \sim 3.91$ lies among the hotter known roAp stars. It has so many characteristics in common with roAp stars that many searches for pulsation have been carried out. References to the photometric searches are given by Martinez & Kurtz (1994); all of those have given null results. Spectroscopic searches have been more successful in finding pulsations in this star; unfortunately, no two studies agree (including the one we are presenting in this paper).

As one of the brightest and best-studied magnetic Ap stars, there have been many magnetic studies of $\beta$ CrB (see Bychkov et al. 2005 for a list of 29 references; see Leroy (1995) and Mathys (1995) for discussions). Its longitudinal magnetic field is polarity-reversing between about ±1000 G with a rotation period of 18.4868 d (see Kurtz 1989); its surface magnetic field strength is 5400 G (Mathys 1995). The magnetic ephemeris is known well (Kurtz 1989; Leroy 1995), so observations testing for pulsation can be accurately related to the magnetic phase at the time of observations. So far, all roAp stars that have been studied sufficiently show times of pulsation maxima that coincide with magnetic extrema. There are competing versions of the oblique pulsator model that explains this (see, e.g., Saio 2005; Bigot & Dziembowski 2002), but all agree that the pulsation is aligned with, or nearly aligned with the magnetic field. While $\beta$ CrB should eventually be examined over its entire rotation cycle for pulsation, searches have concentrated on times near magnetic maximum, and there is no reason to doubt that this is a good strategy for maximising the probability of detection of pulsations.

Ando et al. (1988) suggested that they had detected a signal in the radial velocity variations of $\beta$ CrB at a period near 6.1 min ($\nu$ = 2.7 mHz) with an amplitude of about 360 m s$^{-1}$ near the time of magnetic maximum (magnetic phase 0.06), and that this signal was not present near magnetic quadrature in other observations. From the signal-to-noise (S/N) in their Fig. 5a, we believe that the highest peak is a false alarm. The chance of a noise peak at *some* frequency within the known roAp star range with this S/N is non-negligible, both from statistical arguments (see, e.g., Horne & Baliunas 1986), and from our experience in frequency analysis of photometric and spectroscopic data sets where apparent peaks such as this one often cannot be confirmed with independent data. We show some similar examples that we believe to be spurious in our own data in Fig. 3 of Sect. 4 below. Ando et al.'s second night of data near magnetic maximum was under poor observing conditions, and in our judgment their Fig. 6a does not provide significant support the peak in their Fig. 5a.

Belmonte et al. (1989) observed $\beta$ CrB spectroscopically for 6.5 h. Although they show no periodogram for their data, they state that their observations put an upper limit to any pulsation amplitude of 200 m s$^{-1}$.

Both of the above studies were searching for radial velocities for the spectrum of the star as a whole. It is now clear from many studies that the atmospheres of roAp stars are chemically stratified, and that the radial wavelength of the pulsation modes is short compared to optical depth 1, so that significant amplitude and phase changes in the pulsation can be detected as a function of atmospheric height. Figure 1 of Kochukhov & Ryabchikova (2001) shows this nicely. The presence of radial nodes in the observable atmospheres of roAp stars is well-established; the evidence for this is good for $\alpha$ Cir (Baldry et al. 1999), HD 137949 (33 Lib; Mkrtichian et al. 2003; Kurtz et al. 2005a) and HD 99563 (Elkin et al. 2005a). The latter paper, in particular, shows how strongly pulsation amplitude and phase change as a function of atmospheric height for the roAp star with the highest radial velocity amplitude known (5 km s$^{-1}$).

Thus Kochukhov et al. (2002) made a line-by-line search for radial velocity variations in $\beta$ CrB in a short 85-Å section of spectrum containing lines of Nd III and Pr III, since lines of these ions are known to show the highest pulsation amplitudes in most roAp stars (see, e.g., Kurtz et al. 2005b, who have surveyed 14 roAp stars at high spectral and time resolution). Kochukhov et al.'s observations were obtained at magnetic phase 0.08 – close to magnetic maximum – yet they found no pulsation variation in the Rare Earth element lines, placing an upper limit to the amplitude for the Nd III 6145 Å line of only 30 m s$^{-1}$. They point out that the strong magnetic field of $\beta$ CrB distorts the lines and also that the lines of Pr III and Nd III are weaker in the spectrum of $\beta$ CrB than in other roAp stars, complicating the search for pulsations. Nevertheless, Kurtz et al. (2006) have discovered roAp star oscillations with an amplitude of only 60 m s$^{-1}$ in the extremely magnetic Ap star HD 154708 (Hubrig et al. 2005) at a time when the surface field was measured to be 24.5 kG – the second-strongest magnetic field known in a non-degenerate star, so we know that low amplitude pulsation can be detected in such extreme stars with sufficient high-quality data.

While Kochukhov et al. (2002) found no pulsation for the Rare Earth element lines, they suggested that they found pulsation in a single Fe I line at 6165.36 Å with a frequency of 1.45 mHz and an amplitude of 71 ± 11 m s$^{-1}$. This is surprising because most roAp stars show no pulsation variations in their Fe lines; an exception to this is HD 137949 (Mkrtichian et al. 2003; Kurtz et al. 2005a). In all cases where Fe lines do have detectable variability, H$\alpha$ and the Rare Earth element lines show *much* higher amplitudes (Kurtz et al. 2005b). Because their only detection was for one spectral line, and a surprising one at that, Kochukhov et al. (2002) reasonably labelled their detection as tentative and called for further study.

Hatzes & Mkrtichian (2004) obtained 3 h of high time resolution of spectroscopy of $\beta$ CrB at magnetic phase 0.11 spanning the range 4700–6700 Å with an Iodine vapour cell in the light beam. The use of an Iodine cell is normal in high precision radial velocity studies of extra-solar planets, and there is no doubt that it provides control of the stability of the wavelength scale from spectrum to spectrum, hence gives the most precise radial velocity measurements for the spectrum as a whole. But for line-by-line studies and pixel-by-pixel line profile variability studies it is a compromise, since it decreases the signal-to-noise ratio through additional light losses to the Iodine, and in the deconvolution of the Iodine spectrum from the stellar spectrum.

For the roAp stars there is unprecedented pulsational information in the line profiles, and investigators working in detail on these line profiles desire the highest possible signal-to-noise ratio, hence choose not to use an Iodine cell. See, for example, Kochukhov's (2006) study of HR 3831 and Elkin et al.'s (2005a) study of HD 99563. It is clear that for many modern spectrographs there is good wavelength stability on the time scale of the roAp stars pulsations. For example, Kochukhov (2006) reports for the Coudé Echelle Spectrograph on the ESO 3.6-m telescope that random instrument shifts do not exceed 10 m s$^{-1}$. Kurtz, Elkin & Mathys (see, e.g., Elkin et al. 2005b; Kurtz et al. 2005b) find for the Ultra-Violet and Visual Echelle Spectrograph on the Very Large Telescope that random noise levels in non-variable stellar lines, in interstellar lines, and in telluric lines typically have standard deviations in the few m s$^{-1}$ level and less. For the high resolution spectrograph SARG that we have used in this study on the Telescopio Nazionale Galileo we find stability in telluric lines with a standard deviation less than 2 m s$^{-1}$, as we show in Sect. 3 below.

Hatzes & Mkrtichian (2004) make a strong case they have detected radial velocity variations with a period of 16.2 min ($\nu$ = 1.028 mHz) with an average amplitude of 3.5 ± 0.6 m s$^{-1}$, although they call for further observations to confirm their results. It is a signal in a large range of the spectrum that gives the amplitude of 3.5 m s$^{-1}$, but of course this is not a pulsation amplitude for any particular level in the atmosphere as it is derived from an ensemble of lines that probably have different amplitudes and possibly phases, if $\beta$ CrB is similar to other roAp stars. Hatzes & Mkrtichian (2004) give a good discussion of the false alarm probability for their result, but wisely look for independent confirmation. That they find in a spectral line of Ce II at 6272.026 Å with an amplitude of 130 m s$^{-1}$ in an independent section of spectrum. This amplitude is larger than that seen in some other roAp stars (e.g. HD 116114 – Elkin et al. 2005b; HD 154708 – Kurtz et al. 2006), so is believable in terms of their average amplitude of 3.5 m $s^{-1}$, assuming many lines show no radial velocity variations at all. In our opinion, the detection of the same signal in a large part of the spectrum (5000–6000 Å) and in a spectral line of a Rare Earth element in an independent part of the spectrum makes a strong case that the detection is real and $\beta$ CrB is an roAp star. However, as we show in Sect. 3, we can find no radial velocity variations in four Ce II lines, placing some doubt on their result.

Hatzes & Mkrtichian (2004) argue that their observations of the spectral region around the 6165.36 Å Fe I line rules out the suggested detection of a signal at 1.45 mHz with an amplitude of 71 ± 11 m $s^{-1}$ found by Kochukhov et al. (2002), hence suggest that this result is spurious. Ryabchikova et al. (2004) dispute this, suggesting that because roAp stars are known, in many cases, to be multiperiodic, and to show amplitude modulation, that it is possible that both detections (11.5 min and 16.2 min) are real. For this to be true, it would have to be a beating effect, not a rotation effect, since the magnetic phase of both sets of observations are close (0.09 and 0.11). Ryabchikova et al. (2004) call for further observations to shed light on this.

We therefore decided to obtain new high time resolution, high spectral resolution, high S/N spectra of $\beta$ CrB to try to resolve these issues. We did not use an Iodine cell for the reasons given above, so we do not have the very high precision for the whole spectrum that Hatzes & Mkrtichian (2004) obtained and cannot test their 3.5 m $s^{-1}$ result. We can, however, examine the spectrum line-by-line and we find no confirmation of the variability of the Fe I 6156.36 Å line, nor any other Fe lines at the level suggested by Kochukhov et al. (2002). We also do not find any variability in the Ce II 6272.026 Å line, nor in three other Ce II lines at the level suggested by Hatzes & Mkrtichian (2004). The magnetic phase of our observations is very similar to those of these studies: 0.09 on our first night and 0.14 on our second night.

We concur with Hatzes & Mkrtichian (2004) that the signal in the single Fe I line found by Kochukhov et al. (2002) is likely to be spurious, and we show an example of similar spurious peaks in our own data. While the lack of variability in the Ce II lines places some doubt on the detection of Hatzes & Mkrtichian, their result for the 5000–6000 Å section of spectrum is still strong, so we do not claim to rule it out. As was argued by Ryabchikova et al. (2004) $\beta$ CrB could be multi-periodic with beating suppressing the amplitude for the Ce II lines at the times of our observations.

As all those who have come before us have done, we note the need for a much more extensive, high S/N study of this important star.

## 2. Observations and data reduction

On 2005 June 21 and 22 we obtained a series of echelle spectra of $\beta$ CrB with the high resolution spectrograph (*SARG*) (Gratton et al. 2001) equipped with the polarimeter (Leone et al. 2003) on the 3.55-m *Telescopio Nazionale Galileo* (TNG) (Bortoletto et al. 1998) at the Observatorio del Roque de los Muchachos (La Palma, Spain). On our first night we observed for 1.15 h (JD 2 453 543.54 − .59) and obtained 21 spectra with 3.4-min time resolution in intensity mode. On our second night we observed for 1.37 h (JD 2 453 544.48 − .54) and obtained 25 spectra with a 3.4-min time resolution in polarimetric mode, although for this study of radial velocity variations we used only Stokes $I$ on this second night.

Each spectrum covers the region from 4600 Å to about 7900 Å with a resolution of $R$ = 115 000. Because of the junction of the two CCDs, the $\lambda$6160–6240 interval is not recorded. To avoid fringing, we did not considered wavelengths longer than 7000 Å. By means of the NOAO/IRAF package, bias subtraction, spectra extraction, flat-fielding and wavelength calibration have been performed for the ordinary and extraordinary spectra for each frame. Particularly important is the wavelength calibration obtained with an internal accuracy of $10^{-4}$. Because of the R4 echelle, the S/N is different along any single order, but we have considered only those parts where it is between 100–250. At the edge of the bluest order the S/N drops to 50, but we did not use these noisiest sections of the spectra.

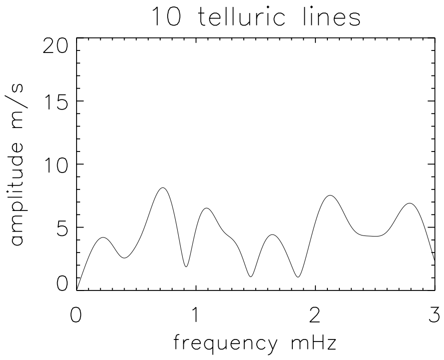


**Fig. 1.** The amplitude spectrum of the radial velocity variations for 10 telluric lines. The standard deviation in amplitude is formally only 1 m $s^{-1}$ from a least squares fit to the data, but we estimate from this diagram that $\sigma$ = 2 m $s^{-1}$ is more realistic.

## 3. Data analysis and results

We measured radial velocities on a line-by-line basis using the centre-of-gravity method for a set of 30 spectral lines in the 5000–7000 Å range. In particular we measured lines of Nd II, Nd III, Pr III and H$\alpha$, since those show the highest amplitudes in other roAp stars. We measured six Fe I lines, including the 6165.36 Å line to compare directly with Kochukhov et al. (2002), and we measured four Ce II lines, including the 6272.026 Å line to compare directly with Hatzes & Mkrtichian (2004). We did this for each night separately, and for the two nights combined, and in no case do we have a detectable signal. We will illustrate here only results from our first night where the spectrograph was used in intensity mode and where the magnetic phase was 0.09 – the same as for the observations of both Kochukhov et al. and Hatzes & Mkrtichian.

In Fig. 1 we show the amplitude spectrum for 10 telluric lines measured in the same way as the stellar lines. The highest noise peaks have amplitudes of on 8 m $s^{-1}$ and the standard deviation of a least squares fit of any frequency to the data gives a formal error of only 1 m $s^{-1}$. We believe this to be fortuitously low and estimate that the rms noise in the telluric lines to be more realistically 2 m $s^{-1}$. It is, in any case, so small that it has no impact on the following discussion of the stellar spectral line radial velocities.

In Fig. 2 we show the amplitude spectra for the Fe I line at 6165.36 Å and for our six Fe I lines together. The top panel of Fig. 2 does not by itself completely rule out a 70 m $s^{-1}$ signal at $\nu$ = 1.45 mHz suggested by Kochukhov et al. (2002); a least

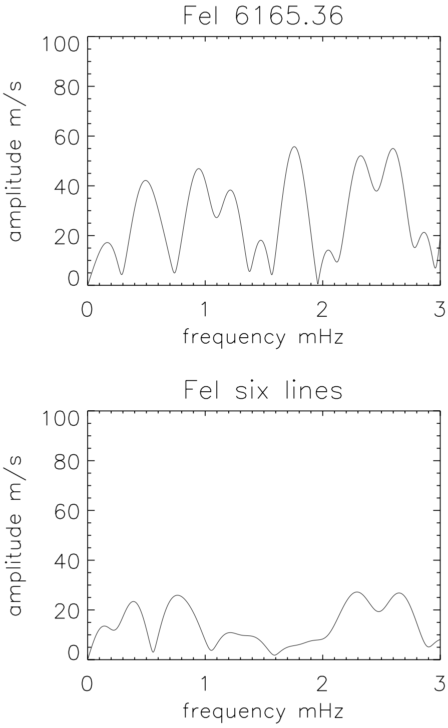


**Fig. 2.** The top panel shows the amplitude spectrum of the radial velocity variations for the Fe I 6165.36 Å line. The bottom panel shows the amplitude spectrum for six Fe I lines. Both panels are for night 1 when the magnetic phase was 0.09.

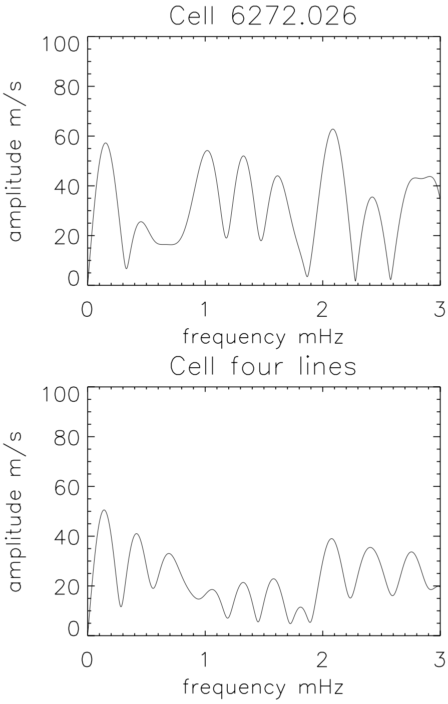


**Fig. 3.** The top panel shows the amplitude spectrum of the radial velocity variations for the Ce II 6272.026 Å line. The bottom panel shows the amplitude spectrum for four Ce II lines. Both panels are for night 1 when the magnetic phase was 0.09.

squares fit of that frequency to the data gives an amplitude of $18 \pm 21$ m s$^{-1}$. The least squares fit to six Fe I lines does rule out Kochukhov et al.'s (2002) amplitude of 70 m s$^{-1}$ with an amplitude of $9 \pm 7$ m s$^{-1}$, under the reasonable assumption that the Fe I lines behave similarly, and assuming that both Hatzes & Mkrtichian (2004) and we have not been so unlucky as to have caught a real multi-periodic signal at low beat phase. The result for our second day at magnetic phase 0.14 is the same. We therefore believe that the signal suggested by Kochukhov et al. (2002) for a single line is spurious.

In Fig. 3 we show the amplitude spectra for the 6272.026 Å Ce II line and for four Ce II lines. The top panel of Fig. 3 does not by itself completely rule out a 130 m s$^{-1}$ signal at $\nu = 1.068$ mHz as found by Hatzes & Mkrtichian (2004); a least squares fit of that frequency to the data gives an amplitude of $47 \pm 22$ m s$^{-1}$. But the least squares fit to four Ce II lines does so with an amplitude of $18 \pm 12$ m s$^{-1}$, again under the reasonable assumption that the Ce II lines behave similarly, and that we have not caught a real multi-periodic signal at low beat phase. Elkin, Kurtz & Mathys (in preparation) find for these same four Ce II lines in HD 101065 amplitudes of $218 \pm 15$ m s$^{-1}$ to $318 \pm 22$ m s$^{-1}$ with the 6272.026 Å line having an amplitude of $230 \pm 18$ m s$^{-1}$. Thus the average for the four lines in that case is greater than for the 6272.026 Å line alone. The result for our second day at magnetic phase 0.14 is the same. We therefore suggest that the signal found for the Ce II 6272.026 Å line by Hatzes & Mkrtichian (2004) is spurious. Although they analysed a chunk of the spectrum at the wavelength of this line, the continuum does not contribute to the measurement of radial velocity, so there is only the blend that is dominated by the Ce II line in their chunk (see their Fig. 3). Our comparison with a set of Ce II lines is therefore a valid test.

While this does not rule out Hatzes & Mkrtichian's (2004) much more robust signal for a large section of the spectrum, it leads to some doubt, since the result for the Ce II 6272.026 Å line was part of their corroborating argument. It also seems likely be the case, if their amplitude of $3.5 \pm 0.5$ m s$^{-1}$ for many lines is correct, that some lines will a much larger amplitude than that and others will show no variability, as is the case for other roAp stars. However, our data do not rule out the possibility that many, or most, lines in the spectrum vary with the same low amplitude, giving the average that Hatzes & Mkrtichian found. That will make $\beta$ CrB truly remarkable, if it should be found to be the case. We also cannot rule out the possibility that the star is multi-periodic and we were observing at time of low beat amplitude.

What we can rule out are amplitudes above 100 m s$^{-1}$ for the lines of Nd II, Nd III, Pr III, Eu II, Fe I, Ba I and H$\alpha$ that we studied at the times of our observations. We do not see believable signal for any of these lines on either of our two nights of observations. Combining a set of 19 good-quality lines from both nights gives us a precision of $\pm 3$ m s$^{-1}$, so if all lines show a similar amplitude, we can rule out anything above about 10 m s$^{-1}$. It seems more probable to us, given the known behaviour of other roAp stars, that if the 1.068-mHz signal is confirmed, some lines will be found to have much larger amplitude than 3.5 m s$^{-1}$, and it will be those lines that have generated the signal in the large chunks of spectrum. Proof of pulsation in $\beta$ CrB is important for understanding the roAp-noAp difference, hence understanding both pulsation driving and damping in roAp stars. Thus we, too, call for a more intensive spectroscopic study of this star.

## 4. Some comments

While calculation of false alarm probability is an important exercise when a signal may be in some doubt, it is usually not sufficient to persuade sceptics of the reality of the signal. To do that,

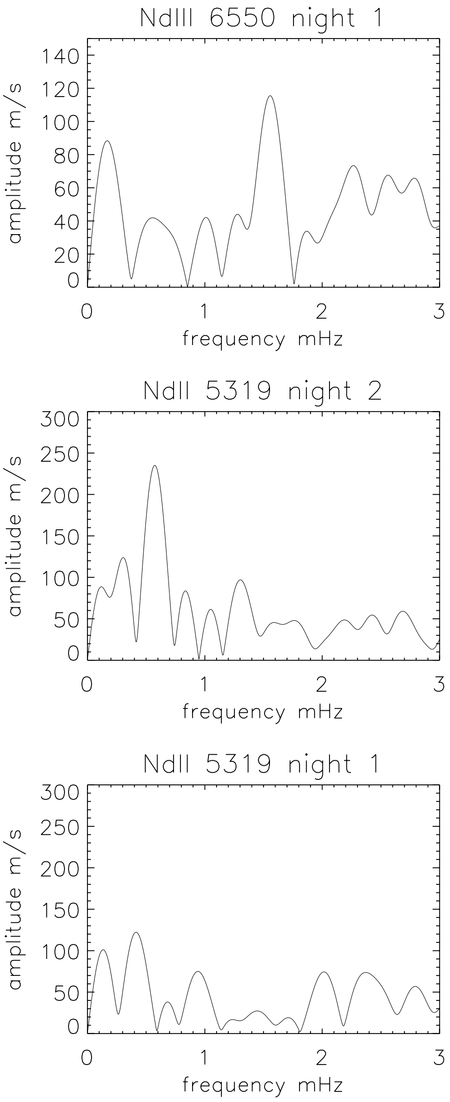


**Fig. 4.** The top panel shows the amplitude spectrum of the radial velocity variations for the Nd III 6550.330 Å line on our first night. This line often shows high radial velocity amplitude in other roAp stars, so it caught our attention. The middle panel shows the amplitude spectrum the Nd II 5319.815 Å line on our second night. This line also often shows high radial velocity amplitude in other roAp stars, so again the peak in intriguing, but it cannot be confirmed for our first night, as is shown in the bottom panel. Neither of the peaks in the top two panels can be found in any other line either, so they are spurious.

it is necessary to find the signal independently in separate data sets. Those can be separate lines in the same spectrum, separate sections or chunks of the spectrum, or in completely different sets of spectra. The problem with trusting in statistical calculations is that they require well-behaved and completely understood noise. There are many cases in helio- and asteroseismology of statistically significant results that later are shown to be spurious. Some examples are the vigorous debates about solar-like oscillators until a few years ago, about detection of g modes in the sun still, and about oscillations in Procyon.

When searching through periodograms (produced by any method) for roAp star oscillations, any peak standing out apparently above the noise in the frequency range of known roAp stars will attract attention. When searching hundreds or thousands of frequencies for dozens or hundreds of spectral lines, apparently significant peaks will be found. Of course, calculation of false alarm probability can give an indication of how much they should be trusted, but only an indication. Given the complexities of data acquisition, reduction and analysis, there may be unrecognised noise sources, so extra caution is needed.

In Fig. 4 we show the amplitude spectra for two lines that in other roAp stars show high amplitudes. In both cases here there are intriguing peaks, but they are not found in any other line on either night, and they are not present in the same line on the other night, so must be considered to be spurious. We suggest that the peaks for a single Fe I line by Kochukhov et al. (2002) and for a single Ce II line by Hatzes & Mkrtichian (2004) are probably similarly spurious.

We also point out that both Kochukhov et al. (2002) and Hatzes & Mkrtichian (2004) show phase diagrams for the frequencies they have found where the variation can be seen. While no claim is made for these diagrams in either paper, it is important to note that they do *not* provide a corroboration of the purported signal. Any high signal in a periodogram will produce a phase diagram where the variation can be seen. That is why there is a high peak in the periodogram. The periodogram and the phase diagram are just two different ways of looking at the same signal – whether or not that signal is in the star, or is spurious. What a phase diagram will show that is useful is whether the entire range of phase is well-covered by the data set.

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