Mon. Not. R. Astron. Soc. **337,** L1–L5 (2002)

Discovery of rapid radial velocity variations in the roAp star 10 Aql and possible pulsations of β CrB

O. Kochukhov,[1★] J. D. Landstreet,[2] T. Ryabchikova,[3,4] W. W. Weiss[4] and F. Kupka[4]

[1]*Uppsala Astronomical Observatory, Box 515, S-751 20 Uppsala, Sweden*
[2]*Department of Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada*
[3]*Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya 48, 109017 Moscow, Russia*
[4]*Institute for Astronomy, University of Vienna, Türkenschanzstraße 17, 1180 Vienna, Austria*

Accepted 2002 July 17. Received 2002 July 17; in original form 2002 June 3

ABSTRACT

We report discovery of radial velocity variations in rare earth spectral lines of the roAp star 10 Aql with amplitudes of between 30 and 130 m s^{-1} and periods of about 11 min. Radial velocity variations with amplitude 70 m s^{-1} may also have been detected in one spectral line of Fe I in β CrB. If confirmed, our results may indicate that all Ap stars in a certain temperature range pulsate, which means that roAp stars do not exist as a separate class but are only distinguished by higher pulsational amplitudes.

Key words: stars: chemically peculiar – stars: individual: 10 Aql – stars: individual: β CrB – stars: oscillations.

1 INTRODUCTION

10 Aql (HD 176 232, HR 7167) belongs to the group of cool magnetic chemically peculiar stars. Babcock (1958) reported that the star has an effective (mean longitudinal) magnetic field ranging between −315 and +440 G, and appears to show a substantial part of one cycle in five widely spaced field measurements obtained between 1948 and 1956. Preston (1970) found a constant field of +500 G during 10 consecutive nights in 1967. The rotational period of 10 Aql has not yet been established, but taking these data at face value, it could be several years.

10 Aql was discovered to be a rapidly oscillating Ap (roAp) star by Heller & Kramer (1988). It pulsates with three periods of ≈11.6, 12.1 and 13.4 min. All periods have photometric amplitudes well below 1 mmag, one of the lowest amplitudes found among roAp stars. No independent confirmation of the photometric variability has been published, and sometimes this star was considered as a questionable member of the roAp star group. 10 Aql is being considered as a target for a careful study of the roAp phenomenon during the space mission *COROT*.

Only a few among the 32 known roAp stars have been investigated for the radial velocity (RV) variations. Based on a line-by-line analysis, Savanov et al. (1999) and Kochukhov & Ryabchikova (2001a); Kochukhov & Ryabchikova (2001b) have shown that the highest amplitudes of the RV variations are observed in Pr III and Nd III spectral lines in the three roAp stars γ Equ, α Cir and HD 83 368. We present in this Letter the results of a similar study of RV variations in 10 Aql.

To estimate the accuracy of our RV amplitude measurements we also acquired time-series observations of the well-known cool Ap star β CrB (HD 137 909, HR 5747), for which numerous attempts to search for photometric high-overtone pulsations have produced null results (see Martinez & Kurtz 1994, and references therein). This star has atmospheric characteristics similar to roAp stars, and two independent time-series observational runs with Fabry–Perot spectrometers have produced controversial results. Ando et al. (1988) found evidence of RV variations with an amplitude ≈400 m s^{-1} at a frequency about 2.7 mHz in two consecutive nights, while a null result was obtained in two other nights corresponding to a different phase of the magnetic variations. Belmonte et al. (1989) found β CrB to be constant at a level of 200 m s^{-1} during 6.5 h of monitoring.

A description of the observations and of our reduction procedure is given in Section 2. Pulsational behaviour of individual metal lines in 10 Aql and β CrB is presented in Section 3. Discussion and conclusions are in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The observations discussed in this paper were obtained using the single-order $f/4$ Gecko coudé spectrograph with the EEV1 CCD at the 3.6-m Canada–France–Hawaii telescope. The details of each series of observations are given in Table 1. The exposure times adopted represent compromises between the need to sample the spectrum for only a small fraction of the expected period, and the need to have a reasonable signal-to-noise ratio in each spectrum.

These spectra cover approximately the spectral window 6105–6190 Å. This wavelength interval contains strong Nd III and Pr III lines as well as strong and weak lines of other elements such as Si, Ca, Cr, Fe and Ba. The spectra have a resolving power, determined

★E-mail: oleg@astro.uu.se

Table 1. Journal of spectroscopic observations of β CrB and 10 Aql.

Star	UT date (2001)	Exposure time (s)	Dead time (s)	No of exposures	Duration of observations (h)	Start HJD (245 2000+)	End HJD (245 2000+)	Typical SNR	Minimum period detectable (min)
β CrB	4 April	90	41	49	1.8	8.93454	9.00720	220	4.3
10 Aql	2 October	120	44	90	4.0	184.73428	184.90327	150	5.5
10 Aql	3 October	120	44	83	3.7	185.72275	185.87794	150	5.5

from the widths of a number of ThAr comparison lines, of about 115 000.

The spectra were reduced using standard IRAF (Image Reduction and Analysis Facility) tasks. Each stellar, flat and calibration frame had a mean bias subtracted and was then cleaned of cosmic ray hits and extracted to one dimension. Extracted stellar spectra were divided by an extracted mean flat-field, and the continuum was fit with a three-segment cubic spline, using the same rejection parameters for all spectra so that the continuum fit is as uniform as possible. The wavelength scale was established using about 40 lines of a ThAr emission lamp, resulting in an RMS scatter about the adopted pixel-wavelength relation of about 3×10^{-4} Å. The wavelength scale was linearly interpolated between ThAr lamp spectra taken before and after the stellar series, but the spectra were not resampled to a linear wavelength spacing. Finally, all spectra were shifted to the heliocentric frame of reference before analysis.

3 PULSATIONAL SPECTROSCOPIC VARIABILITY

3.1 10 Aql

We studied RV variations of lines in the spectrum of 10 Aql following the same scheme that was successfully used by Kochukhov & Ryabchikova (2001a) in the analysis of the roAp star γ Equ. First we computed separate standard deviation spectra for each of the two sets of time-resolved observations of 10 Aql. However, with this method we detected no clear signs of variations of any spectral lines comparable to those found in other roAp stars.

As the next step, we measured radial velocity shifts of each of ~140 absorption lines in the 6105–6188 Å spectral interval, using the centre-of-gravity method to determine line centres. These time-series data sets were analysed with the periodogram method of Horne & Baliunas (1986), which complements standard period search technique with an assessment of the reliability of the detected signal. The main advantage of the periodogram method in comparison with the usual Fourier transform of unevenly sampled data is that periodogram analysis allows for a rigorous statistical estimate of the probability that a given peak is a true signal (see Horne & Baliunas 1986; Scargle 1982). We note that for 10 Aql the uncertainties of our *individual* RV measurements are of the same order as the pulsational amplitude and hence a plot of RVs versus time with a fitted sinusoidal solution can only provide a personal impression on how 'convincing' is the detection of pulsations, but cannot substitute a statistical probability estimate.

RV variations were found in three spectral lines: Nd III 6145.07 Å, Eu II 6173.03 Å and Gd II 6180.43 Å. The Nd III line has a relatively low pulsational amplitude of only ≈30 m s^{-1}. Nevertheless, being the strongest of all three features, it provided the most reliable detection of non-radial pulsations during both nights of our observations of 10 Aql. This is illustrated in Fig. 1, where we present periodograms and RV measurements for the neodymium line. Variations of the Gd II line were also securely detected on both nights. The Eu II spectral line shows clear variations only in the first data set. The accuracy of our individual RV measurements was about ≈30 m s^{-1} for the Nd III line and about 130–150 m s^{-1} for the Eu II and Gd II spectral features. These error estimates are compatible with the RMS scatter around the mean curves.

To determine amplitudes and phases of the RV variations of spectral lines of rare earth elements (REE), we fitted a cosine curve to RV data, counting pulsational phase from the arbitrary heliocentric Julian date 245 2184.0. Results of this analysis are summarized in Table 2, which also lists periods and probability estimates derived with periodogram analysis. Radial velocity variations of the Eu II and Gd II lines are illustrated in Fig. 2.

For other spectral lines, only upper limits on the possible RV variations could be determined. For example, we found that strong and medium strength Ca I lines (6122.22, 6163.76, 6166.44, 6169.04 and 6169.56 Å) are constant to within 15–20 m s^{-1}, while Fe I, Fe II and Cr II spectral lines do not show variations above ≈25 m s^{-1}. It is also worth noting that Pr III spectral lines (e.g. 6160.24 Å), which are strong and show large pulsational variability in the spectrum of γ Equ (Kochukhov & Ryabchikova 2001a), are relatively weak in the wavelength region of 10 Aql studied here. Thus we were not able to reach any definite conclusions on whether or not the Pr III absorption features share the pulsational behaviour of the Nd III 6145.07 Å line.

The spectroscopic observational material used in the abundance analysis of 10 Aql by Ryabchikova et al. (2000) made possible only crude estimates or upper limits for the magnetic field modulus and rotational velocity. The high quality of the present spectra allows us to obtain a direct measurement of the magnetic field modulus as well as to improve the estimated projected rotational velocity. For this purpose we used an averaged spectrum of 10 Aql. Only one line in the whole spectral region, Fe I 6173.34 Å, clearly shows magnetic splitting. This line has a pure triplet Zeeman splitting pattern with Landé factor $z = 2.5$. Spectral synthesis of this line using the SYNTHMAG code (Piskunov 1999) results in the following values for magnetic field modulus and rotational velocity: $B_s = 1.5 \pm 0.1$ kG, $v_e \sin i = 2.0 \pm 0.5$ km s^{-1}. This is the first direct determination of the disc-averaged magnetic field modulus of 10 Aql. Fig. 3 shows a comparison between the observed and calculated profiles of the Fe I λ 6173.34 Å line. The value of B_s that we find is consistent with the small values of the mean longitudinal field observed by Babcock (1958) and Preston (1970). Note that the value of $v_e \sin i$ that we determine, which is different from zero at about the 4σ level, suggests that the rotation period of this star is probably less than about 1×10^2 d.

3.2 β CrB

Recent time-resolved high-resolution spectroscopic observations of roAp stars, including the first RV study of 10 Aql, presented in this paper, suggest that very efficient analysis of low-amplitude non-radial pulsations of magnetic stars can be carried out by focusing

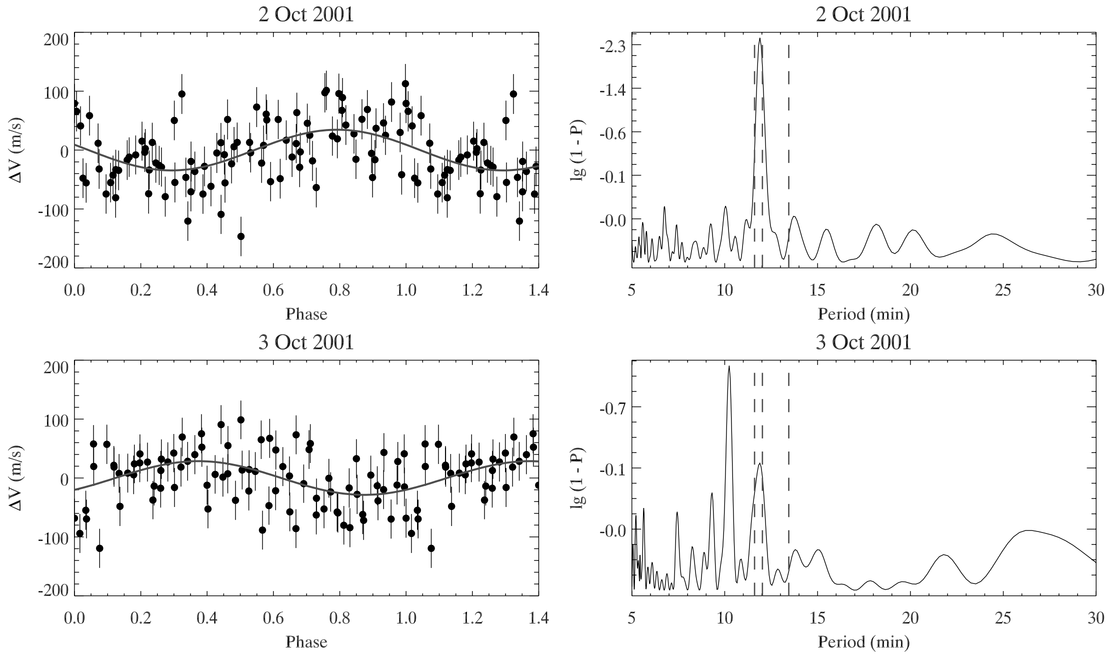

Figure 1. Radial velocity variations of the Nd III 6145.07 Å line in the spectrum of 10 Aql. The upper panels refer to our first observing night, while the lower panels illustrate analysis of the data set secured for the second night. Left panels show individual RV measurements (symbols) phased using the most probable periods. The best cosine fit to the data is shown by the solid line. Right panels show periodograms for our RV data. Note that the units of the vertical axis in these panels correspond to the log of the false-alarm probability, while vertical dashed lines identify photometric pulsation frequencies of 10 Aql detected by Heller & Kramer (1990).

on certain spectral features, in particular absorption lines belonging to the spectra of doubly ionized REE. In order to gain a better understanding of the dichotomy between pulsating and apparently constant cool Ap stars, we attempted to detect or at least place a stringent upper limit on the RV variations of individual metal lines in β CrB, for which no evidence of short-term photometric variability exists.

Our analysis of β CrB was similar to the study of 10 Aql described above. First we investigated standard deviation spectra (no excess of deviation associated with any particular spectral features was found), and then measured RVs of all spectral lines and blends in the 6102–6192 Å region. It should be emphasized that the strong magnetic field of β CrB noticeably affects many lines in the studied spectral interval via Zeeman broadening and splitting. As a result most spectral lines are broad and distorted compared with the spectrum of 10 Aql. This somewhat complicates line-by-line radial velocity analysis. In addition, doubly ionized REE lines, which are primary RV diagnostics in roAp stars, are weak in the spectrum of β CrB. Owing to these difficulties, analysis of the Nd III 6145.07 Å line allowed us to place an upper limit of only $\approx$40 m s^{-1} on the possible RV variations. At the same time we found that other strong absorption features were constant at the level of 20–30 m s^{-1}.

However, further careful RV analysis revealed intriguing evidence of possible short-term variations of the Fe I 6165.36 Å line. This spectral line is unblended and only weakly affected by the magnetic broadening (its Landé factor is $z = 0.69$). RV measurements of this line suggested the presence of pulsations with period 11.5 ± 0.5 min and semi-amplitude 71 ± 11 m s^{-1}. Fig. 4 compares RVs determined from Fe I 6165.36 with a nearby line of Ca I at 6166.44Å. The latter does not show the coherent signal evident in Fe I 6165.36 Å, confirming that RV variations of the iron line are probably not due to an unrecognized instrumental effect. Unfortunately other Fe I lines of strength similar to Fe I 6165.36 Å are badly blended and we could not confirm our tentative detection of rapid oscillations in β CrB.

Thus, although our line-by-line RV analysis clearly shows that high-amplitude pulsational RV variations are absent in β CrB, we cannot exclude low-amplitude pulsational variability in specific spectral features, in particular weak Fe I lines. At the moment we feel that the quality and quantity of our time-resolved spectroscopic data collected for β CrB does not allow us to claim definite detection of p-mode pulsations. We plan further spectroscopic monitoring of this cool Ap star in order to clarify its pulsational behaviour.

Table 2. Pulsational radial velocity variations of REE lines in the spectrum of 10 Aql. P is the probability that a real signal was detected in RV data, τ is the period estimated from the periodogram analysis, while A and φ are the amplitude and phase derived from the least-squares fitting of RV curves.

Ion	λ (Å)	2001 October 2				2001 October 3			
		P	τ (min)	A (m s^{-1})	φ	P	τ (min)	A (m s^{-1})	φ
Nd III	6145.07	0.99	11.89 ± 0.29	34.5 ± 6.8	0.792 ± 0.033	0.95	10.24 ± 0.19	28.6 ± 6.6	0.373 ± 0.038
Eu II	6173.03	0.92	11.81 ± 0.41	127.5 ± 26.6	0.340 ± 0.034	0.36	11.45 ± 0.27	83.9 ± 25.2	0.784 ± 0.047
Gd II	6180.43	0.98	11.70 ± 0.41	134.7 ± 28.0	0.292 ± 0.031	0.99	11.74 ± 0.26	129.1 ± 25.5	0.485 ± 0.032

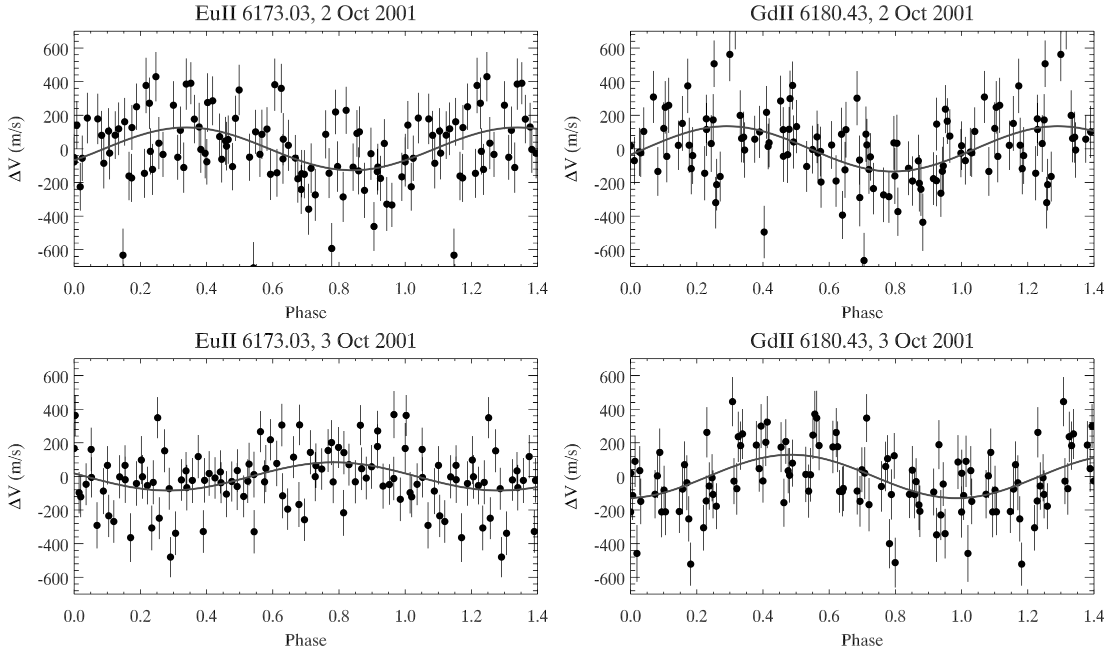

Figure 2. Radial velocity variations of the Eu II 6173.03 Å (left panels) and Gd II 6180.43 Å (right panels) lines in the spectrum of 10 Aql. The upper panels correspond to our first observing night, while the lower panels illustrate analysis of the data set secured for the second night. Each panel shows individual RV measurements (symbols) phased using the most probable periods. The best cosine fits to the data are shown by the solid lines.

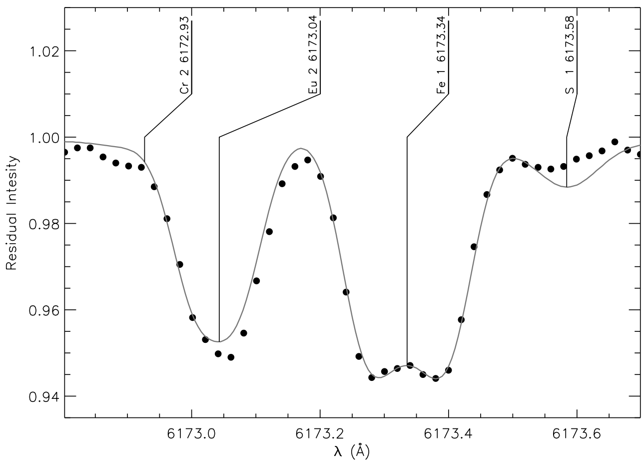

Figure 3. Comparison between observed (symbols) and computed (solid line) spectrum of 10 Aql in the region of Fe I 6173.34 Å spectral line.

4 DISCUSSION

Radial velocity variations of spectral lines (especially lines of rare earth elements) with one or more of the pulsation periods have previously been reported for three roAp stars (HD 83 368, α Cir and γ Equ). In this paper we have clearly established the occurrence of RV variations in several lines of 10 Aql and possibly detected variations in one line of β CrB. It appears that the RV variations that we observe in these two stars are smaller in amplitude than those detected to date in other stars; our observations show that very low amplitude RV variations are detectable, and that for some stars a velocity standard error of no more than a few tens of m s^{-1} is necessary to detect even principal pulsation periods.

As is found for the other stars, we observe that the variations of 10 Aql are most clearly visible in spectral lines of the rare earth elements, but in 10 Aql the largest amplitudes are visible in singly ionized rare earth elements rather than in doubly ionized ones. We confirm the generally noted behaviour that the amplitude of RV variations depends strongly on the spectral line studied, and that the rare earths somehow sample the vibrating region much more sensitively than do most spectral lines.

In contrast to 10 Aql, the tentative detection of RV variations in β CrB is in an iron line. If confirmed, this is a remarkable difference between the behaviour of RV variations in this star compared to other roAp stars. Our results on RV variations in β CrB raise a question about the existence of roAp stars as separate group: do all Ap stars in the roAp temperature range pulsate, but some with extremely low amplitudes?

With only a two-night series of 10 Aql (whose rotation period is unknown), and a one-night series of β CrB ($P_{\rm rot}$ = 18.5 d), we are unable to provide much useful information about variation of the amplitude of RV variations with rotational phase. However, the apparently significant differences between the periods of RV variations of the Nd III line in 10 Aql that we observed on October 2 and 3 suggests that the rotation period of this star might be only a few days. This conflicts with the period suggested by the magnetic field data (see above), but if the period is as short as a few days, the small value of $v_{\rm e} \sin i$ indicates a small inclination angle. Alternatively, period variations may be related to finite lifetimes of pulsation modes rather than rotational modulation. In this scenario, 10 Aql may behave similarly to γ Equ, which exhibits strong night-to-night variation of pulsational behaviour due to highly variable mode structure (Martinez et al. 1996).

Our observations confirm that pulsations in roAp stars can be studied through the RV variations of spectral lines. It is clear that such observations should provide a valuable new window for asteroseismology and offer new insights in the study of the roAp phenomenon.

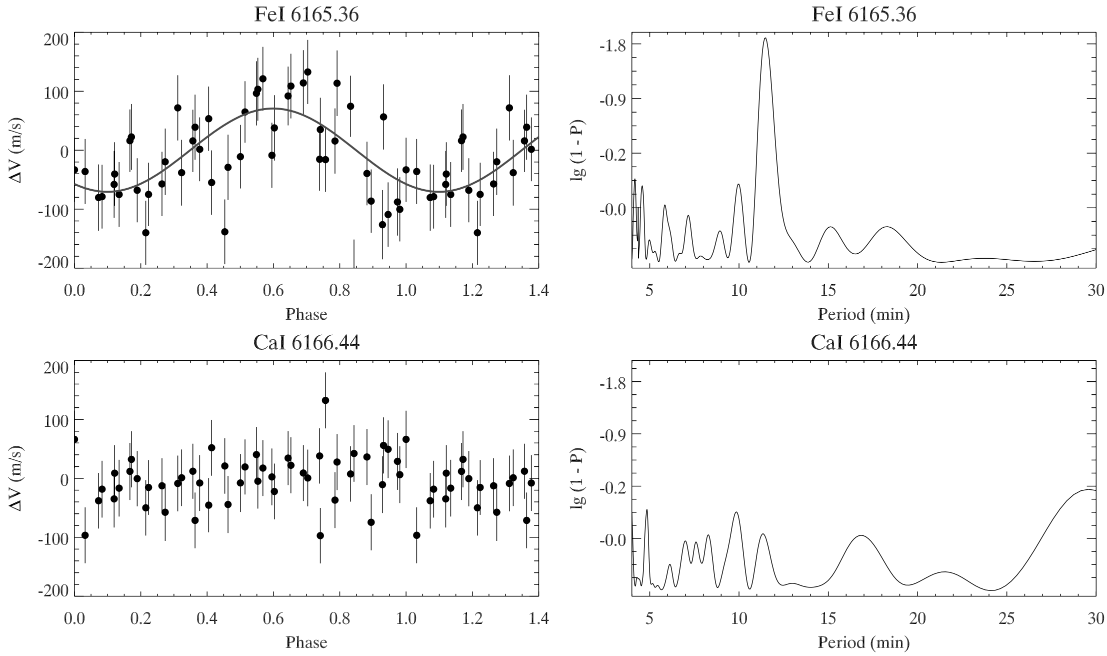

Figure 4. Radial velocity variations of the Fe I 6165.36 Å and Ca I 6166.44 Å lines in the spectrum of β CrB. Left panels show individual RV measurements (symbols) phased with the period of 11.5 min. The best cosine fit to the RVs of the Fe I line is shown by the solid curve. Right panels show periodograms for RV data. The units of the vertical axis correspond to the log of the false-alarm probability.

ACKNOWLEDGMENTS

This paper is based on observations obtained at the Canada–France–Hawaii Telescope, which is operated by the National Research Council of Canada, the Centre National de Recherche Scientifique of France, and the University of Hawaii. This work was supported by the Swedish Naturvetenskapliga forskningsrådet, by the Austrian Fonds zur Förderung der wissenschaftliche Forschung (projects *P13 936-TEC*, and *P14 984*), and by the Natural Sciences and Engineering Research Council of Canada. TR also acknowledges financial support by the 'Jubilaeumsfonds der Oesterreichischen Nationalbank' and Russian Federal program 'Astronomy'.

REFERENCES

Ando H., Watanabe E., Yutani M., Shimizu Y., Nishimura S., 1988, PASJ, 40, 249
Babcock H. W., 1958, ApJS, 3, 141
Belmonte J. A., Bell C. R., Leeper M., Pallé P. L., Pietraszewski K. A. R. B., Renton R. E., Roca Cortés T., 1989, A&A, 221, 41
Heller C. H., Kramer K. S., 1988, PASP, 100, 583
Heller C. H., Kramer K. S., 1990, MNRAS, 244, 372
Horne J. H., Baliunas S. L., 1986, ApJ, 302, 757
Kochukhov O., Ryabchikova T., 2001a, A&A, 374, 615
Kochukhov O., Ryabchikova T., 2001b, A&A, 377, L22
Martinez P., Kurtz D. W., 1994, MNRAS, 271, 129
Martinez P. et al., 1996, MNRAS, 282, 243
Piskunov N. E., 1999, in Stenflo J., Nagendra K. N., eds, 2nd Workshop on Solar Polarization. Kluwer Academic Publishers, Dodrecht, p. 515
Preston G. W., 1970, PASP, 82, 878
Ryabchikova T. A., Savanov I. S., Hatzes A. P., Weiss W. W., Handler G., 2000, A&A, 357, 981
Savanov I. S., Malanushenko V. P., Ryabchikova T. A., 1999, Astron. Lett., 25, 802
Scargle J. D., 1982, ApJ, 263, 835

This paper has been typeset from a TEX/LATEX file prepared by the author.