Astronomy & Astrophysics manuscript no. 11419
December 10, 2008

Letter to the Editor

Discovery of very low amplitude 9-minute multiperiodic pulsations in the magnetic Ap star HD 75445*

O. Kochukhov[1], S. Bagnulo[2], and G. Lo Curto[3]

[1] Department of Physics and Astronomy, Uppsala University, SE-751 20, Uppsala, Sweden
[2] Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland, UK
[3] European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Casilla 19001 Santiago 19, Chile

Received 25 November 2008 / Accepted 08 December 2008

ABSTRACT

We discovered pulsational radial velocity variations in the cool Ap star HD 75445 – an object spectroscopically very similar to the bright rapidly oscillating Ap (roAp) star γ Equ. Based on high-resolution time-series spectroscopy obtained with the HARPS spectrometer at the European Southern Observatory 3.6-m telescope, we detected oscillations in Nd II and Nd III lines with a period close to 9 min and amplitudes of 20–30 m s^{-1}. Substantial variation of the pulsational amplitude during our 3.8 h observing run reveals the presence of at least three excited non-radial modes. The detection of extremely low amplitude pulsations in HD 75445 indicates that the roAp excitation mechanism produces variability with the radial velocity amplitude anywhere between few tens m s^{-1} and several km s^{-1}. This supports the idea that many, if not all, cool Ap stars occupying the roAp instability strip may harbour non-radial pulsations which currently remain undetected due to very small photometric and radial velocity amplitudes.

Key words. stars: atmospheres – stars: chemically peculiar – stars: oscillations – stars: individual: HD 75445

1. Introduction

Rapidly oscillating Ap (roAp) stars are magnetic chemically-peculiar stars pulsating in non-radial, magnetoacoustic *p*-modes with periods close to 10 min. Pulsations in roAp stars are believed to be driven by the opacity mechanism operating in the hydrogen ionization zone (Balmforth et al. 2001). The presence of strong magnetic fields in roAp stars enhances the driving of the high-overtone oscillations through the suppression of convection, influences pulsation frequencies, and determines the global geometry of the pulsational perturbations (Dziembowski & Goode 1996; Saio 2005).

Strongly inhomogeneous vertical distribution of chemical elements combined with the rapid transformation of the outward propagating pulsation waves is responsible for the unique spectroscopic pulsation signature of roAp stars (Ryabchikova et al. 2002). In particular, the lines of rare-earth elements (REEs) and the cores of the hydrogen lines pulsate with 10–100 times higher amplitudes than the rest of the spectral features (Kochukhov & Ryabchikova 2001; Mkrtichian et al. 2003; Kurtz et al. 2006).

The observed roAp instability strip is constrained to the $T_{\rm eff}$ range 6400–8100 K, although theoretical stability calculations (Cunha 2002) predict pulsations in stars as hot as 9500 K and are unable to account for the unstable modes observed in stars with $T_{\rm eff} \leq 7400$ K. At the same time, the coexistence of pulsating and apparently constant Ap stars in the same region of the H-R diagram has been a long-standing puzzle (e.g., Martinez & Kurtz 1994). It is now understood that the time-resolved photometric techniques employed to detect and study variability in most of the 37 known roAp stars are insensitive to the low-amplitude pulsations observed in recent spectroscopic time-series analyses (Hatzes & Mkrtichian 2004; Elkin et al. 2005). This leads to the suggestion that all magnetic Ap stars in a certain temperature range may oscillate, but some have amplitudes below the photometric detection threshold (Kochukhov et al. 2002).

We are testing this hypothesis with a high-precision survey of a sample of bright cool magnetic Ap stars using the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph at the European Southern Observatory (ESO). The first result of our observations – the discovery of 10.9-minute oscillations in the Ap star HD 115226 – was reported by Kochukhov et al. (2008). Here we present the discovery of a new rapidly oscillating Ap star, HD 75445, which pulsates with one of the lowest radial velocity (RV) amplitudes known among roAp stars.

2. Observations and data reduction

We have used the HARPS spectrograph (Mayor et al. 2003) at the ESO 3.6-m telescope at La Silla to monitor HD 75445 in the context of our search for low-amplitude variability in bright cool Ap stars (ESO program 079.D-0118). The star was observed on the night of April 15, 2007. The observations have started at the barycentric JD 2454205.47129 and continued for 3.8 hours. We collected 120 consecutive 80 s exposures, separated by the dead time of 31 s. The resulting time resolution of 111 s allows investigating variations with frequencies up to $\nu = 4.5$ mHz ($P = 3.7$ min).

The extraction of one-dimensional spectra and barycentric velocity correction of the wavelength scale was performed with the help of the HARPS pipeline. Our spectra have a nominal resolving power $R \equiv \lambda/\Delta\lambda = 115\,000$, and cover a wavelength range from 3780 to 6910 Å, with a 30 Å gap near 5320 Å. Individual exposures of HD 75445 have peak signal-to-noise ra-

Send offprint requests to: O. Kochukhov, e-mail: oleg@fysast.uu.se

* Based on observations collected at the European Southern Observatory, Chile (ESO programs 68.D-0254, 079.D-0118)

tio of 70 per 15 mÅ pixel at λ 6000 Å. In the final reduction step one-dimensional extracted spectra of HD 75445 were post-processed to achieve consistent continuum normalization following the procedure described in Kochukhov et al. (2007).

We did not employ the simultaneous ThAr method available at HARPS, avoiding contamination of the stellar signal. Instead, we took a ThAr reference spectrum at the beginning and at the end of the stellar observations. Using these calibrations, we estimate that the instrumental drift within the time series was below 0.1 m s^{-1}. For the moderate signal-to-noise ratio of individual spectra of HD 75445 the dominant source of noise in the radial velocity measurements is the photon noise (≥ 2 m s^{-1}) rather than the instrumental precision, which is of the order of the measured drift.

3. Basic properties of HD 75445

The southern chemically-peculiar star HD 75445 (HIP 43257, CD −38°4907) was classified as a Sr-Eu object by Bidelman & MacConnell (1973). Its Strömgren photometric indices, $b-y = 0.159$, $m_1 = 0.218$, $c_1 = 0.729$ (Vogt & Faundez 1979), Hβ = 2.801 (Maitzen et al. 2000), indicate $T_{\rm eff} = 7600$–7700 K according to the calibrations by Moon & Dworetsky (1985) and Napiwotzki et al. (1993). Geneva colors yield $T_{\rm eff} = 7680$ K (Kochukhov & Bagnulo 2006), in good agreement with the Strömgren photometry.

Kochukhov & Bagnulo (2006) investigated the evolutionary state of HD 75445 using Hipparcos parallax and photometric $T_{\rm eff}$. They determined $\log L = 1.17 \pm 0.06\,L_\odot$, $M = 1.81 \pm 0.05\,M_\odot$ and a fractional stellar age 0.56–0.72 of the main sequence lifetime. Ryabchikova et al. (2004) included HD 75445 in the abundance analysis study of a sample of roAp and non-pulsating Ap stars. Adopting $T_{\rm eff} = 7700$ K and $\log g = 4.3$, they showed that HD 75445 has close to solar Fe abundance, moderate enhancement of Cr and Mn, 1.6 dex overabundance of Co, and a very large overabundance of several REEs. Similar to many known roAp stars, HD 75445 exhibits ionization anomaly in Pr and Nd, with doubly ionized lines of these elements giving 1.3–2.0 dex higher abundance than the lines of first ions. Ryabchikova et al. (2008) examined Ca stratification and isotopic composition of HD 75445. They reported a 2.0 dex step-like change of the Ca concentration at $\log \tau_{5000} = -0.9$ and detected the presence of heavy Ca isotopes (^{46}Ca and ^{48}Ca) in the upper atmospheric layers. This study also inferred spectroscopic $T_{\rm eff} = 7650$ K using the Hα line.

Ryabchikova et al. (2004) commented on the spectroscopic similarity of HD 75445 and the bright roAp star γ Equ (HD 201601). This point is illustrated in Fig. 1 with new very high quality, R = 115 000 spectra available for both stars (mean HARPS spectrum for HD 75445 and mean UVES spectrum derived from the archival time series data set of γ Equ). The spectra of these two stars are nearly identical, the only difference being slightly broader line profiles of γ Equ due to a stronger mean surface field strength of this star. The spectra of the two stars are, however, remarkably discrepant in the region of the resonance Li i doublet at λ 6708 Å, which is strong in γ Equ but entirely absent in HD 75445 (Kochukhov 2008).

Mathys et al. (1997) detected Zeeman splitting in the Fe ii 6149 Å line of HD 75445 and measured the mean field modulus $\langle B \rangle = 2985 \pm 42$ G with 9 spectra recorded over the period of 450 d in 1994–1995. Ryabchikova et al. (2004) provided three additional measurements of $\langle B \rangle$, 2915, 2957, and 2873 G, for the spectra obtained in 2000–2001. The splitting of Fe ii 6149 Å

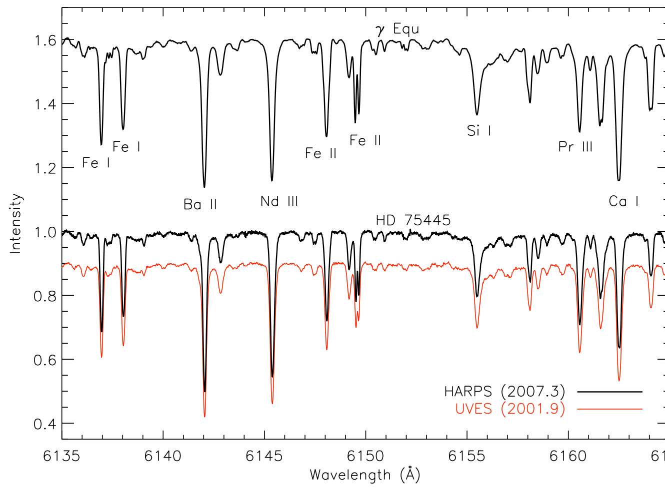

Fig. 1. Comparison of the 6135–6165 Å region in the spectra of the new roAp star HD 75445 and the well-known bright roAp star γ Equ. The UVES spectrum of γ Equ is shown on top, with the identification for the strongest spectral features. The mean HARPS spectrum of HD 75445 (middle, thick curve) is compared with the UVES observation of this star (bottom, thin curve) obtained 5.4 years before the HARPS observations. The UVES spectra are shifted vertically for display purposes.

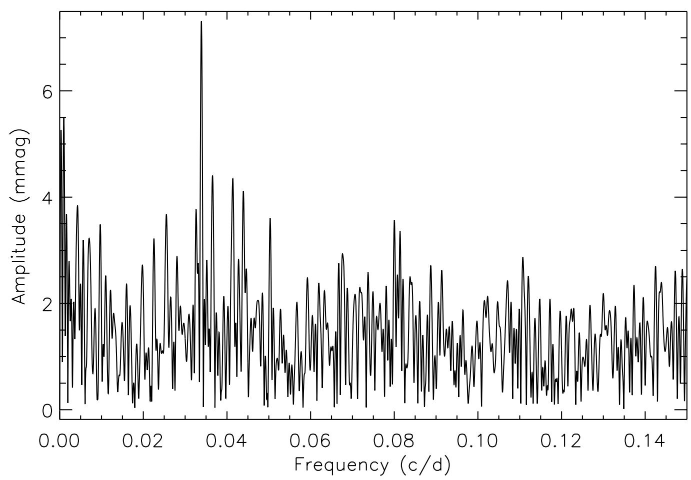

Fig. 2. Amplitude spectrum for the ASAS photometry of HD 75445 obtained after 2003.6.

in our mean HARPS spectrum (2007.3) and in the UVES spectrum from 2001 (Ryabchikova et al. 2008) is consistent with $\langle B \rangle = 3030$ G. In summary, the full set of 14 $\langle B \rangle$ measurements shows no evidence of periodic field strength variation.

We have searched for long-period rotational brightness modulation in HD 75445 using the Hipparcos epoch photometry (ESA 1997) and the ASAS database (Pojmanski 2002). No periodic variability with an amplitude above 5 mmag is visible in the Hipparcos light curve. The ASAS photometry of HD 75445 shows erratic brightness changes before 2003, which are probably instrumental in nature. Measurements obtained after 2003.6 do not deviate much from the mean value $V = 7.14$. The amplitude spectrum computed for the ASAS observations of HD 75445 during 2003.6–2008.8 shows a marginal 7 mmag variability with a 29.5 d period (Fig. 2). This is consistent with our estimate of $v_{\rm e} \sin i \leq 2$ km s^{-1} obtained by fitting profiles of magnetically insensitive Fe i lines at λ 5434, 5576, and 5691 Å. Comparison of the mean HARPS spectrum with the UVES observation obtained 5.4 years before our observing run shows no detectable changes in the line profiles (Fig. 1), suggesting a very long rotation period.

Spectroscopic similarity of HD 75445 to γ Equ, its prominent REE ionization anomaly, and $T_{\rm eff} < 8000$ K make this star an obvious candidate for the search of non-radial oscillations (Ryabchikova et al. 2004). However, no photometric pulsation signature exceeding one mmag was detected for this star by Martinez (private communication). Here we show that HD 75445 is indeed a roAp star but pulsating with an amplitude well below the current detection threshold of the ground-based time-resolved photometry.

4. Analysis of radial velocity variation

We measured radial velocities of lines in the spectrum of HD 75445 using the centre-of-gravity technique (Kochukhov & Ryabchikova 2001). Spectral line identification was based on the atomic line data extracted from the VALD database (Kupka et al. 1999), which includes the DREAM compilation of the REE line parameters (Biémont et al. 1999). The list of Nd III transitions was further extended using the study by Ryabchikova et al. (2006).

Previous time-resolved spectroscopic analyses of roAp stars (Kochukhov & Ryabchikova 2001; Mkrtichian et al. 2003; Ryabchikova et al. 2007a,b) demonstrated that maximum pulsation amplitudes are always found in singly and doubly ionized REE absorption features, such as Nd II, Nd III, and Pr III. A number of strong and medium-strength lines of REE ions are present in the spectrum of HD 75445. However, observational data available to us do not have high enough signal-to-noise ratio to see pulsations in individual lines. We have decreased the noise in velocity curves by averaging RV measurements for all lines of the same REE ions. Among rare-earths, only Nd II and Nd III have sufficient number of lines in the spectrum of HD 75445 to yield precise combined RV measurements.

Using 29 lines of Nd III and 56 lines of Nd II we reach the noise level of 3–5 m s^{-1} in the amplitude spectra and reveal conspicuous amplitude peaks in the 1.8–2.0 mHz frequency range, suggesting the presence of oscillations with an amplitude of 20–30 m s^{-1} (Fig 3, Table 1). These oscillation signatures are highly significant. The probability that noise would produce a peak with observed amplitude at *any* frequency in the studied range (False Alarm Probability, Horne & Baliunas 1986) is 7×10^{-5} for Nd II and 4×10^{-6} for Nd III. We also applied a bootstrap randomization technique (Kuerster et al. 1997), which is a more rigorous method of establishing statistical significance of a peak in amplitude spectrum. Out of 10^5 randomly shuffled data sets which we have created from the original mean Nd II and Nd III RV curves none exhibits spurious peaks with the observed amplitude in the frequency range 0–4.5 mHz. Thus, the probability that noise would create the signal detected in Nd II and Nd III lines is less than 10^{-5}.

Applying similar analysis procedure to 15 telluric lines in the 6275–6315 Å region we find no oscillations above 8 m s^{-1} with a noise level of 3 m s^{-1}. Similarly, for the combined RV curve of 49 Fe I and Fe II lines, not expected to show significant variation in a low-amplitude roAp star, we find maximum amplitude of 6 m s^{-1} with a noise level of 2 m s^{-1}. The stability of telluric lines and the stellar Fe features confirms that variation detected in the Nd lines of HD 75445 is not due to an instrumental artifact.

The complex appearance of the Nd II and Nd III amplitude spectra in Fig. 3 suggests a multiperiodic pulsation. The presence of several excited modes in HD 75445 becomes apparent if the mean RV data is analysed in the time domain. We found that

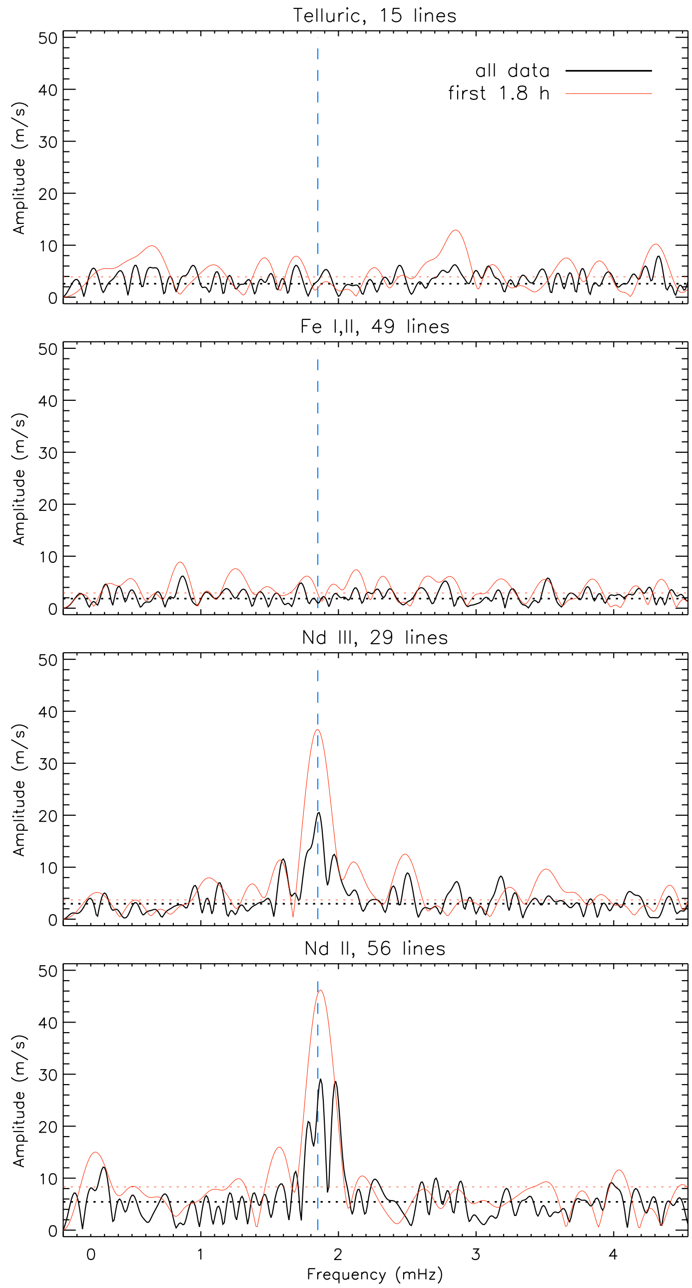

Fig. 3. From the top panel to the bottom panel: amplitude spectra for the average radial velocity curves of 15 telluric lines, 49 lines of Fe I and II, 29 lines of Nd III, and 56 lines of Nd II. The vertical dashed line shows the main pulsation frequency ν = 1.85 mHz. In each panel the amplitude spectrum of the whole data set (thick curve) is compared to that of the first 1.8 h of the spectroscopic monitoring (thin curve). Horizontal dotted lines show corresponding noise levels.

in the first 55 observations of HD 75445, corresponding to the initial 1.8 h of our time-resolved observations, pulsation variability stands out clearly. The amplitude spectra of this partial data set, illustrated in Fig. 3, indicate nearly monoperiodic pulsation. The least-squares fitting of this part of the oscillation curve yields amplitudes of 36 and 46 m s^{-1} as well as pulsation periods of 8.93 ± 0.05 min and 9.04 ± 0.04 min for the singly and doubly ionized Nd, respectively. There is a small lag of 0.44 ± 0.19 rad between the RV maxima of the two Nd ions. Similar to other roAp stars (Ryabchikova et al. 2007a), Nd III in HD 75445 shows a later maximum compared to Nd II.

Table 1. Frequency analysis of the average radial velocity curves of telluric lines, Fe I and II, Nd III and Nd II. N indicates the number of lines measured. $A_{\rm max}$ gives the highest radial velocity amplitude, followed by the estimate of False Alarm Probability of the corresponding signal. The last two columns give the amplitude of the variation with $\nu = 1.85$ mHz ($P = 9.01$ min) and the noise estimate.

Ion	N	$A_{\rm max}$ (m s^{-1})	FAP	A (m s^{-1})	σ (m s^{-1})
Full data set					
Telluric	15	7.9	0.31	2.5 ± 2.5	2.6
Fe I,II	49	6.2	0.31	1.5 ± 1.8	1.8
Nd II	56	29.1	6.6E-05	24.6 ± 4.8	4.9
Nd III	29	20.5	3.6E-06	20.4 ± 3.0	3.0
First 1.8 h					
Nd II	56	46.2	8.7E-06	44.2 ± 5.5	5.5
Nd III	29	36.5	1.1E-06	36.4 ± 3.8	3.7

The prominent sinusoidal variation of Nd lines is subdued after about 2 h from the beginning of our observations, presumably due to beating of several excited modes as seen in other multiperiodic roAp stars (e.g., Sachkov et al. 2008). Tentative least-squares analysis suggests the presence of at least three significant frequencies: $\nu_1 = 1.81$ mHz ($P_1 = 9.20$ min), $\nu_2 = 1.85$ mHz ($P_2 = 9.01$ min), and $\nu_3 = 1.99$ mHz ($P_3 = 8.37$ min). The length of our time series does not allow fully resolving ν_1 and ν_2. On the other hand, ν_2 and ν_3 are resolved, and ν_3 has a higher relative amplitude for Nd II.

5. Discussion

In this paper we have established the presence of multiperiodic pulsations in the cool magnetic Ap star HD 75445 using combined RV measurements of the lines belonging to Nd II and Nd III. The star exhibits oscillations with three frequencies, which have different amplitude ratios for the two Nd ions. The phase lag between RV curves of Nd II and Nd III can be interpreted in the framework of the outwardly propagating pulsational perturbation, which first reaches the layer where Nd II lines form and, after some delay, is seen in the higher atmospheric layer probed by stronger Nd III lines (Ryabchikova et al. 2007a; Mashonkina et al. 2005). The difference in the amplitude ratios of the frequency components of the Nd II and Nd III RV curves can be ascribed to different vertical cross-sections of the three pulsation modes.

HD 75445 is the 38th known roAp star. Its discovery stands out because the star's pulsation amplitude is significantly lower than for other roAp stars discovered to date using time-resolved spectroscopy. For example, HD 218994 (Gonzalez et al. 2007) and HD 115226 (Kochukhov et al. 2008) pulsate with an amplitude ≥ 500 m s^{-1}, while for HD 116114 (Elkin et al. 2005) and HD 154708 (Kurtz et al. 2006) pulsations with an amplitude of 50–100 m s^{-1} were reported. Only for β CrB (HD 137909) comparable RV amplitudes of 20–30 m s^{-1} were found in individual lines of singly ionized REEs (Kurtz et al. 2007). However, β CrB is in many respects different from other roAp stars. It is an evolved star with a long pulsation period and a chemical composition deviating from that of typical roAp star (Ryabchikova et al. 2004). In contrast, HD 75445 appears to have average roAp characteristics and is, in fact, a spectroscopic twin of the well-known roAp star γ Equ. Nevertheless, it pulsates with an unusually low RV amplitude. This shows that although the atmospheric chemical composition, in particular the REE ionization anomaly, is helpful in selecting roAp candidates, it does not have a direct connection to the amplitude of oscillations in the line-forming region.

Kurtz et al. (2006) noted the tendency for weaker roAp oscillations to be found in stars with stronger fields. However, HD 75445 has the mean field modulus significantly weaker than many roAp stars but also shows an exceptionally low pulsation amplitude. We therefore conclude that a low-amplitude roAp pulsation can be present in cool Ap stars with any field strength. Although there are theoretical reasons to believe that magnetic field alters the amplitude of the photospheric oscillations in few strong-field stars, a parameter other than the field intensity defines pulsation amplitude for other roAp stars.

Detection of the very low amplitude pulsations in HD 75445 suggests that the roAp excitation mechanism produces oscillations with no apparent lower amplitude threshold. Thus, many cool Ap stars may possess pulsations with RV amplitudes $\ll 100$ m s^{-1}, which currently can be detected with time-resolved spectroscopy only in bright sharp-line stars such as HD 75445.

References

Balmforth, N. J., Cunha, M. S., Dolez, N., Gough, D. O., & Vauclair, S. 2001, MNRAS, 323, 362
Bidelman, W. P. & MacConnell, D. J. 1973, AJ, 78, 687
Biémont, E., Palmeri, P., & Quinet, P. 1999, Ap&SS, 269, 635
Cunha, M. S. 2002, MNRAS, 333, 47
Dziembowski, W. A. & Goode, P. R. 1996, ApJ, 458, 338
Elkin, V. G., Riley, J. D., Cunha, M. S., Kurtz, D. W., & Mathys, G. 2005, MNRAS, 358, 665
ESA. 1997, ESA Special Publication, Vol. 1200, The HIPPARCOS and TYCHO catalogues
Gonzalez, J. F., Hubrig, S., & Savanov, I. 2007, Informational Bulletin on Variable Stars, 5794, 1
Hatzes, A. P. & Mkrtichian, D. E. 2004, MNRAS, 351, 663
Horne, J. H. & Baliunas, S. L. 1986, ApJ, 302, 757
Kochukhov, O. 2008, A&A, 483, 557
Kochukhov, O. & Bagnulo, S. 2006, A&A, 450, 763
Kochukhov, O., Landstreet, J. D., Ryabchikova, T., Weiss, W. W., & Kupka, F. 2002, MNRAS, 337, L1
Kochukhov, O. & Ryabchikova, T. 2001, A&A, 374, 615
Kochukhov, O., Ryabchikova, T., Bagnulo, S., & Lo Curto, G. 2008, A&A, 479, L29
Kochukhov, O., Ryabchikova, T., Weiss, W. W., Landstreet, J. D., & Lyashko, D. 2007, MNRAS, 376, 651
Kuerster, M., Schmitt, J. H. M. M., Cutispoto, G., & Dennerl, K. 1997, A&A, 320, 831
Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
Kurtz, D. W., Elkin, V. G., Cunha, M. S., et al. 2006, MNRAS, 372, 286
Kurtz, D. W., Elkin, V. G., & Mathys, G. 2007, MNRAS, 380, 741
Maitzen, H. M., Paunzen, E., Vogt, N., & Weiss, W. W. 2000, A&A, 355, 1003
Martinez, P. & Kurtz, D. W. 1994, MNRAS, 271, 129
Mashonkina, L., Ryabchikova, T., & Ryabtsev, A. 2005, A&A, 441, 309
Mathys, G., Hubrig, S., Landstreet, J. D., Lanz, T., & Manfroid, J. 1997, A&AS, 123, 353
Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20
Mkrtichian, D. E., Hatzes, A. P., & Kanaan, A. 2003, MNRAS, 345, 781
Moon, T. T. & Dworetsky, M. M. 1985, MNRAS, 217, 305
Napiwotzki, R., Schoenberner, D., & Wenske, V. 1993, A&A, 268, 653
Pojmanski, G. 2002, Acta Astronomica, 52, 397
Ryabchikova, T., Kochukhov, O., & Bagnulo, S. 2008, A&A, 480, 811
Ryabchikova, T., Nesvacil, N., Weiss, W. W., Kochukhov, O., & Stütz, C. 2004, A&A, 423, 705
Ryabchikova, T., Piskunov, N., Kochukhov, O., et al. 2002, A&A, 384, 545
Ryabchikova, T., Ryabtsev, A., Kochukhov, O., & Bagnulo, S. 2006, A&A, 456, 329
Ryabchikova, T., Sachkov, M., Kochukhov, O., & Lyashko, D. 2007a, A&A, 473, 907
Ryabchikova, T., Sachkov, M., Weiss, W. W., et al. 2007b, A&A, 462, 1103
Sachkov, M., Kochukhov, O., Ryabchikova, T., et al. 2008, MNRAS, 389, 903
Saio, H. 2005, MNRAS, 360, 1022
Vogt, N. & Faundez, A. M. 1979, A&AS, 36, 477