Contrib. Astron. Obs. Skalnaté Pleso **38**, 301 – 310, (2008)

The roAp phenomenon – many unsolved issues

H. Shibahashi

Department of Astronomy, University of Tokyo, Tokyo 113-0033, Japan
(E-mail: shibahashi@astron.s.u-tokyo.ac.jp)

Received: January 15, 2008; Accepted: March 6, 2008

Abstract. Many issues have arisen with the increasing variety of observations of roAp stars. I will discuss the blue-to-red motion in the line profile variation which have recently been found in Nd III and Pr III lines in many roAp stars. To understand the rapid oscillations in Ap stars, the influence of magnetic fields and chemical peculiarity must be taken into account. I will discuss the wave propagation in a stratified plane atmosphere with a magnetic field as fundamental concepts.

Key words: stars: chemically peculiar – stars: oscillations – stars: variables: other

1. Introduction

It was thought for a long time on empirical grounds that chemical peculiarity in A-type stars and pulsation are mutually exclusive. But in 1978, rapid low-amplitude (by classical-variable standards) light variations were discovered by Kurtz in the magnetic Ap star HD 101065, and within a few years several more such stars were discovered (Kurtz, 1982). Surprisingly, these stars have pulsation periods of only about 10 minutes, substantially shorter than the dynamical timescale $2\pi(R^3/GM)^{1/2}$, which for main-sequence A-type stars is typically about 2 hours. These observations established the concept of 'rapidly oscillating Ap stars' (roAp stars).

Magnetic fields of the order of a kilogauss are detected in many of the Ap stars. Their apparent magnetic field strength varies periodically and almost sinusoidally, and this periodic variation is likely to be caused by the rotation of the star, in which the magnetic axis is inclined to the rotational axis. Though the presence of a strong magnetic field has so far been confirmed only for some roAp stars, the oscillation amplitude of the light variation of such roAp stars has been found to be modulated with the variation of magnetic field strength. Kurtz (1982) showed that amplitude modulation of the rapid oscillations in such roAp stars is well-explained in terms of one or more axisymmetric dipole modes whose axis is aligned with the magnetic axis and inclined to the rotational axis of the star. This is called the oblique-pulsator model. Taking into account the technical difficulty of detecting magnetic fields, all roAp stars are believed to be magnetic stars. Indeed, in many cases, even though no magnetic field has yet been detected, the pulsation amplitudes of light variation are found to vary periodically with a time scale of several days. This implies that the oscillations in Ap stars are not radial pulsations, and that they are strongly influenced by the global magnetic field of the star. There are currently 36 known members of that class, including a new one reported at this conference by González *et al.* (2008).

With the increasing number of observations of roAp stars, rapid oscillations seen in these stars appear to be positively correlated with chemical peculiarity, particularly with a Sr-Cr-Eu overabundance. Why are the oscillations associated with anomalous chemical abundances? Why do the oscillations have such short periods? How does the magnetic field affect the oscillations? Many questions have arisen with the discovery of roAp stars. To answer them, the influence of magnetic fields and chemical peculiarity must be taken into account. In this review, I will discuss the wave propagation in a stratified plane atmosphere with magnetic fields as fundamental background.

There are many comprehensive reviews of roAp stars; recent ones are those included in the proceedings of the Mmabatho meeting (e.g., Houdek, 2003; Shibahashi, 2003), those included in the proceedings of IAUS 224 held at Poprad (e.g., Balona, 2004; Kurtz *et al.*, 2004), a lecture given by Gough (2005) in the Roger Tayler memorial lectures, and review talks given by Kochukhov (2007) and Cunha (2007) in the Vienna workshop. For readers interested in these stars, I recommend consulting these reviews as well.

2. Recent progress: photometric observations

The primary pulsation periods of roAp stars are typically $\sim 10\,\mathrm{min}$. The very high frequencies of oscillations of roAp stars are naturally interpreted as very high overtone p-mode oscillations. The eigenfrequency $\nu_{n,\ell}$ of such a high order p-mode with a low degree is, to first order, given by

$$\nu_{n,\ell} \simeq \nu_0(n + \ell/2 + \varepsilon). \tag{1}$$

Here,

$$\nu_0 \equiv \left[2\int_0^R c^{-1}dr\right]^{-1}, \tag{2}$$

where c denotes the sound speed, ℓ is the degree, n is the radial order of the mode, and ε is a constant which is dependent on the equilibrium structure of the star. Hence, the frequencies of such p-modes with even and odd ℓ alternate with a separation of $\nu_0/2$, which is estimated to be a few tens of μHz for A-type main-sequence stars. This means that observations longer than ten hours are necessary to resolve the adjacent modes. Besides that, the pulsational amplitudes vary synchronously with apparent magnetic strength, of which the variation period is typically several days. The power spectrum shows then a fine structure in which each of the side-components is separated from the central peak. The observational time span must then be longer than of order of ten days in order to resolve such fine structure.

Ground-based network observations or uninterrupted observations from space are obviously suitable for high resolution in frequency. The WET (Whole Earth Telescope) collaboration is an example for the former. Kurtz *et al.* (2005 a) carried out a WET campaign for HR 1217 over 35 days and the precision of the derived amplitudes is as good as 14 μmag. The observations by MOST and COROT are examples of the latter cases. MOST performed continuous high-precision photometry of γ Equ for 19 days, and from this observation 7 frequencies in γ Equ were identified (Gruberbauer *et al.*, 2008). In addition, amplitude and phase modulation of the primary frequency due to beating with a closely spaced frequency, which had never before been resolved, were measured. This casts doubts on theories that such modulation is due to a stochastic excitation mechanism (Gruberbauer *et al.*, 2008). MOST also performed continuous photometric observations of 10 Aql. The detail can be seen in Huber *et al.* (2008).

3. Recent progress: spectroscopic observations

The atmospheres of Ap stars are chemically inhomogeneous, and the inhomogeneities are likely to map the oscillations. Spectroscopic observations are required to analyze the oscillations for this purpose, and much work has been done on the effect of pulsation on the spectral lines.

During the early phase of spectroscopic investigations, observations were done with low-resolution spectroscopy. It was found that, for HD 83368, the radial velocities show the same 180° phase reversal at magnetic quadrature as the photometric variations, which confirms the oblique pulsator model for this star (Baldry *et al.*, 1998; Baldry, Bedding 2000). In the case of α Cir, it was found that some lines are apparently pulsating in anti-phase with others. Baldry *et al.* (1998) interpreted this in terms of a high-overtone standing wave with a velocity node in the atmosphere of the star. Bisector measurements of the H α line show that the velocity amplitude and phase of the principal oscillation mode vary significantly depending on height in the H α line. This fact confirms the existence of a radial node in the atmosphere of the star. Therefore it has been suggested that the use of spectral lines which form at different levels in the atmosphere can be used to gain depth information about the eigenfunction.

Recently high-resolution spectroscopic observations of a number of roAp stars have been carried out (Savanov *et al.*, 1999; Kochukhov, Ryabchikova 2001 a, b; Balona, Zima 2002; Kochukhov *et al.*, 2002; Balona, 2002; Balona, Laney 2003; Kurtz *et al.*, 2003; Mkrtichian *et al.*, 2003; Sachkov *et al.*, 2004; Elkin *et al.*, 2005 a, b; Kurtz *et al.*, 2005 b; Kochukhov *et al.*, 2007; Ryabchikova *et al.*, 2007). Since the allocated observational time of big telescopes is restricted, the frequency resolution is generally lower than the photometric observations. Nevertheless, spectroscopic observations with high S/N, high spectral resolution and high time resolution are remakable. Because of the high overtones, the vertical wavelengths of the pulsation modes in roAp stars are short compared to atmospheric optical depth $\tau = 1$, so that the pulsation behavior can be probed as a function of atmospheric depth by examining lines of different strengths that form at different depths. Recent analyses clearly show that the amplitude and phase of the oscillations are dependent on individual lines and ions, and they suggest that the atmospheres of these stars are chemically highly stratified. Such observations also enabled bisector measurements of various rare-earth element lines forming at different levels in the atmosphere (Kurtz *et al.*, 2003; Ryabchikova *et al.*, 2007), from which we can study the depth dependence of the oscillations. The most striking finding is that, in some roAp stars (e.g., HD 166473), pulsation phases reduced in terms of bisector analyses vary smoothly with the intensity level of the line, while some other lines like Hα line show no such variation (Kurtz *et al.*, 2003). This implies that atmospheric layers showing standing wave feature and those showing running wave features coexist in these stars. Probably the oscillations are quasi-standing waves in the lower atmosphere, and have a component leaking into the outer layers through a tunneling effect.

4. Blue-to-red motion in line profile variation

When a star pulsates nonradially, the phase of the motion varies over the stellar surface. This can produce characteristic variations in the spectrum line profiles. The temporal line variations induced by sinusoidal pulsation must themselves exhibit odd or even symmetry with respect to time reversal; the line shape must oscillate sinusoidally. Indeed, line profile variation (LPV) seen in spectral lines formed nearer the photosphere, such as the H α line, exhibit the expected continuous sinusoidal motion (see Kurtz *et al.*, 2004). However, it was found that, rather than moving back and forth continuously, features in the lines of Nd III and Pr III in the spectrum of γ Equ appear to move smoothly only from blue to red (Kochukhov, Ryabchikova 2001 a), but return to the blue discontinuously. Similar LPV has been seen in Nd III and Pr III lines in other roAp stars (Kochukhov *et al.*, 2007). What does this mean? Kochukhov and Ryabchikova (2001 a) adopted for γ Equ, which is hardly rotating at all (Leroy *et al.*, 1994), the moment procedure that is used for quantifying the LPV of rapidly rotating B stars, and once claimed the LPV to be caused by (prograde) modes of degree $\ell = 2$ or 3 and azimuthal order satisfying $|m| = \ell$ or $\ell - 1$. That argument is inconsistent with the oblique-pulsator model, which requires the pulsations to be axisymmetric. But it is clear that an interpretation requiring rotational broadening in a non-rotating star cannot be correct.

To account for the enormously strong Nd III and Pr III lines compared with the Nd II and Pr II lines, a layer of highly enhanced rare-earth abundance is postulated to be present high in the atmosphere. Indeed, that layer is inferred, depending on whether one uses an LTE or NLTE analysis, to occupy optical depths $\tau_{5000} \lesssim 10^{-9}$, where $\rho \lesssim 10^{-5}\rho_{\rm ph}$, $\rho_{\rm ph}$ being the photospheric density (Ryabchikova *et al.*, 2002) or $\tau_{5000} \simeq 3\times10^{-4}$, where $\rho \simeq 0.025\rho_{\rm ph}$ (Mashonkina *et al.*, 2005). Shibahashi *et al.* (2008) note that the extent of LPV in Nd III and Pr III lines is much greater than any movement evident in the Pr II and Nd II lines which are formed lower in the atmosphere, and they infer that the amplitude of the waves is likely to be much greater in the region in which the Pr III, and the Nd III, lines are formed. Roughly speaking, one might expect the velocity amplitude of an acoustic wave to increase with height in proportion to $\rho^{-1/2}$. Therefore, if the inverse timescale of the pulsational motion exceeds the acoustic cutoff frequency in the diffuse upper atmosphere so that the atmosphere supports outwardly running waves driven by the pulsation beneath, the velocity in the upper atmosphere could be consistent with the mean widths of the Nd III and Pr III lines, which are observed to be about $20\,{\rm km\,s^{-1}}$. The broadening of the mean lines cannot be ascribed to real macroturbulent or microturbulent motions, and the broadening due to Zeeman splitting cannot account for the whole of the observed width. Thus Shibahashi *et al.* (2008) argue that pulsational broadening is likely to be the dominant influence on the widths of the doubly ionized rare-earth lines. The pulsation amplitude in the Nd III and Pr III line-forming region then appears to be comparable with the sound speed, which is probably of the order of $10\,{\rm km\,s^{-1}}$. Therefore one should anticipate shocks. Shibahashi *et al.* (2008) propose that the properties of the observed LPV can in principle be explained as a manifestation of a shocked wave train propagating upwards through an acoustically thick layer high in the atmosphere, and demonstrate that this is consistent with the underlying pulsation being an axisymmetric low-degree, probably dipole oscillation more-or-less aligned with the magnetic axis, in accord with the oblique-pulsator model (see Figure 1).

One might suspect that the saw-tooth shape of the shock wave would be unsuitable for an explanation for the almost sinusoidal time-variation of the first moment of the observed LPV (see, e.g., Kochukhov *et al.*, 2007). A careful inspection of the observed LPV, however, shows that a new component appears on the blue side before the red feature has disappeared. This behavior could be indicative of the line-forming region extending over a range of height great enough for a new shock to arrive at the bottom before the observable wake of the previous one has disappeared at the top: this is indicative of a layer that is not acoustically thin. The spectrum line is weak, so the line-forming region is optically thin, and the entire portion of the shock train within the region can be seen at once. When different intervals of the shock train are sampled by the rare-earth element region the shape of the overall line changes. Under such circumstances the movement of the first moment of the line can be smoothly undulatory, indeed even roughly sinusoidal, and its value is certainly not a straightforward estimate of radial velocity. Shibahashi *et al.'s* (2008) simulation demonstrate these features and succeeded in reproducing the major spectral characteristics of LPV of the rare-earth lines presented by Kochukhov and Ryabchikova (2001).

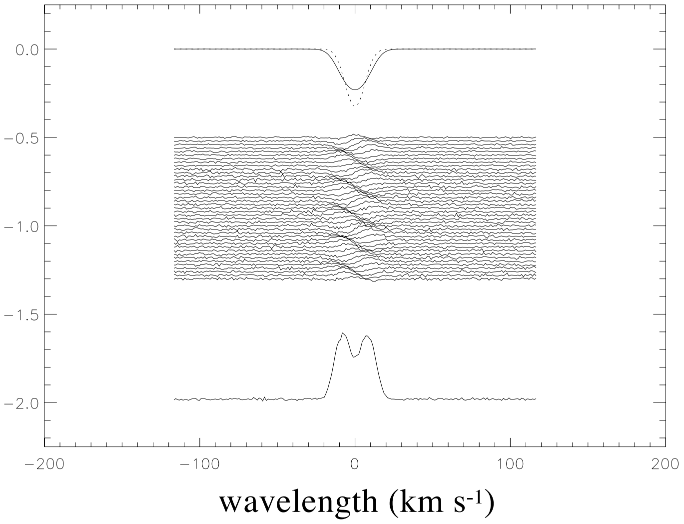

Figure 1. A stacked sequence of synthetic residual spectra based on a shock wave hypothesis, each displaced downwards by 0.02 from its predecessor and plotted against wavelength in velocity units. The upper continuous curve is the mean of the raw spectra, $\langle I \rangle$; the dotted curve is a single intrinsic spectrum, suffering no Doppler broadening. The lowermost curve is the standard deviation of the spectra from their mean, plotted on a scale 33 times larger than the others. The spectra are presumed to have been produced in a spot by a low-degree mode of oscillation such as an aligned dipole. From Shibahashi *et al.* (2008).

In contrast, Kochukhov *et al.* (2007) presume the thickness of the line-forming region to be negligible and invoke turbulence, which they believe to be convection, and which is presumed to vary in such a manner as to leave the depth of the line centre invariant. In their interpretation, Doppler broadening due to the pulsation is assumed to be small and the main broadening is due to turbulence. Kochukhov *et al.* (2007) presume that the line widths are modulated with pulsation as a consequence of the periodic expansion and compression of turbulent layers in the upper layers and that this variation occurs approximately in quadrature with the radial velocity changes.

Though Kochukhov *et al.'s* (2007) model and Shibahashi *et al.'s* (2008) model are quite different, it is difficult at present to differentiate between them on empirical grounds alone. From the theoretical point of view, even if one disregards the fact that the stratification of the atmosphere is bound to be convectively stable, it seems hardly possible for buoyancy to be so severe as to produce the near-sonic, or perhaps even supersonic, convective velocities that would be required to account for the observations, particularly because the atmosphere is effectively transparent. Moreover, a dynamical theory of the LPV would require also an explanation of the phase relation between the turbulent broadening and the acoustic wave, which currently is missing.

5. For the better understanding of oscillations of magnetic stars

Even though the oscillations in roAp stars have essentially an acoustic nature, they are strongly influenced by the global magnetic field of the star, particularly in the outer layers of the star, where the magnetic and gas pressure become comparable. Many studies have been carried out to investigate the overall effect of the magnetic field on eigenoscillations (Dziembowski, Goode 1996; Bigot *et al.*, 2000; Cunha, Gough 2000; Saio, Gautschy 2004; Saio, 2005; Cunha, 2006; Sousa, Cunha 2007). The presence of the magnetic field leads to an additional buoyancy force in the outer layer of the star and changes the wave characteristics there.

In this section, I will discuss, for the instruction purpose, the wave propagation in a stratified plane-parallel isothermal atmosphere with a uniform magnetic field under a constant gravitational field, as fundamental concepts. The basic equation governing the linear adiabatic equations reduces to

$$\begin{aligned}\frac{\partial^2 \boldsymbol{\xi}}{\partial t^2} &= \left(c^2 + v_{\rm A}^2\right)\nabla(\nabla\cdot\boldsymbol{\xi}) + \nabla(\boldsymbol{g}\cdot\boldsymbol{\xi}) + c^2 A(\nabla\cdot\boldsymbol{\xi})\mathbf{e}_{\rm z} \\ &\quad + v_{\rm A}^2\left[(\mathbf{e}_{\rm B}\cdot\nabla)^2\boldsymbol{\xi} - \mathbf{e}_{\rm B}(\mathbf{e}_{\rm B}\cdot\nabla)(\nabla\cdot\boldsymbol{\xi}) - (\mathbf{e}_{\rm B}\cdot\nabla)\nabla(\mathbf{e}_{\rm B}\cdot\boldsymbol{\xi})\right]. \qquad (3)\end{aligned}$$

Here, $\boldsymbol{\xi}$ is the displacement vector, $\boldsymbol{g}$ is the gravitation field, $A \equiv (1-\gamma^{-1})H_\rho^{-1}$, where γ is the ratio of the specific heats and H_ρ is the density scale height, $v_{\rm A}^2 \equiv B^2/(\mu\rho)$ is the square of the Alfven speed, and $-\mathbf{e}_{\rm z}$ and $\mathbf{e}_{\rm B}$ are the unit vectors toward the gravitational direction and the magnetic field, respectively. The perturbation to the gravitational field is neglected. Note that c^2 and A are constant in the present case.

Let us define the Cartesian coordinate so that the local vertical z increases outwardly and the the x-axis of the horizontal coordinates is parallel to the horizontal component of the equilibrium magnetic field. It should be recalled that the global magnetic field of Ap stars is well described in terms of a dipole field. Hence (x,z)-plane and the y-axis should be regarded as a meridional plane and the azimuthal direction with respect to the magnetic axis of the star at a given point on the stellar surface, of which the magnetic latitude θ is $\cos^{-1}(\mathbf{e}_{\rm x}\cdot\mathbf{e}_{\rm z})$. Since the global oscillations in roAp stars are axisymmetric with respect to the magnetic axis, $\partial\boldsymbol{\xi}/\partial y = 0$ in the local analysis.

It is instructive to consider a simple solution of plane waves of the form

$$\boldsymbol{\xi}(\boldsymbol{r},t) \propto \exp\left(\frac{z}{2H_\rho}\right)\exp[i(\omega t + k_{\rm z}z)]. \qquad (4)$$

The exponentially growing factor with height z arises so as to conserve wave energy in vertical direction. Where $k_{\rm z}H_\rho \gg 1$, the angular frequency ω and the wavenumber $\boldsymbol{k}$ must then satisfy (McLellan, Winterberg 1968; Thomas, 1983)

$$\omega^4 - \omega^2 \left[\left(c^2 + v_{\rm A}^2\right)\left(k_{\rm x}^2 + k_{\rm z}^2\right)\right] + (\gamma - 1)g^2 k_{\rm x}^2 + c^2 v_{\rm A}^2 \left(k_{\rm x}^2 + k_{\rm z}^2\right)\left(\boldsymbol{k}\cdot\mathbf{e}_{\rm B}\right)^2 = 0. \quad (5)$$

The dispersion relation (5) represents the two magneto-atmospheric wave modes in which compressive, buoyant, and magnetic forces all play a role. It is quadratic in ω^2 and has two pairs of real roots $\omega = \pm\omega_1$, $\pm\omega_2$. For a given horizontal wavenumber $k_{\rm x}$ and a given frequency ω, there are two magneto-atmospheric wave modes of $k_{\rm z,1}$ and $k_{\rm z,2}$; we call them a short wave and a long wave, respectively. The motion is then described in terms of a linear combination of an upward propagating short wave, a downward propagating short wave, an upward propagating long wave, and a downward propagating long wave. These wave components are, in general, independent and decoupled from each other. As far as they would be independent in the entire system, we would only have to deal with one of them. However, in the case of $k_{\rm z,1} \simeq k_{\rm z,2}$, a short wave and a long wave are degenerate and they cannot be distinguishable. If such degeneracy occurs at a certain layer in the star, the wave comes to have a mixed character. Then all the components should be taken into account, and only the components being coherent in the entire system are retained as eigenmodes. For high frequency mode ($\omega^2 \gg k_{\rm x}^2 c^2$ and $\omega^2 \gg N^2 \equiv -gA$), such degeneracy is realized where $c \simeq v_{\rm A}$. In the case of a star with $B = 1\,$kG, the local Alfven speed becomes equal to the sound speed near the photosphere, and then the acoustic wave and the magnetic wave couple with each other there. As a consequence, the eigenmode in such a system is a mode with energy leakage.

References

Balona, L.A.: 2002, *Mon. Not. R. Astron. Soc.* **337**, 1059

Balona, L.A.: 2004, in *Proc. IAU Symp.* 224: *The A-Star Puzzle*, eds.: J. Zverko, J. Žižňovský, S.J. Adelman and W.W. Weiss, Cambridge Univ. Press, Cambridge, 325

Balona, L.A., Laney, C.D.: 2003, *Mon. Not. R. Astron. Soc.* **344**, 242

Balona, L.A., Zima, W.: 2002, *Mon. Not. R. Astron. Soc.* **336**, 873

Baldry, I.K., Kurtz, D.W., Bedding, T.R.: 1998, *Mon. Not. R. Astron. Soc.* **300**, L39

Baldry, I.K., Bedding, T.R.: 2000, *Mon. Not. R. Astron. Soc.* **318**, 341

Bigot, L, Provost, J., Berthomieu, G., Dziembowski, W.A., Goode, P.R.: 2000, *Astron. Astrophys.* **356**, 218

Cunha, M.S.: 2006, *Mon. Not. R. Astron. Soc.* **365**, 153

Cunha, M.S.: 2007, *Comm. in Asteroseismology* **150**, 48

Cunha, M.S., Gough, D.O: 2000, *Mon. Not. R. Astron. Soc.* **319**, 1020

Dziembowski, W.A., Goode, P.R.: 1996, *Astrophys. J.* **458**, 33

Elkin, V.G., Kurtz, D.W., Mathys, G.: 2005, *Mon. Not. R. Astron. Soc.* **364**, 864

Elkin, V.G., Riley, J.D., Cunha, M.S., Kurtz, D.W., Mathys, G.: 2005, *Mon. Not. R. Astron. Soc.* **358**, 665

González, F., Hubrig, S., Savanov, I.: 2008, *Contr. Astron. Obs. Sk. Pleso* **38**, 411

Gough, D.O.: 2005, in *Astronomy & Geophysics* **46**, *The Roger Tayler Memorial Lectures*, ed.: S. Bowler, Royal Astron. Soc., London, 16

Gruberbauer, M., Saio, H., Huber, D., Kallinger, T., Weiss, W.W., Guenther, D.B., Kusching, R. , Matthews, J.M., Moffat, A.F.J., Rucinski, S., Sasselov, D., Walker, G.A.H.: 2008, *Astron. Astrophys.* **480**, 223

Houdek, G.: 2003, in *Magnetic Fields in O, B and A Stars: Origin and Connection to Pulsation, Rotation and Mass Loss*, eds.: L.A. Balona, H.F. Henrichs and R. Medupe, Astron. Soc. Pacific, San Francisco, 45

Huber, D., Saio, H., Gruberbauer, M., Weiss, W.W., Rowe, J., Hareter, M., Kallinger, T., Reegan, P., Matthews, J.M., Kuschnig, R., Günther, D.B., Moffat, A.F.J., Rucinski, S., Sasselov, D., Walker, G.A.H.: 2008, *Contrib. Astron. Obs. Skalnaté Pleso* **38**, 413

Kochukhov, O.: 2007, *Comm. in Asteroseismology* **150**, 39

Kochukhov, O., Ryabchikova, T.: 2001 a, *Astron. Astrophys.* **374**, 615

Kochukhov, O., Ryabchikova, T.: 2001 b, *Astron. Astrophys.* **377**, L22

Kochukhov, O., Ryabchikova, T., Weiss, W.W., Landstreet, J.D., Lyashko, D.: 2007, *Mon. Not. R. Astron. Soc.* **376**, 651

Kurtz, D.W: 1982, *Mon. Not. R. Astron. Soc.* **200**, 87

Kurtz, D.W., Elkin, V.G., Mathys, G.: 2003, *Mon. Not. R. Astron. Soc.* **343**, L5

Kurtz, D.W., Elkin, V.G., Mathys, G., Riley, J., Cunha, M.S., Shibahashi, H., Kambe, E.: 2004, in *Proc. IAU Symp.* 224: *The A-Star Puzzle*, eds.: J. Zverko, J. Žižňovský, S.J. Adelman and W.W. Weiss, Cambridge Univ. Press, Cambridge, 343

Kurtz, D.W., Elkin, V.G., Mathys, G.: 2005 a, *Mon. Not. R. Astron. Soc.* **358**, L6

Kurtz, D.W., Cameron, C., Cunha, M.S., Dolez, N., Vauclair, G. et al.: 2005 b, *Mon. Not. R. Astron. Soc.* **358**, 651

Leroy, J.L., Bagnulo, S., Landolfi, M., Landi Degl'Innocenti, E.: 1994, *Astron. Astrophys.* **284**, 174

Mashonkina, L., Ryabchikova, T., Ryabtsev, A.: 2005, *Astron. Astrophys.* **441**, 309

McLellan, A., Winterberg, F.: 1968, *Sol. Phys.* **4**, 401

Mkrtichian, D.E., Hatzes, A.P., Kanaan, A.: 2003, *Mon. Not. R. Astron. Soc.* **345**, 781

Ryabchikova, T., Sachkov, M., Weiss, W.W., Kallinger, T., Kochukhov et al.: 2007, *Astron. Astrophys.* **462**, 1103

Ryabchikova, T., Piskunov, N., Kochukhov, O., Tsymbal, V., Mittermayer, P., Weiss, W.W.: 2002, *Astron. Astrophys.* **384**, 545

Sachkov, M., Ryabchikova, T., Kochukhov, O., Weiss, W.W., Reegan, P., Landstreet, J.D.: 2004, in *Proc. IAU Colloq.* 193: *Variable stars in the local group*, eds.: D.W. Kurtz and K.R. Pollard, Astron. Soc. Pacific, San Francisco, 208

Saio, H.: 2005, *Mon. Not. R. Astron. Soc.* **360**, 1022

Saio, H., Gautschy, A: 2004, *Mon. Not. R. Astron. Soc.* **350**, 485

Savanov, I.S., Malanushenko, V.P., Ryabchikova, T.A.: 1999, *Astron. Letters* **25**, 802

Shibahashi, H.: 2003, in *Magnetic Fields in O, B and A Stars: Origin and Connection to Pulsation, Rotation and Mass Loss*, eds.: L.A. Balona, H.F. Henrichs and R. Medupe, Astron. Soc. Pacific, San Francisco, 55

Shibahashi, H., Gough, D., Kurtz, D.W., Kambe, E.: 2008, *Publ. Astron. Soc. Japan* **60**, 63

Thomas, J.H.: 1983, *Ann. Rev. Fluid Mech.* **15**, 321

Hiromoto Shibahashi and Mikhail Sachkov

Michael Maitzen