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Theory of roAp stars

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Abstract

I will discuss some fundamental mathematical features of eigenoscillations of a magnetic star after deriving the basic equations. I will also discuss the wave propagation in a stratified plane atmosphere with magnetic fields as fundamental basics, and then describe how to solve global modes. Finally, it is stressed that the theoretical investigation of line profile variation beyond a single-surface approximation is necessary in order to compare the observations of roAp stars, of which the vertical wavelength of oscillation is as short as the thickness of the line-forming layer, with high time-resolution, high spectral resolution, and high signal-to-noise ratio.

Introduction

In many Ap stars strong magnetic fields have been detected, and the observed magnetic field strength has been found to vary almost sinusoidally with time. The oblique rotator model is widely accepted to explain this variation. In this model, the star is thought to have a more-or-less axisymmetric magnetic field whose symmetry axis is inclined to the rotation axis of the star. The observed magnetic field strength then varies with the rotational phase of the star. The rapidly oscillating Ap (roAp) stars are cool Ap stars which pulsate with short periods in the range of 4-15 min. Some roAp stars are well-known oblique magnetic rotators, and it is a reasonable presumption that they all are. The oscillation amplitude of the light variations of these stars has been found to be modulated with the rotation period, the latter often being inferred from the variation of magnetic field strength. To explain this phenomenon, Kurtz (1982) proposed the oblique pulsator model, which presumes the star to be pulsating in a dipole mode whose axis of symmetry is aligned with that of the field, which itself is inclined to the rotation axis. The model was proposed simply to account for the observations, and has been reasonably successful in doing so. The magnetic fields of roAp stars must have a big influence on oscillations of these stars.

Linear adiabatic oscillations of a magnetic star

Basic equations

The basic equations governing linear, adiabatic oscillations of a non-rotating, magnetic star are the equations of conservation of momentum, mass and entropy, and the induction equation in the MHD approximation, which are given by

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{\rho'}{\rho^2}\nabla p - \frac{1}{\rho}\nabla p' + \frac{1}{\mu\rho}(\nabla \times \mathbf{B}') \times \mathbf{B}, \tag{1}$$

$$\frac{\partial \rho'}{\partial t} = -\mathbf{v}\cdot\nabla\rho - \rho\nabla\cdot\mathbf{v}, \tag{2}$$

$$\frac{\partial p'}{\partial t} = -\mathbf{v}\cdot\nabla p - \Gamma_1 p\nabla\cdot\mathbf{v}, \tag{3}$$

$$\frac{\partial \mathbf{B}'}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}), \tag{4}$$

where $\mathbf{v}$ denotes the velocity, ρ the density, p the pressure, $\mathbf{B}$ the magnetic field, μ the permeability, $\Gamma_1 \equiv (\partial \ln p/\partial \ln \rho)_S$, S the entropy. Here the quantities with a prime denote the Eulerian perturbations, and those without a prime denote the equilibrium quantities. The only exception is the velocity $\mathbf{v}$; since no velocity field is assumed in the equilibrium state, the velocity field is denoted without a prime though it is assumed a small quantity. The perturbation to the gravitational potential field is neglected for simplicity, and the accuracy of this approximation is reasonably good for short wavelength oscillations. The last term on the right-hand side of equation (1) denotes the Lorentz force. As for the equilibrium magnetic field, a force-free field is assumed. Substitution of (2)-(4) into (1) after taking its time derivative leads the set of basic equations to a form expressed with only $\mathbf{v}$:

$$\begin{aligned}\rho\frac{\partial^2\mathbf{v}}{\partial t^2} &= \nabla(\mathbf{v}\cdot\nabla p) + \nabla(\Gamma_1 p\nabla\cdot\mathbf{v}) - \frac{1}{\rho}(\mathbf{v}\cdot\nabla\rho)\nabla p - (\nabla\cdot\mathbf{v})\nabla p \\ &\quad + \frac{1}{\mu}[\nabla\times\{\nabla\times(\mathbf{v}\times\mathbf{B})\}]\times\mathbf{B} \\ &\equiv \mathcal{L}(\mathbf{v}) + \mathcal{M}(\mathbf{v}),\end{aligned} \tag{5}$$

where the operator $\mathcal{L}(\mathbf{v})$ denotes the first three terms (the non-magnetic part) of the first line of the middle of equation and the operator $\mathcal{M}(\mathbf{v})$ denotes the fourth term (the Lorentz force term). Taking a Fourier transform of (5) with respect to time, $\mathbf{v}(t,\mathbf{r}) = \int \mathbf{v}_\omega(\mathbf{r})e^{i\omega t}d\omega$, and then applying $\int e^{-i\omega' t}d\omega'$ to it, we get an equation with respect to $\mathbf{v}_\omega(\mathbf{r})$:

$$-\omega^2\rho\mathbf{v}_\omega = \mathcal{L}(\mathbf{v}_\omega) + \mathcal{M}(\mathbf{v}_\omega). \tag{6}$$

Self-adjointness

Taking the scalar product of $\mathcal{L}(\mathbf{v}_\omega)$ of equation (6) with $\tilde{\mathbf{v}}_{\omega'}$ and integrating it throughout the stellar volume, we obtain

$$\begin{aligned}\int \tilde{\mathbf{v}}_{\omega'}\mathcal{L}(\mathbf{v}_\omega)dV &= -\int(\mathbf{v}_\omega\cdot\nabla p)(\nabla\cdot\tilde{\mathbf{v}}_{\omega'})dV - \int(\tilde{\mathbf{v}}_{\omega'}\cdot\nabla p)(\nabla\cdot\mathbf{v}_\omega)dV \\ &\quad - \int \Gamma_1 p\,(\nabla\cdot\mathbf{v}_\omega)(\nabla\cdot\tilde{\mathbf{v}}_{\omega'})dV \\ &\quad - \int p\left(\frac{d\ln\rho}{d\ln p}\right)(\mathbf{v}_\omega\cdot\nabla\ln p)(\tilde{\mathbf{v}}_{\omega'}\cdot\nabla\ln p)dV \\ &\quad + \int(\Gamma_1 p\nabla\cdot\mathbf{v}_\omega)\tilde{\mathbf{v}}_{\omega'}\cdot d\mathbf{S},\end{aligned} \tag{7}$$

where $\int dV$ and $\int d\mathbf{S}$ mean the integral over the volume and the integral over the surface, respectively. Hence, if

$$\int(\Gamma_1 p\nabla\cdot\mathbf{v}_\omega)\tilde{\mathbf{v}}_{\omega'}\cdot d\mathbf{S} = 0, \tag{8}$$

then

$$\int \tilde{\mathbf{v}}_{\omega'}\mathcal{L}(\mathbf{v}_\omega)dV = \int \mathbf{v}_{\omega'}\mathcal{L}(\tilde{\mathbf{v}}_{\omega'})dV. \tag{9}$$

That is, the operator $\mathcal{L}$ is self-adjoint under the zero-boundary condition, as first proven by Chandrasekhar (1964). Similarly, it is easily shown that

$$\begin{aligned}\int \tilde{\mathbf{v}}_{\omega'}\mathcal{M}(\mathbf{v}_\omega)dV &= \int [\nabla\times(\mathbf{v}_\omega\times\mathbf{B})]\cdot[\nabla\times(\tilde{\mathbf{v}}_{\omega'}\times\mathbf{B})]dV \\ &\quad + \int \{[\nabla\times(\mathbf{v}_\omega\times\mathbf{B})]\times(\tilde{\mathbf{v}}_{\omega'}\times\mathbf{B})\}\cdot d\mathbf{S}. \end{aligned} \tag{10}$$

Therefore, if

$$\int \{[\nabla\times(\mathbf{v}_\omega\times\mathbf{B})]\times(\tilde{\mathbf{v}}_{\omega'}\times\mathbf{B})\}\cdot d\mathbf{S} = 0, \tag{11}$$

then

$$\int \tilde{\mathbf{v}}_{\omega'}\mathcal{M}(\mathbf{v}_\omega)dV = \int \mathbf{v}_\omega\mathcal{M}(\tilde{\mathbf{v}}_{\omega'})dV. \tag{12}$$

That is, in the case that both the conditions (8) and (11) are satisfied, from equation (6),

$$\omega^2\int \tilde{\mathbf{v}}_{\omega'}\cdot\mathbf{v}_\omega\rho dV = \omega'^2\int \mathbf{v}_\omega\cdot\tilde{\mathbf{v}}_{\omega'}\rho dV. \tag{13}$$

This means that, in this case, the squared eigenfrequency is purely real and the eigenfunctions are orthogonal to each other. Note that the condition (11) is not realistic.

Local treatment

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. 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. It is instructive to consider the wave propagation in a plane isothermal atmosphere under a constant gravitational field and with a uniform magnetic field. Let us define the Cartesian coordinate so that the local vertical z increases outwardly and 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 $\cos^{-1}(\mathbf{e}_x\cdot\mathbf{e}_z)$. Since the global oscillations in roAp stars are axisymmetric with respect to the magnetic axis, $\partial\mathbf{v}_\omega/\partial y = 0$ in the local analysis. In this case, equation (6) is reduced to

$$\begin{aligned}-\omega^2\mathbf{v}_\omega &= \left(c^2+v_{\rm A}^2\right)\nabla(\nabla\cdot\mathbf{v}_\omega)+\nabla(\mathbf{g}\cdot\mathbf{v}_\omega)+(\Gamma_1-1)\mathbf{g}(\nabla\cdot\mathbf{v}_\omega)\\ &\quad + v_{\rm A}^2\left[(\mathbf{e}_{\rm b}\cdot\nabla)^2\mathbf{v}_\omega-\mathbf{e}_{\rm b}(\mathbf{e}_{\rm b}\cdot\nabla)(\nabla\cdot\mathbf{v}_\omega)-(\mathbf{e}_{\rm b}\cdot\nabla)\nabla(\mathbf{e}_{\rm b}\cdot\mathbf{v}_\omega)\right],\end{aligned} \tag{14}$$

where $\mathbf{g}$ is the gravitational field, c is the sound speed defined by $c^2\equiv\Gamma_1 p/\rho$, $v_{\rm A}$ denotes the Alfven speed defined by $v_{\rm A}^2\equiv B^2/(\mu\rho)$, and $-\mathbf{e}_z$ and $\mathbf{e}_{\rm B}$ are the unit vectors toward the gravitational direction and the magnetic field, respectively.

Let us consider a simple solution of plane waves of the form

$$\mathbf{v},\ \frac{p'}{\rho},\ \frac{\rho'}{\rho}\propto\exp\left(\frac{z}{2H_\rho}\right)\exp(i\mathbf{k}\cdot\mathbf{x}) \tag{15}$$

and

$$\mathbf{B}'\propto\exp\left(-\frac{z}{2H_\rho}\right)\exp(i\mathbf{k}\cdot\mathbf{x}) \tag{16}$$

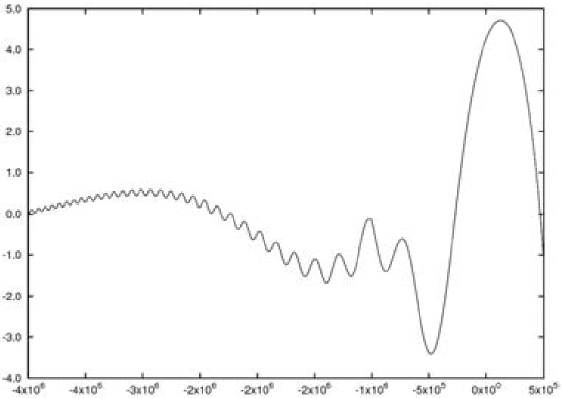

Figure 1: An example of eigenoscillation of plane atmosphere composed of a polytrope layer and an isothermal atmosphere with a magnetic field (Tsunedomi, unpublished, 2008)

with an assumption of $k_z \gg H_\rho$, where $H_\rho \equiv -dz/d\ln\rho$ is the density scaleheight. Then, the following dispersion relation is obtained:

$$\omega^4 - \omega^2 k^2 (c^2 + v_{\rm A}^2) + (\Gamma_1 - 1) g^2 k_x^2 c^2 + c^2 v_{\rm A}^2 k^2 (\mathbf{k}\cdot\mathbf{e}_{\rm B})^2 = 0. \tag{17}$$

Note that $g^2(\Gamma_1 - 1)/c^2 \equiv N^2$ is the square of the buoyancy frequency. We regard this dispersion relation as an equation to give k_z as a function of a given set of (k_x, ω):

$$\begin{aligned} k_z^4 c^2 v_{\rm A}^2 \quad &+ \quad k_z^2 \left\{ -\omega^2 (c^2 + v_{\rm A}^2) + c^2 v_{\rm A}^2 k_z^2 \right\} \\ &+ \quad \left\{ \omega^4 - \omega^2 k_z^2 (c^2 + v_{\rm A}^2)? + N^2 k_h^2 c^2 \right\} = 0 \end{aligned} \tag{18}$$

This gives four kinds of waves: (i) outward going long wave, (ii) outward going short wave, (iii) inward going long wave, and (iv) inward going short wave. These wave components are, in general, independent and decoupled from each other. If they were independent in the entire system, we would only have to deal with one of them. However, at a certain layer in the star, a short wave and a long wave are degenerate and cannot be distinguishable, so that the wave comes to have a mixed character. Then all the components should be taken into account, and only the wave being coherent in the entire system are retained as eigenmodes (see Fig. 1, also see Sousa & Cunha 2008). The inward going short wave is expected to be eventually dissipated, since the wavelength becomes soon shorter and shorter with depth (Roberts & Soward 1983). The eigenfrequencies are then expected to be complex. If the outward going wave from the stellar surface induces a magnetic field perturbation far from the star, wave energy is also leaked through electromagnetic radiation.

How to solve global modes

The angular dependence of the eigenfunction can be described in terms of a series of spherical harmonics, even if the expansion might be an infinite series. It is well-known that in the case of non-rotating, non-magnetic, spherically symmetric stars, their pulsation eigenmode is described by a single spherical harmonic, $Y_l^m(\theta, \phi)$ (see, e.g., Unno et al. 1989), decoupled from other harmonics with different degrees l' and m'. However, this is not the case for a magnetic star. In other words, a pulsation mode in a magnetic star cannot be referred to by a set of (l, m). If the Lorentz force is weak enough throughout the whole star, we may regard the effects of the magnetic field as small perturbations and expand the eigenfunction in terms of a series of eigenfunctions of the non-magnetic case. In general, however, the Lorentz force comes to dominate over the gaseous pressure force above the photosphere and hence the validity of such a perturbation method breaks down in the high atmosphere.

We outline here how to formulate the eigenfunction of a magnetic star. We adopt a general expansion in terms of a series of spherical harmonics. It should be noted that the azimuthal dependence of the eigenfunctions can be assumed to have a specific form $\exp(im\phi)$ with an integer m, where ϕ denotes the azimuthal angle. For a given value of m, the eigenfunction is expressed by a summation of the components which are proportional to $Y_l^m(\theta, \phi)$ with $l \geq |m|$. The velocity field $\mathbf{v}_\omega(\mathbf{r})$ for a nonradial oscillation eigenmode with a given m can be described as (Saio & Gautschy 2004)

$$\begin{aligned} \mathbf{v}_\omega(\mathbf{r}) &= \sum_{l=|m|}^{\infty} \left\{ \mathbf{e}_\mathrm{r} \Xi_l(r) + \mathbf{e}_\theta \left[H_l(r) \frac{\partial}{\partial\theta} + T_l(r) \frac{1}{\sin\theta} \frac{\partial}{\partial\phi} \right] \right. \\ & \left. + \mathbf{e}_\phi \left[H_l(r) \frac{1}{\sin\theta} \frac{\partial}{\partial\phi} + T_l(r) \frac{\partial}{\partial\theta} \right] \right\} Y_l^m(\theta, \phi), \end{aligned} \tag{19}$$

where $\mathbf{e}_i$ denotes the unit vector in the i-direction and $\Xi_l(r)$, $H_l(r)$, and $T_l(r)$ are functions of r being dependent on l. In particular, in the case of axisymmetric modes ($m = 0$), the oscillation velocity field is described as

$$\mathbf{v}_\omega(\mathbf{r}) = \sum_{l=0}^{\infty} \left\{ \mathbf{e}_\mathrm{r} \Xi_l(r) + \mathbf{e}_\theta H_l(r) \frac{\partial}{\partial\theta} \right\} Y_l^0(\theta, \phi), \tag{20}$$

With substitution of equation (20) into equation (6), the basic equations are reduced to ordinary differential equations with respect to $\{\Xi_l(r)\}$ and $\{H_l(r)\}$ for $l \geq |m|$. Though the set of $\Xi_l(r)$ and $H_l(r)$ are decoupled in the non-magnetic case from those with any other $l' \neq l$, the situation is different in the case of a magnetic star. As derived by Saio & Gautschy (2004), the governing equations for nonradial oscillations of a magnetic star are two independent infinite systems of fourth-order coupled differential equations concerning $\{\Xi_l(r)\}$ and $\{H_l(r)\}$; one with $l = 2j - 1$ for $j = 1, 2, \ldots$ (odd modes) and the other with $l = 2j - 2$ for $j = 1, 2, \ldots$ (even modes). If we take account of the perturbation to the gravitational potential, which is ignored here, the equations become sixth-order. Also if we take account of the nonadiabatic effect due to radiation, the order becomes higher by two (Saio 2005). Practically, in numerical computations the series have to be truncated at some j and the $4 \times n_j$ first-order differential equations for complex variables are solved, where n_j denotes the truncation size of j.

Indirect effects of the presence of a magnetic field

It should be pointed out here that the presence of magnetic fields influence the pulsation of the star not only through the Lorentz force appearing in the last term of equation (5). It also affects the equilibrium structure of the star by suppressing the convection or influencing the chemical diffusion. As a consequence, the thermal structure of the equilibrium state must be somewhat different from the non-magnetic case, and the oscillation properties of the star should then be affected. Suppression of convection has a great influence on the stability of oscillations (Balmforth et al. 2001, Cunha 2001, Saio 2005).

Line profile variation

Prior to the last decade, most observations of roAp stars have concerned the light variations. Recently, some new, striking results of spectroscopic observations with high time resolution, high spectral dispersion, and high signal-to-noise ratio became available. High-quality spectroscopic observations are more sensitive for the detection and study of pulsation in roAp stars, and they are quite remarkable indeed. Some lines of rare earth elements show enigmatic blue-to-red line profile variation (Kochukhov & Ryabchikova 2001), which is interpreted as a manifestation of a train of shock waves propagating upward through the atmosphere (Shibahashi et al. 2008) or as a consequence of the line width modulation due to the periodic expansion and compression of turbulent layers in the higher atmosphere (Kochukhov et al. 2007). Since the oscillations found in roAp stars are high overtones (they oscillate so rapidly!), the vertical wavelengths of the oscillations are so short 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 observations also enabled bisector measurements of various lines forming at different levels in the atmosphere (Kurtz et al. 2005, Ryabchikova et al. 2007), from which we can study the depth dependence of the oscillations. The bisector analyses of variation of spectral lines of roAp stars potentially provide us with information of the 3D structure of the atmosphere of those stars. In order to extract such information, numerical simulation of line profile variation beyond a single-surface approximation, by taking account of finite thickness of the line forming layer, is necessary. Such a project has justbeen started by my colleagues and me.

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DISCUSSION

Kepler: What strength magnetic field will inhibit pulsation in a roAp star? The question is in light of the discovery of variations in a 1MG white dwarf: can it be pulsation?

Shibahashi: I have thought of magnetic field as a possible excitation agent but have not considered such an occasion. In an extremely strong magnetic field the fluid motion would be inhibited perpendicular to the field. Nevertheless fluid motion along the field lines would be possible. I am currently not sure if eigen-oscillations having discrete eigenfrequencies are possible.

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Pulsation in the atmosphere of roAp stars

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Abstract

High time resolution spectroscopy of roAp stars at large telescopes has led to a major breakthrough in our understanding of magnetoacoustic pulsations in these interesting objects. New observations have allowed to uncover a number of intricate relations between stellar oscillations, magnetic field, and chemical inhomogeneities. It is now understood that unusual pulsational characteristics of roAp stars arise from an interplay between short vertical length of pulsation waves and extreme chemical stratification. Here I review results of recent studies which utilize these unique properties to map 3D pulsation geometry using a combination of Doppler imaging, vertical pulsation tomography, interpretation of line profile variation, and ultraprecise space photometry. I also describe recent attempts to interpret theoretically the complex observational picture of roAp pulsations.

Introduction

Rapidly oscillating Ap (roAp) stars represent an interesting subgroup of chemically peculiar (SrCrEu type) magnetic A stars pulsating in high-overtone, low degree *p*-modes. These stars are found at or near the main sequence, close to the cool border of the region occupied by the magnetic Ap/Bp stars (Kochukhov & Bagnulo 2006). According to the series of recent spectroscopic studies (e.g., Kochukhov et al. 2002; Ryabchikova et al. 2004), effective temperatures of roAp stars range from about 8100 down to 6400 K. Their atmospheres are characterized by diverse chemical abundance patterns, but typically have normal or below solar concentration of light and iron-peak elements and a very large overabundance of rare-earth elements (REEs). Similar to other cool magnetic A stars, roAp stars possess global fields with a typical strength of a few kG (Mathys et al. 1997), although in some stars the field intensity can exceed 20 kG (Kurtz et al. 2006b). These global magnetic topologies are most likely the remnants of the fields which were swept at the star-formation phase or generated by dynamo in convective pre-main sequence stars, decayed to a stable configuration (Braithwaite & Nordlund 2006) and now remain nearly constant on long timescales. The slow rotation and stabilizing effect of the strong magnetic field facilitates operation of atomic diffusion (Michaud et al. 1981; LeBlanc & Monin 2004), which is responsible for the grossly non-solar surface chemistry and large element concentration gradients in Ap-star atmospheres (Ryabchikova et al. 2002, 2008; Kochukhov et al. 2006). Variation of the field strength and inclination across the stellar surface alters the local diffusion velocities (Alecian & Stift 2006), leading to the formation of spotted chemical distributions and consequential synchronous rotational modulation of the broad-band photometric indices, spectral line profiles, longitudinal magnetic field and mean field modulus (e.g., Ryabchikova et al. 1997).

Pulsations in cool Ap stars were discovered 30 years ago (Kurtz 1978) and were immediately recognized to be another manifestation of the prominent influence of unusually strong magnetic fields on the stellar interiors and atmospheres. Currently (mid 2008), 40 cool Ap stars are known to pulsate, with several new roAp stars discovered by high-resolution spectroscopic observations (Hatzes & Mkrtichian 2004; Elkin et al. 2005; Kurtz et al. 2006b; Kochukhov et al. 2008a, 2008b; Gonzáles et al. 2008). Oscillations have amplitudes below 10 mmag in the Johnson's B filter and 0.05–5 km s^{-1} in spectroscopy, while the periods lie in the range from 4 to 22[1] min. The amplitude and phase of pulsational variability are modulated with the stellar rotation. A simple geometrical interpretation of this phenomenon was suggested by the oblique pulsator model of Kurtz (1982), which supposes an alignment of the low angular degree modes with the quasi-dipolar magnetic field of the star and resulting variation of the aspect at which pulsations are seen by the distant observer. Recent theoretical studies (Bigot & Dziembowski 2002; Saio 2005) indicated that the horizontal pulsation picture of *p*-mode pulsations in magnetic stars is far more complicated: individual modes are distorted by the magnetic field and rotation in such a way that pulsational perturbation cannot be approximated by a single spherical harmonic function.

The question of the roAp excitation mechanism has been debated for many years but now is narrowed down to the κ mechanism acting in the H I ionization zone with the additional influence from the magnetic quenching of convection and composition gradients built up by the atomic diffusion (Balmforth et al. 2001; Cunha 2002; Vauclair & Théado et al. 2004). However, theories cannot reproduce the observed temperature and luminosity distribution of roAp stars and have not been able to identify parameters distinguishing pulsating Ap stars from their apparently constant, but otherwise very similar, counterparts. On the other hand, impressive success has been achieved in calculating magnetic perturbation of oscillation frequencies (Cunha & Gough 2000; Saio & Gautschy 2004) and inferring fundamental parameters and interior properties for multiperiodic roAp stars (Cunha et al. 2003; Gruberbauer et al. 2008; Huber et al. 2008).

Photometric studies of roAp pulsations

Majority of roAp stars were discovered by D. Kurtz and collaborators using photometric observations at SAAO (see review by Kurtz & Martinez 2000). Few roAp stars were also observed in coordinated multi-site photometric campaigns (Kurtz et al. 2005a), which allowed to deduce frequencies with the precision sufficient for asteroseismic analysis. However, low amplitudes of broad-band photometric variation of roAp stars, low duty cycle and aliasing problems inevitably limit precision of the ground-based photometry. Instead of pursuing observations from the ground, recent significant progress has been achieved by uninterrupted, ultra-high precision observations of known roAp stars using small photometric telescopes in space. Here the Canadian MOST space telescope is the undisputed leader. The MOST team has completed 3–4 week runs on HR 24712, γ Equ, 10 Aql, HD 134214, and HD 99563.

Asteroseismic interpretation of the frequencies deduced from the MOST data for γ Equ (Gruberbauer et al. 2008) and 10 Aql (Huber et al. 2008) yields stellar parameters in good agreement with those determined in detailed model atmosphere studies. At the same time, magnetic field required by the seismic models to fit observed frequencies is 2–3 times stronger than the field modulus inferred from the Zeeman split spectral lines. This discrepancy could be an indication that magnetic field in the *p*-mode driving zone is significantly stronger than the surface field or it may reflect limitations of theoretical models.

MOST photometry of γ Equ has also revealed the presence of a very close frequency pair giving modulation of pulsation amplitude with $\approx$18 d period (Huber et al. 2008). It is possible that this frequency beating is responsible for significant discrepancy of radial velocity amplitudes found for γ Equ in different spectroscopic observing runs (Sachkov et al. 2008b). This amplitude variation could not be ascribed to the rotational modulation because the rotation period of this star exceeds 70 years (Bychkov et al. 2006).

[1] The longest roAp pulsation period corresponds to the second mode recently detected by high-precision HARPS observations of the evolved Ap star HD 116114.

Spectroscopy of roAp pulsations

High-quality time-resolved spectra of roAp stars have proven to be the source of new, incredibly rich information, which not only opened new possibilities for the research on magnetoacoustic pulsations but yielded results of wide astrophysical significance. Numerous spectroscopic studies of individual roAp stars (e.g., Kochukhov & Ryabchikova 2001a; Mkrtichian et al. 2003; Ryabchikova et al. 2007a), as well as comprehensive analysis of pulsational variability in 10 roAp stars published by Ryabchikova et al. (2007b), demonstrated pulsations in spectral lines very different from those observed in any other type of nonradially pulsating stars. The most prominent characteristic of the RV oscillation in roAp stars is the extreme diversity of pulsation signatures seen in the lines of different elements. Only a few stars show evidence of $<$50 m s^{-1} variation in the lines of iron-peak elements, whereas REE lines, especially those of Nd II, Nd III, Pr III and Dy III, exhibit amplitudes from a few hundred m s^{-1} to several km s^{-1}. The narrow core of Hα behaves similarly to REE lines (Kochukhov 2003; Ryabchikova et al. 2007b), suggesting line formation at comparable atmospheric heights.

Pulsation phase also changes significantly from one line to another (Kochukhov & Ryabchikova 2001a; Mkrtichian et al. 2003), with the most notorious example of 33 Lib where different lines of *the same ion* pulsate with a 180° shift in phase, revealing a radial node, and show very different ratios of the amplitude at the main frequency and its first harmonic (Ryabchikova et al. 2007b). Several studies concluded that, in general, roAp stars show a combination of running (changing phase) and standing (constant phase) pulsation wave behaviour at different atmospheric heights.

Another unusual aspect of the spectroscopic pulsations in roAp stars is a large change of oscillation amplitude and phase from the line core to the wings. Bisector variation expected for the regular spherical harmonic oscillation is unremarkable and should exhibit neither changing phase nor significantly varying amplitude. Contrary to this expectation of the common single-layer pulsation model, roAp bisector amplitude often shows an increase from 200–400 m s^{-1} in the cores of strong REE lines to 2–3 km s^{-1} in the line wings, accompanied by significant changes of bisector phase (Sachkov et al. 2004; Kurtz et al. 2005b; Ryabchikova et al. 2007b).

The ability to resolve and measure with high precision pulsational variation in individual lines allows to focus analysis on the spectral features most sensitive to pulsations. By co-adding radial velocity curves of many REE lines one is able to reach the RV accuracy of ~ 1 m s^{-1}. This led to the discovery of the low-amplitude oscillations in HD 75445 (Kochukhov et al. 2008b) and HD 137909 (Hatzes & Mkrtichian 2004). The second object, well-known cool Ap star β CrB, was previously considered to be a typical non-pulsating Ap (noAp) star due to null results of numerous photometric searches of pulsations (Martinez & Kurtz 1994) and the absence of prominent REE ionization anomaly found for nearly all other roAp stars (Ryabchikova et al. 2001, 2004). The fact that β CrB is now revealed as the second brightest roAp star corroborates the idea that *p*-mode oscillations could be present in all cool Ap stars but low pulsation amplitudes prevented detection of pulsations in the so-called noAp stars (Ryabchikova et al. 2004).

Despite improved sensitivity in searches of the low-amplitude oscillations in roAp candidates and numerous outstanding discoveries for known roAp stars, the major drawback of the high-resolution spectroscopic monitoring is still a relatively small amount of observing time available at large telescopes for these projects. As a result, only short time-series spanning 2–4 hours were recorded for most roAp stars, thus providing an incomplete picture for multiperiodic pulsators where different frequencies cannot be resolved in such short runs. Observations on different nights required to infer detailed RV frequency spectrum were secured only for a few roAp stars (Mkrtichian & Hatzes 2005, Kochukhov 2006). In recent multisite spectroscopic campaign carried out for 10 Aql using two telescopes on 7 different observing nights (Sachkov et al. 2008), we found that beating of the three dominant frequencies leads to strong changes of the apparent RV amplitude during several hours. This phenomenon could explain puzzling modulation of RV pulsations on the timescale of 1–2 hours detected in some roAp stars (Kochukhov & Ryabchikova 2001b; Kurtz et al. 2006a).

Interpretation of roAp oscillations

The key observational signature of roAp pulsations in spectroscopy – large line-to-line variation of pulsation amplitude and phase – is understood in terms of an interplay between pulsations and chemical stratification. The studies by Ryabchikova et al. (2002, 2008) and Kochukhov et al. (2006) demonstrated that light and iron-peak elements tend to be overabundant in deep atmospheric layers (typically $\log\tau_{5000} \geq -0.5$) of cool Ap stars, which agrees with the predictions of self-consistent diffusion models (LeBlanc & Monin 2004). On the other hand, REEs accumulate in a cloud located above $\log\tau_{5000} \approx -3$ (Mashonkina et al. 2005). Then, the rise of pulsation amplitude towards the upper atmospheric layers due to exponential density decrease does not affect Ca, Fe, and Cr lines but shows up prominently in the core of Hα and in REE lines. This picture of the pulsation waves propagating outwards through the stellar atmosphere with highly inhomogeneous chemistry has gained general support from observations and theoretical studies alike. Hence the properties of roAp atmospheres allow an entirely new type of asteroseismic analysis – vertical resolution of *p*-mode cross-sections simultaneously with the constraints on distribution of chemical abundances.

The two complimentary approaches to the pulsation tomography problem have been discussed by Ryabchikova et al. (2007a, 2007b). On the one hand, tedious and detailed line formation calculations, including stratification analysis, NLTE line formation, sophisticated model atmospheres and polarized radiative transfer, can supply mean formation heights for individual pulsating lines. Then, the pulsation mode structure can be mapped directly by plotting pulsation amplitude and phase of selected lines against optical or geometrical depth. On the other hand, the phase-amplitude diagram method proposed by Ryabchikova et al. (2007b) is suitable for a coarse analysis of the vertical pulsation structure without invoking model atmosphere calculations but assuming the presence of the outwardly propagating wave characterized by continuous change of amplitude and phase. In this case, a scatter plot of the RV measurements in the phase-amplitude plane can be interpreted in terms of the standing and running waves, propagating in different parts of the atmosphere.

To learn about the physics of roAp atmospheric oscillations one should compare empirical pulsation maps with theoretical models of the *p*-mode propagation in magnetically-dominant ($\beta << 1$) part of the stellar envelope. Sousa & Cunha (2008) considered an analytical model of the radial modes in an isothermal atmosphere with exponential density decrease. They argue that waves are decoupled into the standing magnetic and running acoustic components, oriented perpendicular and along magnetic field lines, respectively. The total projected pulsation velocity, produced by a superposition of these two components, can have widely different vertical profile depending on the magnetic field strength, inclination and the aspect angle. For certain magnetic field parameters and viewing geometries the two components cancel out, creating a node-like structure. This model can possibly account for observations of radial nodes in 33 Lib (Mkrtichian et al. 2003) and 10 Aql (Sachkov et al. 2008).

The question of interpreting the line profile variation (LPV) of roAp stars has received great attention after it was demonstrated that REE lines in γ Equ exhibit unusual blue-to-red asymmetric variation (Kochukhov & Ryabchikova 2001a), which is entirely unexpected for a slowly rotating nonradial pulsator. Kochukhov et al. (2007) showed the presence of similar LPV in the REE lines of many other roAp stars and presented examples of the transformation from the usual symmetric blue-red-blue LPV in Nd II lines to the asymmetric blue-to-red waves in the Pr III and Dy III lines formed higher in the atmosphere. These lines often show anomalously broad profiles (e.g., Ryabchikova et al. 2007b), suggesting the existence of an isotropic velocity field of the order of 10 km s^{-1} in the uppermost atmospheric layers.

Kochukhov et al. (2007) proposed a model of interaction between this turbulent layer and pulsations that has successfully reproduced asymmetric LPV of doubly ionized REE lines. An alternative model by Shibahashi et al. (2008) obtains similar LPV by postulating formation of REE lines at extremely low optical depths, in disagreement with the detailed NLTE calculations by Mashonkina et al. (2005), and requires the presence of shock waves in stellar atmospheres, which is impossible to reconcile with the fact that observed RV amplitudes are well below the sound speed.

Oblique pulsations and distortion of modes by rotation and magnetic field precludes the application of the standard mode identification techniques to roAp stars. A meaningful study of their horizontal pulsation geometry became possible by using the method of pulsation Doppler imaging (Kochukhov 2004a). This technique derives maps of pulsational fluctuations without making *a priori* assumption of the spherical harmonic pulsation geometry. The application of this method to HR 3831 (Kochukhov 2004b) provided the first independent proof of the oblique pulsator model by showing alignment of the axisymmetric pulsations with the magnetic field. At the same time, Saio (2005) showed that the observed deviation of the oscillation geometry of HR 3831 from a oblique dipole mode agrees well with his model of magnetically distorted pulsation.

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DISCUSSION

Dziembowski: What is the effective temperature of the roAp star with the longest observed pulsation period?

Kochukhov: This star (HD 116114) has effective temperature $T_{\rm eff} = 8000$K, which is close to the upper limit of roAp temperature range.

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Interferometric and seismic constraints on the roAp star α Cir

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Abstract

We present new constraints on the rapidly oscillating Ap star α Cir, derived from a combination of interferometric and photometric data obtained with the Sydney University Stellar Interferometer (SUSI) and the *WIRE* satellite. The highlights of our study are:

1. The first determination of the angular diameter of an roAp star.
2. A nearly model-independent determination of the effective temperature of α Cir, which is found to be lower than previously estimated.
3. Detection of two new oscillation frequencies allowing a determination of the large separation of α Cir.

Based on this new information, we have computed non-magnetic and magnetic models for α Cir. We show that the value of the observed large separation found from the new data agrees well with that derived from theoretical models. Moreover, we show how the magnetic field may explain some of the anomalies seen in the oscillation spectrum and how these in turn provide constraints on the magnitude and topology of the magnetic field.

Individual Objects: α Cir

Introduction

α Circini [HR 5463, HD 128898, HIP 71908, $V = 3.2$] is the brightest known rapidly oscillating peculiar A-type (roAp) star. The roAp stars are main sequence chemically peculiar (CP) pulsators with effective temperatures ranging from 6 500 to 8 500 K. Since CP stars show abnormal flux distributions in their spectra, their effective temperatures are very difficult to determine. Temperatures can be estimated from photometric indices or spectral analysis, but due to the peculiar nature of these stars, values are likely to be affected by systematic effects.

The roAp stars also present the highest oscillation frequencies observed in the main sequence part of the instability strip, with typical values ranging from 1 to 3 mHz. The high frequencies of the oscillations observed in roAp stars indicate that these are high radial order, low degree acoustic modes. Since the oscillations are of high radial order we can, in principle, use the asymptotic theory to study the oscillation spectrum. However, these oscillations are affected by an intense magnetic field that will perturb the frequencies from the asymptotic trend.

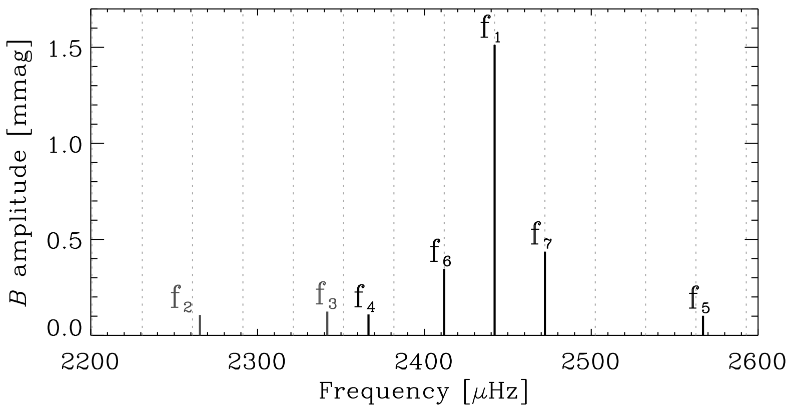

Figure 1: Frequencies detected in α Cir from the *WIRE* data, f_4, f_6, f_1, f_7, f_5. We have included f_2 and f_3 from Kurtz et al. (1994). The vertical dashed lines mark half the large separation (the mean of $f_1 - f_6$ and $f_7 - f_1$).

α Cir is one of the best studied roAp stars and, as such, both seismic and non-seismic data for this star are available in the literature. However, to date, the large frequency separation (defined as the difference between the frequencies of modes of the same degree and consecutive radial orders) of α Cir cannot be reconciled with that expected from an effective temperature around 8 000 K, suggested by most determinations found in the literature, and the luminosity derived from the *Hipparcos* parallax (Matthews et al. 1999).

Detection of the large separation

α Cir was observed for 84 d during four runs with the *WIRE* satellite in the period from 2000–2006 (Bruntt et al., private communication). During the last two runs, we collected simultaneous ground-based Johnson *B* observations on 16 nights with the 0.5-m and 0.75-m telescopes at the South African Astronomical Observatory (SAAO) and 2 hr of high-cadence, high-resolution spectra from the Ultraviolet and Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT). The oscillation frequencies detected in the *WIRE* data are shown in Figure 1. The f_6 and f_7 frequencies have not been observed before, and are present in both the *WIRE* and SAAO data sets. The $f_6 + f_1 + f_7$ frequencies have the highest amplitudes and form a triplet with a nearly equidistant frequency spacing of $30.173 \pm 0.004\,\mu$Hz. We interpret this spacing as either the large frequency separation or half of that.

Asteroseismology

Non-magnetic model

Bruntt et al. (2008) determined the effective temperature of α Cir by combining the measured angular diameter of the star obtained with the Sydney University Stellar Interferometer (SUSI) and its bolometric flux, computed from calibrated spectra. They found a nearly model-independent value for the effective temperature of 7420 ± 170 K, which is lower than all previous determinations found in the literature. The new values for the effective temperature

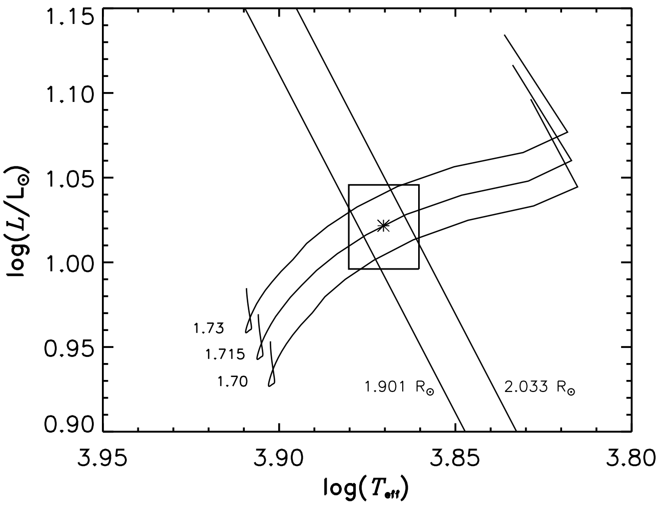

Figure 2: The position of α Cir in the HR diagram, with three evolutionary tracks for masses of 1.70, 1.715 and 1.73 $M_{\odot}$. The constraints on the fundamental parameters are indicated by the 1-σ error box ($T_{\rm eff}$, $L/L_{\odot}$) and the diagonal lines (radius).

and luminosity, derived from the *Hipparcos* parallax and the interferometric radius, were used to place α Cir in the Hertzsprung-Russell (HR) diagram as shown in Figure 2.

Three CESAM (Morel 1997) evolutionary tracks that go through the 1-σ error box are shown in Figure 2. We chose the model that best fitted the position of the star in the HR diagram and its parameters are given in Table 1. We calculated the theoretical oscillation frequencies for that model with the linear adiabatic oscillation code Aarhus Adiabatic Pulsation Package (ADIPLS; Christensen-Dalsgaard 2008). From these theoretical frequencies we calculated the large frequency separation and obtained a value of $\Delta\nu = 60.4\,\mu$Hz. Comparing this value with the observed frequency spacing we conclude that this model reproduces well the observed separation between the three principal modes. Moreover, we conclude that the observed large frequency separation of α Cir is $60.346 \pm 0.008\,\mu$Hz and, thus, that the frequencies f_6, f_1 and f_7 must correspond to modes of alternating even-odd spherical degrees. This new value is significantly larger – and much more secure – than the $50\,\mu$Hz suggested by Kurtz et al. (1994).

Magnetic models

Inspecting Figure 1, where the spacing between the dashed vertical lines correspond to half of the large separation, we note that only the three principal modes seem to follow the trend expected in the asymptotic regime. In particular, f_4, which was also observed by Kurtz et al. (1994), is separated from f_6 by $\simeq 3/4$ of the large separation ($f_6 - f_4 = 45.41\ \mu$Hz). Consequently, the oscillation frequencies computed with the model in Table 1 (hereafter called the *non-magnetic model*) do not reproduce well the separation between the principal mode and the frequencies f_2, f_3, f_4 and f_5. Moreover, the frequencies of the three principal modes have nearly equal separations: $(f_1 - f_6) = 30.1746 \pm 0.0009\,\mu$Hz and $(f_7 - f_1) = 30.1707 \pm 0.0005\,\mu$Hz. In fact, the difference between these two "half separations", which we

Table 1: Global parameters of the CESAM model used for α Cir. The following input parameters were used: $X_0 = 0.70$, $Y_0 = 0.28$, $\alpha = 1.6$ and no overshooting. X_0 and Y_0 are the initial H and He abundances and α is the mixing length parameter.

	$M/\mathrm{M}_\odot$	$\log(L/\mathrm{L}_\odot)$	$\log T_{\mathrm{eff}}$ [K]	$R/\mathrm{R}_\odot$	Age (Myr)
CESAM model	1.715	1.022	3.87	2.0	900

Table 2: The values of $\delta\nu_{nl}$ and $(f_6 - f_4)$ for the observations and for the best-fitting non-magnetic and magnetic models. The strength and topology of the magnetic field are given for the three magnetic models.

	B_p [kG]	Topology	$\delta\nu_{nl}$ [μHz]	$(f_6 - f_4)$ [μHz]
Observed values	–	–	+0.004	45.41
Non-magnetic model	–	–	+2.5	30.2
Magn. model 1	1.4	Quadrupolar	−0.66	44.76
Magn. model 2	1.4	Quadrupolar	+0.53	40.57
Magn. model 3	1.4	Dipolar	−0.81	50.81

Table 3: For each of the three best magnetic models and for the best non-magnetic model we list the values of l for the four frequencies f_4, f_6, f_1, and f_7.

	l_{f_4}	l_{f_6}	l_{f_1}	l_{f_7}
Non-magnetic model	1	0	1	0
Magn. model 1	3	2	3	2
Magn. model 2	1	3	2	3
Magn. model 3	0	2	3	2

will denominate by $\delta\nu_{\mathrm{obs}}$, is only $0.004 \pm 0.001\,\mu$Hz. After computing theoretical $\delta\nu_{nl}$ values for all combinations of mode degrees with $l \leq 3$ for the non-magnetic model, we found that the minimum absolute value taken by this quantity is $\delta\nu_{nl} = 2.5\,\mu$Hz. This value is obtained for combinations of modes of degree $l = 0$ and 2, around the frequency $2450\,\mu$Hz.

Since α Cir is an roAp star, it has a strong magnetic field. We have therefore speculated if the effect of the magnetic field on the oscillations may explain the small value of $\delta\nu_{\mathrm{obs}}$. To investigate this possibility, we used a code (Cunha 2006) to compute the magnetic perturbations to the frequencies obtained for our non-magnetic model. As input parameters we considered modes of degrees $l = 0, 1, 2$ and 3, a magnetic field at the pole, B_p, within a range of values appropriate for α Cir, (see Bruntt et al. 2008: Sec. 6.1, for a review) and a dipolar or quadrupolar magnetic field topology. The three magnetic models that best reproduce the features of the oscillation spectra of α Cir are shown in Table 2 and the values of l that correspond to each frequency for these models are given in Table 3.

Conclusions and discussion

We have summarized the main results of an intensive study of the roAp star prototype α Cir, part of which has been published in Bruntt et al. 2008. Our team has made the first interferometrically-based determination of the effective temperature of an roAp star. The new value of $T_{\mathrm{eff}} = 7420 \pm 170$ K is lower than all values found in the literature. Additionally, new seismic data for α Cir were acquired with the *WIRE* satellite and with the 0.5-m and 0.75-m telescopes at SAAO. Two new frequencies were found in both the *WIRE* and SAAO data and they form a triplet with the known dominant frequency. The triplet is nearly equally spaced with a separation of $30.173 \pm 0.004\,\mu$Hz, which we interpret to be half the large separation. Using the new global parameters of the star, we computed a non-magnetic model for α Cir. The large separation of this model is in good agreement with the observed large separation, but the model fails to explain the nearly equidistant spacing as well as the secondary frequencies.

In an attempt to understand these discrepancies we computed magnetic perturbations to the frequencies of the non-magnetic model. We found that the magnetic model that best reproduces the oscillation spectrum has a quadrupolar topology and a magnitude of 1.4 kG. From this model, we identify the largest amplitude mode, f_1, as being an $l = 3$ mode. We note that due to the magnetic effect, the eigenfunctions in roAp stars are distorted. Thus, it is possible that modes of degree higher than l = 2 may generate lower-degree components near the surface that, in turn, may be observed (e.g. Cunha 2005). Also, we find that the magnitude is rather sensitive to the position where one of the boundary conditions of the magnetic code is applied. To overcome this problem, and test the robustness of our results, we are currently implementing a different atmospheric model in our code. Thus, the results presented here for the magnetic models are still preliminary.

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