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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.

Session: STARS - effects of magnetic field on stellar pulsation

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

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[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 (Kochukhov, Bagnulo & Lo Curto, in preparation).

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 multi-periodic 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 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., this meeting). This amplitude variation could not be ascribed to the rotational modulation because rotation period of this star exceeds 70 years (Bychkov et al. 2006).

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 non-radially 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 made possible 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 multi-site 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 recieved 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 non-radial 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 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 the 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 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. 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 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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