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Asteroseismology of magnetic stars

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Abstract.

Precision asteroseismology requires a detailed modelling of stellar structure and pulsations. It means that even if some effects are small they must be taken into account for an accurate confrontation of theory and observations. Studies of the last decade have shown that magnetic field is quite ubiquitous among stellar objects. Thus, by studying pulsators with measurable magnetic filed one can derive seismic inferences about a distortion caused by the magnetic field inaccessible in other manner. Here we discuss the latest achievements of synergies between asteroseismic inferences and magnetic field measurements.

Key words: asteroseismology – magnetic field – stars: rotation – stars: oscillations

1. Introduction

The magnetic field and rotation are intrinsic features of stars. Their effects modify both stellar structure and oscillations. Besides the Sun, the surface magnetic field has been detected in various pulsating variables, including main sequence stars, giants, white dwarfs and neutron stars. Their asteroseismic analysis can yield an independent determination of many parameters connected with both stellar properties and magnetic field features. The most obvious example are rapidly oscillating chemically peculiar A type stars (roAp; Kurtz, 1982). The stars are interpreted as rapid rotators with rotation axis oblique to the pulsation axis which is aligned to magnetic field symmetry axis. The magnetic field splits the pulsational modes into multiple components. From the ratio of the different peak amplitudes, one can deduce the geometry of the system, determine the magnetic field configuration and the ratio of the Lorentz force to the Coriolis force (Shibahashi, 2001). In case of solar like oscillators, a combination of the photometric observations and asteroseismic analysis allows to calibrate age-rotation-magnetic activity relation. Another interesting application of asteroseismology is to discover the internal magnetic field confined into the stellar cores.

The paper is organized as follows. In Sect. 2, we give a short description of the theory of stellar pulsation under the influence of the magnetic field and rotation. In Sects. 3, 4, 5 we introduce the different types of pulsating stars that exhibit a presence of a magnetic field. The last section contains a summary.

2. Magnetic field - rotation - pulsation interaction

2.1. Basic properties

In general, an interaction between the magnetic field, rotation and stellar pulsations is a very complicated issue. To study the effects, we need to include into the pulsational equations additional factors associated with the Coriolis, centrifugal and Lorentz forces. A linearized equation for nonradial adiabatic pulsations under the influence of rotation and magnetic field can be written in the following form (Unno et al., 1989; Shibahashi & Takata, 1993):

$$\mathcal{L}(\boldsymbol{\xi}) - \omega^2\boldsymbol{\xi} + \omega\mathbf{M}(\boldsymbol{\xi}) + \mathbf{N}(\boldsymbol{\xi}) + \mathbf{B}(\boldsymbol{\xi}) = 0, \tag{1}$$

where the operator $\mathcal{L}$ describes the linear, adiabatic oscillations of the nonrotating and non-magnetic star, $\boldsymbol{\xi}$ is the mass element displacement and ω is the angular pulsational frequency. First and second order effects of the rotational velocity field are described by the operators $\mathbf{M}$ and $\mathbf{N}$, respectively. The magnetic field effects are contained in the operator $\mathbf{B}$. The magnetic field perturbation is described by $\frac{\partial \mathbf{B}'}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}_0)$.

The effect of the magnetic field is measured by the ratio the Alfvén velocity to the sound velocity, c_A/c_s, which compares the Lorentz force with the pressure-gradient force. In most stellar models the values of c_A is comparable or larger than c_s only in the outer layers, e.g., in the case of roAp stars these are layers from the He II ionization zone. The frequency perturbation is proportional to the ratio of the total magnetic energy to the total gravitational energy of a star.

As in the case of higher order effects of rotation, the angular dependence of the eigenfunctions cannot be expressed by a single spherical harmonic. In the framework of the perturbation theory, the expansion in a sum of the spherical harmonics with $\ell = 2j - 1$ for odd modes and $\ell = 2(j - 1)$ for even modes $(j = 1, 2, 3, ...)$.

The magnetic field affects both the equilibrium structure and oscillations in the second order of magnitude. In contrast, the rotation affects the equilibrium structure in the second order, while their effects on the oscillations appear already in the first order. This means that in the first approximation we can discard the rotational effects when building equilibrium model and concentrate only on the pulsation-rotation interaction. In case of magnetic field, we need to take special care in preparing both the equilibrium and pulsation models.

2.2. The oblique pulsator model

The oblique pulsator model was developed to describe the frequency pattern found in roAp stars (see Sect. 3), but this model can also be used, e.g., to described pulsating magnetic B-type stars. In the simplest approach, we assume that the oscillation symmetric axis coincides with the magnetic axis which is inclined to the rotational axis (Stibbs, 1950; Kurtz, 1982). More advanced studies allow the magnetic axis to be inclined to both the pulsation and rotation axes (Bigot & Dziembowski, 2002). The rotational modulation of the pulsational amplitude causes splitting of the single frequency peak into $2\ell+5$ components. Their relative amplitudes depend on various properties of a star (i.e. Dziembowski & Goode, 1985; Shibahashi & Takata, 1993). It means that observations of the fine structure in the oscillation spectra can be used as a probe of the internal rotation and magnetic field. Such studies are very challenging but potentially highly rewarding because they can provide the information on the degrees of the pulsation modes, magnetic geometries and the strength of the magnetic field. For example, the radial mode ($\ell = 0$) distorted by the dipolar magnetic field gains an additional quadrupolar character ($\ell = 2$). Rotational modulation of the mode amplitude splits the frequency peak in the power spectrum into five components separated by the rotational frequency. The ratio of the amplitudes of the outer components to the inner components is given by (Shibahashi & Takata, 1993; Shibahashi, 2001):

$$\frac{A_2 + A_{-2}}{A_1 + A_{-1}} \simeq \frac{1}{4} |\tan\beta \tan i|, \tag{2}$$

where β is the angle between the rotation and magnetic axes and i is the inclination angle. In other words, detection of the five components of the distorted radial mode allow us to constrain the geometry of the magnetic field and rotation axis independently from polarimetric determinations.

The dipole axisymmetric mode influenced by the dipolar magnetic field is characterised by a superposition of the dipole axisymmetric mode, dipole non-axisymmetric modes and octupolar modes ($\ell = 3$) with azimuthal numbers $m = 0, \pm 1$. This leads to the occurrence of a triplet which can be used as a diagnostic tool. The relative amplitudes of its components depend strongly on the stellar magnetic field and rotation (Shibahashi & Takata, 1993):

$$\frac{A_1 + A_{-1}}{A_0} \simeq |\tan\beta \tan i|, \qquad \frac{A_1 - A_{-1}}{A_1 + A_{-1}} \simeq \frac{C_{n\ell=1}\Omega}{\omega^{mag}_{|m|=0} - \omega^{mag}_{|m|=1}}, \tag{3}$$

where $\omega^{mag}_{|m|}$ is the perturbation of the pulsational frequency caused by magnetic field. $C_{n\ell}$ is a Ledoux constant (Ledoux, 1951), Ω is the rotational frequency and $mC_{n\ell}\Omega$ is the first effect of the Coriolis force. The right side of the second Eq. (3) is a measure of the ratio of the Coriolis force to the Lorentz force. In principle, it is possible to estimated the magnetic field strength of roAp stars, provided that the rotational velocity is known. Also, due to the rotational amplitude modulation every component of the triplet splits into seven components producing as many as 21 frequencies grouped in seven triplets. This structure is very characteristic and can be easily recognised in the power spectra.

3. Rapidly oscillating Ap star

The roAp stars were discovered by Kurtz (1982). A few dozen of roAp stars have been identified so far. The stars are main sequence object and can be found near the classical instability strip. Their light variations are caused by pulsations in high-order acoustic modes (p modes) propagating in the presence of a strong magnetic field (so called magneto-acoustic modes). The roAp stars exhibit strong abundance anomalies, which are usually non-uniform on the stellar surface. The chemical peculiarities are regarded as a result of an atomic diffusion. It seems, that all A-type stars that are not chemically peculiar do not posses a surface magnetic field (Shorlin et al., 2002; Bagnulo et al., 2006). On the other hand, all Ap stars do posses a surface magnetic field of the order of several kG (Aurière et al., 2007). This clearly indicates that the Ap phenomenon is connected with the magnetic field (Wade et al., 2009).

An excellent example of a roAp star is HR 1217 which was one of the first discovered stars of this type (Kurtz, 1982). It is also one of the best studied roAp stars since it was a target of a lot of observations, (including multi-site campaigns; Kurtz et al., 2002, 2005). Kurtz et al. (2005) derived a series of six triplets with nearly equal spacing. Five triplets had alternating spacing of 33.4 μHz and 34.5 μHz. The sixth frequency triplet was separated by 50 μHz from fifth triplet. The highest triplet did not follow the asymptotic relation. This effect was explained by Cunha & Gough (2000); Cunha (2006), who found that at the frequencies of maximal magneto-acoustic coupling the influence of the magnetic field on the frequency value is much larger than in other cases. This should cause the decrease of the frequency spacing indicating a missing triplet separated by about 34.6 μHz from the fifth triplet. Indeed, the missing modes were found in the data gathered during world-wide observational campaign called Whole Earth Telescope (Kurtz et al., 2002), supporting the theory of Cunha and Gough.

From polarimetric measurements of the surface magnetic field of HR 1217 Bagnulo et al. (1995) found a polar field strength of 3.9 kG, an inclination $i = 137^\circ$ and a magnetic obliquity of $\beta = 150^\circ$. The rotation period is of the order $P_{\rm rot} = 12.46$ d (Kurtz et al., 2005; Ryabchikova et al., 2005) while Lüftinger et al. (2008) found that the magnetic field of the star can be quite well described as a simple dipole. The value of the left side of the first Eq. (3) is consistent with the inclination i and obliquity β derived by Bagnulo et al. (1995) strongly supporting the oblique pulsator model. Also, Ryabchikova et al. (2007) measured the radial velocities of pulsational modes as a function of a depth inside of the stellar atmosphere. The authors derived the phase shifts between the radial velocities and photometric light changes and constrained the pulsational velocity in the atmosphere which turned out to be slightly smaller that the sound speed.

4. Magnetic pulsating B-type stars

The majority of intermediate and massive main sequence stars show no evidence of surface magnetic fields. Detailed spectropolarimetric surveys like MiMes (Magnetism in Massive Stars; Alecian et al., 2014; Wade et al., 2016), BinaMIcS

(Binarity and Magnetic Interactions in various classes of stars; Alecian et al., 2015), BOB (B fields in OB stars; Hubrig et al., 2014) or BRITE spectropolarimetric survey (Neiner & Lèbre, 2014) brought however positive detection of magnetic field in a few B-type stars, including some β Cep variables.

The star β Cep itself pulsates in at least six frequencies (Aerts et al., 1994; Telting et al., 1997) and has a surface magnetic field that changes sinusoidally. This indicates that the magnetic axis is oblique to the rotation axis (Henrichs et al., 2013). The observed equidistant structures composed of five components in the frequency spectrum has been interpreted by Shibahashi & Aerts (2000) as a manifestation of magnetic perturbation of a radial mode. Since the star pulsates also in an independent quadrupole mode, the authors were able to determine the mass of the star, its evolutionary status and properties of the magnetic field. They derived that the star is on the main sequence and its mass is about $9\,\mathrm{M}_\odot$. The value of the inclination, i, was calculated from the rotational velocity $V\sin i \approx 25\ \mathrm{km\,s^{-1}}$ and the rotational period of the order of 6 days. This gave $i \approx 30°$ and $\beta = 100°$ (see Eq. 2). These results, although very interesting, may not be valid. Henrichs et al. (2013) derived a different value of the rotational period of β Cep. The new period is twice the value used by Shibahashi & Aerts (2000), i.e. 12 days. This gives a larger inclination $i \approx 60°$. The angle between the magnetic field and the rotation axis does not change significantly, $\beta \approx 96°$. This example shows that the analysis of magnetic pulsators gives large prospects but the results depends strongly on the observational constraints.

Another interesting example of a pulsating magnetic B-type star is HD 96446 (Neiner et al., 2012). This is a helium rich star that exhibits a strong large-scale magnetic field. Measuring of the magnetic field on the surface of a pulsating star is not an easy task. Between the subexposures there can be significant radial velocity shifts caused by the pulsational motion. To exclude the impact of the pulsation on the magnetic field measurements, the careful corrections of the individual spectra have to be taken into account. Otherwise, the magnetic field can be significantly underestimated. Such detailed studies were performed by Järvinen et al. (2017) who found the average value of the magnetic field of the order 4 kG and determined the inclination angle $i \approx 18°$ and the magnetic field obliquity $\beta \approx 40°$. The other interesting phenomenon connected with HD 96446 is that the magnetic field determined from different lines are shifted in phase. This indicates that the chemical elements are distributed inhomogeneously on the stellar surface. Although the star pulsates in p-modes, no detailed asteroseismic investigation has been performed, yet.

HD 43317 is a very interesting star because it is a magnetic hybrid β Cep/SPB pulsator. The surface magnetic filed is of the order of 1–1.5 kG and it seems to be in a dipolar configuration (Pápics et al., 2012; Buysschaert et al., 2017). The magnetic field can modify the internal structure of the star since the Lorentz force competes with the pressure gradient. The magnetic field stabilizes the differential rotation causing the uniform rotation and the overshooting from the convective core should be less efficient. These effects can be studied through an asteroseismic analysis. The presence of both high-order g-modes (SPB-type) and low-order p- and g-modes (β Cep-type) gives an unique possibility of studying the entire star (the former modes penetrate the deep interior of the star, while the later the outer layers). As of HD 96446, no asteroseismic analysis has been performed.

5. Oscillating Red Giants

The oscillations of red giant stars are driven by turbulent motions in the outer convective envelope, similarly to the oscillations present in the Sun. Also, very similar are the oscillation power spectra (see for example Bedding et al., 2011).

The very interesting features of these kind of pulsations are constant relative amplitudes of modes with different mode degrees. Some stars, however, exhibit unexpectedly small amplitudes of the dipole modes (about 20% of oscillating red giants). Also, it was noticed that the higher the frequency at maximum power the lower the amplitudes of the dipole modes. No clear correlations with stellar parameters were found, although a lower limit on the mass seems to exist at about $1.1\,\mathrm{M}_\odot$ (García et al., 2014).

One of the most promising hypothesis explaining this phenomenon assumes that the dipole modes are effectively dumped in the radiative cores of red giants. Higher degree modes do not penetrate near core regions so they are not dumped. Fuller et al. (2015) and Cantiello et al. (2016) claimed that the strong internal magnetic field can be responsible for the dipole mode energy leakage. The wave that tunnels into the core gains a higher mode degree character (see Sect. 2.2). Such a modified mode can not leave the inner part of the star since it is effectively reflected back by the evanescence zone, which is thicker for higher mode degrees (the so-called magnetic greenhouse effect).

Assuming some reasonable model, it is possible to calculate the minimal value of the magnetic field strength in the vicinity of the hydrogen burning shell. In some particular cases, where the so-called transition frequency between the depressed and normal dipole modes can be identified, it is possible to estimate the value of the magnetic field in the hydrogen burning layers. This was the case of KIC8561221 for which Fuller et al. (2015) found a magnetic field strength of the order of 10^7 G.

Further theoretical studies by Lecoanet et al. (2017) showed, that the gravity dipole waves that tunnels into the core are effectively conversed into magnetosonic waves, which then are dissipated in the stellar interior.

It seems, that observations of solar-like oscillations in red giants with depressed dipole modes allow us to constrain the internal magnetic field strength. This hypothesis, although very promising, was questioned in the work by Mosser et al. (2017), who claimed, that the mechanism responsible for dumping modes can not significantly impact the stellar structure, as strong magnetic field would certainly do. Further studies are needed in order to resolve this issue.

6. Summary

Magnetic fields have been found in different types of stars. Some magnetic stars pulsate, which gives a possibility of deriving constrains inaccessible in other ways, i.e., the information on the magnetic field geometry and field strength, including the internal magnetic field confined into the red giant cores.

However, the pulsation-magnetic fields interaction is very complicated. To derived reliable constrain on stellar parameters the long term polarimetric and photometric observations are needed in order to characterize the stellar magnetic field and oscillations, respectively. Due to these requirements, a detailed magneto-asteroseismic analysis of many stars is still lacking.

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Discussions during the welcome reception

Oleg Kochukhov