New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
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Combining seismology and spectropolarimetry of hot stars

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Abstract. Asteroseismology and spectropolarimetry have allowed us to progress significantly in our understanding of the physics of hot stars over the last decade. It is now possible to combine these two techniques to learn even more information about hot stars and constrain their models. While only a few magnetic pulsating hot stars are known as of today and have been studied with both seismology and spectropolarimetry, new opportunities - in particular *Kepler*2 and BRITE - are emerging and will allow us to rapidly obtain new combined results.

Keywords. stars: early-type, stars: magnetic fields, stars: oscillations (including pulsations)

1. Introduction

Over the last decade, two major steps have been done in parallel leading to substantial progress in the field of hot stars:

1) asteroseismology, in particular with space-based facilities such as MOST, CoRoT and *Kepler* but also with multi-site spectroscopic campaigns, has allowed us to study the pulsations of hot stars with high precision and thus their internal structure (see Aerts, this volume),

2) spectropolarimetry, with the new generation of high-resolution instruments Narval at TBL, ESPaDOnS at CFHT and HarpsPol at ESO, has allowed us to study the magnetic fields of hot stars and their circumstellar magnetospheres (see Grunhut, this volume).

We have now reached a point where these two techniques can be and should be combined to increase the physics we can probe in hot stars.

About 10% of hot stars are found to be magnetic with oblique dipolar fields above ~ 100 G at the pole (Wade *et al.* 2013). A similar occurence of magnetic fields is observed in pulsating hot stars and in non-pulsating ones (Neiner *et al.* 2011). The presence of this magnetic field impacts the power spectrum of pulsations that we observe in β Cep, Slowly Pulsating B (SPB) and roAp stars. In particular magnetic splitting of the pulsation modes occurs. The width of this splitting is directly related to the strength of the field, but the amplitude of the components of the splitted multiplet depends on the obliquity of the dipolar magnetic field compared to the rotation/pulsation axis (see e.g. Shibahashi & Aerts 2000). Therefore the number of peaks that can be detected in the power spectrum with current instrumentation depends on the magnetic geometry.

Knowing this information is very important to perform a proper pulsation mode identification and thus compute a correct seismic model.

Conversely, knowing the pulsation properties of a hot star is important when studying its magnetic field. Indeed, the Zeeman Stokes signature of the magnetic field observed in spectropolarimetry, which allows us to derive the longitudinal field value and magnetic configuration, depends on the intensity of the line profiles and thus on how the lines are deformed by pulsations. In particular, variations of the line profiles due to pulsations should be taken into account when measuring the longitudinal magnetic field. To derive proper magnetic field strength and geometry, one thus needs to model the intensity line profiles taking pulsations into account.

2. Magnetic modelling of pulsating stars

The Phoebe2.0 code (Degroote *et al.* 2013) allows users to model various surface observables such as the light curve or line profiles of a star with pulsations, spots, one or more companions, etc. The code has recently been modified to also provide the possibility to include an oblique magnetic dipole field at the surface of the modeled star.

Thanks to this code, we have modeled the line profile variations due to pulsations of the star β Cep and the corresponding Stokes V profiles due to the magnetic field (see Neiner *et al.* 2013).

β Cep is the first pulsating B star discovered to host a magnetic field (Henrichs *et al.* 2000) and its field configuration has thus been well studied since then. Donati *et al.* (2001) proposed that $B_{pol} = 360$ G, the inclination angle i is 60° and the obliquity angle β is 85°. Henrichs *et al.* (2013) showed that $B_{pol} > 306$ G (since $B_{max} = 97$ G), with the same inclination angle $i = 60°$ but $\beta = 96°$.

We have used 56 new Narval observations of β Cep and applied the LSD technique (Donati *et al.* 1997) to produce LSD Stokes I and V profiles. The I profiles vary mostly with the pulsation periods, while the Stokes V profiles clearly vary with both the pulsation periods and rotation period (because of the rotational modulation due to the field obliquity).

We fitted these LSD I and V profiles with Phoebe2.0. Our model results in $B_{pol} = 370$ G and $\beta = 92°$, compatible with the values published in the literature when ignoring pulsations. However, the most striking result is that the inclination angle we find is different from the one published so far. We find that $i = 46°$ rather than $i = 60°$ (Neiner *et al.*, in prep.).

This shows that ignoring pulsations in magnetic studies of pulsating stars introduces large errors in the geometrical configuration that is deduced from the Stokes profiles. Therefore, it is necessary to take pulsations into account, especially when their amplitude is large and in the case of radial modes, to obtain the proper geometry.

3. Seismic modelling of magnetic stars

The second pulsating B star discovered to host a magnetic field is V2052 Oph (Neiner *et al.* 2003). Its magnetic field was recently analysed in more details thanks to new Narval observations (Neiner *et al.* 2012). It was found that the magnetic field of V2052 Oph has a polar strength of $B_{pol} \sim 400$ G with an obliquity of $\beta \sim 35°$ and an inclination of $i \sim 70°$.

A multi-site spectroscopic (Briquet *et al.* 2012) and photometric (Handler *et al.* 2012) campaign also allowed us to reanalyse its pulsations in more details. The stellar pulsations are dominated by a radial mode but two non-radial low-amplitude prograde modes are

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also detected. Rotational modulation is also clearly present due to the oblique magnetic field. Moreover, we found that the seismic models that reproduce best the observations are those in which no or very small overshooting is added ($\alpha = 0.07 \pm 0.08\,\mathrm{H_p}$). Such a low overshooting parameter is not common in β Cep stars especially when they rotate as fast as V2052 Oph ($v \sin i = 80\,\mathrm{km\,s^{-1}}$) and when rotational mixing is thus expected.

The reason for this lack of macroscopic internal mixing is the presence of the magnetic field. Indeed, using the criteria proposed by Zahn (2011) based on Mathis & Zahn (2005) or by Spruit (1999), we derive that mixing is inhibited in V2052 Oph when $\mathrm{B_{pol}} \sim 70\,\mathrm{G}$ and 40 G, respectively (Briquet *et al.* 2012). This critical field value is 6 to 10 times weaker than the observed polar field strength of V2052 Oph. Therefore, the seismic model of V2052 Oph is the first observational proof that internal mixing is inhibited by magnetic field.

The criteria proposed by Zahn (2011) and Spruit (1999), however, use several crude approximations. We have thus started to devise a new more precise critical field criterion, computing the magnetic torque with realistic non-axisymmetric geometry, i.e. taking obliquity into account (Mathis *et al.*, in prep.). This criterion is of the form:

$$\mathrm{B}^2_{\mathrm{crit}} = 4\pi\rho R^2\Omega/t_{\mathrm{AM}} * F(\beta), \tag{3.1}$$

where ρ is the density of the star, R is its radius, Ω is its angular velocity, t_{AM} is the characteristic time for the angular momentum evolution (due to the wind or to structural adjustments), and F is a function of the obliquity angle β.

We will apply this criterion to all known magnetic hot stars. This will allow us to provide a new constraint for seismic models from spectropolarimetry, i.e. to tell if overshoot should be added in the seismic models or fixed to 0. Spectropolarimetry also already allows us to constraint these models by providing the geometry and in particular the inclination angle.

4. New opportunities for seismic studies of magnetic stars

MOST observed several bright pulsating OB stars and a few magnetic hot stars, but had not observed any pulsating magnetic hot star so far. While MOST will ceased its observations at the end of August 2014, one of its last target from May 29 to June 27, 2014, was V2052 Oph. Therefore a MOST light curve of this well-studied magnetic pulsating star has just become available (see Fig. 1). We hope to be able to identify magnetic splittings in the power spectrum of the pulsations of this star.

CoRoT observed many OB stars. None of them were known to be magnetic at the time of observations. However, targets observed in the “seismo” fields of CoRoT are sufficiently bright to be observed with high-resolution spectropolarimetry. This was done with Narval for all hot stars. Among these targets, one of them, HD 43317, was found to be magnetic (Briquet *et al.* 2013). HD 43317 is a hybrid (β Cep + SPB) pulsator and thus exhibits both p and g pulsation modes. In addition, regular frequency spacing was detected in its power spectrum (Pápics *et al.* 2012). A first seismic model was computed (Savonije 2013). However, the subsequent discovery of the magnetic field in HD 43317 calls for a reinterpretation of the observations, in particular in terms of magnetic splittings, and a new seismic model taking the magnetic field into account. The fact that HD 43317 shows p modes, g modes, rotational modulation and a magnetic field provides a wealth of constraints for such a model.

Finally, *Kepler* observed only one field of view optimised for the detection of exoplanets around solar-type stars. This field unfortunately did not contain O stars nor early-B stars.

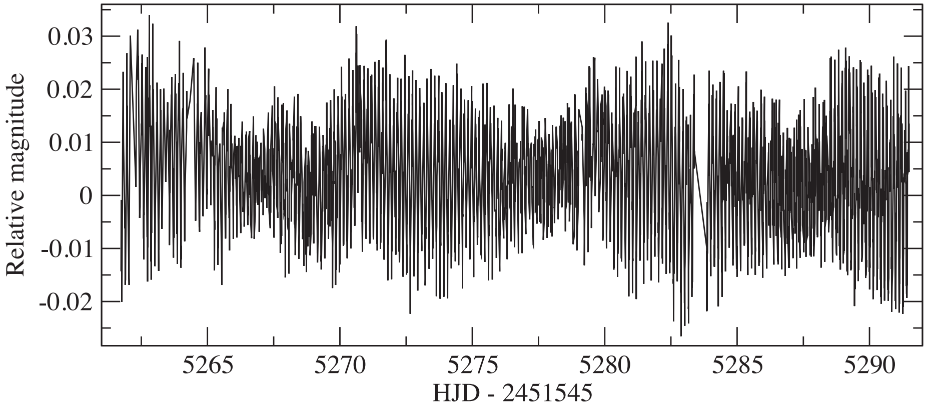

Figure 1. MOST light curve of the magnetic pulsating B star V2052 Oph.

It did contain some late-B stars and thus SPB stars, but none of them are known to be magnetic and these targets are too faint for current spectropolarimeters to detect a field unless it would be many kG in strength.

As a consequence, only very few magnetic pulsating stars could be observed so far with space-based photometry. New opportunities are however opening now: *Kepler*2 and BRITE.

4.1. *Kepler2*

Following the failure of several reaction wheels in *Kepler*, the spacecraft's objectives have been redefined into a new mission called *Kepler*2 (or K2). K2 is limited to pointing fields near the ecliptic plane and has to change field about every 3 months. As a consequence, the new fields of K2 include all kinds of targets.

In particular, Field 0 included 35 magnetic hot stars, among which 7 were observed between March 8 and May 30, 2014. Field 2 also contains 5 magnetic hot stars, which have been requested for observation in the second semester of 2014. Several magnetic hot stars will also be observable in the forthcoming Fields 4, 5, 7 and 9.

These K2 data will multiply tenfold the number of magnetic hot stars observed with high-precision space photometry. Many of these targets are expected to pulsate and will thus provide a unique opportunity for combined seismic and spectropolarimetric studies.

4.2. *BRITE*

The BRIght Target Explorer (BRITE) is an Austrian, Polish and Canadian constellation of nano-satellites (Weiss *et al.* 2014). Each participating country builds two nano-satellites: one providing photometry in the red band and the other one in the blue band. Using two colours allows one to more easily identify the pulsation modes of hot stars thanks to the difference in mode amplitude in the two colours.

The constellation is already composed of two Austrian, one Polish and one Canadian nano-satellites. The second Polish nano-satellite should be launched soon, while the second Canadian nano-satellite unfortunately failed to separate from the upper-stage of the launch vehicle during its launch in June 2014.

BRITE concentrates on targets brighter than V=4. As a consequence it mostly observes hot stars and evolved stars. There are $\sim$ 600 stars with V$\leqslant$ 4, among which $\sim$300 are hotter than F5, i.e. are stars in which a fossil magnetic field can be detected.

As of now, we know 8 magnetic pulsating OB stars with V$\leqslant$ 4: β Cen, ζ Ori A, τ Sco, β Cep, ϵ Lup, ζ Cas, ϕ Cen and β CMa.

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Since BRITE targets are very bright, they can very easily be observed in spectropolarimetry with a very good magnetic field detection threshold. We have thus started a large survey of all stars with V$\leqslant$ 4 with Narval (for stars with a declination $\delta > -20°$; PI Neiner), ESPaDOnS (for stars with $-45 < \delta < -20°$; PI Wade) and HarpsPol (for stars with $\delta < -45°$; PI Neiner). We aim at a detection threshold of $B_{pol} = 50$ G for all fossil field stars i.e. hotter than F5, and $B_{pol} = 5$ G for cooler stars with a magnetic field of dynamo origin. These very high quality data will also provide an ideal spectroscopic database, e.g. for the determination of the stellar parameters of all BRITE targets.

The spectropolarimetric observations of BRITE targets started in February 2014. We have already discovered 9 new magnetic stars. However, these are mainly cool stars. The hottest one, ι Peg, is a F5V star and a SB2 spectroscopic binary.

5. Conclusion

Combined magnetic and seismic observational studies can now be performed on bright hot stars. Such studies provide better and stronger constraints for models, e.g. on internal mixing or on the geometrical configuration of the star (inclination and field obliquity). They thus allow us to better understand the physics at work inside hot stars.

Conversely, ignoring one or the other aspect (pulsations or magnetism) can lead to substantially wrong results, therefore combined studies should be performed whenever possible. To this aim, *Kepler*2 and BRITE will provide new opportunities.

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Discussion

Henrichs: Congratulations with this beautiful work. Now that there is a new determination of the inclination angle of β Cep, I wonder if the UV wind behavior with its asymmetry could be modelled as well. In particular the asymmetry of the equivalent width at opposite orientation pointed to an off-centered wind configuration. Would this be reproduced? And what about the wind profiles themselves?

Neiner: In the Phoebe2.0 model of β Cep, we introduced as many observational constraints as possible. This includes not only the variable intensity line profiles and the magnetic Stokes V profiles, but also, e.g., constraints on the stellar parameters such as the distance or mass obtained thanks to speckle interferometry and radial velocities. As far as the UV is concerned, we have used the rotational modulation that you derived from the UV wind variations, but we have not modeled the wind line profiles themselves. Our model points to a mainly dipolar (but oblique) magnetic field.

Maeder: What may be the typical value of this new factor F that accounts for the obliquity in the expression of the critical field?

Neiner: This factor is composed of trigonometric functions of the obliquity β corresponding to the projection of the Lorentz force in the reference frame associated to the rotation axis. The exact details of this factor are still under investigation by Stéphane Mathis.

Meynet: When you say that in the magnetic star the mixing is inhibited, do you mean that the core does not seem to present any extension due to an overshoot or do you mean that there is no extension of the convective core and no mixing at all in the radiative zone, or no mixing in the radiative zone?

Neiner: In the CLES code that we used to model V2052 Oph, α only corresponds to core overshooting, so this model shows that there is no extension of the convective core. However, the critical field criteria concern any kind of mixing in the whole radiative zone, not only the extension of the core, and thus these criteria show that any mixing is inhibited in this star by the magnetic field. (See Mathis *et al.*, this volume, for more details.)

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