Open Access Online Journal on Astronomy and Astrophysics
Acta Astrophysica Taurica
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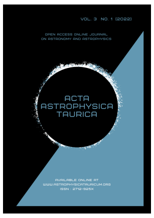

Acta Astrophys. Tau. 3(1), 1–5 (2022) doi:10.31059/aat.vol3.iss1.pp1-5

Magnetic field of pulsating stars

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Submitted on October 15, 2021

ABSTRACT

To date, magnetic fields have been detected in various types of pulsating stars. For several of these stars, the variability of the magnetic field with their radial pulsation period was confirmed. The physical mechanism of the pulsation variability of the magnetic field remains unknown. We discuss the current state of the problem of magnetic field variability over pulsation cycles in radially pulsating stars.

Key words: stars, pulsations, magnetic field, spectropolarimetry

1 Introduction

Pulsations have been found in stars at different evolutionary stages. In the past decade, the parallel development of two astrophysical techniques has provided significant progress in the study of pulsating stars:

- The rapid development of astroseismology, in particular thanks to space photometric missions such as MOST, CoRoT, and Kepler supported by multi-site spectroscopic campaigns, made it possible to study stellar pulsations and the internal structure of stars with high precision.
- On the other hand, the new generation of high-resolution spectropolarimetric instruments and techniques have allowed us to study the magnetic fields of pulsating stars.

We have now reached a point where these two techniques can be and should be combined to advance our understanding of the physics of pulsating stars.

One of the unexplored issues is the possibility of generating a magnetic field by pulsating mechanisms and its variability with a period of pulsations. During the pulsation cycle, the size and shape of a star change. And since in astrophysical objects the magnetic field is frozen into the plasma (i.e., the lines of force move with it), it can be assumed that both the magnitude and direction of the integral vector of the magnetic field are varied during the pulsation cycle. We present a short review of the current state of studying the magnetic field variability in radially pulsating stars of different types.

2 Stellar magnetic field measurement technique

Spectropolarimetric studies of stellar magnetic fields usually involve measuring the longitudinal component of the magnetic field by calculating the splitting of spectral lines caused by the splitting of atomic energy levels in the stellar magnetic field (Zeeman effect). If the magnetic field is parallel to the line-of-sight, the original spectral line is divided into two sets of σ components (the linearly polarized π components are not visible in this case). These σ-components have opposite circular polarizations.

The wavelength displacement of σ components from its original wavelength:

$$\Delta\lambda_{\rm B} = \frac{e}{4\pi m_e c^2} z\lambda^2 B_{\rm e} = 4.67 \times 10^{-13} z\lambda^2 B_{\rm e}, \tag{1}$$

where e is the elementary charge, m_e is the electron mass, c is the speed of light, z is the effective Landé factor, λ is the wavelength in Å, and $B_{\rm e}$ is the longitudinal magnetic field in gauss.

3 Magnetic field of pulsating stars

3.1 β Cephei stars

3.1.1 Low-amplitude pulsator γ Peg

γ Peg (HD 886, Sp B2 IV) is one of the most low-amplitude radial pulsator. It has one of the weakest amplitude variations in radial velocity $2K = 7$ km/s and a short pulsation period of 0.15 day (3.6 h). The first attempts to detect the magnetic field on γ Peg performed by Babcock (1958), Rudy, Kemp (1978), and Landstreet (1982) were unsuccessful due to large errors reaching several tens of gauss. However, using χ^2 statistics, Rudy, Kemp (1978) concluded that γ Peg shows strong evidence for a magnetic field. High-precision measurements of the magnetic field on γ Peg were carried out by Butkovskaya, Plachinda (2007). They also studied the

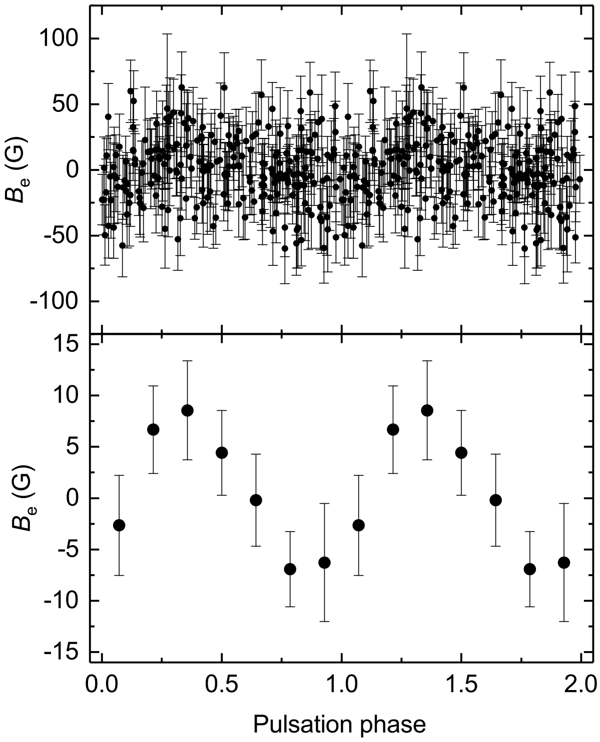

Fig. 1. Longitudinal magnetic field of γ Peg folded with the 0.15-day pulsation period. Individual measurements (top panel) and averaged by 7 bins values (bottom panel) are presented. From each individual value mean-per-night magnetic field is subtracted to eliminate stellar rotation.

variability of the magnetic field with the 0.15-day pulsation period of the star and found that the longitudinal component of the field varies sinusoidally with an amplitude of 7 G. The longitudinal magnetic field of γ Peg phased with the pulsation period is represented in Figure 1. The pulsational variation of the magnetic field can be seen more clearly for averaged data. In the bottom panel of Figure 1, the data are binned and averaged within 7 bins, where each bin consists of about 30 field measurements.

It should be noted that the pulsation curve of the magnetic field demonstrates extrema at the phases of maximum compression and expansion of the star. So, owing to the magnetic field being frozen into the plasma, the initial hypothesis is that the radial pulsations of the star result in the homothetic variation of the magnetic dipole. But numerical simulations performed by the authors show that in the case of γ Peg the observed amplitude of the longitudinal magnetic field variation must be some tenths of gauss, which is by an order of magnitude less than the measured amplitude.

3.1.2 Slowly rotating β Cep star ξ^1 CMa

ξ^1 CMa (HD 46328, B0.5 IV) is a radially pulsating β Cephei-type star that was identified by Shultz et al. (2017) as very slowly rotating with a rotation period of over 30 years. The star was first reported to be magnetic by Hubrig et al. (2006). The magnetic field of the star was later confirmed by Silvester et al. (2009) and Shultz et al. (2017). ξ^1 CMa is the only slowly rotating B-type star with a magnetosphere detectable in H_α and the only known early-type magnetic star with H_α emission modulated by both pulsation and rotation (Shultz et al., 2017) and with magnetospheric X-ray emission modulated by pulsation (Oskinova et al., 2014).

Shultz et al. (2017) found that the longitudinal component of the magnetic field of ξ^1 CMa exhibits a clear long-term modulation with the above-mentioned 30-year period, but also shows evidence for short-term variability with the 0.2-day (5 h) pulsation period (see Figure 21 in their paper). They concluded that the maximum of field should occur at phase 0.25, when the star is at its most contracted state, and minimum at phase 0.75, when the star is at its most extended state. The authors concluded that an obvious mechanism that might produce such an effect is conservation of the magnetic flux throughout radial pulsation cycles.

3.1.3 Extremely large pulsator BW Vul

BW Vul (HD 199140, Sp B2III, $V = 6.52^m$) is well known for its largest amplitude of brightness variation (0.2^m in the visual domain) and radial velocity variation (of 200 km s^{-1}) among β Cephei stars. It pulsates in the radial mode with a period of about 0.2 days (~5 h) and demonstrates a complex velocity curve, which has two discontinuities during each pulsation cycle, surrounding a nearly constant velocity phase called stillstand. These features, along with the line doubling in spectra of BW Vul, are explained by the propagation of shock waves through the atmosphere of the star (Fokin et al., 2004).

BW Vul was studied spectropolarimetrically at CFHT ESPaDOnS on 2011 June 21 and 2011 July 03. The first attempt to measure the magnetic field of this star and to study its behavior with a pulsation period was made by Butkovskaya et al. (2017). Because of short exposures (25 s), the maximal signal-to-noise ratio of a single spectrum was very low (only about 70), which led to the large errors in the measurement of its magnetic field. The mean-per-night longitudinal magnetic field measured by the authors was not statistically significant within the large errors. But folding of the individual measurements of magnetic field in phase with the well-known 0.2-day radial pulsation period allows them to assume that the star may have a magnetic field that varies with the pulsation cycle in a complex manner.

In Figure 2 the longitudinal magnetic field measured in hydrogen and helium lines is folded in phase with the period of radial pulsation of BW Vul. The pulsation phases are calculated according to the ephemeris $\mathrm{HJD_{max}} = 2455758.769 + 0.2010439 \times E$ (Odell, 2012), where the pulsation phase $\phi = 0$ corresponds to the maximum in the visual light curve (i.e. to the minimum of the stellar radius). In their original paper Butkovskaya et al. (2017) have shown pulsation curves of the magnetic field plotted from three hydrogen and eight helium lines (see Figures 1 and 2 in their paper). Here in Figure 2 we illustrate only two of them obtained by the He I 4921 Å and H_α lines. The rest of the lines also demonstrate a complex behavior of the magnetic field with the pulsation period, but, possibly due to large errors, this variability is not so pronounced. The magnetic field measured in the helium line, as in the case of γ Peg, demonstrates a maximum near the phase of maximum compression of the star. The magnetic

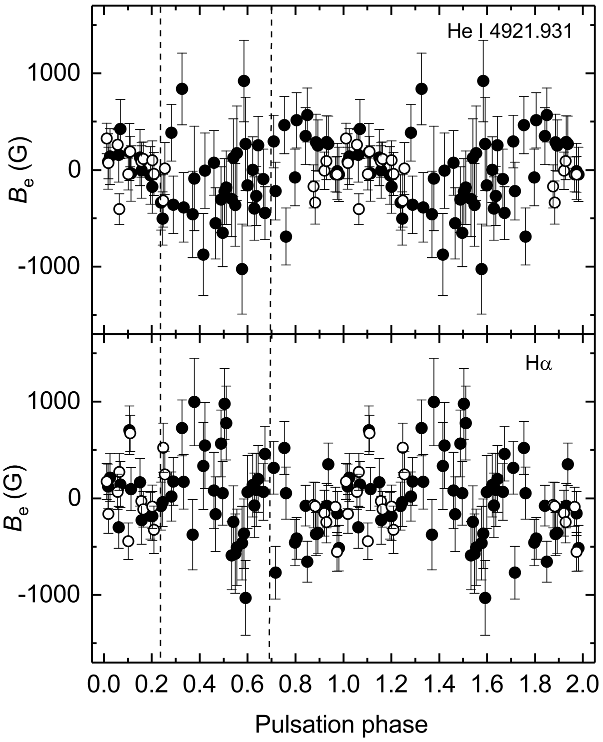

Fig. 2. Longitudinal magnetic field of BW Vul measured in lines He I 4921 Å (top panel) and H_α (bottom panel) folded with the 0.2-day pulsation period. The phases between ~0.25 and 0.7 when the stellar photosphere is strongly perturbed by shock waves (about 30 minutes) are shown by dashed lines.

field measured in the hydrogen line demonstrates a complex variability over the phases of shock wave propagation. Undoubtedly, the more precise spectropolarimetric observations of BW Vul are needed to measure the magnetic field on this star and more clearly study its behavior during the pulsation cycle.

3.2 RR Lyrae stars

RR Lyrae variables are the old low-mass giants of spectral class A or F. RR Lyrae variables pulsate in the radial fundamental mode (type RRab), the radial first overtone (type RRc), and both of these radial modes simultaneously (type RRd). The pulsation periods of such stars are 0.2–1.2 days, and the magnitude of the brightness variation is up to 2^m. Considerable fraction of RR Lyrae stars demonstrates the Blazhko effect (Blazhko, 1907), which consists in the periodic brightness amplitude/phase modulation on timescales of tens to hundreds of times the pulsation period (Kolenberg, Bagnulo, 2009). To date, the origin of the Blazhko effect is still unexplained. The most widely used hypotheses to explain this effect are:

1. A nonlinear resonance between the radial fundamental mode and a nonradial mode (Cox, 1993).
2. Adaptation of the oblique pulsator model for roAp stars (Kurtz, 1982) to Blazhko stars. This model assumes that the dipole magnetic field deforms the radial mode, which leads to the appearance of a quadrupole component (l = 2) for which the axis of symmetry coincides with the axis of the magnetic dipole. And as the star rotates, at different phases of its rotation period we see different superpositions of pulsation components causing the observed amplitude modulation (Cousens, 1983; Shibahashi, Takata, 1995). According to this model, a magnetic field of about 1 kG is needed to produce the observable amplitude modulation.
3. The model proposed by Stothers (2006) in which the turbulent convection inside the hydrogen and helium ionization zones becomes cyclically weakened and strengthened owing to the presence of a transient magnetic field that is generated in situ by either a turbulent or a rotational dynamo mechanism.

Today, the question whether RR Lyrae stars are magnetic is still a matter of debate. Because RR Lyrae variables are faint stars, this greatly limits the possibilities of spectropolarimetric studies of these objects. Until recently, RR Lyr (V = 7.2–8.2) was the only object of this kind that had been intensively observed with spectropolarimetric techniques. And the results of these observations are contradictory. Babcock (1958) and Romanov et al. (1987, 1994) reported a strong variable magnetic field on RR Lyr with a strength of up to 1.5 kG. Babcock found no correlation of the magnetic field behavior with the pulsation period. Romanov et al. reported that the magnetic field varies with an amplitude of up to 1.5 kG over the 0.567 d pulsation cycle, and its average intensity shows a periodic long-term variation corresponding to the 40.8 d Blazhko period. On the other hand, Preston (1967) and Chadid et al. (2004) reported no evidence for a magnetic field in the photosphere of RR Lyr.

Kolenberg, Bagnulo (2009) performed a spectropolarimetric survey of 17 relatively bright southern RR Lyrae stars using the FORS1 instrument at ESO VLT. They determined mean longitudinal magnetic fields of stars in the sample with a typical error bar of <30 G. All their measurements resulted in null detections within 3σ. The authors also determined an upper limit for the strength of the dipole field in the stars of their sample at 130 G with a 95% confidence level. Figure 3 in Kolenberg, Bagnulo (2009) shows the absolute value of the mean longitudinal field as a function of the pulsation phase. Although this plot refers to different stars with different geometric configurations, the higher field values are located near phase $\phi = 0$. According to the authors, it could potentially reveal the presence of a cyclic variability of the magnetic field over the pulsation cycle due to the magnetic flux conservation, because the stellar radius and surface are minimum shortly before phase zero and attain their highest value around phase $\phi = 0.5$. Also Kolenberg, Bagnulo (2009) do not confirm a correlation of Blazhko modulation with the presence of a strong, quasi-dipolar magnetic field for RR Lyrae stars, but they noted that more complex magnetic field morphologies may be detected with high-resolution spectropolarimetric observations.

3.3 Classical Cepheid η Aql

The first attempts to detect a magnetic field on the classical Cepheid η Aql were made by Borra et al. (1981) and Borra et al. (1984), and they detected no magnetic field on this star. The presence of the magnetic field on η Aql was established by Plachinda (2000), who also showed the pulsation modulation of the longitudinal component of the field in the range from −100 to +50 G. Most remarkably, he pointed out an apparent discontinuity in the field variation (around phase $\phi = 0.62$) and attributed it to an abrupt change in the magnetic field configuration associated with the passage of a shock wave through the atmosphere. Two years later, Wade et al. (2002) reported no statistically significant longitudinal magnetic field on η Aql and claimed that η Aql is a non-magnetic star, at least at a level of 10 G. But more recent investigation by Grunhut et al. (2010) found clear Zeeman signatures in Stokes V parameter for η Aql and 8 other supergiants.

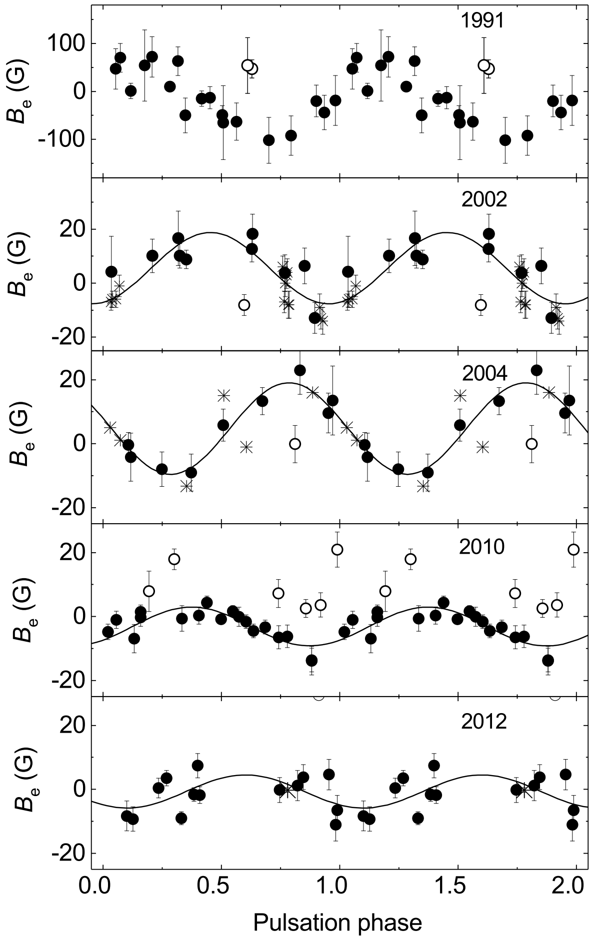

Fig. 3. Longitudinal magnetic field of η Aql folded in phase with the 7.176726-day pulsation period. Our data obtained in different years are marked by filled and empty circles. Data by other authors are marked by snows, i.e. data from Wade et al. (2002) and Grunhut et al. (2010) in the second panel; data by Borra et al. (1981) and Borra et al. (1984) in the third panel; data by Grunhut et al. (2010) in the bottom panel. Fitting sinusoids are shown by strong lines. Empty circles represent data that have not been taken into account for the fits. The reason for the deviation from the common curve is still unknown.

Figure 3 shows the pulsation modulation of the longitudinal magnetic field of η Aql in different years. It can be seen that in contrast to the aforementioned β Cephei-type pulsators, the amplitude, mean field, and phases of the maximum and minimum field of η Aql vary from year to year. The reason for these variations is unknown.

4 Summary

Asteroseismology and spectropolarimetry have significantly advanced us in understanding the physics of pulsating stars over the last decade. It is now possible to combine these two techniques to learn even more information about pulsating stars and constrain their models.

To detect and study the pulsational variability of the magnetic field, we need time series of magnetic field measurements overlapping the pulsation period of a star. However, most measurements of the magnetic field of pulsating stars were obtained within the monitoring programs, in which only a few measurements of the magnetic field were performed for each target. That is why, although to date the magnetic field has been reliably recorded in different types of pulsating stars, the variability of the magnetic field with a pulsation period is confirmed for only a few targets, and the nature of the pulsating variability of the magnetic field remains unknown. Without solving this problem, the detailed magnetohydrodynamic modeling of physical processes in the atmospheres of pulsating stars will be incomplete.

Acknowledgements. Plachinda S. acknowledge the support of Ministry of Science and Higher Education of the Russian Federation under Grant number 075-15-2020-780 (N13.1902.21.0039).

References

Babcock H.W., 1958. Astrophys. J. Suppl. Ser., vol. 3, pp. 141–210.

Blazhko S., 1907. Astron. Nachr., vol. 175, pp. 325–327.

Borra E.F., Fletcher J.M., Poeckert R., 1981. Astrophys. J., vol. 247, pp. 569–576.

Borra E.F., Edwards G., Mayor M., 1984. Astrophys. J., vol. 284, pp. 211–222.

Butkovskaya V., Plachinda S., 2007. Astron. Astrophys., vol. 469, pp. 1069–1076.

Butkovskaya V.V., Plachinda S.I., Pankov N.F., 2017. Astron. Nachr., vol. 338, pp. 938–943.

Chadid M., Wade G.A., Shorlin S.L.S., Landstreet J.D., 2004. Astron. Astrophys., vol. 413, pp. 1087–1093.

Cousens A., 1983. Mon. Not. Roy. Astron. Soc., vol. 203, pp. 1171–1182.

Cox A.N., 1993. Proc. IAU Coll., vol. 139, pp. 409.

Fokin A., Mathias Ph., Chapellier E., et al, 2004. Astron. Astrophys., vol. 426, pp. 686–693.

Grunhut J.H., Wade G.A., Hanes D.A., Alecian E., 2010. Mon. Not. Roy. Astron. Soc., vol. 408, pp. 2290–2297.

Hubrig S., Briquet M., Scholler M., et al., 2006. Mon. Not. Roy. Astron. Soc.: Letters, vol. 369, iss. 1, pp. L61–L65.

Kolenberg K., Bagnulo S., 2009. Astron. Astrophys, vol. 498, no. 2, pp. 543–550.

Kurtz D.W., 1982. Mon. Not. Roy. Astron. Soc., vol. 200, pp. 807–859.

Landstreet J.D., 1982. Astrophys. J., vol. 258, pp. 639–650.

Odell A.P., 2012. Astron. Astrophys, vol. 544, pp. A28–A31.

Oskinova L.M., Nazé Y., Todt H., et al., 2014. Nature Communications, vol. 5, p. 4024.

Plachinda S.I., 2000. Astron. Astrophys, vol. 360, pp. 642–646.

Preston G.W., 1967. in: The Magnetic and Related Stars, R.C. Cameron (ed.), pp. 3.

Romanov Yu.S., Udovichenko S.N., Frolov M.S., 1987. Sov. Astr. Lett., vol. 13, pp. 29–31.

Romanov Yu.S., Udovichenko S.N., Frolov M.S., 1994. Bull. Spec. Astrophys. Obs., vol. 38, pp. 169–170.

Rudy R.J., Kemp J.C., 1978. Mon. Not. Roy. Astron. Soc., vol. 183, pp. 595–603.

Shibahashi H., Takata M., 1995. ASP Conf. Ser., vol. 83, pp. 42–43.

Shultz M., Wade G.A., Rivinius Th., et al., 2017. Mon. Not. Roy. Astron. Soc., vol. 471, iss. 2, pp. 2286–2310.

Silvester J., Neiner C., Henrichs H.F., et al., 2009. Mon. Not. Roy. Astron. Soc., vol. 398, pp. 1505–1511.

Stothers R.B., 2006. Astrophys. J., vol. 652, no. 1, pp. 643–649.

Wade G.A., Chadid M., Shorlin S.L.S., et al., 2002. Astron. Astrophys., vol. 392, pp. L17–L20.