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Differential rotation in magnetic chemically peculiar stars

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Abstract. Magnetic chemically peculiar (mCP) stars constitute about 10% of upper-main-sequence stars and are characterized by strong magnetic fields and abnormal photospheric abundances of some chemical elements. Most of them exhibit strictly periodic light, magnetic, radio, and spectral variations that can be fully explained by a rigidly rotating main-sequence star with persistent surface structures and a stable global magnetic field. Long-term observations of the phase curves of these variations enable us to investigate possible surface differential rotation with unprecedented accuracy and reliability. The analysis of the phase curves in the best-observed mCP stars indicates that the location and the contrast of photometric and spectroscopic spots as well as the geometry of the magnetic field remain constant for at least many decades. The strict periodicity of mCP variables supports the concept that the outer layers of upper-main-sequence stars do not rotate differentially. However, there is a small, inhomogeneous group consisting of a few mCP stars whose rotation periods vary on timescales of decades. The period oscillations may reflect real changes in the angular velocity of outer layers of the stars which are anchored by their global magnetic fields. In CU Vir, V901 Ori, and perhaps BS Cir, the rotational period variation indicates the presence of vertical differential rotation; however, its exact nature has remained elusive until now. The incidence of mCP stars with variable rotational periods is currently investigated using a sample of fifty newly identified Kepler mCP stars.

Key words: stars: chemically peculiar – stars: rotation – stars: individual: σ Ori E, CU Vir, V901 Ori, and BS Cir – space vehicles: Kepler

1. Introduction

Main-sequence stars comprise an inhomogeneous group of stellar objects burning hydrogen in their cores. The most striking differences are encountered between stars of the upper and lower main sequence. Lower-main-sequence stars display solar-type activity powered by the dissipation of local magnetic fields that are generated by an interplay of convective motion in subphotospheric layers and differential latitudinal rotation (DLR). Characteristics of DLR can be traditionally derived by tracking solar-type spots and astero/helioseismology.

Unfortunately, we have only scarce information about the rotational periods of individual upper main sequence stars because of the lack of standard solar-type star rotation tracers such as spots, flares, and active regions. Nielsen et al. (2013) analysed more than 12 000 Kepler stars including a few representatives of early spectral types. They found that the early spectral-type stars rotate faster (one revolution in less than 5 days) than the late spectral types. No evidence was drawn about the possibility of a differential rotation. Based on a study of Kepler data, Balona & Abedigamba (2016); Balona et al. (2016) recently suggested the existence of stellar activity and differential rotation in A-type stars. However, their findings, although tempting, are controversial and not generally accepted.

Fortunately, the magnetic chemically peculiar stars (mCPs) of the upper main sequence boast stable photometric and spectroscopic spots and strong magnetic fields. These can be utilized for precise analyses of their rotation periods. Thus, we can determine whether or not hot main sequence stars rotate differentially (Mikulášek, 2016, and references therein).

2. On the variability and physics of magnetic CP stars

Most of the mCP stars exhibit strictly periodic light, magnetic, radio, and spectral variations that can be adequately explained by a rigidly rotating MS star with persistent surface structures and stable magnetic field frozen into the surface of the star. The phase curves of various rotation tracers (light curves, spectral line intensities, and the effective magnetic field $\langle B_z \rangle$) contain information about the rotation of regions of different latitude.

This enables us not only to determine the rotational period but also to search for the presence of latitudinal differential rotation. See e.g., the mutual phase shifts in V901 Ori depicted in Fig. 1, taken from Mikulášek (2016). The strict equality of the periods derived from the phase curves of different tracers supports the concept of solidly rotating mCP stars without any latitudinal differential rotation.

The hardening of the outer parts of the star is due to the global magnetic field intervening not only with the stellar body but also its close environment. Magnetic field plays its decisive role just in outer, rarified parts of the star - in the

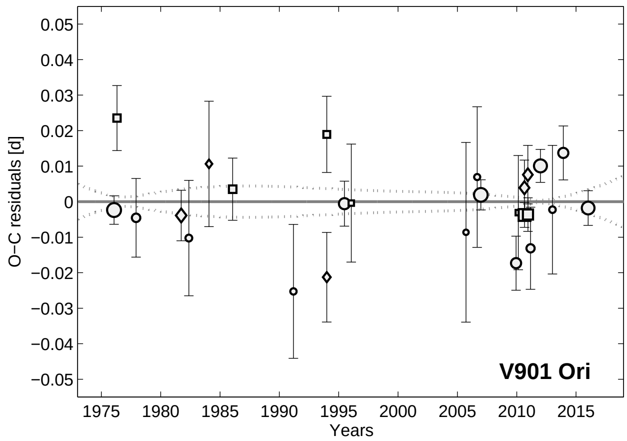

Figure 1. O-C residuals of individual sets of observations of V901 Ori that were obtained by different techniques and related to various structures on the surface (for details see Mikulášek, 2016). Circles mark results based on photometric measurements (silicon spots) while squares and diamond signs correspond to spectropolarimetric (magnetic field geometry) and spectroscopic (helium spots) observations. The areas of markers are proportional to the weights of individual phase shift determinations. Dotted lines denote the one σ uncertainty in the model fit.

magnetosphere and in the photospheric and subphotospheric layers, where the density of magnetic field energy exceeds the density of thermal kinetic energy.

Assuming magnetic induction of $B \sim 2$ kG at an optical depth $\tau = 1$ with a temperature of $T \sim 10^4$ K, density $\rho = 10^{-6}$ kg m^{-3}, and pressure $P_{\rm g} = 6\times10^{-4}$ atm $= 60$ Pa, we obtain a kinetic energy density of the thermal motion: 90 J m^{-3}, while the magnetic field energy density amounts to $\eta_B = \frac{B^2}{2\,\mu_0} \sim 16\,000$ J m^{-3}.

Both energy densities are equal at an optical depth of $\tau \sim 100$. Outer layers of the star are dominated by a magnetic field, while in inner parts the role of stellar magnetism is essentially negligible. The mass of the shell dominated by the magnetic field is about 2×10^{-9} $M_\odot$. Such a light shell will be able to glide on the inner part of the star and exhibit different rotation than the stellar interior. In this case, even a weak transport of the angular momentum through the stellar wind escaping the magnetosphere can brake the rotation of the visible part of a mCP star.

3. Magnetic CP stars with variable rotational periods

Using the method introduced and then developed by Mikulášek et al. (2008, 2011), and Mikulášek (2016), we analyzed archival, ground-based time series data of several dozens of mCP stars, with the hope of detecting possible varia-

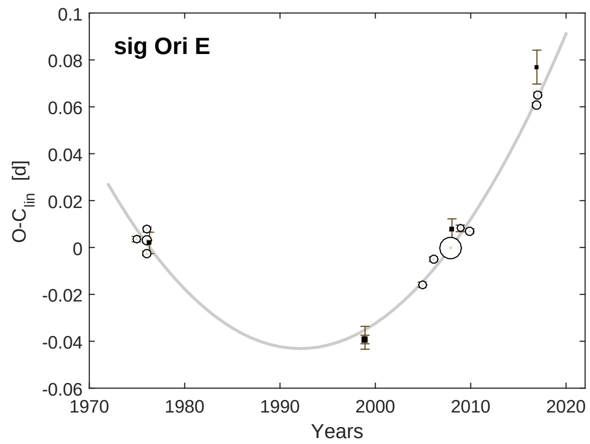

Figure 2. The O-C$_{\rm lin}$ diagram of σ Ori E with the parabolic fit and the mean values of individual sets of observations (see Mikulášek, 2016). Circles are based on the analysis of photometric data; black squares correspond to the analysis of helium lines' intensities. The areas of the symbols express the weights of observational sets.

tions in their rotational period. We found that the periods of almost all mCPs are constant to within the uncertainties of measurement.

However, some of mCPs (CU Vir, V901 Ori, σ Ori E, and BS Cir) were found to have slowly changing periods. These odd mCP stars form a very heterogeneous sample, and it is entirely possible that the mechanism(s) responsible for the observed period changes are different in each object. Unfortunately, the real incidence of mCP stars exhibiting period variations is unknown. A preliminary analysis of the sample of fifty new Kepler mCP stars has yielded no new candidates. However, research in this respect continues.

The nature of the lengthening period observed in BS Circini is still unknown. It may be the result of an internal differential rotation, or it could be the consequence of the precessional motion of the axis of the magnetically distorted star (Mikulášek et al., 2015, 2017). Magnetic braking through angular momentum loss caused by wind escaping from the extended magnetosphere apparently is only effective in particular cases of hot mCPs such as σ Ori E (Townsend et al., 2010; Mikulášek, 2016).

The period oscillations of at least CU Vir can be interpreted as a consequence of torsional waves that may disseminate in magnetic rotating stars (Krtička et al., 2017). Period changes in the hot mCP star V901 Ori may be caused by angular momentum loss through a stellar wind modulated by gradual reconfiguration of its extended magnetosphere, which is anchored in the stellar surface (Mikulášek et al., 2017).

4. Speculations on internal differential rotation

While the surface latitudinal differential rotation has been observed in the Sun and some sun-like stars, the properties of internal rotation in main-sequence stars remains unclear. Nevertheless, it is generally believed that the radiative regions rotate as a solid body while differential rotation develops in convective zones or cores.

Because the outer parts of mCP stars are dominated by the global magnetic field and envelopes overlying the convective cores are radiative, we do not expect any latitudinal differential rotation. However, some changes in the angular velocities of the envelopes and the 'solid' shell dominated by the magnetic field may exist in stars where the shell is braked by stellar wind escaping from the magnetosphere. It is important to note that the internal magnetic field provides an elastic connection between the outer envelopes and the surface 'solid' shell. Therefore we can expect either a firm interconnection between them (σ Ori E) or a more flexible one, allowing some cyclic oscillations (CU Vir). Possible changes in the intensity of the dynamical interaction with the environment may modulate the oscillations as well (V901 Ori).

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References

Balona, L. A. & Abedigamba, O. P. 2016, *Mon. Not. R. Astron. Soc.*, **461**, 497

Balona, L. A., Švanda, M., & Karlický, M. 2016, *Mon. Not. R. Astron. Soc.*, **463**, 1740

Krtička, J., Mikulášek, Z., Henry, G. W., Kurfürst, P., & Karlický, M. 2017, *Mon. Not. R. Astron. Soc.*, **464**, 933

Mikulášek, Z. 2016, *Contributions of the Astronomical Observatory Skalnate Pleso*, **46**, 95

Mikulášek, Z., Janík, J., Krtička, J., Zejda, M., & Jagelka, M. 2015, in ASP Conf. Ser., Vol. **494**, *Physics and Evolution of Magnetic and Related Stars*, ed. Y. Y. Balega, I. I. Romanyuk, & D. O. Kudryavtsev, 189

Mikulášek, Z., Krtička, J., Henry, G. W., et al. 2011, *Astron. Astrophys.*, **534**, L5

Mikulášek, Z., Krtička, J., Henry, G. W., et al. 2008, *Astron. Astrophys.*, **485**, 585

Mikulášek, Z., Krtička, J., Janík, J., et al. 2017, in ASP Conf. Ser., Vol. **510**, *Stars: From Collapse to Collapse*, ed. Y. Y. Balega, D. O. Kudryavtsev, I. I. Romanyuk, & I. A. Yakunin, 220

Nielsen, M. B., Gizon, L., Schunker, H., & Karoff, C. 2013, *Astron. Astrophys.*, **557**, L10

Townsend, R. H. D., Oksala, M. E., Cohen, D. H., Owocki, S. P., & ud-Doula, A. 2010, *Astrophys. J., Lett.*, **714**, L318