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# Rotational properties of magnetic chemically peculiar stars

**M. Netopil[1,2], E. Paunzen[2], S. Hümmerich[3] and K. Bernhard[3]**

[1] *Institute for Astrophysics, University of Vienna, Türkenschanzstraße 17, 1180 Vienna, Austria, (E-mail: mn.netopil@gmail.com)*

[2] *Department of Theoretical Physics and Astrophysics, Masaryk University, Kotlárská 2, 611 37 Brno, Czech Republic*

[3] *Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e.V. (BAV), Berlin, Germany*

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**Abstract.** The magnetic chemically peculiar (mCP) stars of the upper main sequence exhibit strong and globally organized magnetic fields that are inclined to the rotational axis and facilitate the development of surface abundance inhomogeneities resulting in photometric and spectroscopic variability. Photometric time series data are much easier to obtain than spectroscopic/polarimetric data or are available from large surveys, thus the number of known rotational periods increased significantly during the last years. Furthermore, Gaia data allow us to place an unprecedentedly large sample of mCP stars in the Hertzsprung-Russell diagram and to investigate evolutionary effects. In this paper we review the rotational properties of mCP stars and discuss open issues of stellar rotation in the presence of strong magnetic fields.

**Key words:** stars: chemically peculiar – stars: magnetic field – stars: rotation – stars: evolution

## 1. Introduction

Stellar rotation is an important physical property that can have a significant influence on stellar evolution. For example, the main-sequence lifetime of a $3\,M_\odot$ star is extended by about 30 percent when comparing the evolutionary tracks by Ekström et al. (2012) for non-rotating models and for a rotation rate of $\upsilon_{ini}/\upsilon_{crit} = 0.4$, the peak of the observed velocity distribution of young B-type stars according to Huang et al. (2010). For most stars, rotation can only be inferred by spectroscopic data and the spectral line broadening, which is used to estimate the projected surface velocity on the line of sight ($\upsilon \sin i$). However, for some star groups photometry is a very powerful tool to obtain a direct estimate of the rotation period. Many active stars show large star spots that may cause brightness variations observable even with smaller ground-based telescopes, but high-precision satellite data by Kepler, for example, also allows to study rotation based on star spots with much lower contrast levels (e.g. Reinhold & Gizon, 2015).

Photometry is also a very well suited tool for deriving the rotational period for a group of hotter stars. Chemically peculiar (CP) stars are upper main sequence objects (spectral types early B to early F) with spectra that are characterized by abnormally strong (or weak) absorption lines that indicate peculiar surface elemental abundances. The observed chemical peculiarities are thought to arise from the diffusion of chemical elements due to the competition between radiative pressure and gravitational settling. CP stars constitute about 10% of upper main sequence stars and are commonly subdivided into four classes according to Preston (1974): metallic line (or Am) stars (CP1), magnetic Ap stars (CP2), HgMn stars (CP3), and He-weak stars (CP4). The CP2 and the CP4 objects (also known as Bp/Ap or mCP stars) are notorious for exhibiting strong, globally organized magnetic fields of up to several tens of kiloGauss. Their atmospheres are enriched by various elements such as Si, Cr, Sr, or Eu and usually present surface abundance patches or spots. These lead to photometric variability, which is considered to be caused by rotational modulation and is explained in terms of the oblique rotator model (Stibbs, 1950). As a result, the observed photometric period is the rotational period of the star. mCP stars that exhibit this phenomenon are normally classified as $\alpha 2$ Canum Venaticorum (ACV) variables.

Besides the Galactic mCP stars, representatives in the Large Magellanic Cloud have been discovered (Paunzen et al., 2006, 2011b). However, these stars show no or only weak evidence of variability (Paunzen et al., 2013). This can be either due to the accuracy of the available photometric data or caused by different conditions during star formation that result in the absence of photometric spots of overabundant optically active chemical elements.

## 2. Knowledge of rotational periods

For a long time the knowledge of mCP star periods increased only at a moderate level, but with the availability of Hipparcos epoch photometry we noticed a huge improvement. This resulted in a list of about 360 stars with known periods in the latest compilation by Renson & Catalano (2001). The onset of large photometric surveys during the last years provided the basis for another boost of knowledge. A first attempt was made by Wraight et al. (2012) using lightcurves obtained with the STEREO spacecraft. They were able to derive reliable periods for 82 mCP stars. However, a significant enlargement of the sample was provided by a series of papers using data from the The All Sky Automated Survey (ASAS) or the SuperWASP survey (Bernhard et al., 2015a,b; Hümmerich et al., 2016). These authors derived rotational periods for more than 750 mCP stars including a large fraction of hitherto unstudied objects. We also refer to the summary paper by Hümmerich et al. (2018, these proceedings). Furthermore, numerous additional stars are classified as ACV in variable star catalogues, for example in the International Variable Star Index of the AAVSO (VSX, Watson et al., 2006).

The above listed sources were merged by Netopil et al. (2017) to construct a list that includes period values for more than 1300 objects, covering almost four times more stars than the previous catalogue by Renson & Catalano (2001). Certainly, some more objects were studied on an individual basis, thus a careful evaluation of the literature published during the last one and a half decades is still an essential task to obtain a complete census of our knowledge of mCP star periods. Nonetheless, the compilation by Netopil et al. (2017) provides an unprecedented basis for detailed investigations of rotational properties.

## 3. Previous studies of rotational properties

In the course of time it became clear that mCP stars rotate less rapidly than chemically-normal type objects of the same spectral type and that they are not rapid rotators seen pole-on (e.g. Wolff, 1967). Later, based on some cluster stars, Hartoog (1977) concluded that there is no magnetic braking on a time scale up to one Gyr. He also proposed that most of the angular momentum (AM) is probably lost in the pre-main-sequence phase. Furthermore, comparisons of the velocity distributions suggest that mCP stars rotate about three to four times slower than normal type objects (Abt & Morrell, 1995). Thanks to Hipparcos parallax data and spectroscopic surface gravities, North (1998) was then able to investigate evolutionary effects in more detail. Based on a sample of about 100 field stars with known periods he concluded that the observations are entirely compatible with conservation of angular momentum. This finding was also confirmed by more recent studies (e.g. Kochukhov & Bagnulo, 2006; Hubrig et al., 2007), although the first reference notes that for lower mass mCP stars an additional AM loss on the main sequence cannot be ruled out.

Calculations by Stępień & Landstreet (2002) showed that it is fairly clear that mCP stars achieve their unusually low AM prior to the main sequence stage, which was already postulated by Hartoog (1977), as mentioned above. An observational confirmation was then presented by Alecian et al. (2013), who investigated a sample of Herbig Ae/Be stars with and without magnetic fields. It was shown that the magnetic stars have already lost most of their angular momentum, despite their young ages. Although the sample was still based on only a small number of magnetic objects, the conclusion can be considered as a confident one.

## 4. A rejuvenation study of rotational properties

The large number of available rotation periods and the first data release of the Gaia satellite mission allow a detailed reinvestigation of some rotational properties. Therefore, Netopil et al. (2017) compiled photometric data to estimate effective temperatures using the calibrations by Netopil et al. (2008) and to place a substantial sample of mCP stars in the Hertzsprung-Russell diagram

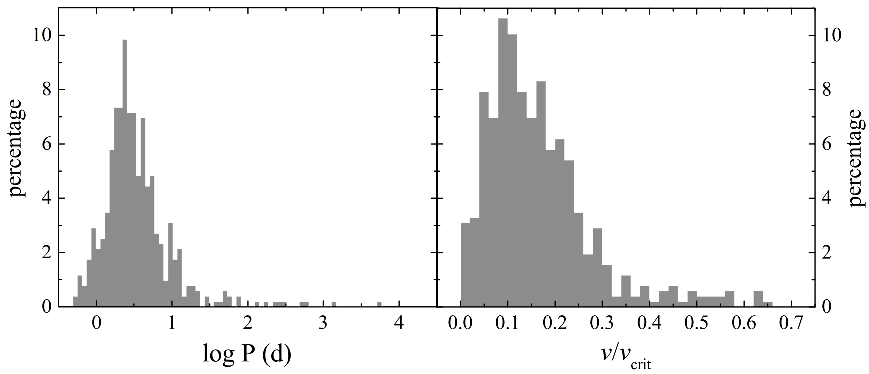


**Figure 1.** Distribution of periods and rotation rates $v/v_{\rm crit}$ based on the working sample of 518 mCP stars by Netopil et al. (2017). We adopted a binning so that both distributions show a comparable percentage at the maximum peaks.

(HRD). Although ACV characteristics already provide a reasonable hint at the mCP nature, they also used spectral types, photometric peculiarity indices, and magnetic field measurements to define a final working sample of 518 objects. Figure 1 shows the distribution of the adopted periods. The long-period tail of the distribution was recognized already for example by Wolff (1975), suggesting that a powerful deceleration mechanism has operated in these stars. This might be a result of the inclination of the magnetic and rotation axes, which are fairly closely aligned in stars with longer periods (Landstreet & Mathys, 2000). However, the distribution of the ratio of equatorial velocity ($V_{\rm eq}$) to the mass and time dependent critical velocity ($v/v_{\rm crit}$) shows also a tail of fast rotators (right panel of Fig. 1). This provides a stringent constraint for models of mCP stars, the efficiency of diffusion and its interplay with mixing processes. For only a few of the fast rotators the magnetic field has yet been measured, but all of these display field strengths of the order of 1.5 kG. Moreover, the fast rotators all have comparable masses of about $3\,{\rm M}_{\odot}$. However, this might not be an intrinsic property, because the mass distribution of all mCP stars peaks at this mass (see Fig. 3 by Netopil et al., 2017).

The comprehensive sample by Netopil et al. (2017) allowed an investigation of the rotational periods as a function of gravity by adopting narrower mass groups ($0.5\,{\rm M}_{\odot}$) than in previous studies. For all mass ranges they found excellent agreement with the evolutionary models by Georgy et al. (2013). This suggests conservation of angular momentum during the main sequence evolution without evidence of additional magnetic braking, which confirms previous conclusions. However, the very slow and very fast rotators cannot be explained by the increase of period during main sequence evolution alone. The period data were also transformed to $V_{\rm eq}$ and to the velocity ratio $v/v_{\rm crit}$. The latter

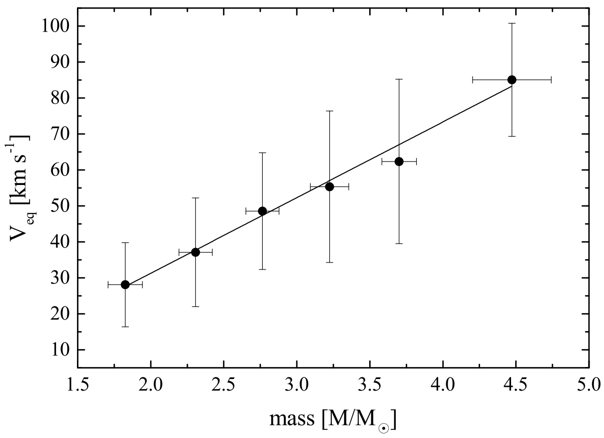


**Figure 2.** Median equatorial velocities of mCP stars as a function of mass based on the data by Netopil et al. (2017). The solid line represents the linear fit $V_{\rm eq}= -11(3) + 21(1) M/{\rm M}_{\odot}$.

represents a value that shows little dependence on evolutionary effects (Zorec & Royer, 2012). Netopil et al. (2017) investigated its dependence on mass, and Fig. 2 explores this in terms of $V_{\rm eq}$. Thus, consideration of the mass dependence is of importance in studies requiring the inclusion of stars with quite different masses. Based on 180 objects with available $v \sin i$ data the authors also investigated the inclination of the rotational axes. As expected, they found that these are randomly distributed, which confirms the previous conclusion by Abt (2001) using data for 102 stars. The increase of the number of objects is mostly based on the fact that more period data has become available, but we still notice a lack of spectroscopic studies.

Most of the results mentioned above are confirmations of previous studies, but the important link between rotation and magnetic field strength has not been considered yet. Usually, previous studies evaluated this relation only in the period domain. Kochukhov & Bagnulo (2006) concluded that their results indicate that the surface field is more intense in slowly rotating stars. On the other hand, Hubrig et al. (2007) note that stronger magnetic fields tend to be found in hotter, younger and more massive stars, as well as in stars with shorter rotation periods. Recently, Mathys (2017) significantly improved our knowledge by additional measurements of the mean magnetic field modulus, the most reliable measure of the actual field strength. He concluded that very strong magnetic fields ($\gtrsim 7.5$ kG) are found only in stars with rotation periods shorter than $\sim 150$ days. Furthermore, he notes that there are some atypical mCP stars which should not be considered for a generalised conclusion. One of these objects is HD 215441 (Babcock's star), the strongest magnetic mCP star.

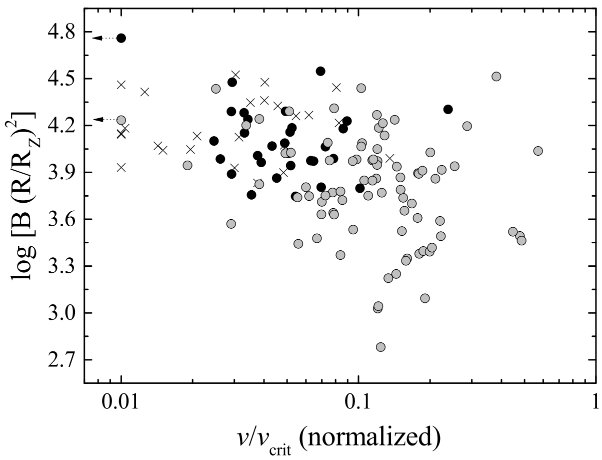


**Figure 3.** Magnetic fluxes as a function of normalized rotation rates. Black circles represent single stars from the sample of Mathys (2017), crosses SB systems in the last reference, and grey circles the data of Netopil et al. (2017) for stars with phase covered longitudinal field measurements. For the sake of a better representation we adopt a rotation rate of 0.01 for the slowest rotating stars, which represent approximately the error of this parameter for the slow rotators. The symbol at the very top left side represents Babcock's star.

Netopil et al. (2017) used the velocity ratio $v/v_{\mathrm{crit}}$ and the derived mass dependency of rotation to normalize their data sample. By adopting conservation of magnetic flux, they were able to show that the slowest rotating stars indeed show the strongest magnetic field. Thus, Babcock's star does not seem to be atypical at least in respect to rotation. Babcock's star is more massive than the very long-period objects, and its rotation rate, corrected for mass, is therefore actually lower, and it was braked more efficiently owing to its very strong magnetic field. However, the sample by Netopil et al. (2017) only includes a fraction of the stars listed by Mathys (2017). Figure 3 follows their investigation and shows an update by including about two third of the stars with a measured mean magnetic field modulus. A large fraction represents binary stars, and their inclusion certainly does not support the conclusion by Netopil et al. (2017). However, rotation might be influenced by both, the magnetic field and tidal braking by the companion. Thus, binary stars should be excluded from such an analysis. Furthermore, the position in the HRD clearly suffers from larger errors when the mass ratio is not very well known. We also note that the rotation period is still unknown for several objects in the list by Mathys (2017). An investigation of these objects will be of importance to obtain an even more profound picture between rotation and magnetic field strength. In addition, the possible binary nature of many little-studied objects requires more attention.

## 5. Conclusions

We reviewed some rotational properties of mCP stars. These cover the distribution of periods and their evolution on the main sequence, which suggests conservation of angular momentum, or the linear mass dependency of rotation. We also show a possible link between rotation and magnetic field strength. Although we notice a significant increase in the knowledge of rotation periods, we unfortunately still lack sufficient additional spectroscopic data. Beside the somewhat over-represented number of long-period stars, the distribution also shows a tail of very fast rotators. These are not yet fully explored, but they may also be in part the result of erroneous period data. Aliasing might be a problem for stars with sparse sampling or objects with very small amplitudes, for example. An additional influence might result from not correctly identified double-wave ACVs. These factors still has to be taken into account, but also the use of evolutionary models shows some open issues (see discussion by Netopil et al., 2017). We still do not know which metallicity is the proper choice for mCP stars. In addition, the width of the main sequence differs from model to model, mostly as a result of the adopted overshooting parameter. Also, evolutionary models appropriate for mCP objects do not yet take into account the magnetic field, which in turn offers another free parameter in the fitting procedure to obtain reliable parameters such as the mass. However, stellar age in particular is the most uncertain parameter for field stars. The investigation of more open cluster stars in respect to mCP nature or rotation period such as done by Paunzen et al. (2011a,c, 2014) would be imperative to further improve our knowledge.

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Melissa Munoz and Lilia Ferrario

Corinne Fletcher and Yaël Nazé