Ap stars with variable periods
Mikulášek Z. 1, 2, Krtička J. 1, Janík J. 1, Zejda M. 1, Henry G. W. 3, Paunzen E. 1, Žižňovský J. 4, Zverko J. 5

1 Department of Theoretical Physics and Astrophysics, Masaryk University, Kotlárská 2, CZ 611 37, Brno, Czech Republic, email: mikulas@physics.muni.cz
2 Observatory and Planetarium of Johann Palisa, VŠB – Technical University, Ostrava, Czech Republic
3 Tennessee State University, Nashville, Tennessee, USA
4 Astronomical Institute of Slovak Academy of Science, Tatranská Lomnica, Slovak Republic
5 Tatranská Lomnica 133, Slovak Republic

Abstract The majority of magnetic chemically peculiar (mCP) stars exhibit periodic light, magnetic, radio, and spectroscopic variations that can be adequately modelled as a rigidly-rotating main-sequence star with persistent surface structures. Nevertheless, there is a small sample of diverse mCP stars whose rotation periods vary on timescales of decades while the shapes of their phase curves remain unchanged. Alternating period increases and decreases have been suspected in the hot CP stars CU Vir and V901 Ori, while rotation in the moderately cool star BS Cir has been decelerating. These examples bring new insight into this theoretically unpredicted phenomenon. We discuss possible causes of such behaviour and propose that dynamic interactions between a thin, outer, magnetically-confined envelope braked by the stellar wind, and an inner faster-rotating stellar body are able to explain the observed rotational variability.

1. Introduction
The magnetic chemically peculiar (mCP) stars with abnormal surface chemical composition and strong, global magnetic fields are the most suitable test beds for studying rotational evolution in upper (B2 to F6) main sequence (MS) stars. The overabundant elements in their atmospheres are concentrated into large spot regions that persist for decades to centuries. As an mCP star rotates, periodic variations in its brightness, spectrum, and magnetic field are observed. Combining both new and archival observations of mCP stars collected over the past several decades, we can reconstruct their period evolution (if any) with high accuracy.

The article is dedicated to one of its co-authors – Dr. Jozef Žižňovský who passed away on 15 June 2013.
2. Period changes due to stellar evolution

The abnormal chemical abundances, spottedness, and strong global magnetic fields have no influence on the inner structure of mCP stars, which are evolving as regular upper-main-sequence stars. For such stars that are mildly rotating and without significant angular momentum loss (Meynet \& Maeder [11]), evolutional models predict their moments of inertia $J(t)$ and their rotational periods $P(t)$ should change roughly according to the simple relations:

$$J(t) = J_0 \exp \left( \frac{t}{\tau_{\text{MS}}} \right) \Rightarrow \frac{\dot{P}}{P} = \frac{j}{J} = \frac{1}{\tau_{\text{MS}}}, \Rightarrow P(t) = P_0 \exp \left( \frac{t}{\tau_{\text{MS}}} \right),$$

where $\tau_{\text{MS}}$ is the MS duration of an individual star, and $P_0$ and $J_0$ are the ZAMS values of rotational period and moment of inertia. These relations predict that we should observe slowing of these stars' rotation.

Even for the most massive He-strong mCP stars with MS lifetimes $\tau_{\text{MS}} = 30$ Myr, we estimate that $\dot{P} \leq 9 \times 10^{-11} \text{d}^{-1} P$. For the B2Vp He-strong star V901 Ori (HD 37776) with the period of $P = 1.538 \text{d}$ we obtain $\dot{P} \simeq 1.4 \times 10^{-10}$. Even though V901 Ori is one of the best monitored mCP stars, the uncertainty in its value of $\delta P = 5 \times 10^{-10}$ is several times larger than the expected evolutionary changes. Consequently, the rotational slowing driven by stellar evolution of MS stars is too small to measure with current techniques. If evolutionary changes are the only driver of rotational evolution, we would expect rotational periods in mCP stars to be quite constant.

3. mCP stars with variable periods

Careful period analyses of several dozen mCP stars have been done to date. These analyses confirm the expectations that CP star periods are, in general, stable within the uncertainties of their measurement. However, there is a small subgroup of mCP stars whose light curve shapes and spectroscopic variability remain stable, but whose rotational periods are variable (Pyper et al. [13, 15], Mikulášek et al. [8, 9, 7], Townsend et al. [18]).

Here we examine period changes in three of the best-observed mCP stars – V901 Ori, CU Vir, and BS Cir.
Ap stars with variable periods

Figure 1. a) Changes in the rotational period of V901 Ori in seconds. Time dependence of the period is approximated by a parabola reaching its maximum in 2007. b) Changes in times of zero phase in days can be well fitted by a cubic parabola.

3.1. He-strong V901 Orionis

V901 Ori = HD 37776 is a very young He-strong B2p mCP star located in the emission nebula IC 432 and has a strong \( B_s \approx 20 \) kG, complex, global magnetic field (Thompson & Landstreet \[17\], Kochukhov et al. \[3\]). Observed moderate light variations are caused by spot regions of over-abundant silicon and helium (Krtička et al. \[5\]).

Precise photometric and spectroscopic observations enabled Mikulášek et al. \[10,8\] to see continuous rotational deceleration, increasing the period of 1.5387 d by a remarkable 18 s during the last 37 years! The deceleration was interpreted in terms of the rotational braking of the outer stellar layers caused by angular momentum loss through the stellar magnetosphere. A complication with this interpretation, noted by Mikulášek et al. \[8\], was the negative value of the period's second derivative: \( \dot{P} = -29(13) \times 10^{-13} \text{d}^{-1} \), which implied that the rotational braking could soon change to accelera-
Presently, we have about 3500 photometric and spectroscopic measurements of V901 Ori, spanning nearly four decades. We find $\dot{P} = 1.77(5) \times 10^{-8}$, $\tau_{\text{spin}} = P/\dot{P} = 2.38(7) \times 10^5$ yr (only 1\% of $\tau_{\text{MS}}$). Our current rate of the period increase is $\dot{P} = -32(4) \times 10^{-13}$ d$^{-1}$, implying that the deceleration of the stellar rotation had already switched to acceleration by 2007 ± 2 yr (Fig. 1b).

3.2. Silicon mCP Star CU Virginis

The rapidly-rotating silicon mCP star CU Vir (HD 124224, HR 5313), with a period of 0.5207 d, displays more complex period changes. It is a hot silicon mCP star with a mass and radius of 3 $M_\odot$ and 2 $R_\odot$, respectively (Stepiń [16]) and $T_{\text{eff}} = 13000$ K, log $g = 4.0$ (Kuschnig et al. [6]). CU Vir is the only known MS star that shows variable radio emission, resembling the radio lighthouse of pulsars (Trigilio et al. [19]). It also displays strong variations in its brightness and the spectral lines of He I, Si II, H I, and other ions. The nature of its light variability in UV and optical regions was studied in detail by Krtička et al., [4].

Occasional rapid increases in its rotation period have been reported. Pyper et al. [13] discovered an abrupt increase in the period from 0.5206778 to 0.52070854 d that occurred around 1984. Pyper et al. [15] recently discussed period changes in the star based on their 2820 precise Stromgren $uvby$ values obtained with the Four College Automated Photometric Telescope (FCAPT) between 1998 and 2012. They found the $O-C$ values from 1993 forward implied a constant period of 0.5207137 d, which is the longest of its reported periods.

Mikulášek et al. [7] collected and analyzed all available observations of CU Vir containing phase information between 1949 and 2011. They demonstrated that the shape of the phase curve was constant over several decades while the period was continuously changing. The rotation period gradually shortened until the year 1968 when it reached its minimum. The period then started to lengthen, reaching a maximum at the end of their data set. Much smaller stochastic-like period changes on a timescale of several years were also reported.

This is confirmed by our time series analysis also based on the recently published FCAPT photometry from 1998–2012 (Pyper et al. [15]) as well as our own measurements from 2011–2013. In total, we have 17 936 individual
measurements of CU Vir including 17,241 photometric measurements in passbands from 200 to 753 nm as well as spectroscopic, magnetic, and radio observations. The period variations $P(t)$ can be well approximated by the simple antisymmetric cubic parabola (see Fig. 2a). We assert that $P(t)$ reached its local minimum in the year 1968.7, $P_{\text{min}} = 0.52067138$ d, and its local maximum in the year 2003.9: $P_{\text{max}} = 0.52071628$ d; we find the range of observed periods to be 3.9 s. The rotational deceleration rate reached a maximum of $\dot{P} = 5.5 \times 10^{-9} = 0.165$ s yr$^{-1}$.

We can quantify the deceleration rate using the spin-down time, $\tau$, defined as $\tau = P(t)/\dot{P}$, where $P(t)$ is the instantaneous rotation period at the time $t$ and $\dot{P}$ is the mean rate of rotational deceleration. The paradox
Figure 3. Light curves of BS Cir plotted versus the phase calculated by means the quadratic ephemeris. The areas of individual symbols are inversely proportional to their uncertainty, marked also by error bars. The observed light curves can be modelled if we assume two photometric spots of different colors centred at phases -0.001 and 0.475.

of CU Vir is, according to Mikulášek et al. [9], that its spin-down time, $\tau \sim 6 \times 10^5$ years, is more than two orders of magnitude shorter than the estimated age of the star – $9 \times 10^7$ yr (Kochukhov & Bagnulo [2]). For details see section 4.

3.3. SrCrEu mCP star BS Circinus

Both V901 Ori and CU Vir are among the hotter and thus more massive and younger mCP stars. To round out our sample of mCP stars,
Ap stars with variable periods

Figure 4. The $O-C$ curve of BS Cir can be well fitted by a parabola. The period is lengthening linearly, $P = 5.6(4) \times 10^{-9}$, while the mean period is $\overline{P} = 2.204285$ d. The 1-σ uncertainties from the fit are denoted by dashed lines. The areas of individual symbols are inversely proportional to their uncertainty, marked also by error bars.

We included several moderately cool SrCrEu mCP stars in our sample. These stars have relatively large photometric amplitudes, especially in the Strömgren $v$ and $y$ passbands. We find these cooler SrCrEu mCP stars (BS Cir, CQ UMa, CS Vir, and VV Scl) all have stable periods with the exception of BS Cir = HD 125630 = HIP 70346. Combining all available kinematic, photometric, and spectroscopic data on BS Cir we derive the following astrophysical parameters: $T_{\text{eff}} = 8800 \pm 500$ K, $L = 41.7 \pm 1.4 L_\odot$, $M = 2.32 \pm 0.14 M_\odot$, age = $510^{+30}_{-150}$ Myr. The star has a bipolar magnetic field with $B_p$ of several kG (Kochukhov & Bagnulo [2] and Hubrig et al. [1]).

Our period analysis of BS Cir is based on all available observational material, including 14488 individual photometric measurements in 11 data sets that cover, more or less evenly, a time interval of 38 years. The
weighted scatter in these data of one measurement is 0.017 mag. BS Cir is among the best photometrically observed mCP stars. The observed light curves were acquired in 9 filter passbands and show very disparate shapes and amplitudes at various effective wavelengths. Fortunately, all of the light curves can be easy modelled if we assume two different photometric spots centred at phases $-0.0014 \pm 0.0005$ and $0.4752 \pm 0.0010$, which are likely to be the phases of the magnetic field positive and negative extrema.

We determine the mean rotational period and its time derivative to be $P = 2.2042850(6)$ d, $\dot{P} = 5.6(4) \times 10^{-9} = 0.181(13)$ s yr$^{-1}$, respectively. The rate of period increase is well determined: $P/\delta P > 13.7$. The spin-down time is $\tau_{\text{spin}} = P/\dot{P} = 1.05(8)$ Myr, that is 0.2% of the estimated age of the star. Our method for determining the spin-down rate of BS Cir is able to distinguish spin-down times seven times longer.

4. Nature of the observed period changes

There are several standard explanations for period variations in mCP stars, all of which assume that mCP stars rotate as solid bodies: (1) changes in the radius and mass distribution during MS evolution, (2) changes due to angular momentum loss via a standard stellar wind, (3) changes caused by angular momentum loss via a magnetized stellar wind, (4) precession of the rotational axis, and (5) light-time effects caused by an undetected companion in a binary system.

The first three mechanisms are expected to cause lengthening of the rotational periods at a constant rate, mathematically: $\dot{P} > 0$, $\ddot{P} = 0$. The spin-down time of evolutionary period changes (30 Myr minimum) is always at least three time larger than the present limit of detection – 10 Myr. The spin-down time caused by a standard stellar wind is several orders larger than the evolutionary timescale and, therefore, completely undetectable. Angular momentum loss via a magnetized stellar wind is detectable only in the extremely hot mCP stars with very strong magnetic fields ($B_p > 5$ kG). The only known mCP star for which the observed spin-down time of 1.34 Myr (Townsend et al. [18]) agrees with theoretical predictions is very rare hot Be+He-strong hybrid object $\sigma$ Ori E.

The fourth mechanism, precession of the rotational axis, should manifest by cyclic changes in the shape of the light curves, but this is not observed. In addition, the amplitude of precessionally-induced period changes are generally negligible (Mikulášek et al. [8]). Finally, the fifth mechanism,
Ap stars with variable periods

cyclic changes in the observed period due to the light-time effect from an invisible companion, should be accompanied by radial velocity variations, but radial velocity changes are not observed (Pyper et al. [14], Mikulášek et al. [8]).

The discovery of variable rotation in the cooler SrCrEu mCP star BS Cir shows that this phenomenon may occur across all mCP types and maybe all upper MS stars.

Therefore, we “abandon the assumption of the rigid rotation,” as suggested by Stępień [16], and examine the alternative concept that the structure of the surface layers of mCP stars are dominated by global magnetic field and can rotate differentially from the denser interior of a star. The magnetic field contributes to immobilization of the outer parts of mCP stars in the vertical direction and also prevents the spot structures from dissolving in the horizontal direction. The magnetic field could accomplish this only if its energy density is larger than the energy of the stellar dissipative motions. Simple calculations show that, in the photospheres of A and B-type stars, even very weak magnetic field is sufficient.

If the magnetic fields of upper MS stars are fossil fields, then all photospheres should be, to some extent, controlled by magnetic field. Consequently, transient spot structures on moderately hot ‘normal’ (non-CP) MS stars are possible. The depth of magnetic field dominance (the thickness and endurance of spot structures) strongly depends on the strength of the magnetic field. Such an ‘eggshell’ surface layer(s) dominated by magnetic field may behave as a solid body. Even weak interaction with the outer environment or the stellar interior may be able to accelerate or decelerate this layer very effectively.

These considerations and speculations are a challenge for theoreticians modelling the structure of upper MS stars.

Acknowledgements. This work was funded by the grant of GAČR P209/12/0217 and SoMoPro (3SGA5916).

References
1. Hubrig, S., North, P., Schöller, M., Mathys, G. 2006, Astronomische Nachrichten, 327, 289
2. Kochukhov, O., & Bagnulo, S. 2006, ApJ, 726, 24
3. Kochukhov, O., Lundin, A., Romanyuk, I., & Kudryavtsev, D. O. 2011, A&A, 450, 763
4. Krtička, J., Mikulášek, Z., Lüftinger, T., et al. 2012, A&A, 537, 14
5. Krtička, J., Mikulášek, Z., Zverko, J. et al. 2007, A&A, 470, 1089
6. Kuschnig R., Ryabchikova, T. A., Piskunov, N. E. et al. 1999, A&A, 348, 924
7. Mikulášek, Z. Krtička, J., Henry, G. W. et al. 2011, A&A, 534, L5
8. Mikulášek, Z., Krtička, J., Henry, G. W. et al. 2008, A&A, 485, 585
9. Mikulášek, Z., Krtička, J., Janík J. et al. 2011, in Magnetic Stars, Proceedings of the International Conference, SAO RAS 2010, Eds: I. I. Romanyuk and D. O. Kudryavtsev, 52
10. Mikulášek, Z., Krtička, J., Zverko, J. et al. (2007) in Active OB-Stars: Laboratories for Stellar and Circumstellar Physics, ASP Conference Series, Vol. 361, Proceedings of the conference held 29 August - 2 September, 2005 at Hokkai-Gakuen University, Sapporo, Japan. Edited by S. Stefl, S. P. Owocki, and A. T. Okazaki. San Francisco: Astronomical Society of the Pacific, 2007., 466
11. Meynet, G., Maeder, A. 2006, Stars with the B[e] Phenomenon, ed. M. Kraus & A. S. Miroshnichenko, ASP Conference Series, Vol. 355, 27
12. Pyper, D. M., & Adelman, S. J. 2004, The A-Star Puzzle, IAU Symposium No. 224, eds. J. Zverko, J. Žižňovský, S. J. Adelman, & W. W. Weiss (Cambridge University Press, Cambridge), 307
13. Pyper, D. M., Ryabchikova, T., & Malanushenko, V. 1997, BAAS, 29, 811
14. Pyper, D. M., Ryabchikova, T., Malanushenko, V. et al. 1998, A&A, 339, 822
15. Pyper, D. M., Stevens, I. R., Adelman, S. J. 2013, MNRAS, 431, 2106
16. Stępień, K. 1998, A&A, 337, 754
17. Thompson I. B., Landstreet J. D., 1985, ApJ, 289, 9
18. Townsend R. H. D., Oksala M. E., Cohen D. H., Owocki S. P., ud–Doula A., 2010, ApJ, 714, 318
19. Trigilio, C., Leto, P., Leone, F., Umana, G., & Buemi, C. 2000, A&A, 362, 281