Magnetic Stars, 2011, pp. 52 – 60

Magnetic Chemically Peculiar Stars with Unsteady Periods

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Abstract. Photometrically and spectroscopically variable chemically peculiar (CP) stars are the optimum laboratories for testing the rotational evolution of main sequence stars. A vast majority of well–studied CP stars have quite steady rotational periods (e. g. SrCrEu star CQ UMa). However, there are several CP stars that exhibit apparent period variations. The origin of the period variations is unclear in many cases. We describe the observed period variations of several individual CP stars, especially V901 Ori, σ Ori E, HR 7355, CU Vir, SX Ari, and EE Dra. The CP stars with unsteady periods now represent a very diverse group with dissimilar O–C diagrams and time scales. We also discuss the causes of the period changes found and a possible cyclicity or chaoticity of them.

1 Introduction

Stars originate from a gravitational collapse of dense parts of molecular clouds. Every star, besides its matter, inherits a fraction of the angular momentum of the mother cloud, consequently each star does rotate.

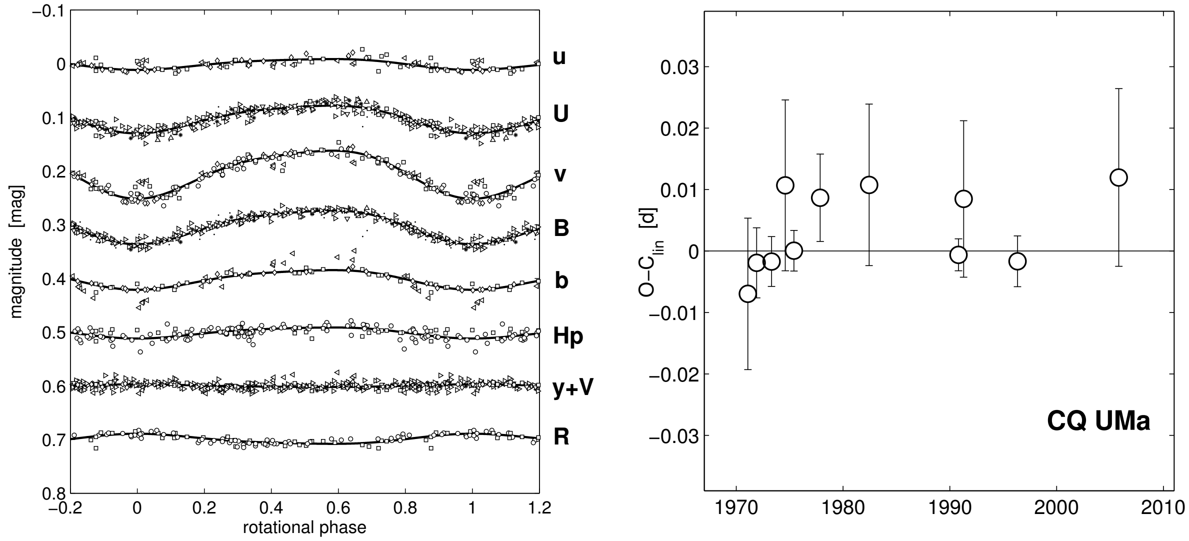
Stars spend the prevailing part of their active lifetime as main sequence objects. During the whole MS stage the stellar angular momentum is largely conserved. For example, the stellar wind takes away a significant fraction of the total angular momentum only in the case of very massive stars. Besides the angular momentum the rotational period of a main sequence star is also determined by its instant radius, and the inner distribution of its mass and angular momentum. The development of the rotational period will be then gradual on the scale of $10^7 - 10^9$ years.

The evolutionary models corresponding to CP stars show that the equatorial rotational velocity remains practically constant during the MS epoch (see e. g. Meynet & Maeder, 2000). How can we test it?

Global data on the rotational period of a MS star and its evolution can be derived from the $v \sin i$ rotational broadening. However,the method cannot be applied to an individual single star, since we do not know the values of its radius and inclination.

To find out the rotational period changes (if any), a much finer instrument is needed. Spotty magnetic chemically peculiar (mCP) stars with a global magnetic field and stable surface structures, whose periods of light, spectral and magnetic filed variations is equal to the rotational one, can serve as the best such instrument.

Combining both the present and archive photometric, spectroscopic and spectropolarimetric observations collected during many decades, one can reconstruct the development of the rotation at least of the outer parts of a star with high accuracy.



(a) (b)

Figure 1: (a) CQ UMa light curves in u, U, v, B, b, Hp, $V+y$ and R–bands. Note the disappearance of variations in $V+y$ and the antiphase variations in the R–band. The linear ephemeris: $M_0 = 2444384.432$, $P = 2.^{\mathrm{d}}4499120(27)$. (b) The time development of the difference between the observed (O) and calculated (C) times of the zero phase according to this linear ephemeris depicts the so–called ‘O–C diagram’. No trend in the diagram indicates that the rotational period of the star is constant over the decades.

Careful period analyses of several dozens of mCP stars have been done. They confirmed the expectations that the rotational periods of most of upper MS stars are quite steady. However, a few stars show period changes, the origin of which has not been completely understood yet.

2 Individual Stars

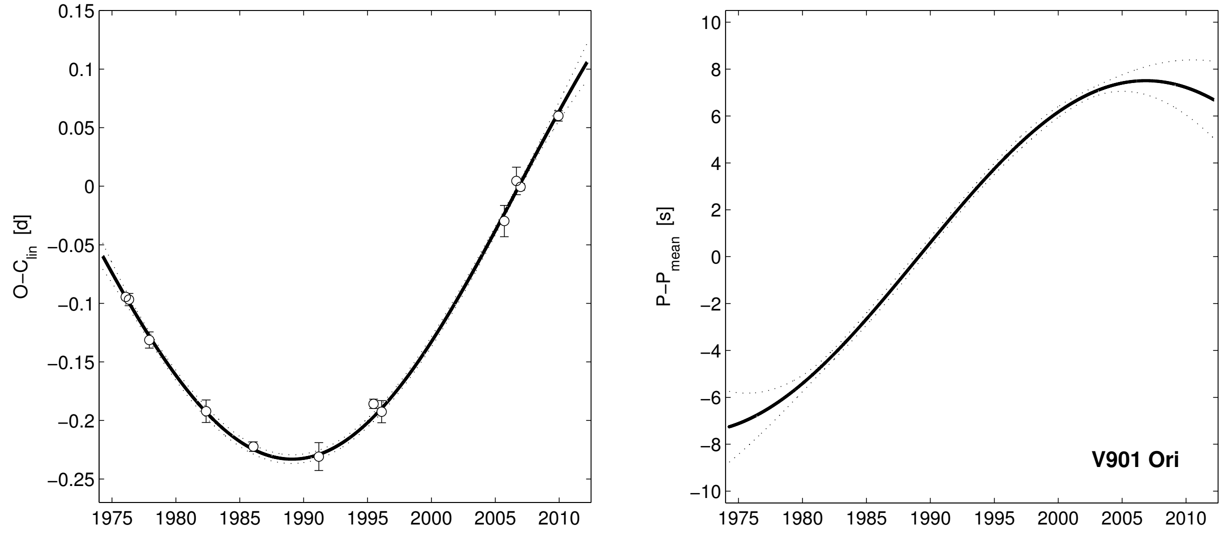
2.1 SrCrEu mCP Star CQ Ursae Majoris

As an example of the strictly periodic star we mention is CQ UMa = HR 5153 = HD 119213. This “cool” SrCrEu mCP star displays a prominent variation in the Strömgren v–band with antiphase changes in the red band (see Fig. 1a).

We used 1365 individual observations collected in 11 various sources of photometric data that cover a time interval of 42 years (6262 revolutions of the star). The mean period: $P = 2.^{\mathrm{d}}4499120(27)$ can be then derived with the accuracy of 0.23 s. The linear fit in the O–C diagram is depicted in Fig. 1b (the phases of minima are computed for the v–band). The time derivative of the period **is** $\dot{P} = (3 \pm 7)$ s/cen (seconds per century) that means the period is stable as for most of other CP stars. However, there are CP stars showing indubitable changes of their periods.

2.2 He–Strong mCP Star V901 Orionis

V901 Ori = HD 37776 is a very young hot star (B2 IV) residing in the emission nebula IC 432, with a complex (quadruple) global magnetic field (Thompson & Landstreet, 1985; Kochukhov et al., 2011). It can be ranked among the He–strong mCP stars, however, the light variations are due to the spots of overabundant Si and He (Krtička et al., 2007).



(a)

(b)

Figure 2: (a) The nonlinear trend in the O–C diagram of V901 Ori documents an extraordinarily strong increase of the period in the time interval of 1976 − 2005. Now (the end of 2010) the period is nearly constant. The O–C values were calculated relatively to the linear ephemeris: $M_0 = 2445724.669$, $P = 1\overset{\mathrm{d}}{.}5386754$ published by Adelman (1997b). (b) The dependence of the difference between the observed and the mean periods (in seconds) on time does not exclude the possibility of cyclic variations of the period.

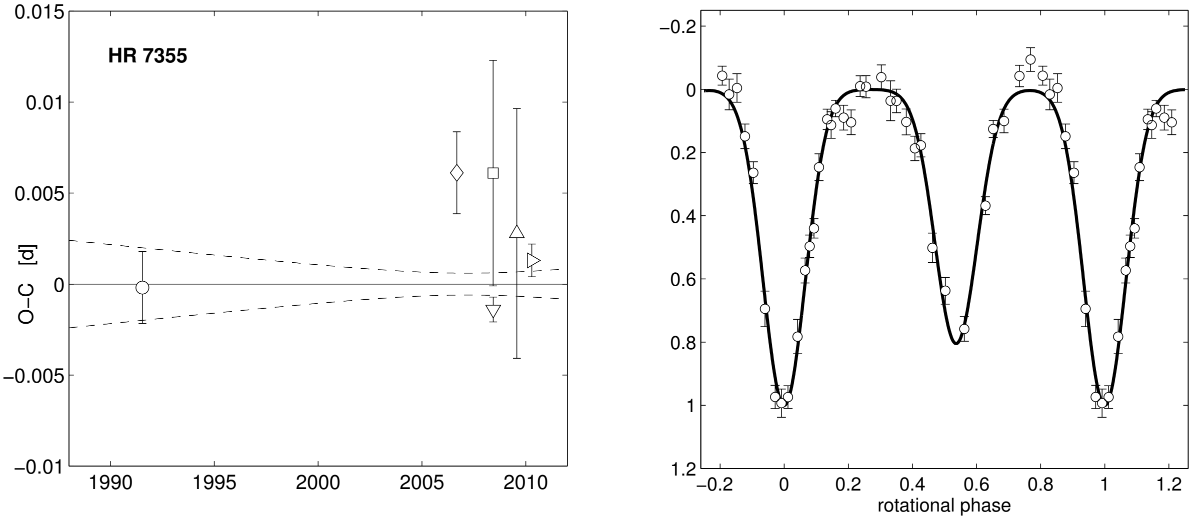
Using photometry and spectroscopy, Mikulášek et al. (2008) proved that the observed period of about $1\overset{\mathrm{d}}{.}5387$ has been gradually changing. The O–C diagram (see Fig. 2a) can be formally fitted with a smooth curve either of a 4–th order polynomial or a segment of a cosinusoid. The maximum increase of the period $\dot{P}_{\max} = 2.10(16) \cdot 10^{-8} = 66(5)\,\mathrm{s/cen}$ took place around the year 1989. The mean increase of the period during the recent 35 years is only $\overline{\dot{P}} = 1.7 \cdot 10^{-8} = 53\,\mathrm{s/cen}$. The value of $\dot{P}$ is now (at the end of 2010) definitely much smaller: $\dot{P} = -8(7) \cdot 10^{-9} = -25(22)\,\mathrm{s/cen}$.

Ruling out the light–time effect in a binary star, the precession of rotational axis, and the evolutionary changes as possible causes of the period change, we interpret it in terms of braking of the star's rotation (at least of its surface layers) due to the angular momentum loss through events in the stellar magnetosphere (Mikulášek et al., 2008). However, this mechanism is unable to explain the possible acceleration of the rotation nowadays.

2.3 Helium–Strong mCP Star σ Orionis E

The spectrum of a very young star σ Ori E = HD 37479 is a hybrid of a classical He–strong mCP star and a B emission–line star (Walborn, 1974). The light curves in the optical domain, namely in the u (U)–band, are unusual for the CP stars: the narrow and deep minima cannot be explained in terms of photometric spots on the surface only. A contribution of "eclipses" by magnetospheric "clouds" (Landstreet & Borra, 1978; Townsend et al., 2005) must be allowed.

Townsend et al. (2010) discovered recently a smooth rotational braking in a moderate rate $\dot{P} = 7.7\,\mathrm{s/cen}$ based on their U observations obtained within 2004 − 2009, and the u observations obtained in 1977 by Hesser et al. (1977). Townsend et al. (2010) explained the observed spin–down of the star by the magnetic braking through the line–driven stellar wind.



(a) (b)

Figure 3: (a) The up–to–date O–C diagram of HR 7355 does not indicate any period changes. The open circle: Hipparcos observations, the diamond: ASAS measurements; the square and △: observations published by Mikulášek et al. (2010); ∇: the R measurements of Oksala et al. (2010); ▷: our unpublished UBV observations. (b) The light curve of HR 7355 represented by normal points. The narrow minima cannot be merely due to photometric spots as it is common in the CP stars.

2.4 Helium–Strong mCP Star HR 7355

The O–C diagram of another He–strong, very rapidly rotating mCP star HR 7355 = HD 180182 ($P = 0\overset{\mathrm{d}}{.}5214$) with emission lines is similar to the above discussed stars. This suggest HR 7355 might be also a spin–down of hot mCP star (Mikulášek et al., 2010). The only puzzling aspect is the rather advanced age of the star (20 Myr).

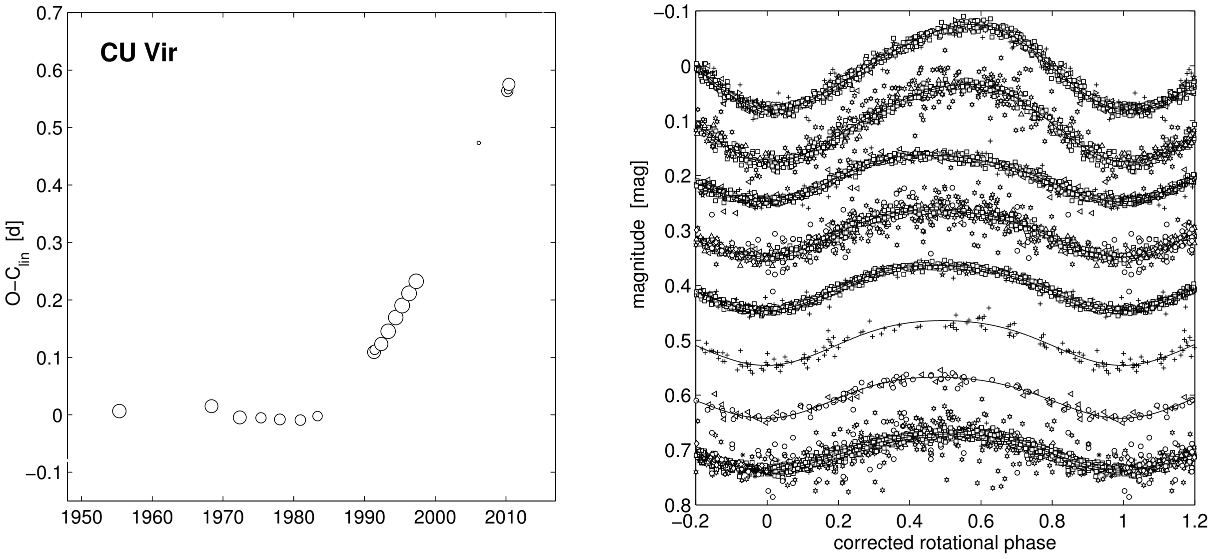
However, the recent revision of the ASAS data on HR 7355 (Pojmański et al., 2010) and the two new extended sets of photometry, obtained recently by Oksala et al. (2010) and our group, ruled out this suspicion reliably. The latest O–C diagram, Fig. 3a, does not indicate any change of the period. The new light curves show the star is an "elder sister" of σ Ori E with eclipses (as it was proposed in Rivinius et al., 2008), but no braking (now).

2.5 Silicon mCP Star CU Virginis

The famous very fast–rotating silicon mCP star CU Vir = HD 124224 = HR 5313 may show another type of period changes. Amplitudes of the light and spectral variations (He I, Si II, H I, and other) are relatively large. CU Vir is among the most frequently studied mCP stars, consequently, its behaviour is reliably documented. Moreover, CU Vir is a unique main sequence radio pulsar (Trigilio et al., 2008; Ravi et al., 2010).

Pyper et al. (1998) discovered an abrupt increase of the period from $0\overset{\mathrm{d}}{.}5206778$ to $0\overset{\mathrm{d}}{.}52070854$ that occurred approximately in 1984 and Pyper & Adelman (2004) discussed two possible scenarios of the explanation of the observed O–C diagram, namely a continually changing period or two constant periods.

The mean deceleration of the period of CU Vir during the past 60 years is $\overline{\dot{P}} = 2.4 \cdot 10^{-9} = 7.6\,\mathrm{s/cen}$. The estimated maximum increase (near 1984) is $\dot{P}_{\mathrm{ex}} = 5.7 \cdot 10^{-9} = 18\,\mathrm{s/cen}$. Our photometric and spectroscopic observations obtained in 2009 − 2010 indicate that the period is now



(a) (b)

Figure 4: (a) The O–C diagram of CU Vir for the times of light minima derived from the available photometries (Hardie, 1958; Blanco & Catalano, 1971; Winzer, 1974; Molnar & Wu, 1978; Pyper & Adelman, 1985; Sokolov, 2000; Pyper et al., 1998; Pojmański et al., 2001) and our new unpublished data according to the ephemeris in Pyper et al. (1998): $M_0 = 2435178.6417$, $P = 0^{\rm d}\!.5206778$. The size of an open circle correspond to the weight of the value, standard accuracy of the value is $0^{\rm d}\!.0025$. Two or three linear segments can fit the course. Eventually, a more complex smooth function (Pyper et al., 1998; Pyper & Adelman, 2004) can be used. (b) The light curves in u, U, v, B, b, $W\beta$, Hp and $V+y$–bands (arranged from top to bottom) were assembled from 7097 individual photometric observations. Note the gradual change of the shape of the light curves with the effective wavelength of a particular colour band. The points, tightly adjoined the light curves, corrected for the change of period, show that shapes of the individual light curves are constant over the past sixty years.

constant.

Presently, we are recalculating the whole O–C diagram using all available data, containing phase data. The results will be published in forthcoming papers.

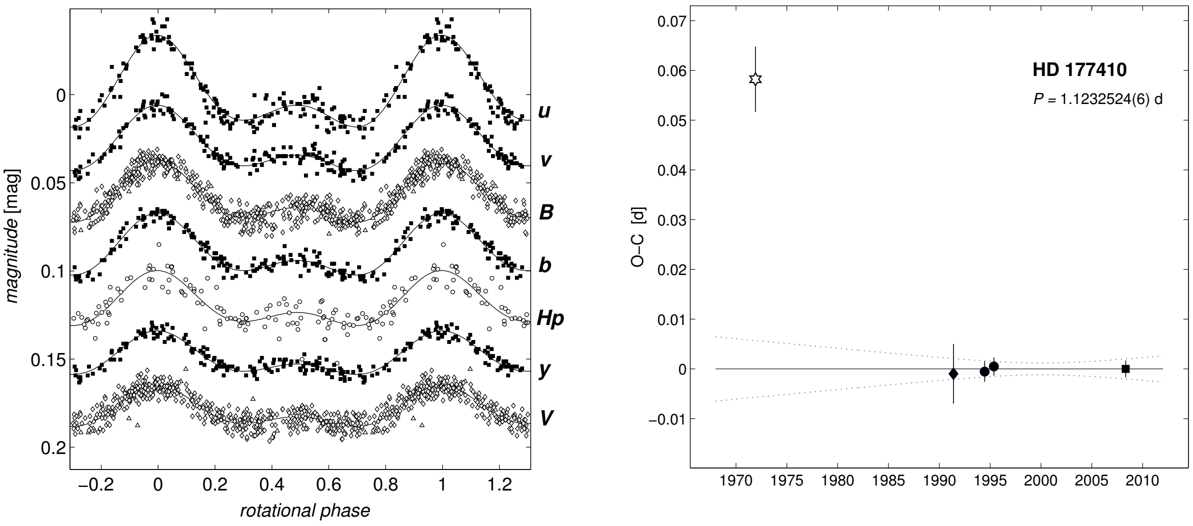
The shapes of the light curves of V901 Ori and CU Vir, the prototypes of mCP stars with large period variations are non–variable, thus excluding precession as the cause of observed period changes (for details see Mikulášek et al., 2008).

2.6 Silicon mCP Star SX Arietis

SX Ari = 56 Ari = HD 19832 is a fast rotating ($P = 0^{\rm d}\!.728$) Si mCP star. Historically, it was the first mCP star, where the unsteady period was revealed (Musiełok, 1998).

The behaviour of this star is complex: according to Adelman et al. (2001) the secular rotational braking with a moderate rate of 2 s/cen is superimposed over the cyclic variations of shapes and amplitudes of light curves (Žižňovský et al., 2000; Shore & Adelman, 1976) with a period of about five years, what could be attributed to the precession of the rotational axis of a magnetically distorted star.

On the basis of a precise Four College Photometric Telescope *uvby* photometry several other mCP stars were revealed with light curves also indicating precession (see the review paper by Pyper & Adelman, 2004): e. g. 108 Aqr (Adelman, 1997b), 20 Eri (Adelman, 2000), V1093 Ori (Pyper & Adel-



(a)

(b)

Figure 5: (a) Light curves of EE Dra (HD 177410) obtained in the u, v, B, b, Hp, y and V–bands. Observed changes can be explained through uneven distribution of Si, Fe and other chemical elements (for details see Krtička et al., 2009). (b) O–C diagram constructed from the times of light maxima, derived from all the available photometry. The first O–C value corresponds to the discussed observations of Winzer (1974).

man, 2004), MW Vul (Adelman & Young, 2005). As the changes of their periods are marginal (if any), we do not include them among the stars with unsteady rotation.

2.7 Silicon CP Star EE Draconis

The enigmatic EE Dra (HR 7224 = HD 177410) seemed to be a quite ordinary fast–rotating Si CP star. Its rotational period, based on the Winzer (1974), Hipparcos (ESA, 1998) and Adelman (1997a) photometries is $P = 1\overset{\mathrm{d}}{.}1232$. This star, however, contrary to the common magnetic CP stars, has not revealed a magnetic field, which is very likely due to its weakness (Krtička et al., 2009; Shulyak et al., 2010).

The star exhibits a double–wave light curve (see Fig. 5a) and strong variations of silicon lines. Adelman (2004) reported an unprecedent rise of the amplitude of the light variation from the typical 0.04 to 0.21 mag and an abrupt change of the period from the former $1\overset{\mathrm{d}}{.}123$ to 101 days. He attributed it to precession.

Later, Lehman et al. (2006, 2007) observed the star spectroscopically and confirmed the period $1\overset{\mathrm{d}}{.}1232$. Krtička et al. (2009) then obtained new BV photometry and refined the period to $P = 1\overset{\mathrm{d}}{.}123524(6)$.

Not only Adelman's (2004) finding indicates an oddity of this star, Winzer's (1974) data, which otherwise seems to be correct, lie out the other ones, as can be seen on the O–C diagram, Fig. 5b. Does this mean a quick lengthening of the period between 1975 and 1990? Do the observations between 2003 and 2004 (Adelman, 2004) mean a reaction to the previous braking?

Table 1: Summary of CP stars with unsteady periods, P — the period, τ — the spin–down time in Myr, Π — the estimated duration of the cycle

HD number	name	P [d]	$\overline{\dot{P}}$ [s/cen]	$\dot{P}_{\mathrm{ex}}$ [s/cen]	τ [Myr]	Π [yr]
19832	SX Ari	0.728	2	–	3	<250
37776	V901 Ori	1.539	53	66	0.25	~ 90
37479	σ Ori E	1.198	8	–	1.3	<200
124224	CU Vir	0.521	8	18	0.6	~ 60
177410	EE Dra	1.123	1	–	10	<500

3 Nature of Period Changes of mCP Stars

The known chemically–peculiar stars with unsteady periods represent a relatively diverse group; their O–C diagrams are different, the common properties are rare, if any. It evokes a situation when Edward Pigott (1753 – 1825) set up the first catalogue of variable stars: it comprised only several objects, but almost each of them represented other type of variability. Similarly, the causes of the period instabilities of mCP stars may be different.

The spin–down time (SDT), $\tau = P/\overline{\dot{P}}$, quantitatively represents the rate of the changing period of a star. All the known cases of the period changes are positive (see Table 1) implying braking of rotation, which implies that the process is irreversible. Assuming that the SDT is constant, one can estimate the maximum time–interval of the duration of the process (the rotational period of the star cannot be shorter than the critical one).

3.1 Spin-Down or Cycle?

Except for the extremely young σ Ori E the SDT values are much shorter than the ages of the stars. Does it mean that the rotational braking sometimes begins long after the star arrives at MS? Why? Why then do not we see a larger percentage of CP stars with extremely long periods? Is it possible to brake the whole star so drastically? Are the abrupt changes of the period of CU Vir reported by Pyper et al. (1998); Pyper & Adelman (2004) astrophysically permitted (the most dramatic case)? The last question was brilliantly discussed by Stępień (1998), who clearly proved that one has to abandon the assumption of the necessity of a rigid rotation and to admit that the outer layers, controlled by magnetic field and denser inner parts can rotate differently. This possibility was discussed and developed also in Mikulášek et al. (2008, 2010).

The nature of CP stars leads us to the speculation about cyclic variations of angular velocity in the outer layers fixed by a global magnetic field of several mCP stars. Let us assume the simple sine course of such angular velocity variation with the period Π. Then it is useful to introduce a parameter Θ_{ex} with the time dimension, where $\Theta_{\mathrm{ex}} = \pi P \sqrt{2/|\dot{P}_{\mathrm{ex}}|}$. Here P is the mean rotational period, $\dot{P}_{\mathrm{ex}}$ is the extremal time derivative of the period (if known). Then the length of the cycle $\Pi = \sqrt{\alpha}\,\Theta_{\mathrm{ex}}$, where α is a dimensionless parameter expressing the amplitude of cyclic changes in the O–C diagram in the units of mean rotational period.

Only two stars from the set of CP stars with unsteady periods, discussed in the previous section have been observed for so long, that we could estimate their maximum time derivatives of the period $\dot{P}_{\mathrm{ex}}$: V901 Ori, and CU Vir (see Tab. 1). After an inspection of their O–C diagrams we have accepted α to be 0.5 as a first estimate. For V901 Ori and CU Vir with their $P = 1\overset{\mathrm{d}}{.}5387$, $\dot{P}_{\mathrm{ex}} = 2.1 \cdot 10^{-8}$ and $P = 0\overset{\mathrm{d}}{.}521$, $\dot{P}_{\mathrm{ex}} = 5.7 \cdot 10^{-9}$ we obtain the following estimates of duration of cycles Π: 90 and 60 years, respectively.

In the case of other CP stars with changing periods we are forced to manage with the estimate of the instant period derivative $\overline{\dot{P}}$ (naturally, $\overline{|\dot{P}|} \leq |\dot{P}_{\mathrm{ex}}|$) we can introduce the similarly defined parameter Θ, $\Theta = \pi P\sqrt{2/|\dot{P}|}$, by means of which we can estimate the maximum duration of the cycle of a particular star: $\Pi \leq \sqrt{\alpha}\Theta$.

The cycle durations Π for individual discussed CP stars are given in Table 1. It appears that only for CU Vir and V901 Ori the expected cycles are short enough to observe them completely or almost completely, the rotational periods of other stars are changing too slow.

We can speculate that the thin outer envelope, dominated by the global magnetic field, frozen in its plasma, performs with respect to the inner part of the rotating star a torsional oscillation along the rotational axis. Assuming that the oscillation period is Π with an amplitude of $A = 2\pi\alpha R$, where R is a radius of the star. The maximum mutual equatorial velocity of the oscillating envelope and the core is then $v = 4\pi^2 R\alpha/\Pi$, the acceleration in turning points $a = 8\pi R\alpha/\Pi^2$. Numerically for $\Pi = 75$ years, $R = 4\,R_{\odot}$ and $\alpha = 0.5$ we get: $A = 13\,R_{\odot}$, $v = 25\,\mathrm{m/s}$ and $a = 7\,\mathrm{m/s}^2$. The torsion force should be connected with alternating protraction and contraction of magnetic field lines. The process of the oscillation excitation is unclear. However, at the moment the speculations are only preliminary, and have to obtain a firmer physical background.

3.2 Where Are the Accelerating mCP Stars?

If we assume the cyclic nature of the period variations, then we should ask: "Do any accelerating mCP stars exist?" "If yes, why do we not see them?" May be, at least one of the stars we discussed is accelerating just now — the famous V901 Ori — (see Fig. 2b).

Acknowledgements. This work was supported by the grants: VEGA 2/0074/09, GAČR 205/08/0003, MUNI/A/0968/2009, and the APVV project SK–CZ–0032–09.

References

Adelman S. J., 1997, A&A, 122, 249

Adelman S. J., 1997, A&AS, 125, 65

Adelman S. J., 1999, Baltic Astronomy, 8, 369

Adelman S. J., 2000, A&AS, 146, 13

Adelman S. J., 2004, MNRAS, 351, 823

Adelman S. J., Malanushenko V., Ryabchikova T., Savanov I. 2001, A&A, 375, 982

Adelman S. J., Young K. J., 2005, A&A, 429, 37

Blanco C., Catalano F., 1971, AJ, 76, 630

ESA, 1998, The Hipparcos and Tycho Catalogs, Celestia 2000, SP–1220

Hardie P., 1958, ApJ, 127, 620

Hesser J. E., Ugarte P. P., Moreno H., 1977, ApJ, 216, L31

Kochukhov O., Lundin A., Romanyuk I., Kudryavtsev D., 2011, ApJ, 726, 24

Krtička J., Mikulášek Z., Henry G. W., Zverko J., Žižňovský J., Skalický J., Zvěřina P., 2009, A&A, 499, 567

Krtička J., Mikulášek Z., Zverko J., Žižňovský J., 2007, A&A, 470, 1089

Landstreet J. D., Borra E. F., 1978, ApJ, 224, 5

Lehmann H., Tkachenko A., Fraga L., Tsymbal V., Mkrtichian D. E., 2007, A&A, 471, 941

Lehmann H., Tsymbal V., Mkrtichian D. E., Fraga L., 2006, A&A, 457, 1033

Meynet G., Maeder A., 2000, A&A, 361, 101

Mikulášek Z., Krtička J., Henry G. W., de Villiers S. N., Paunzen E., Zejda M., 2010, A&A, 511, L7

Mikulášek Z., Krtička J., Henry G. W., Zverko J., Žižňovský J., Bohlender D., Romanyuk I. I., Janík J., Božić H., Korčáková D., Zejda M., Iliev I. Kh., Škoda P., Šlechta M., Gráf T., Netolický M., Ceniga M., 2008, A&A485, 585

Musiełok B., 1988, IBVS, 3257

Molnar M. R., Wu C.–C., 1978, A&A, 63, 335

Oksala M. E., Wade G. A., Marcolino W. L. F., Grunhut J., Bohlender D. A., Manset N., Townsend R. H. D., 2010, MNRAS, 405, 51

Pojmański G., 2001, ASP Conf. Ser., 246, 53

Pyper D. M., Adelman S. J., 1985, A&AS, 59, 369

Pyper D. M., Adelman S. J., 2004, IAUS, 224, 307

Pyper D. M., Ryabchikova T., Malanushenko V., Kuschnig R., Plachinda S., Savanov I., 1998, A&A, 339, 822

Ravi V., Hobbs G., Wickramasinghe D., Champion D. J., Keith M., 2010, MNRAS, 408, 99

Rivinius T., Štefl S. A., Townsend R. H. D., Baade D., 2008, A&A, 482, 255

Shore S. N., Adelman S. J., 1976, ApJ, 209, 816

Shulyak D., Krticka J., Mikulášek Z., Kochukhov O., Lüftinger T., 2010, A&A, 524, 66

Sokolov N. A., 2000, A&A, 353, 707

Stępień K., 1998, A&A, 337, 754

Thompson I. B., Landstreet J. D., 1985, ApJ, 289, 9

Townsend R. H. D., Oksala M. E., Cohen D. H., Owocki S. P., ud–Doula A., 2010, ApJ, 714, 318

Townsend R. H. D., Owocki S. P., Groote D., 2005, ApJ, 630, 81

Trigilio C., Leto P., Umana C. S., Leone F., 2008, MNRAS, 384, 1437

Walborn W. N. R., 1974, ApJ, 191, L95

Winzer J. E., 1974, Ph.D. Thesis, Univ. Toronto

Žižňovský J., Schwartz P., Zverko J., 2000, IBVS, 4835