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Research Note

On a mechanism of an abrupt change of period of CU Virginis

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Abstract. A sudden lengthening of the observed rotation period of a magnetic Ap star, CU Vir, reported recently by Pyper et al. (1998), is discussed in terms of the possible mechanisms which can influence the rotation period of a single star. It is shown that none of the known mechanisms is able to change the rotation period of a rigidly rotating star by the observed amount ($\Delta P/P \approx 4.9 \times 10^{-5}$) so abruptly as suggested by the analysed data. If we abandon an assumption of the rigid rotation, the strength of the observed magnetic field is sufficient to modify the moment of inertia of the outer envelope of the star by the required amount. The star may be in a state of torsional oscillations resulting from an interaction of meridional circulations and internal magnetic field.

Key words: stars: chemically peculiar – stars: individual: CU Vir – stars: variables: other – stars: magnetic fields – stars: rotation

1. Introduction

Pyper et al. (1998) reported recently on a sudden change of the variability period of a magnetic Ap star CU Virginis = HD 124224. CU Vir is a chemically peculiar star with the second shortest known period of about a half of a day. It has been frequently observed for the last 45 years, hence its period is known with a relatively high accuracy. A detailed discussion of all the available observations led Pyper et al. (1998) to the conclusion that the star increased abruptly the variability period in 1985. The best fit to the $O - C$ diagram is obtained when a constant period of 0.5206778 of a day is adopted for the epoch JD $<$ 2446000 and a longer, but also constant, period of 0.52070308 of a day is adopted for JD $>$ 2446000.

The occurence of a jump in the observed period of an Ap star is totally unexpected. In no case before a convincing evidence for an observation of a change of the variability period of such a star had been found. In fact, the generally accepted oblique rotator model of a magnetic Ap star suggests a stability of the variation period, identified with the stellar rotation period. The present statistical data on variablity periods of Ap stars give no evidence for their substantial variation during the Main Sequence (MS) phase of evolution. The observations are in agreement with a slow spin-down of stars caused by the increase of the moment of inertia of a star evolving accross the MS. For a recent, more detailed discussion of this problem see Stępień (1998).

The observed change of period of CU Vir cannot be connected with evolutionary changes of the star because of the vast difference between the observed and expected time scale of the change. Another mechanism must be involved. The present paper discusses several physically reasonable mechanisms influencing a stellar rotation period in application to CU Vir.

It will be useful first to determine the basic physical parameters of CU Vir. The effective temperature can be determined from the $uvby$ photometry using the calibration given by Stępień (1994). The value of the reddening free index $[u - b]$ equal to 0.847 (Hauck & Mermilliod 1980) corresponds to $T_{\rm eff}$ = 12 300 K. The rotational broadening of lines resulted in the following, published values of $v \sin i$: 135 km/s (Abt et al. 1972), 130 km/s (Wolff & Preston (1978)), 115 km/s (Abt & Morrell 1995) and 147 km/s (Hatzes 1997). The last author gives also a value of $i = 60^\circ$ which results in the value of the stellar radius $R = 1.74 R_\odot$. This is very close to (but slightly less than) a zero age MS radius of a star with the adopted effective temperature (VandenBerg 1985). Note, however, that any of the previously published values of $v \sin i$ results in the even smaller value of the radius if we keep $i = 60^\circ$ or in a substantially lower value of i if we adopt a larger value for R (Stępień 1989). A relatively large amplitude of light and spectrum variations of CU Vir compared to other Ap stars favors a larger value of inclination. Therefore a round value of 2 $R_\odot$, close to the value resulting from Hatzes' analysis, is here adopted. This value of the radius, together with the adopted value for effective temperature indicates a mass M of about 3 $M_\odot$ for CU Vir. From a fit of a model magnetic field to the observed magnetic curve, Hatzes (1997) obtained a value of the surface magnetic field of 3200 G (neglecting the decentering of the dipole). The last stellar parameter used in the calculations below is the observed relative change of the period $\Delta P/P \approx 4.9 \times 10^{-5}$. Although a possibility exists that the change is spurious, it looks rather well documented, so it will be accepted here as real. We also assume that CU Vir is a single star in agreement with the conclusion reached by Pyper et al. (1998).

2. Spin down of the whole star

Angular momentum (AM) of a rigidly rotating star J is equal to $I\omega$, where I is the stellar moment of inertia and ω angular velocity. The change of the rotation rate is thus

$$\frac{\Delta\omega}{\omega} = \frac{\Delta J}{J} - \frac{\Delta I}{I} = 4.9 \times 10^{-5} \,. \tag{1}$$

A decrease of the rotation rate ($\Delta\omega < 0$) can result from an ejection of high AM mass ($\Delta J < 0, \Delta I < 0$ but small), accretion of low AM mass from interstellar medium ($\Delta J \approx 0, \Delta I > 0$), acceleration and subsequent ejection of the interstellar mass entering the stellar magnetosphere ($\Delta J < 0, \Delta I = 0$), or redistribution of mass within the star ($\Delta J = 0, \Delta I > 0$). We will discuss all these mechanisms and show that none of them can produce the change of the rotation period with the observed magnitude.

Due to a very short time scale of the observed period change, the mass loss could not proceed via a stationary magnetized wind. The matter would have to be lost in a form of one, or several blobs. We assume that the ejected mass is forced by the magnetic field into corotation with the star up to a distance r_c where centrifugal force is equal to the gravitational force and then it breaks loose

$$\Delta J = \Delta M r_c^2 \omega \,, \tag{2}$$

where

$$r_c = \left(\frac{GM}{\omega^2}\right)^{1/3} \,, \tag{3}$$

and G is the gravity constant.The mass loss reduces also the stellar moment of inertia by

$$\frac{\Delta I}{I} = \frac{\alpha \Delta M}{k^2 M} \,. \tag{4}$$

Here $I = k^2 M R^2$, kR is the gyration radius (k describes the mass distribution inside the star) and $0 < \alpha < 1$, depending on geometry of the mass loss process. From Eqs. (1)-(4) one gets the following relation between mass loss and the angular velocity change

$$\frac{\Delta M}{M} = k^2 \left(\frac{r_c^2}{R^2} - \alpha\right)^{-1} \frac{\Delta\omega}{\omega} \,. \tag{5}$$

Adopting $k^2 = 0.1$ for a MS star, $\alpha = 1$ and all the numerical values corresponding to CU Vir, one gets $\Delta M/M \approx -1.7 \times 10^{-6}$. This is the minimum amount of mass the star must eject to decrease its rotation period by the observed amount. It is several orders of magnitude more than contained in the whole atmosphere of the star. Loss of such an amount of mass would expose deeper layers and completely wipe out any observed chemical peculiarities. Observers did not report any appreciable change of the spectrum of CU Vir connected with the period change. A similar amount of matter would have to be accreted to obtain the observed spin down. This is also in a clear contradiction with spectral observations.

The same estimate applies approximately to the mechanism of ”propeller”. A star acts as a propeller when it penetrates an interstellar cloud and the matter swept by the moving stellar magnetosphere (with a radius not less than the corotation radius) enters it as a result of the Taylor instability, is forced into corotation by the magnetic field and is subsequently ejected carrying away stellar AM. The moment of inertia of the star is preserved during such a process but AM decreases. To estimate the minimum necessary density of such a cloud let us assume a relative velocity of 10 km/s and a time scale of the process equal 40 years (i.e. maximum acceptable, based on observations of CU Vir). If all the required mass is contained in a cylinder with the radius r_c, we get a minimum density of 5×10^{12} atoms per cubic centimeter. This is again an unreasonably high number.

Finally let us consider a change of the moment of inertia due to an internal redistribution of stellar mass. It is well known that the internal magnetic field influences the mass distribution because it produces an additional field of force (e.g. Mestel & Moss 1977). The importance of this force, relative to the gravity force, is measured by the parameter λ_H giving the ratio of the magnetic energy to the gravitational energy of the star

$$\lambda_H = \frac{4\pi H_{\rm surf}^2 R^4}{GM^2} \,. \tag{6}$$

With parameters adopted for CU Vir one gets $\lambda_H = 2 \times 10^{-8}$. This is more than 3 orders of magnitude less than observed. The magnetic field of CU Vir is thus about two orders of magnitude too weak to alter the moment of inertia of the star by the required amount.

We conclude that all the considered mechanisms are incompatible with observations and that the discrepancy in each case is several orders of magnitude.

3. Spin down of the outer stellar envelope

A possible way out of this dilemma is to abandon the assumption of rigid rotation. As it is well known, a dipole like magnetic field increases inwards much slower than the gas density and pressure. According to the results of model calculations of rotating magnetic stars (Moss 1974,1977; Mestel & Moss 1977) rapidly rotating stars with moderate magnetic fields (called the Low Flux stars by the above authors) can be divided into two parts. The magnetic perturbation is much less than centrifugal in the inner part of the star, hence meridional circulations flow there unimpeeded. However, the ratio of the magnetic to centrifugal perturbation increases rapidly in the outer layers due to the decrease of density. As a result, the magnetic terms dominate in the outer envelope. The calculations of Mestel & Moss (1977) indicate that the transition occurs at $r \approx 0.8 - 0.85R$. The mass contained above this radius in the outer envelope dominated by the magnetic field is $q_{\rm env} = 3.4 \times 10^{-4} M$ or $8.2 \times 10^{-5} M$, respectively (I thank Wojtek Dziembowski for providing me with detailed model calculations for a 3 $M_\odot$ star).The maximum possible magnetic perturbation is measured by the parameter λ_H.

To calculate its value for the envelope of mass $q_{\rm env}M$, one M in Eq. (6) should be replaced by $q_{\rm env}M$. We get thus in case of CU Vir $\lambda_H(\rm env) = 6 \times 10^{-5}$ or 2.6×10^{-4}, respectively, which means that the observed magnetic field of this star is strong enough to alter the moment of inertia of its outer envelope by the required amount, compare Eq. (1).

This conclusion is in agreement with the discussion of Shore & Adelman (1976) who argued that dynamical effects of the stellar magnetic field on the outer envelope of the star can lead to a free precession due to a magnetic distortion of the envelope. They adopted a mass of the envelope to be of the order of 10^{-4}, similar as following from the above considerations.

The above mechanism requires the envelope not strictly corotating with the stellar interior in spite of the fact that the star possesses a large scale magnetic field. How it can be? Let us first note that the isorotation law, requiring a constant rotation rate along each magnetic force applies only to the stationary fields. An oblique dipole field, observed in CU Vir, cannot be stationary inside a rapidly rotating star but it must evolve under the influence of meridional circulations (Mestel & Moss 1977; Moss 1977). It will very likely assume a complicated, three dimensional structure varying in time. One can speculate about a possible source of a sudden change of the rotation period within such a model. The interaction of meridional circulations with the magnetic field close to the interface between the circulation dominated interior and the magnetically dominated envelope may lead to a slow building of the prolate density distribution of the envelope. The moment of inertia of the envelope decreases relative to the nonmagnetic state. When the limiting state is reached the configuration relaxes rapidly to the oblate shape, which increases the moment of inertia. The process starts again. It does not have to influence the surface and atmospheric layers where the magnetic pressure is always much larger than the gas pressure. A nonuniformity in rotation develops a toroidal component of the internal magnetic field which should increase until it forces the envelope into corotation with the interior. The star may be in a state of long period torsional oscillations forced by the interaction of meridional circulations with the stellar magnetic field. Future observations will show how does the rotation period of CU Vir behave. Frequent monitoring of the variability of 56 Ari, another short period Ap star with a well defined light curve and accurately known period of about 0.73 of a day may help in a deeper understanding of the discussed process.

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