# Why are magnetic Ap stars slowly rotating?

**K. Stępień**

*Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland*

**Abstract.** Observational data on rotation of Ap stars suggest that the bulk of their rotation rates form a separate Maxwellian distribution with an average value 3-4 times lower than the normal star distribution. No evidences for a significant angular momentum (AM) loss on the main sequence (MS) have been found. It is thus concluded that Ap stars must lose a large fraction of their initial angular momentum (AM) in the pre-MS phase of evolution, most probably as a result of the interaction of their primordial magnetic fields with accretion disks and stellar winds. The observationally most acceptable values of accretion rate from the disk, $10^{-8} M_\odot$ /year, of mass loss rate via a magnetized wind, $10^{-8} M_\odot$ /year, and of the surface magnetic field, 1 kG on the ZAMS, result in the AM loss in full agreement with observations.

There exists a separate group of extremely slowly rotating Ap stars, with periods of the order of 10-100 years. They are too numerous to come from the distribution describing the bulk of Ap stars. It is conjectured that their extremely low rotation rates are the result of additional AM loss on the MS.

**Key words:** Stars: rotation – Stars: chemically peculiar – Stars: early type

## 1. Introduction

The A and B type stars with peculiar spectra have been recognized as having unusually sharp spectral lines as soon as their spectra were analyzed with large enough dispersion. In fact, low $v \sin i$ values were the reason why Babcock (1947) included them into his search for stellar magnetic fields. He believed at that time that strong magnetic fields are coupled with rapid rotation but because of instrumental reasons he selected early type stars with sharp lines, assuming that the low values of $v \sin i$ are the result of low $i$, not $v$ values. Later, when the variation periods of Ap stars (typically of several days) were identified as their rotation periods, according to the oblique rotator theory (Stibbs, 1950), it became apparent that the low $v \sin i$ values are the result of the low rotation rates of these stars. The presently known values of the rotation periods of peculiar stars are in agreement with the conclusion that the stars rotate on average much slower that normal stars of the same spectral types (Catalano & Renson, 1997 and references therein).

The observed chemical peculiarities of Ap stars are explained as resulting from the diffusion of different ions under the influence of the radiative force (Michaud, 1970; Michaud & Proffitt, 1993). A slow rotation rate was assumed

Contrib. Astron. Obs. Skalnaté Pleso **27**, (1998), 205– 212.

**Table 1.** Ap stars with extremely long periods.

| HD | Sp | $P$ (years) |
|---|---|---|
| 9996 | A0 SiCrSr | 22 |
| 94660 | A0 EuCrSi | $\gtrsim 7.5$ |
| 110066 | A1 SrCrEu | 13.5 or 27 |
| 137949 | F0 SrCrEu | $\gtrsim 75$ |
| 187474 | A0 EuCrSi | 6.5 |
| 201601 | A9 SrEu | 75 |

to be *condicio sine qua non* for a diffusive segregation of elements to occur in atmospheres of these stars although the role of the magnetic field must also be very important for the development and distribution of over- and under-abundances over the stellar surface (Pyper, 1969; Babel 1993). Recently Abt & Morrel (1995) went one step further suggesting that the slow rotation is also a sufficient condition for the Ap star phenomenon to occur. They propose the existence of a threshold for A stars, such that all stars rotating slower than that should be chemically peculiar, even if not yet recognized as such.

The rotation distribution of Ap stars cannot be interpreted as a slow rotation tail of the normal star distribution. A statistical investigation of rotation velocities of peculiar stars indicates that their distribution can be approximated by the Maxwellian one with an average value 3-4 times lower that for normal stars (Preston, 1970; Wolff, 1981; Abt & Morrel, 1995). In addition, several Ap stars with extremely long rotation periods of more than 5 years are known (Table 1). Note that all belong to cooler Ap stars of the CrSrEu type. The periods of these stars, if interpreted as rotation periods, cannot be part of the Maxwellian distribution describing the bulk of the rotation periods of peculiar stars, because the probability of finding even one rotator with such a long period in the known sample of Ap stars is exceedingly small (Preston, 1970). We have to assume that they form a separate population of Ap stars in which a special mechanism of spin down is (or has been) operating.

The slow rotation of A and B peculiar stars can be a result of one or more of the following circumstances: (i) they are formed from protostellar clouds with particularly low angular momentum (AM), (ii) they lose extra AM in the pre main sequence (PMS) phase of evolution, (iii) they lose AM on the MS.

The first possibility seems unlikely. Open clusters contain a substantial number of peculiar stars which have been formed simultaneously with the other cluster members. Had they been formed from a low rotation tail of the protostellar cloud distribution, they would have become part of the same stellar distribution, which contradicts the observations.

The second and third possibility were a subject of investigation of several authors in the past. Abt (1979) measured $v \sin i$ values of Ap stars in a number of stellar clusters of known ages and found a significant decrease of the rotation

rate of at least hot peculiar stars with age. That was confirmed by Wolff (1981). Unfortunately, their conclusion relied heavily on the data points from the Orion association for which only three $v \sin i$ values had been measured. Wolff (1981) discussed also possible mechanisms for AM loss of Ap stars, based on the interaction of their magnetic fields with the stellar environment. More accurate and numerous data on the rotation periods of peculiar stars in young clusters obtained later, showed that the period distribution of peculiar cluster members is indistinguishable from the distribution of field Ap stars, assumed to be much older (Borra et al. 1985; North, 1984a, 1987). North (1984b) discussed the dependence of the observed period of field Ap stars on gravity, treated as a measure of age for a given mass. He concluded that the rotation period increases when $\log g$ decreases just as expected from the conservation of AM during the MS life, without "...the least suggestion of any braking mechanism". But recently Pyper et al. (1998) showed that the short-period Ap star CU Vir abruptly increased its period by about $5 \times 10^{-5}$ of its value. Because the reason for this change seems at present completely obscure, and it is not clear what is its relation to possible evolutionary period changes during the MS life, that case will be ignored and it will be assumed in the following that the observational data do not show significant AM loss of Ap stars during their MS life.

This leaves us with the hypothesis that progenitors of peculiar stars are born with normal rotation rates but they lose a large fraction of their initial AM in the PMS phase, hence they rotate 3-4 times slower than normal stars when they land on the ZAMS. This hypothesis will be the subject of the rest of the paper.

## 2. PMS evolution of intermediate mass stars

An important difference appears in the PMS evolution of intermediate mass stars (IMS), compared to low mass stars. Time spent in a fully convective phase decreases rapidly for stars with masses above 1.5 $M_\odot$, reaching $10^4$ years for 2 $M_\odot$ and zero for masses above 2.4 $M_\odot$ (Palla & Stahler, 1993). It makes the survival of a primordial magnetic field much more probable for IMS than for solar type stars. On the other hand, a convection zone connected with the deuterium burning is very shallow in IMS, which makes the existence of strong dynamo generated fields very unlikely. Indeed, the observations of Herbig Ae/Be stars indicate that their activity level is not correlated with rotation, as would dynamo theory predict, but with effective temperature (Böhm & Catala, 1995). The absence of the dynamo generated fields in IMS is also in agreement with the observational data on rotation of these stars. The comparison of the rotation velocities of Herbig Ae/Be stars with the ZAMS stars of the same mass shows that the IMS do not lose a measurable amount of AM during the PMS phase if their AM is conserved in shells during the approach to the ZAMS (Böhm & Catala, 1995). This is not, however, the case for Ap stars which rotate much slower than the normal stars of the same spectral types (Wolff, 1981; Abt &

Morrel, 1995). Consequently, they must lose a large fraction of the initial AM in the PMS phase.

Detailed models of the PMS evolution of IMS were computed by Palla & Stahler (1993). The results show that the PMS phase of these stars is rather short: from slightly less than about $10^7$ years for a 2 $M_\odot$ down to $2 \times 10^5$ years for a 5 $M_\odot$ star. This is substantially less than adopted e. g. by Wolff (1981) after Iben (1965). Shorter time scales require a more efficient spin down mechanism.

Observations of Herbig Ae/Be stars show the presence of stellar winds with a mass loss rate of $10^{-8} M_\odot$ /year or more, as well as the presence of circumstellar matter, very likely in the form of accretion disks (Catala, 1989; Palla, 1991). We can expect accretion rates not much different from those observed in T Tauri stars, i. e. $10^{-9} - 10^{-8} M_\odot$ /year (Basri & Bertout, 1989).

Considering the AM loss of Ap stars it will be assumed that they preserve primordial magnetic fields through the protostellar phase and the magnetic field interacts with both the stellar wind and the accretion disk during the PMS phase of evolution, which influences the stellar AM. Details of this process will be discussed in the next Section.

## 3. AM loss mechanism of magnetic Ap stars

We will consider now the evolution of the stellar AM during the PMS evolution. The AM of a rigidly rotating star is given by $I\omega$, where $I$ is the moment of inertia of the star and $\omega$ its angular velocity. Assuming that the time derivative of AM is equal to the total torque $T$ exerted on the star we have

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{I}\left(T - \omega\frac{\mathrm{d}I}{\mathrm{d}t}\right). \tag{1}$$

According to our assumptions, the total torque will consist of three parts, $T = T_{mag} + T_{acc} + T_{wind}$, where $T_{mag}$ comes from the magnetic star-disk linkage, $T_{acc}$ is due to magnetic accretion of the matter from the disk and $T_{wind}$ is connected with the magnetized wind. Let us discuss each of these terms separately.

The recent observations indicate that some of Herbig Ae/Be stars are surrounded by massive, optically thick disks, whereas others are disk-less (Hillenbrand et al., 1992; Grinin, 1992; Böhm & Catala, 1995; Corcoran & Ray, 1997). This suggests that a typical time scale of the disk life is probably shorter than the PMS life time of an IMS.

The expression for the magnetic torque was derived by Armitage & Clarke (1996). The maximum efficiency of the torque is reached when the radius of the magnetosphere (identical with the radius of the inner edge of the disk) is equal to the corotation radius. We will assume this for simplicity, and any possible variations of efficiency of this or the other considered mechanisms will be accounted for later by introducing arbitrary, multiplicative weights. We have

thus

$$T_{mag} = -\mu^2\omega^2/3GM, \tag{2}$$

where $\mu = BR^3$ is the stellar magnetic dipole moment, assumed here to be constant, $G$ is the gravity constant, $B$ is the intensity of the surface magnetic field, and $R$ and $M$ are radius and mass of the star, respectively.

To consider $T_{acc}$ it is assumed that the matter is accreted from the inner edge of the disk along the magnetic field lines. If the radius of the inner edge is much larger than $R$, the accretion torque can be approximated by

$$T_{acc} = \dot{M}_{acc}(GM)^{2/3}/\omega^{1/3}, \tag{3}$$

where $\dot{M}_{acc}$ is the accretion rate.

The expression for the torque due to a magnetized wind in case of a dipolar magnetic field is given by (Stępień, 1995)

$$T_{wind} = -\frac{\omega}{3}\dot{M}_{wind}^{3/5}R^{3/5}\mu^{4/5}(2GM)^{-1/5}, \tag{4}$$

where $\dot{M}_{wind}$ is the mass loss rate via the magnetized wind.

The equation (1) for the angular velocity evolution assumes now the form

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{I}\left[\dot{M}_{acc}\frac{(GM)^{2/3}}{\omega^{1/3}} - \frac{\mu^2\omega^2}{3GM} - \frac{\omega}{3}\dot{M}_{wind}^{3/5}R^{3/5}\mu^{4/5}(2GM)^{-1/5} - \omega\frac{\mathrm{d}I}{\mathrm{d}t}\right] \tag{5}$$

Equation (5) is the basic equation solved numerically for the adopted values of free parameters. The discussion of free parameters and the results are given in the next Section.

## 4. Results and discussion

The calculations have been carried out for two values of the stellar mass, 2 and 3 $M_\odot$. The time scales of the PMS evolution, and the dependence of the moment of inertia and stellar radius on time, i.e. $I(t)$ and $R(t)$, were taken from models computed by Palla & Stahler (1993) (see also Böhm & Catala, 1995). Based on the observational results about the accretion rate and mass loss via winds of Herbig Ae/Be stars given in Section 1, the following values have been adopted as typical: $\dot{M}_{acc} = 10^{-8}M_\odot$/year and $\dot{M}_{wind} = 10^{-8}M_\odot$/year. The value of the magnetic moment was adopted as $\mu = 2.7 \times 10^{36}$ in cgs units, which corresponds to the 1 kG dipole field on a 2 $R_\odot$ star. To allow for a possible variation of these values as well as other factors modifying the efficiency of all the considered mechanisms, arbitrary weights were added to the the first three terms in equation (5).

Figure 1 (upper) compares the variation of the rotation period of a 2 $M_\odot$ star when its AM is preserved during the PMS evolution (solid line) and when

the consecutive AM change mechanisms, described by the first three terms in brackets on the right hand side of equation (5) are added. It is assumed that the star emerges from the protostellar phase after $10^6$ years with a rotation period of 5 days, and the PMS phase ends after $8 \times 10^6$ years (Palla & Stahler, 1993). When AM is conserved in a rigidly rotating star its rotation period decreases down to a value of 0.55 of a day on the ZAMS (solid line). When only the accretion is added, the ZAMS period is even shorter, and it is equal to 0.15 of a day (dotted line), because the accretion of a high AM matter from the disk increases the stellar AM, hence spins up the star. When only a wind is added, the resulting ZAMS period reaches a value of 1.35 day (dotted-broken line). The most powerful mechanism influencing the rotation period of a PMS star is the interaction of its magnetic field with the disk. If the disk is massive enough, it will force the stellar rotation in a relatively short time to an approximate value of the corotation period at the edge of the magnetosphere (Armitage & Clarke, 1996). In our case this is close to 5 days, hence the rotation period of the considered star stays close to this value through the whole PMS evolution (broken line). For the initial rotation periods shorter than 5 days the field-disk linkage slows down the rotation but for values longer that that it spins up the star, so that the final value of about 5 days is always reached.

Figure 1 (lower) demonstrates the result of a simultaneous action of all the considered mechanisms. The constant AM case is repeated from the upper part of the figure for comparison as a dotted-broken line. The solid line describes the evolution of the rotation period of the considered star when all terms in equation (5) are taken into account with weights equal to 1. The resulting ZAMS rotation period is equal to 2.1 days, about four times longer than in case of constant AM. This agrees well with the observations. In addition, the evolution of the rotation period is shown in the case when the importance of the accretion and wind is decreased by a factor of 10, i. e. the corresponding terms in equation (5) were taken with weights equal to 0.1. Physically, this corresponds to e. g. lower accretion and mass loss rates, or shorter time scales of both phenomena. The resulting ZAMS rotation period is equal now to 3.9 days. This can be compared with the value of 1.25 days expected when the considered star preserves AM in shells during its approach to the ZAMS.

Similar calculations have been obtained for a 3 $M_\odot$ star. The main difference between the two cases is the time scale of the PMS evolution which is 7 times shorter for the 3 $M_\odot$ star than for the 2 $M_\odot$ star. To get a 3-4-fold increase of the rotation period, a relatively more efficient AM loss is required. This can be achieved e. g. by an increase of the weight of the term describing the field-disk interaction up to a value of 2 – equivalent to the increase of $\mu$ by a factor of 1.4, see equation (5). Note that this corresponds to a surface magnetic field of about 1.5 kG which would show up in observations as a longitudinal magnetic field of only about 500 G (Preston, 1971).

One concludes that the presence of a moderate primordial magnetic field can explain the observed difference between the average rotation rate of Ap and

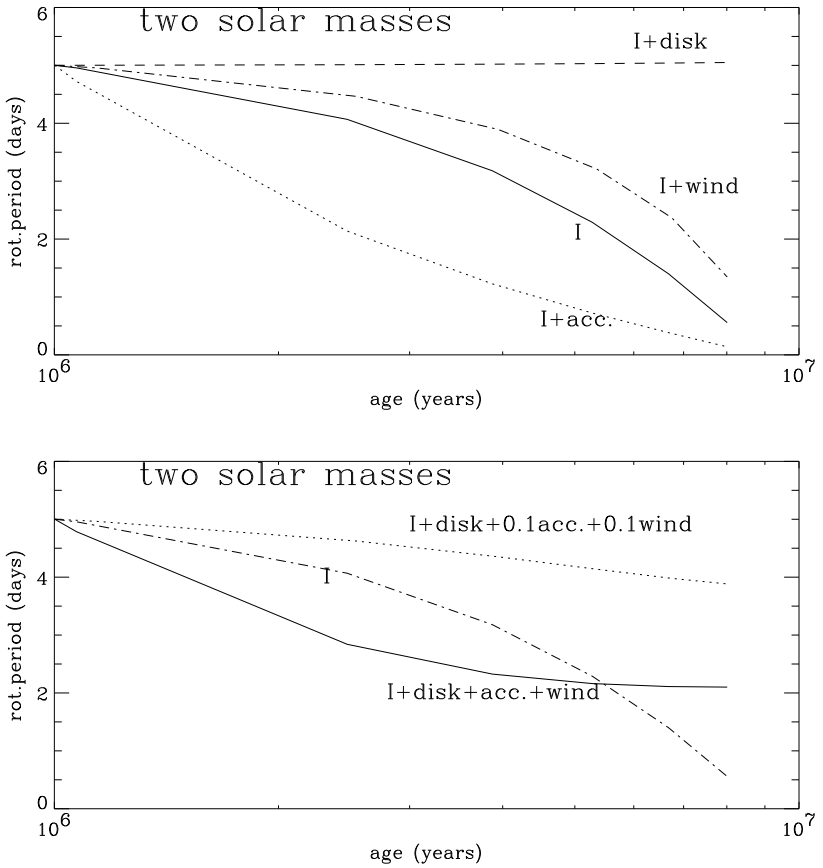


**Figure 1.** The results of model calculations for a 2 $M_{\odot}$ and different mechanisms for stellar AM change (see text)

normal stars. The required values of the parameters describing the interaction between a star and its environment are within the observed ranges. Because the time scales of the existence of disks and winds, mass loss and accretion rates, and the intensity of the magnetic field are expected to vary randomly from one PMS star to another, the resulting ZAMS rotation period is not expected to be strongly correlated with any single parameter.

The discussed AM loss mechanism cannot, however, explain the extremely long rotation periods observed in some stars (Table 1). The required values of the considered parameters are unreasonable. Therefore, it is suggested that those stars lose AM also on the MS because of some exceptional circumstances. Because the accretion disks are not observed around young MS stars we reject this mechanism. A continuous mass loss via a magnetized wind is a more realistic

possibility. With the same intensity as adopted here for the PMS phase, the wind can spin down the star to a rotation period of the order of 100 years just in $2 \times 10^7$ years, which is a tiny fraction of the total MS lifetime of a star with a mass below 2 $M_\odot$. A less intense wind would need, of course, a correspondingly longer time.

**Acknowledgements.** This work was partly supported by the grant 2 P 03D 010 12 from the Committee for Scientific Research.

## References

Abt, H.A.: 1979, *Astrophys. J.* **230**, 485
Abt, H.A., Morrell, N.J.: 1995, *Astrophys. J., Suppl. Ser.* **99**, 135
Armitage, P.J., Clarke, C.J.: 1996, *Mon. Not. R. Astron. Soc.* **280**, 458
Babcock, H.W.: 1947, *Astrophys. J.* **105**, 105
Babel, J.: 1993, in *Peculiar versus Normal Phenomena in A-type and Related Stars*, eds.: M.M. Dworetsky, F. Castelli and R. Farraggiana, A.S.P. Conf. Ser. vol. 44, San Francisco, 458
Basri, G.S., Bertout, C.: 1989, *Astrophys. J.* **341**, 340
Böhm, T., Catala, C.: 1995, *Astron. Astrophys.* **301**, 155
Borra, E.F., Beaulieu, A., Brousseau, D., Shelton, I.: 1985, *Astron. Astrophys.* **149**, 266
Catala, C.: 1989, in *Low Mass Star Formation and Pre-Main-Sequence Evolution*, ed.: Bo. Reipurth, ESO, München, 471
Catalano, F.A., Renson, P.: 1997, *Astron. Astrophys., Suppl. Ser.* **121**, 57
Corcoran, M., Ray, C.: 1997, *Astron. Astrophys.* **321**, 189
Grinin, V.P.: 1992, *Astr. Ap. Trans.* **3**, 17
Hillenbrand, L.A., Strom, S.E., Vrba, F.J., Keene, J.: 1992, *Astrophys. J.* **397**, 613
Iben, I.: 1965, *Astrophys. J.* **141**, 993
Michaud, G.: 1970, *Astrophys. J.* **160**, 641
Michaud, G., Proffitt, C.: 1993, in *Peculiar versus Normal Phenomena in A-type and Related Stars*, eds.: M.M. Dworetsky, F. Castelli and R. Farraggiana, A.S.P. Conf. Ser. vol. 44, San Francisco, 439
North, P.: 1984a, *Astron. Astrophys.* **141**, 328
North, P.: 1984b, *Astron. Astrophys.* **148**, 165
North, P.: 1987, *Astron. Astrophys., Suppl. Ser.* **69**, 371
Palla, F.: 1991, in *Fragmentation of Molecular Clouds and Star Formation*, ed.: K. Falgerone et al., Kluwer, Dordrecht, 331
Palla, F., Stahler, S.W.: 1993, *Astrophys. J.* **418**, 414
Preston, G.W.: 1970, in *Stellar Rotation*, ed.: A. Slettebak, Reidel, Dordrecht, 254
Preston, G.W.: 1971, *Astrophys. J.* **164**, 309
Pyper, D.M.: 1969, *Astrophys. J., Suppl. Ser.* **18**, 347
Pyper, D.M., Ryabchikova, T., Malanushenko, V., Kuschnig, R., Plachinda, S., Savanov, J.: 1998, *Astron. Astrophys.* , in press
Stępień, K.: 1995, *Mon. Not. R. Astron. Soc.* **274**, 1019
Stibbs, D.W.N.: 1950, *Mon. Not. R. Astron. Soc.* **110**, 395
Wolff, S.C.: 1981, *Astrophys. J.* **244**, 221