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Evolution of physical parameters of magnetic BpAp stars

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Abstract. Two main properties distinguishing BpAp magnetic stars from normal stars of the same mass, i. e. slow rotation and the presence of large-scale surface magnetic field, are discussed. It is shown that the angular velocity distribution of periodically variable BpAp stars is exponential, unlike that of normal or rapidly rotating Be stars. Periodicity is observed in stars lying everywhere between ZAMS and TAMS, which indicates that slow rotation and surface nonuniformities (usually associated with the presence of the magnetic field) are developed early in the stellar life. Similar analysis of stars with detected magnetic fields confirms this conclusion. The analyzed data did not allow carrying out a reliable discussion of any possible variability of the rotation rate or magnetic field across the MS.

A mechanism of angular momentum evolution of a magnetic star at the PMS phase is presented. The mechanism explains slow rotation of stars with a strong magnetic field and a rapid rotation of Be stars, assuming that the latter possess weak magnetic fields. Recent detections of such fields in two Be stars support this assumption. The discussed mechanism can also explain the observed properties of extremely slowly rotating BpAp stars.

Arguments are given for survival of the fossil magnetic fields at evolutionary phases beyond the MS.

Key words: stars: chemically peculiar – stars: magnetic fields – stars: rotation – stars: fundamental parameters

1 Introduction

In this lecture I will discuss the upper Main Sequence (MS) stars possessing chemical peculiarities associated with large-scale surface magnetic fields, which are called BpAp stars.

For a long time has been unclear to what extend chemically peculiar stars differ from normal stars of the same mass. Their observed energy distributions and line profiles are markedly different. In addition, many peculiar stars show light and spectral variations usually interpreted as resulting from surface nonuniformities introduced by the surface magnetic field. All these differences make useless normal calibrations of effective temperatures and gravity in terms of color indices or line profiles. Only when observations of energy distributions in a broad wavelength range, including UV, became available, and line-blanketed model atmospheres with chemical compositions characteristic of peculiar stars were calculated, reliable effective temperatures and gravities of some stars could be obtained. They have been used, in turn, to calibrate properly different observables. Thus obtained physical parameters of peculiar stars indicated that they belong to MS. This view was confirmed by North (1993) who analyzed peculiar stars belonging to stellar clusters, for which absolute magnitudes could be determined. Stępień (1989) demonstrated that also radii of periodically variable BpAp stars correspond to the MS stars. Similarly, luminosities of roAp stars, derived from the analysis of their oscillations, place these stars on MS (Kurtz & Martinez 1993). These results were confirmed when the absolute magnitudes of many field peculiar stars became available following measurements of parallaxes by Hipparcos (Gomez et al. 1998). Summing up, because the radii, luminosities, effective temperatures and gravities of peculiar stars are identical with the parameters of normal MS stars of the same mass, we conclude that their internal structure and energy production are also normal. The observed peculiarities are restricted to the surface layers where the radiation leaving a star is finally shaped. Because of high opacity these layers are exceptionally thin: the mass lying above the photosphere of an A0 MS star reaches only a fraction of gram per cm^2!

Still, BpAp stars have two important properties distinctively different from normal MS stars of the same mass. These are rotation rate which is, on average, several times lower and the presence of strong, large-scale, surface magnetic fields. By a strong field I mean a field with the magnetic pressure larger than the gas pressure at the photospheric level. In case of a typical BpAp star this condition is fulfilled for a field of 200–300 Gauss. Some of the important problems in BpAp star research concentrate on the origin of the magnetic fields and of the low rotation rate, possible relation between them and their evolution throughout the stellar life. In the following sections we will address these problems.

2 Statistics of the rotation rates and magnetic fields of BpAp stars

2.1 Rotation rates

It has been known for a long time that BpAp stars have, on average, much less rotation broadened spectral lines compared to normal stars. The projected rotational velocity, $v \sin i$, of these stars is 3–5 times lower than that of normal stars (Wolff 1981, Abt & Morrell 1995). The rotational velocity distribution of normal MS stars is expected to be Maxwellian (Deutsch 1970). Detailed analysis of rotational velocities of a sample of B and A type stars show, however, that a single Maxwellian does not fit the observations and at least bimodal distribution has to be adopted (Deutsch 1970, Wolff et al. 1982, Abt & Morrell 1995, Abt et al. 2002, Stępień 2004). In fact, considering a mechanism for a possible evolution of angular momentum (AM) of newly born intermediate-mass stars, we can actually expect *three* different groups of MS rotators, depending on the presence and intensity of primordial magnetic field (Stępień 2000, 2002): rapid rotators (Be stars), normal stars and slow rotators (BpAp stars). Stępień (2004) compared the $v \sin i$ distribution of about 1700 B-type normal stars with the distribution of Be stars. The observations of Be stars can satisfactorily be fitted with a single Maxwellian. However, the Maxwellian fit to normal stars is much poorer because of excess of very slowly rotating stars, in spite of the fact that all known peculiar stars were excluded (see Fig. 1).

Is it possible that among these, so-called "normal", stars there is still an admixture of unrecognized peculiar stars? This question was addressed by Abt & Morrell (1995) and Abt et al. (2002) who analyzed their own observations of $v \sin i$ of all A-type and B-type stars from the *Bright Star Catalog*. They argue that in case of A-type and late B-type stars all the slowly rotating stars are indeed peculiar even if they are not known as such. Assuming that the rotational velocity distribution of each group can be described by a Maxwellian they determined parameters of the best fitting bimodal distribution. Only in a case of early B-type stars a single Maxwellian was fitted because, as they argue, very few peculiar stars occur within this sample. In no case they report a presence of a peak corresponding to Be stars. This is probably due to a low number of Be stars present in a magnitude-limited sample analysed by the authors. Note however, that an additional peak around $v = 250$ km/s can be seen in their data on early B-type stars where the percentage of Be stars is the highest (see Fig. 3 in Abt et al. 2002).

Let us now concentrate on the rotation distribution of BpAp stars. Because they rotate slowly, typical $v \sin i$ values are often comparable to, or even smaller than the resolution of the used instrument. As a result, stars from the low rotation part of the distribution have often unreliable values of $v \sin i$. If we adopt the paradigm that the distribution of BpAp stars is correctly described by a Maxwellian, like in case of normal stars, we can fit it using only the fast rotating part of the distribution and ignoring the poorly known low rotation part of the distribution. This is an approach adopted by Abt & Morrell (1995) and Abt et al. (2002). They determined parameters of Maxwellian fits to peculiar stars of different spectral types without paying much attention to the data for very slow rotators.

To avoid problems with measuring correct rotation rates of slow rotators by a spectral technique the rotation periods $P_{\rm rot}$ of variable BpAp stars should be used. In fact, rotation periods are a better measure of rotation rates because the correct physical quantity describing stellar rotation is its angular velocity Ω. It can be calculated directly from the rotation period: $\Omega = 2\pi/P_{\rm rot}$. A common use of $v \sin i$ results from the fact that this parameter is relatively easy to measure and can be determined for a large number of stars whereas

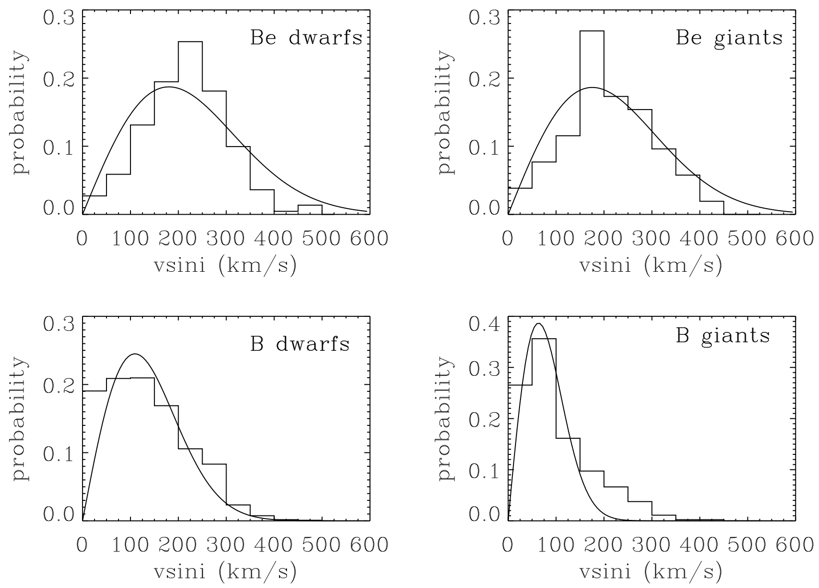

Figure 1: *Observed distributions of* $v \sin i$ *of Be and normal B stars (after Stępień 2004) with the Maxwellians fitted. Note an excess of normal stars with very low values of* $v \sin i$*.*

directly measured rotation periods are known only for few groups of variable stars. Fortunately, BpAp stars belong to one of these groups.

The recently published catalog of periodic peculiar stars contains data on a few hundred stars with reported values of the rotation periods (Catalano & Renson 1998). A large number of additional periodic stars detected by Hipparcos is given in the Fifth Supplement to the catalog (Renson & Catalano 2001). The Hipparcos periods are not subject to selection effects connected with daily aliases or uneven coverage of the sky by ground based observations. Based on the data from the catalog and the supplement the Ω-distribution of peculiar stars was obtained. No discrimination against less reliable values of the reported periods was done. Figure 2 shows the data for about 500 stars together with the best fitting Maxwellian distribution. It is immediately visible that the fit is very poor. In particular, too many stars with very low Ω are present, compared to the prediction. Figure 3 shows the same data with the following exponential fit:

$$f(\Omega) = 0.12\mathrm{e}^{-2.08\times10^4\Omega}\,. \tag{1}$$

The agreement is now much better. This is a new and unexpected result. It was also noted by Glagolevskij and Gerth (2003). Why did Abt & Morrell (1995) and Abt et al. (2002) fail note this effect? There are at least two reasons for that. First, the samples analyzed here and by those authors are not the same. Periodic BpAp stars are presumably all magnetic because we believe that their variability is due to surface nonuniformities introduced by the field. If this is correct, the magnetic field could also have played a decisive role in slowing them down (Stępień 2000, Stępień & Landstreet 2002). The samples of stars analyzed by Abt & Morrell (1995) and Abt et al. (2002) consist of stars with spectral peculiarities of all sorts, including HgMn and Am stars believed not to possess strong surface fields. In addition, they included into the fit several stars with marginal peculiarities not yet recognized as chemically peculiar. The mechanism of spin down of all these stars is very likely quite different from magnetic stars. Besides, as it was already indicated above, these authors have only few observations of very slowly rotating stars with $v \sin i$ values lying to the left of the maximum of the best fitting Maxwellian. Exponential fits to such data, particularly for B8–B9.5 and A5–F0 type stars look at least equally satisfactory as Maxwellians.

The exponential distribution of the angular velocity of BpAp stars needs an interpretation in terms of the braking mechanism (see e. g. Deutsch 1970), but this is beyond the scope of the present paper. Such a fit is, however, bad news for an attempt to detect any possible variations of Ω of these stars across MS. The variations would be relatively easy to detect in case of the Maxwellian distribution by comparing the distribution of young stars (lying close to ZAMS) with that of old stars (close to TAMS). The shift in maxima of both distributions could be interpreted as a measure of systematic change of the rotation velocity as stars

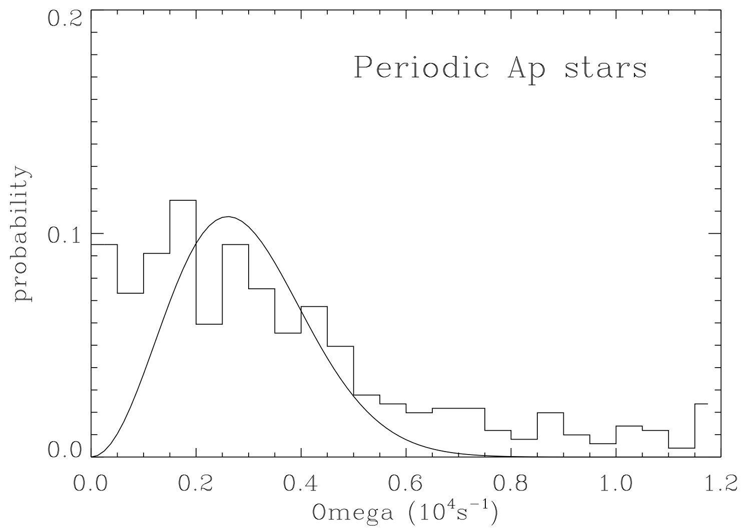

Figure 2: *The observed distribution of angular velocity of periodic peculiar stars with the best fitting Maxwellian distribution. It is apparent that the Maxwellian reproduces the observations very poorly.*

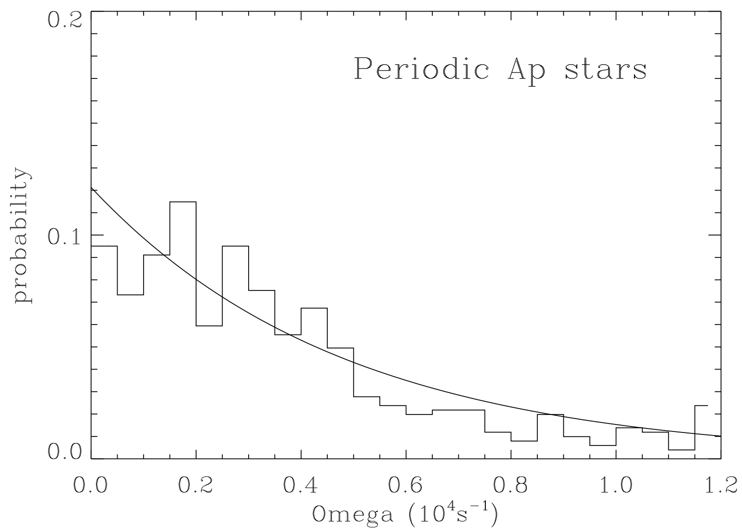

Figure 3: *The observed distribution of angular velocity of periodic peculiar stars with the best fitting exponential distribution. The fit is satisfactory.*

evolve across the MS. Expected differences between two exponential distributions are much more subtle and it is felt that the presently available data are not sufficiently accurate for any reliable discussion of the evolution of Ω across MS. Older data, based on the comparison of rotation periods with surface gravities of BpAp stars indicate that angular momentum of these stars does not change during their MS life (North 1984, 1998).

2.2 Magnetic fields

Hubrig et al. (2000) investigated recently positions in the HR diagram of several BpAp stars with strong magnetic fields. Their analysis showed that such stars avoid a region close to ZAMS. Following this result, they put forward a highly provocative suggestion that magnetic fields appear only in stars which have completed at least 30% of their MS evolution. If correct, this would have far reaching consequences for the origin and evolution of magnetic stars. It is therefore important to verify this supposition. Bagnulo et al. (2003) detected a very strong surface magnetic field of about 15 kG in the star HD 66318 which has completed only about 15 % of its MS evolution. This contradicts the hypothesis of Hubrig et al. (2000). Nevertheless, a larger statistics of young stars possessing magnetic fields would be desirable.

Following the assumption that all the variable BpAp stars are magnetic, one can determine the position of known periodic stars in the HR diagram to see whether a variability is observed within the whole MS band including its part close to ZAMS. A large number of known periodic variables should help in obtaining a reliable statistics. A more straightforward test for the presence of magnetic fields in stars of different age can be obtained from a similar analysis of stars with directly measured fields. The recently published catalog of such stars (Bychkov et al. 2003) is very useful in this respect. Unfortunately, a much lower number of stars with measured fields is known, compared to stars with periodic variations. Bychkov et al. (2003) analyzed the magnetic field distribution of the cataloged stars and they showed that also in this case an exponential fit describes best the observed distribution. This rules out again (like in the case of rotation periods) any reliable analysis of differences between the magnetic field distributions of young and old stars. The positions of both samples of BpAp stars in the HR diagram will be discussed in the next section.

3 Positions of BpAp stars in the HR diagram

3.1 Effective temperatures

It is well known that calibrations of effective temperature in terms of the observational parameters, like color indices or spectral features, based on normal stars do not apply to BpAp stars which have peculiar line strengths and energy distributions. Moreover, because the degree of peculiarity varies from one star to another, the deviations of individual stars from any calibration are expected to be significantly larger than in the case of normal stars possessing a much more uniform chemical composition. The most reliable temperature determination is obtained from a fit of a model atmosphere with the chemical composition identical to the investigated star to its full energy distribution. Unfortunately, very few peculiar stars have been analyzed in such a way (see e. g. Muthsam & Stępień 1980). The existing calibrations of peculiar stars take into account only the first order difference between the energy distributions of normal and BpAp stars, which is the enhanced absorption of UV radiation (due to blanketing effect of numerous and strong lines of overabundant elements) accompanied by reradiation of the absorbed flux in the visual and red part of the spectrum. A few such calibrations have been proposed in the literature (e. g. Moon & Dworetsky 1985, Stępień & Dominiczak 1989, Hauck & North 1993, Napiwotzki et al. 1993, Sokolov 1998 and references therein). Stępień (1994) rediscussed the calibration and, after a careful selection of 19 stars with effective temperatures determined from directly observed energy distributions, which were used as primary standards, he derived a relation between the reddening-free Strömgren index $[u - b]$ and effective temperature:

$$\Theta_e = 0.2 + 0.246[u - b] \tag{2}$$

where $\Theta_e = 5040/T_{\rm eff}$ and $[u - b] = (u - b) - 1.53(b - y)$. For hotter stars with $[u - b] \leq 1.3$, for which the redistribution of the UV flux to visual is the primary peculiarity of the energy distribution, the scatter around the above relation is quite modest with the expected errors of determination of $T_{\rm eff}$ less than 5 %. For cooler stars, in which the UV flux is very low anyway, the differences among visual energy distributions of individual peculiar stars dominate (Adelman & Rayle 2000), resulting in significant differences of the Strömgren indices for stars of the same temperature, and the errors of $T_{\rm eff}$ increase substantially.

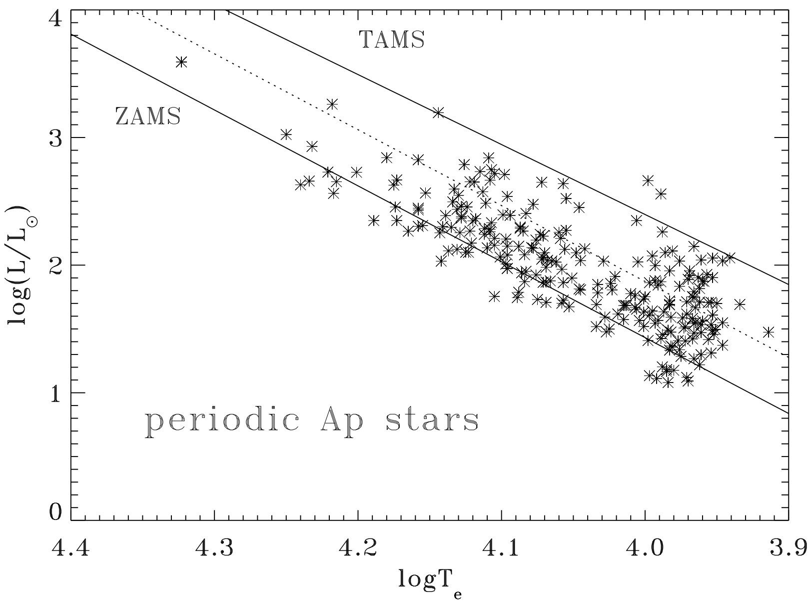

Figure 4: *Positions of periodically variable peculiar stars in the HR diagram. Solid lines describe the limits of MS and the broken line runs in the middle of the MS band.*

Using the above formula the effective temperatures were determined for all periodic BpAp stars observed in the Strömgren photometric system.

3.2 Absolute magnitudes of BpAp stars

Absolute visual magnitudes were determined from the Hipparcos parallaxes of those periodic peculiar stars for which the parallax had been measured and its error is less than 20 %. To determine their luminosities, bolometric corrections are needed. Based on the same standard stars as used for deriving the $[u-b]-T_{\rm eff}$ relation, Stępień (1994) determined the calibration of the bolometric correction BC for BpAp stars in terms of effective temperature:

$$BC = -0.067 - 6.513(\log T_{\rm eff} - 4) \qquad 4.225 \geq \log T_{\rm eff} \geq 4.025 \tag{3}$$

$$BC = -0.187 - 1.704(\log T_{\rm eff} - 4) \qquad 4.025 \geq \log T_{\rm eff} \geq 3.900 \tag{4}$$

As discussed by Stępień (1994), the bolometric corrections of BpAp stars, obtained from the above calibration, are (algebraically) larger than in the case of normal stars of the same effective temperature. Unfortunately, the scatter among the primary standards used by Stępień (1994) is quite significant, so the expected errors of determination of BC of individual stars can reach 0.1–0.2 magnitude.

Sufficient data exist for about 250 periodic stars to determine their effective temperatures and luminosities. Figure 4 shows a part of the HR diagram with these stars plotted. Limits of the MS after Schaller et al. (1992) are marked as solid lines and the broken line divides the MS band into halves roughly separating young stars from the more advanced evolutionary ones.

It is apparent from Fig. 4 that the majority of the investigated stars lies close to ZAMS. In fact, several stars lie even to the left of the MS, which indicates that their luminosities and/or temperatures may be incorrect.

Similar procedure was applied to magnetic BpAp stars from the catalog by Bychkova et al. (2003). To avoid stars with spurious measurements of the magnetic field, only such stars were included into the sample, for which at least three measurements of the magnetic field have been reported with $\chi^2 \geq 4$ and the average value of the field larger than 300 G, i. e. the field is strong as defined in Introduction. About 80 magnetic stars were plotted in Fig. 5. The figure looks very similar to the previous one: the majority of stars is concentrated around ZAMS. This is not surprising as nearly all the magnetic stars belong also to periodic stars. The picture is profoundly different from the one presented by Hubrig et al. (2000) and it suggests that magnetic

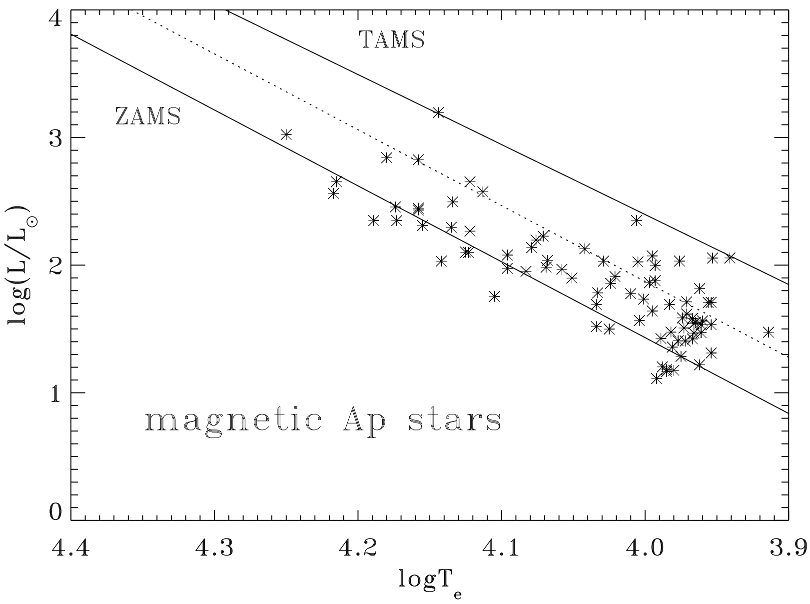

Figure 5: *Positions of BpAp magnetic stars in the HR diagram. Solid lines describe the limits of MS and the broken line runs in the middle of the MS band.*

fields are observed in many young stars lying very close to ZAMS. Possible sources of this discrepancy are discussed in the next subsection.

3.3 Discussion of the luminosities and effective temperatures of BpAp stars

Effective temperatures of the analyzed stars were obtained from the reddening-free Strömgren index $[u-b]$. The parameter Θ_e of BpAp standard stars is a linear function of their $[u-b]$ (Napiwotzki et al. 1993, Stępień 1994a) as it was discussed above. Let us, however, express $[u-b]$ in terms of the standard Strömgren indices:

$$[u-b] = c_1 + 2m_1 + 0.47(b-y) \tag{5}$$

It is immediately apparent that in the case of an abnormal Balmer jump and/or metallicity the index $[u-b]$ may produce a spurious value of temperature. A comparison of a few values of temperatures obtained from $[u-b]$ with the values based on other criteria shows that $[u-b]$ may give in extreme cases a temperature too high by 1000 K (Adelman & Rayle 2000). Obviously a very careful analysis of the temperature of each star, applying several different methods, is necessary before fully reliable values are be obtained.

The absolute magnitudes of the analyzed stars were calculated directly from the parallaxes listed in the Hipparcos catalog. No so-called Lutz-Kelker (LK) corrections were applied (Lutz & Kelker 1973). As it was presented by the original authors, the value of this correction depends on the ratio of the parallax to its error and it should always be negative (in magnitudes), i. e. after applying it the star becomes brighter. The correction has been a subject of debate in literature. Sometimes a confusion arose when its name was used to different effects and the values calculated under specific assumptions were applied carelessly to star samples not fulfilling them. A thorough discussion of this debate and the LK correction itself has recently been given by Smith (2003). He presents evidence that the correction *must not* be applied to individual stars. The author demonstrates that, for a given sample of stars, individual corrections can be positive or negative and only the sample correction (averaged over the whole sample) should be negative, with the value depending on the parallax/error ratio. Contrary to this conclusion Hubrig et al. (2000) applied an individual negative LK correction to each analyzed star which moved it significantly upwards in the HR diagram. In extreme cases the shift amounts to 0.3–0.4 of a magnitude (see Table 1 in Hubrig et al. 2000). This procedure is probably the main reason for an apparent avoidance of the vicinity of ZAMS by the investigated stars. Note that positions of peculiar stars in the HR diagram calculated by Gomez et al. (1998) agree qualitatively with the present results in a sense that in both papers the vicinity of ZAMS is densely populated.

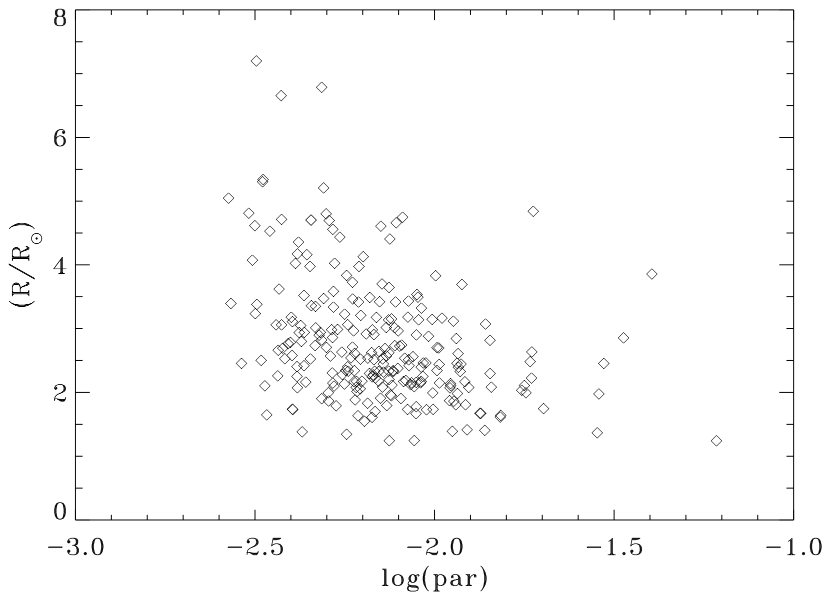

Figure 6: *Radii of periodic peculiar stars calculated from luminosities and effective temperatures versus parallax. No correlation is visible.*

We conclude that the analysis of the positions in the HR diagram of the periodic BpAp stars as well as stars with measured magnetic field does not support the conclusion of Hubrig et al. (2000) that the surface magnetic fields became visible only in older BpAp stars. The magnetic fields manifest their presence already in stars very close to ZAMS.

The radius of a star can be calculated from its absolute bolometric magnitude and effective temperature. Stępień (1994a) obtained radii of several nearby BpAp stars with the then known parallaxes. A surprising correlation appeared between radius and parallax in a sense that the closer the star the smaller its radius. This was, of course, a result of wrong values of stellar luminosities calculated from incorrect parallaxes (although only stars with parallaxes larger than 10 mas were considered). When similarly calculated radii of the presently investigated stars are plotted versus Hipparcos parallax (Fig. 6), no dependence of radius on parallax is seen. This confirms the lack of systematic errors in the adopted absolute magnitudes. If the procedure applied by Hubrig et al. (2000) were correct, such errors should be present among our stars in a sense that luminosities of stars with the larger parallax errors should be underestimated. Such stars are mostly concentrated at low values of parallax, hence we should observe an apparent decrease of radius with decreasing parallax. Such a decrease is not present in Fig. 6 indicating that magnitudes of the investigated stars are not systematically in error. A plot of stellar radius versus effective temperature (Fig. 7) shows that radii of the periodic BpAp stars correspond to the MS objects and, in particular, that their average radius increases with temperature, as expected.

We conclude this section with a statement that the magnetic fields of BpAp stars are visible in stars populating the whole MS band. The above analyzed data do not allow us to rediscuss reliably rotation rate or magnetic field variations across the MS. The hitherto obtained results are in agreement with an assumption that the rotation periods and the magnetic fields of BpAp stars do not vary across the MS except due to evolutionary changes of radius and internal structure of these stars.

4 Model for the PMS evolution of rotation of BpAp stars

Following the conclusion of the previous section, it is assumed that BpAp stars reach ZAMS already rotating slower than their normal counterpart and that their primordial magnetic fields play a decisive role in braking them down in the pre-MS (PMS) phase of evolution.

The model for the PMS evolution of AM of a star possessing a strong primordial magnetic field is presented and discussed in detail by Stępień (2000, 2002) and Stępień & Landstreet (2002).

An isolated star will preserve its AM during the PMS phase of evolution, i.e. $J = I\omega = \text{const.}$, where J is

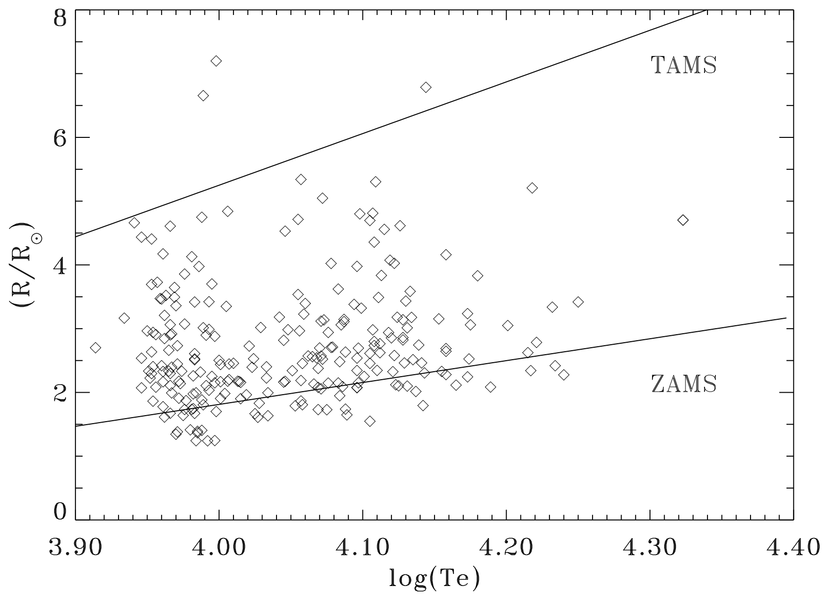

Figure 7: *Radii of periodic peculiar stars versus effective temperature. The limits of the MS are marked with solid lines.*

AM, $I = k^2MR$ is the stellar moment of inertia, ω — angular velocity, M and R — stellar mass and radius, and k^2 — a radius of gyration. Interaction of a star with its environment results in a torque T

$$\frac{\mathrm{dJ}}{\mathrm{dt}} = T\,. \tag{6}$$

It is assumed here that

$$T = T_{\mathrm{disk}} + T_{\mathrm{acc}} + T_{\mathrm{wind}}\,, \tag{7}$$

where T_{disk} results from an interaction of the stellar field with an accretion disk, T_{acc} is the torque exerted by the accreted matter and T_{wind} is due to a magnetized wind. Expressions for all three torques are discussed in Stępień (2000). The results can be summarized as follows.

For the radius of the magnetosphere (= inner radius of the disk) equal to the corotation radius

$$T_{\mathrm{disk}} = -\frac{\mu^2\omega^2}{3GM}\,, \tag{8}$$

where $\mu = B_{\mathrm{surf}}R^3$ is the magnetic moment of the stellar magnetic field and G is the gravity constant. Assuming that the total stellar magnetic flux ϕ is preserved during the PMS contraction of the star, we have $\phi = B_{\mathrm{surf}}R^2 = $ const. and $\mu = \phi R$.

The expression for T_{acc} results from an assumption that all the AM carried with the matter accreted along the magnetic lines adds to the stellar AM

$$T_{\mathrm{acc}} = \frac{(GM)^{2/3}\dot{M}_{\mathrm{acc}}}{\omega^{1/3}} - \omega\dot{M}_{\mathrm{acc}}R^2, \tag{9}$$

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

AM loss of a star due to a magnetized wind is equivalent to AM carried away by the wind matter strictly corotating up to the Alfvén surface. Adopting escape velocity as a wind velocity and a dipolar geometry for the field, we obtain (Stępień 1995)

$$T_{\mathrm{wind}} = -\frac{\omega R^{7/5}\phi^{4/5}\dot{M}_{\mathrm{wind}}^{3/5}}{3(2GM)^{1/5}}\,, \tag{10}$$

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

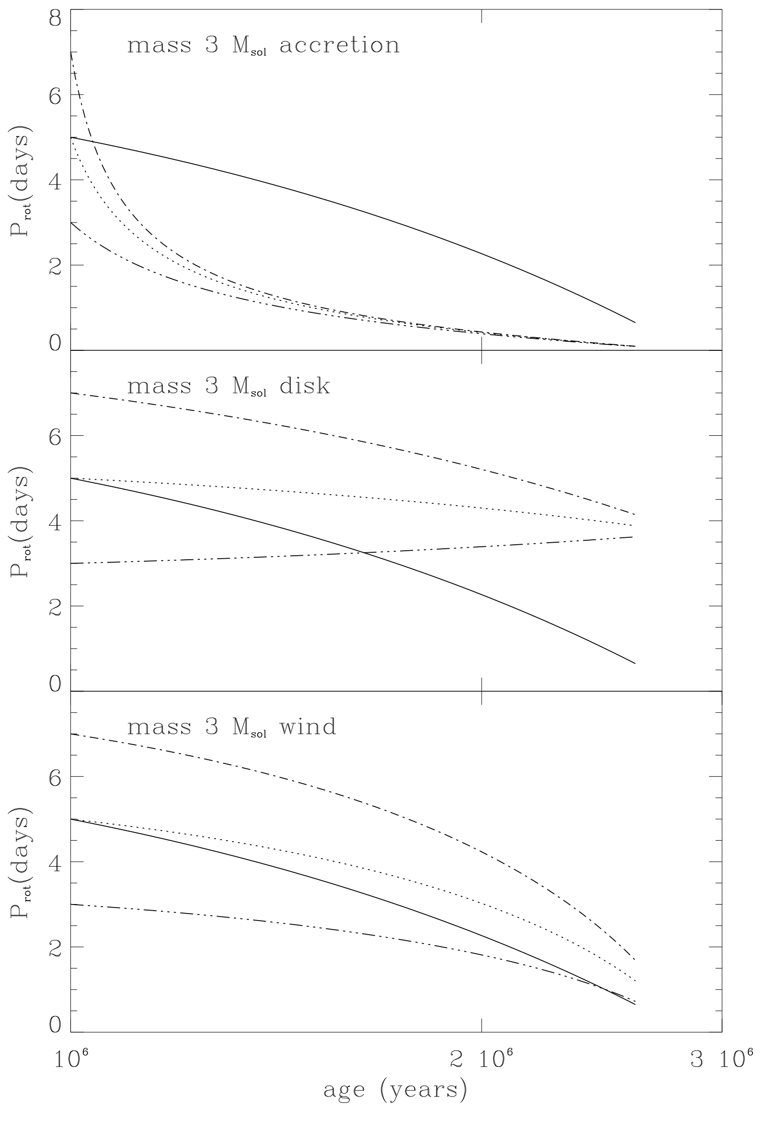

Figure 8: *The results of the individual mechanisms for the interaction of the stellar magnetic field with circumstellar environment in the PMS phase: top — magnetic accretion, middle — disk interaction, bottom — magnetized wind. Solid lines describe in each figure the period variations when the stellar AM is conserved (no interaction) and the other three lines show the evolution of three different initial rotation periods under the influence of the specified mechanism.*

The final equation for the evolution of the stellar angular velocity is

$$
\begin{aligned}
\frac{\mathrm{d}\omega}{\mathrm{d}t} \quad = \quad & \frac{(GM)^{2/3}\dot{M}_{\mathrm{acc}}}{I\omega^{1/3}} - \frac{\phi^2 R^2 \omega^2}{3IGM} \\
& - \frac{\omega R^{7/5}\phi^{4/5}\dot{M}_{\mathrm{wind}}^{3/5}}{3I(2GM)^{1/5}} - \frac{\omega \dot{M}_{\mathrm{acc}} R^2}{I} - \frac{\omega \mathrm{d}I}{I\mathrm{d}t} \, . \qquad (11)
\end{aligned}
$$

The equation was solved with the 4th order Runge-Kutta method. Stellar radii and moments of inertia vary during the PMS phase and their detailed time variability was taken from evolutionary models. Rates of mass accretion and mass loss via a wind were taken from observations, whereas the stellar mass and magnetic flux were treated as free parameters.

Let us first briefly discuss the behavior of Eq. (11). It is nonlinear in ω. As a result a role of each term varies substantially during the evolution of stellar rotation. Newly formed stars are expected to have low to moderate angular velocities because they have large radii. An inspection of Eq. (11) shows that for low ω the first term should dominate, because it is inversely proportional to ω, whereas all the others, directly proportional to ω, are much less important. The star will spin-up quickly due to magnetic accretion. With the increase of ω the role of the first term decreases, whereas the role of the other terms increases, and in particular the second term may become dominant. The stellar moment of inertia decreases in the PMS phase, hence the last term in Eq.(11) is positive. For low or moderate accretion and wind loss rates ω can approach a value for which the second and last terms effectively cancel and a sort of equilibrium rotation period is reached governed by locking of the stellar rotation to the disk. If no disk is present, the wind term causes an exponential increase of the rotation period with the time scale determined by the adopted values of the free parameters. Figure 8 demonstrates how each of the individual mechanisms acts separately. It is seen that all of them tend to produce a uniform rotation, independent of the value of initial period. In other words, magnetic stars lose memory of the initial rotation velocity during their PMS evolution.

The results obtained by Stępień (2000) demonstrated that for a relatively broad range of free parameters the interaction of the stellar magnetic field with the circumstellar environment during the PMS phase of evolution decreases AM of a star with strong magnetic field by a required factor of 3–5. If the magnetized wind exists after the disappearance of the disk, it may slow down a star with a long time of approach to ZAMS to an extremely long rotation period, even of the order of 100 years. This can be achieved only in the case of a lower mass star with a long PMS life time and a strong magnetic field. Figure 9 illustrates this effect. The observations are in agreement with the predictions: very long rotation periods are observed only in stars with masses less than about 2.5 $M_{\odot}$ and strong magnetic fields of several kiloGauss.

Stępień (2002) noted that the mechanism of a rapid spin up of a magnetic star by the magnetic accretion may be effective in producing rapidly rotating Be stars. According to the results of this paper Be stars should possess weak to moderate magnetic fields and they should be, on average, more massive than BpAp magnetic stars. A recently reported detection of the surface magnetic fields with the intensity of a few hundred Gauss on two Be stars (Henrichs et al. 2000, Donati et al. 2001, Henrichs 2004) is in a full agreement with the predictions.

A recent analysis by Landstreet & Mathys (2000) of the extensive set of measurements of magnetic fields for a number of BpAp magnetic stars resulted in an unexpected conclusion that almost all the magnetic stars with rotation periods longer than about a month have the magnetic and rotational axes roughly aligned, unlike the short period magnetic stars in which the inclination of one axis with respect to the other is usually large. The mechanism which can explain this correlation within the model of spin-down of magnetic stars in the PMS phase has been suggested by Stępień & Landstreet (2002). According to the spin-down model very low rotation rates can be achieved when the accretion disk disappears early enough before the star reaches ZAMS. Stępień & Landstreet (2002) argue that the dipole field with the axis perpendicular to the plane of the disk (i. e. aligned with the rotational axis) should be more effective in dispersing the disk matter than in the case of the field with the axis lying close to the disk plane (i e. strongly inclined to the rotational axis). As a result, aligned rotators have a greater chance to get rid of the disk early enough that the magnetized wind slows their rotation down to very low values.

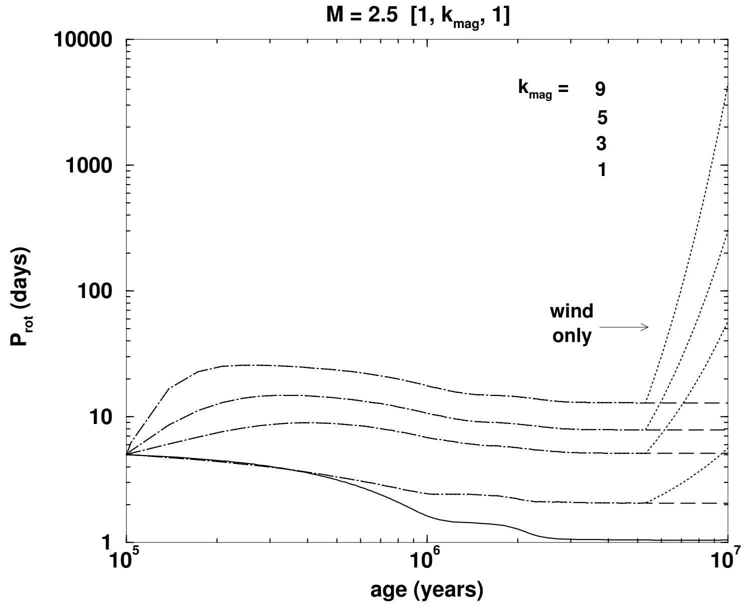

Figure 9: *The evolution of the rotation period of a 2.5 $M_\odot$ star in the PMS phase. A solid line describes the period variations when the stellar AM is conserved. Dot-dashed, then dashed lines show period evolution under an influence of all three torques persisting till ZAMS. Different curves correspond to different intensities of the surface magnetic field, from 1 to 9 kG (bottom to top). Accretion rate and the wind mass loss rate were equal to $10^{-8} M_\odot$/year and were not varied. Dotted lines illustrate a rapid increase of the rotation period when the disk is switched off after a half of the stellar PMS life and only magnetized wind operates.*

5 Beyond the Main Sequence

Large-scale ordered magnetic fields have been unambiguously detected in many BpAp stars lying on, or very close to the MS. Similar fields have also been detected in several white dwarfs (Landstreet 1992). In fact, a comparison of the statistics of magnetic BpAp stars with the statistics of magnetic white dwarfs suggests that the former stars can be progenitors of the latter ones. Unfortunately, we know very little about the behavior of the magnetic field during the intermediate evolutionary phases. Detection of the ordered field has been reported for a number of giant stars, including those of F, G and K spectral type (see e. g. Bychkov et al. 2003). Unfortunately, these detections remain controversial. The derived values of the magnetic field are comparable with the measurement errors, in most cases very few measurements have been obtained and other observers usually do not confirm the detection. Two main problems restrict a reliable analysis of these stars: firstly, the population of the Hertzsprung gap is much more sparse than of the MS, hence, correspondingly, less magnetic giants are expected to be found and secondly, the typical intensities of the surface magnetic field of such stars should be 1–2 orders of magnitude weaker than in MS stars, due to evolutionary expansion of the stars. To be able to follow the evolution of the magnetic field beyond the MS, we must wait for more accurate and effective techniques of measurements.

Even if the large-scale magnetic field survives the early phases of the post-MS evolution, it cannot preserve its regularity when the surface temperature drops enough for the development of the convection zone. The magnetic field will assume a complicated structure, typical of the fields observed on the solar type stars. Rotating stars with subphotospheric convection zones are expected to generate magnetic fields via a dynamo mechanism. The field emerges subsequently above the stellar surface and manifests itself here by producing stellar activity phenomena. The intensity of the observed field increases with the increase of the rotation rate (Stępień 1994b, Saar 1996). Is it possible to distinguish the primordial magnetic field existing in a cool giant possessing a convection zone from the dynamo generated field? It seems that in some cases the answer can be positive. The level of magnetic activity of cool stars increases with the rotation rate. The most active giants are of RS CVn and FK Com type. Their rotation periods are of the order of one or a few weeks. Giants with rotation periods of the order of at least several months show a very low level of coronal and chromospheric activity (Strassmeier et al. 1994, Stępień 1994b). There exists, however, one giant, HR 1362, which shows photometric variability typical of very active, magnetically spotted star. The period of this variability is unusually long for this kind of variations. It is equal to 307 days (Strassmeier et al. 1999). The observed value of $v \sin i$ of HR 1362 is in agreement with an assumption that this period corresponds to the rotation period. In accord with the photometric variations is a very high level of activity observed for HR 1362 (Strassmeier et al. 1994, Stępień 1994b, Strassmeier et al. 1999). Such levels are typical of stars with rotation periods an order of magnitude shorter than present in this star. The properties of HR 1362 can be explained assuming that this star possesses a primordial magnetic field which is much stronger than dynamo generated. Assuming a conservation of AM and the magnetic flux, one can evolve the star backwards, to the MS. The possible progenitor of HR 1362 on the MS had a rotation period of about a week and a several kiloGauss field. It was similar to 53 Cam — a well known BpAp magnetic star. More observations are necessary to trace the fate of the magnetic fields of BpAp stars when they leave MS and evolve to the giant region.

6 Conclusions

The present discussion suggests that the presence of the magnetic field is the sole cause of all the observed properties of BpAp magnetic stars. So far we have not yet identified processes deciding upon the presence or absence of primordial magnetic field and its strength in newly formed stars. We *assume* therefore that some stars are born with a strong magnetic field.

The interaction of the fossil field with the circumstellar matter in the PMS phase of evolution can explain the separation of the initial, uniform distribution of AM of the freshly born stars into three different distributions on the MS corresponding to rapidly rotating Be stars, normal stars and slowly rotating BpAp stars. The mechanism can also explain the observed properties of extremely slowly rotating BpAp stars.

The observations analyzed in this paper indicate that variability is present among BpAp stars lying everywhere between ZAMS and TAMS. A similar conclusion was reached from the analysis of stars with measured magnetic fields. No indication for a variability of the rotation rate or the strength of the magnetic field during the evolution of a star across the MS could be found.

There exist indications that the fossil magnetic fields survive the evolutionary phases beyond the MS, possibly until the star reaches the white dwarf stage. It is to be determined what role they play during all the consecutive evolutionary stages of magnetic stars.

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