Magnetic Ap stars in the H-R diagram[1]

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ABSTRACT

The evolutionary state of magnetic Ap stars is rediscussed using the recently released Hipparcos data. The distribution of the magnetic Ap stars of mass below $3M_\odot$ in the H-R diagram differs from that of the normal stars in the same temperature range at a high level of significance. Magnetic stars are concentrated towards the centre of the main-sequence band. This is shown in two forms of the H-R diagram: one where $\log L$ is plotted against $\log T_{\rm eff}$, and a version more directly tied to the observed quantities, showing the Astrometry-Based Luminosity (Arenou & Luri 1999) against the $(B2 - G)_0$ index of Geneva photometry. In particular, it is found that magnetic fields appear only in stars that have already completed at least approximately 30% of their main-sequence lifetime. No clear picture emerges as to the possible evolution of the magnetic field across the main sequence. Hints of some (loose) relations between magnetic field strength and other stellar parameters are found: stars with shorter periods tend to have stronger fields, as do higher temperature and higher mass stars. A marginal trend of the magnetic flux to be lower in slower rotating stars may possibly be seen as suggesting a dynamo origin for the field. No correlation between the rotation period and the fraction of the main-sequence lifetime completed is observed, indicating that the slow rotation in those stars must already have been achieved before they become observably magnetic.

Subject headings: stars: chemically peculiar — stars: evolution — stars: fundamental parameters — stars: magnetic fields

1. Introduction

Although it is well known that Ap and Bp stars belong to the main sequence (Gomez et al. 1998), the exact evolutionary state of those which have a measured magnetic field has remained somewhat controversial. Studies aimed at establishing it have so far yielded contradictory results. The discussions presented in those previous works were based on the consideration of the membership of magnetic stars in open clusters or associations, of their membership in binary systems, or of indirect arguments inferred from the assumption of a rigid rotator geometry. The debate has been going on until recently, and mutually inconsistent arguments have been put forward to support the view that magnetic Ap and Bp stars are distributed uniformly across the width of the main sequence (North 1993; Wade 1997), or alternatively that they are near the end of their main sequence life (Hubrig & Schwan 1991; Hubrig & Mathys 1994; Wade et al. 1996).

This paper presents a new study of the evolutionary state of Ap and Bp stars using the recently released Hipparcos data (ESA 1997). From the consideration of the latter, it becomes possible to determine the evolutionary state of magnetic stars with more reliability than before. From the resulting knowledge of the positions of Ap and Bp stars in the H-R diagram, the evolution of the magnetic field across the main sequence as well as possible correlations between evolutionary state and other stellar properties are discussed. Possible differences of evolutionary state between magnetic and non-magnetic stars are also investigated.

2. Basic data

2.1. The sample of magnetic stars

For the present study, Hipparcos parallaxes and photometric data have been compiled exclusively for two groups of stars at the surface of which strong magnetic fields have been definitely detected. The first group consists of stars showing spectral lines resolved into their magnetically split components when observed in unpolarized light. 42 such stars are presently known (Mathys et al. 1997). For those stars, accurate measurements of the mean magnetic field modulus ($\langle H \rangle$) are available. The second group includes 14 Ap and Bp stars whose mean quadratic magnetic field $(\langle H^2 \rangle + \langle H_z^2 \rangle)^{1/2}$ has been diagnosed through application of the moment technique (Mathys 1988, 1995; Mathys & Hubrig 1997), that is, from the consideration of the differential magnetic broadening of spectral lines from spectra taken in unpolarized light. Quadratic field determinations are more difficult, considerably less accurate, and more dependent on the geometry of the observation than field modulus measurements (for details, see the cited references).

Accurate Hipparcos parallaxes ($\sigma(\pi)/\pi < 0.2$) have been obtained for 23 stars with resolved magnetically split lines, and for 10 stars with quadratic magnetic field data. Thus the whole sample under study contains 33 magnetic stars.

The basic data for the two samples of magnetic stars are summarized in Tables 1 and 2. The columns are, in order: the HD number of the star, another identifier, the absolute visual magnitude, the mass (in solar masses), the logarithm of the effective temperature (in Kelvin), the logarithm of the luminosity (relative to the Sun), the logarithm of the surface gravity, the radius (in solar radii), the distance d, the relative uncertainty of the parallax, the Lutz-Kelker correction (LK), the fraction f of its main-sequence life completed by the star, interpolated from theoretical evolutionary tracks (Schaller et al. 1992), the magnetic field strength H, and the rotation period P (or a lower limit of it). The latter is given only when a reliable value is available, from the references quoted in Mathys & Hubrig (1997), Mathys et al. (1997), and Mathys (1991).

The determination of the effective temperatures is discussed in Appendix A.

The interstellar reddening was taken into account in some stars farther away than 100 pc, either from the reddening-free parameters X and Y of Geneva photometry and Cramer's (1982) intrinsic $[UBV]$ colours (for the hotter stars), or from the maps of interstellar absorption of Lucke (1978).

The luminosity of the stars has been obtained by taking into account the bolometric correction measured by Lanz (1984): the bolometric corrections BC listed in his Table 6, where the spectral type was replaced by the Geneva $(B2-G)_0$ index, was considered valid for normal stars, and the correction δ_{BC} plotted in his Fig. 4a was added to take the peculiarity into account. For Ap stars cooler than A0, which are not considered by Lanz, we assumed that BC is the same as for normal stars (this is not a crucial hypothesis since BC is relatively small in this range of spectral types) and adopted the standard bolometric correction of Schmidt-Kaler (1982). In addition, a version of the Lutz-Kelker (hereafter LK) correction (Lutz & Kelker 1973) modified to take into account a stellar density varying as a function of the distance from the galactic plane was applied. However, since the opportunity of applying this correction to individual stars seems to remain a matter of debate (see e.g. Arenou & Luri 1999), we also present the H-R diagram in another form where no LK correction is done.

The stellar masses are obtained by interpolation in the evolutionary tracks of Schaller et al. (1992) for a solar metallicity $Z = 0.018$, as explained in North et al. (1997). Indeed, all stars stars were assumed to have a solar *global* metallicity, even though their atmospheric abundances are far from solar, and their evolution was assumed to be unaffected by their peculiar nature (anomalous atmospheric abundances, large-scale magnetic fields). The evolutionary tracks were assumed to be continuous, even at the end of the core-hydrogen burning phase, which may imply a small bias on the mass near the upper envelope of the main sequence.

For the stars HD 110066, HD 116114, HD 137909, and HD 153882, there is an ambiguity of the order of 5% on the interpolated mass, because of the proximity of the terminal-age main sequence (TAMS) and of the possibility that they are making the loop back to the blue.

The radii have been computed from the luminosity and effective temperature from the definition of the latter. Finally, the surface gravity was obtained from mass and radius through its fundamental definition. The errors on $T_{\rm eff}$ and L determinations were linearized and carefully propagated to errors on mass, radius and $\log g$, taking into account the slope of the evolutionary tracks.

The quantity H appearing in Tables 1 and 2 to characterize the magnetic field strength requires a few words of explanation. For the stars with magnetically resolved lines, the value that is given is the average of the measurements of the mean magnetic field modulus, defined as explained in Sect. 4 of Mathys et al. (1997). The use of this single value to characterize the field strength was also justified in Sect. 7.1 of the same reference. For the stars whose spectral lines are not resolved into their magnetically split components, the field modulus cannot be determined. Instead, we take the mean quadratic magnetic field as the quantity most representative of the field strength. As explained by Mathys & Hubrig (1997), the quadratic field is at least equal and generally greater than the field modulus. A typical value of the ratio between the two quantities is 1.35. This value is the mean of the individual values of the ratio between the quadratic field and the field modulus published for stars with resolved magnetically split lines by Mathys & Hubrig (1997). Accordingly, the field strengths H appearing in Table 2 are averages (in the same sense as above) of the measurements of the quadratic field, divided by 1.35. In this way, a more meaningful comparison can be done between the field strengths for stars with and without magnetically resolved lines. Of course, the validity of this approach is limited by the dispersion in the individual ratios of the quadratic field to the field modulus, which for the sample of Mathys & Hubrig (1997) can be quantified by the value of the standard deviation about their mean, 0.24.

2.2. The comparison sample of normal B and A stars

In order to provide a reference for comparison of the positions of strongly magnetic Ap and Bp stars in the H-R diagram with those of normal main sequence stars, we built a sample consisting of all normal, single main-sequence stars of spectral types B7 to F2 from the Bright Star Catalogue (hereafter BSC, Hoffleit & Jaschek 1982) for which accurate Hipparcos parallaxes are available. It contains a total of 416 stars at distances below 100 pc ($\pi > 10$ mas). These stars are single in the sense that all known spectroscopic binaries in the BSC have been discarded, as well as those having a variable radial velocity.

In our analysis of the data of both samples, we applied the appropriate corrections for interstellar absorption and reddening, as well as the Lutz-Kelker (LK) correction (Lutz & Kelker 1973). The LK correction has been made taking into account a stellar density varying as a function of the galactic latitude. For a more detailed explanation on how this correction has been applied, see North (1998a, 1998b). In the case of Ap stars, we have also applied a correction for duplicity, which generally amounted to 0.2 magnitude for SB1 binaries and to 0.75 magnitude for SB2 systems or close visual doubles with $\Delta m \sim 0.0$

like HD 81009. In the case of the SB2 system HD 55719, where the mass ratio q is 0.75 and the Ap star is the secondary, we adopted a correction as large as 1.95 mag from the informations published by Bonsack (1976).

3. Analysis and results

The distribution of the magnetic Ap and Bp stars in the H-R diagram is shown in Fig. 1. The filled symbols correspond to the stars with magnetically resolved lines, with squares and circles distinguishing stars with magnetic field moduli above and below 6 kG, respectively. The positions of the stars with known mean quadratic fields are indicated by open circles. One star, HD 137509, which is marked by an open square, has a mean quadratic field reaching 37 kG. It is one of the strongest magnetic fields known among Ap and Bp stars.

It is quite obvious from Fig. 1 that magnetic stars are only rarely found close to either the zero-age (ZAMS) or terminal-age sequences (TAMS). By contrast, the normal B7–F2 stars fill the whole width of the main sequence band, with some concentration towards the ZAMS (Fig. 2), in agreement with expectations from evolutionary models for normal stars.

Figure 3 shows the cumulative distributions of $\log g$ for the complete sample of magnetic stars (dashed line), for those with magnetically resolved lines only (thick line), and for normal stars (thin line).

A Kolmogorov-Smirnov test applied between the distributions of the normal stars and of each group of magnetic stars shows that the distribution of the values of $\log g$ for the sample of stars with magnetically resolved lines differs from the distribution for non-magnetic stars at a significance level of 99.7%. For the whole sample of magnetic stars, the difference with the non-magnetic stars is significant at the 95.2% level.

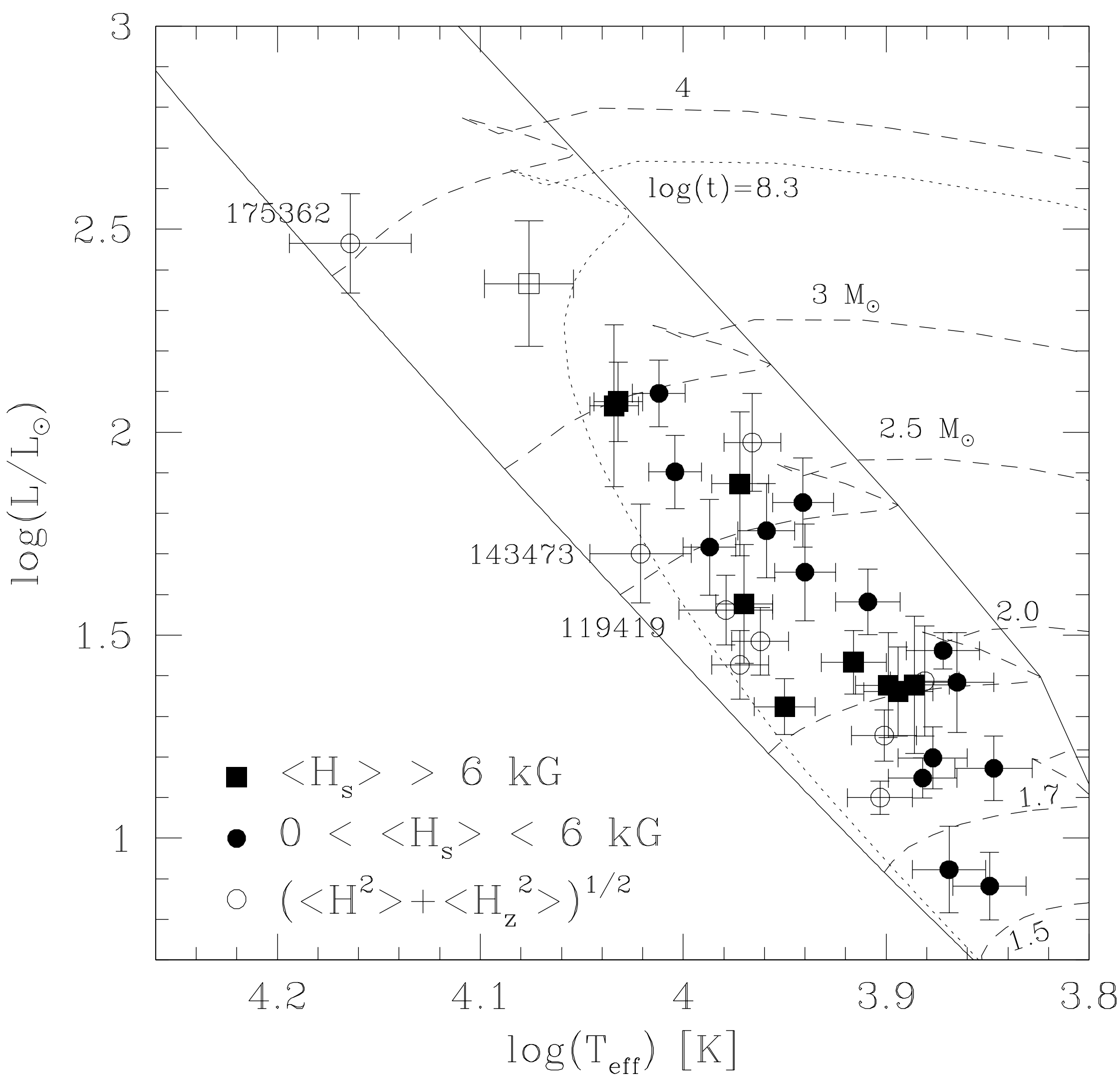

Fig. 1.— H-R diagram for Ap stars with resolved magnetically split lines (*filled symbols*) and for Ap stars whose mean quadratic magnetic field has been determined (*open symbols*). *Filled squares* correspond to stars with a mean magnetic field modulus larger than 6 kG. The *open square* represents HD 137509, which has an extremely strong field. The other hot stars whose effective temperature has not been derived from photometry (see Appendix A) are identified in the figure. The magnetic field strengths considered in this figure are averages over the phases; in the case of the quadratic field, they are furthermore divided by 1.35 (see text for details)

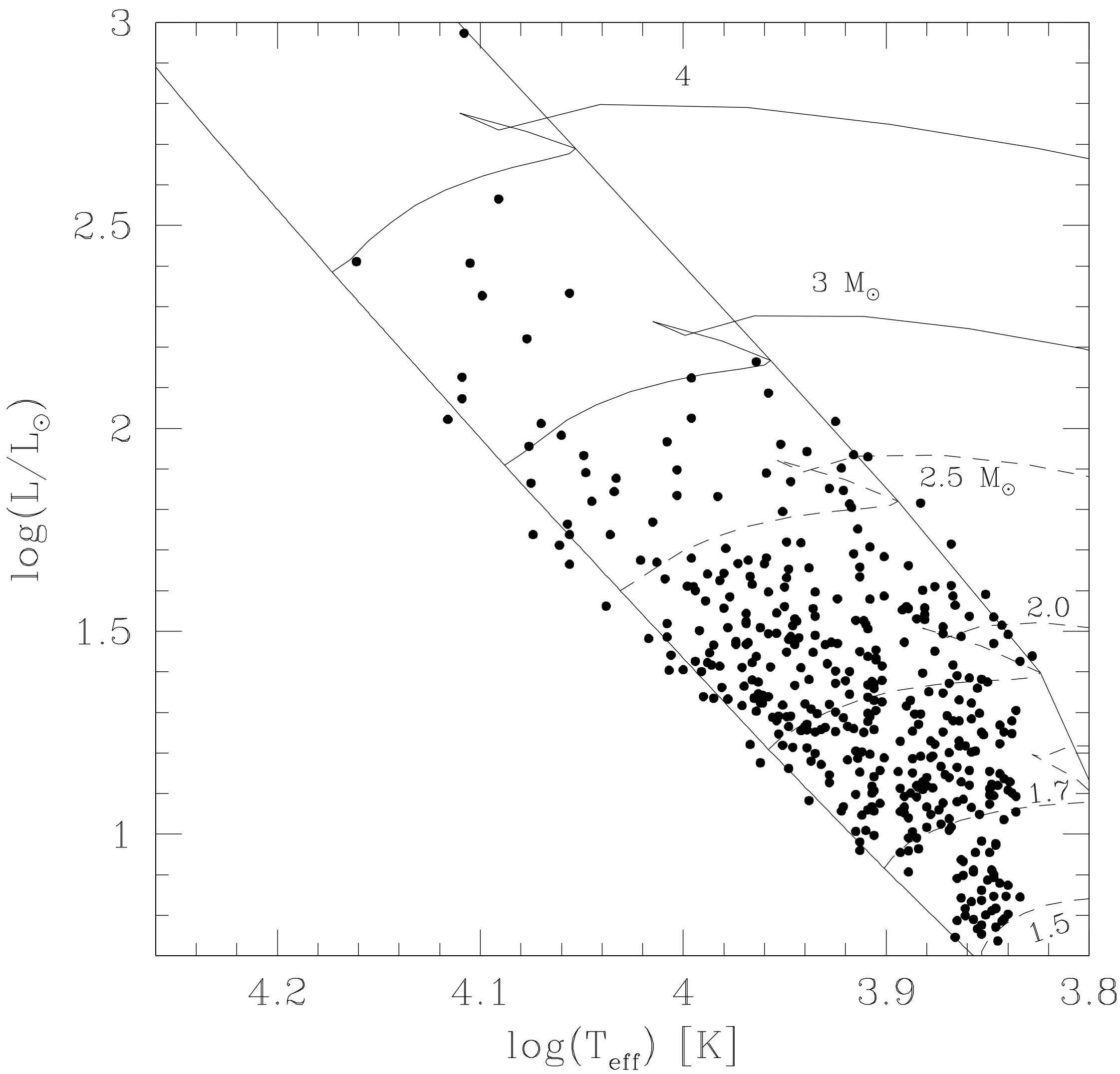

Fig. 2.— H-R diagram for normal, dwarf B7–F2 stars closer than 100 pc. The error bars are not represented, but the relative precision on the parallax is generally better than 10%

If the LK correction is not applied, the KS test then gives significance levels at the 98.4% and 88.7% respectively.

One might consider the case of HD 55719 as uncertain, since it is the secondary in an SB2 system and the correction of the V magnitude for duplicity is very large. We have computed the KS test also without this star, and obtain even higher significance levels: if the LK correction is applied, they are 99.96% for the stars with magnetically resolved lines and 99.0% for the whole sample. Without LK correction, the significance levels become 99.4% and 92.3% respectively.

A 2×2 contingency table analysis (Press et al. 1993) comparing the number of stars with $\log g < 4.1$ and with $\log g > 4.1$ among magnetic stars and normal stars indicates a difference between magnetic and non-magnetic stars at a significance level of 99.7%.

The probability density versus $\log g$ is shown for the three samples in Fig. 4. The most conspicuous features of these histograms are the low percentage of magnetic stars with large values of $\log g$, and the large fraction of magnetic stars with $\log g$ values between 3.7 and 3.9.

In order to show that the effect discussed above is not an artifact of the treatment of the observational data which leads to the $\log L$ vs $\log T_{\rm eff}$ H-R diagram, we also show a version of the H-R diagram which is more directly tied to observed quantities (Fig. 5). It shows what Arenou & Luri (1999) call the Astrometry-Based Luminosity (ABL) $a_{\rm V}$ vs. the $(B2-G)_0$ index. $a_{\rm V}$ is defined by

$$a_{\rm V} = 10^{0.2\,M_V} = \pi 10^{0.2 m_V - 2} \qquad (1)$$

where the parallax π is expressed in mas, and $m_{\rm V}$ is corrected for the visual absorption.

Since the dominant cause of error on $a_{\rm V}$ lies in the parallax (the error on the apparent magnitude may be considered as negligible), the error bars on $a_{\rm V}$ are symmetrical, while

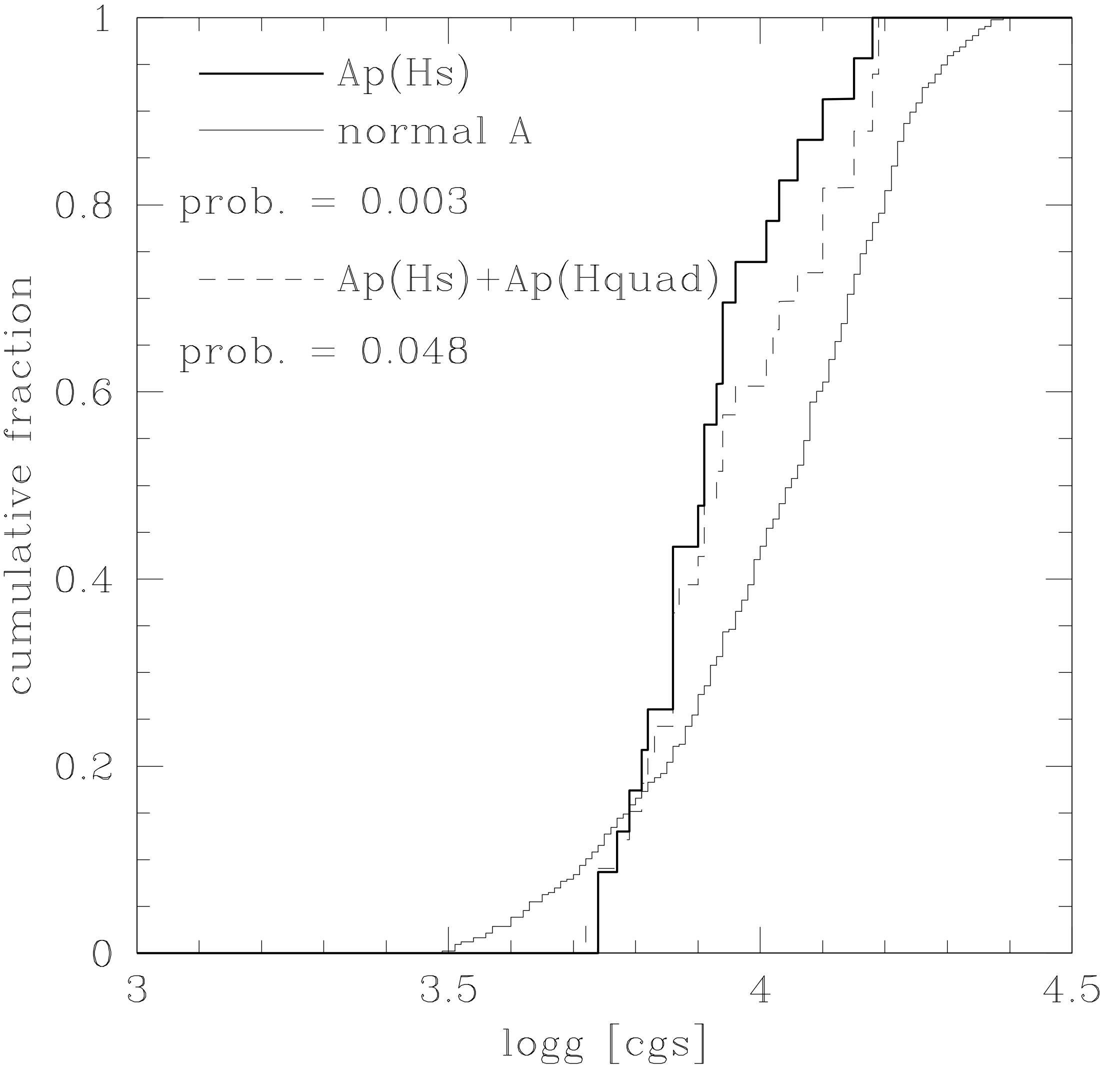

Fig. 3.— Cumulative distribution of $\log g$ for the Ap stars with resolved magnetically split lines (*thick line*), for all the Ap stars for which determinations of either the mean magnetic field modulus or the mean quadratic magnetic field are available (*dashed line*), and for normal B7–F2 main sequence stars (*thin line*)

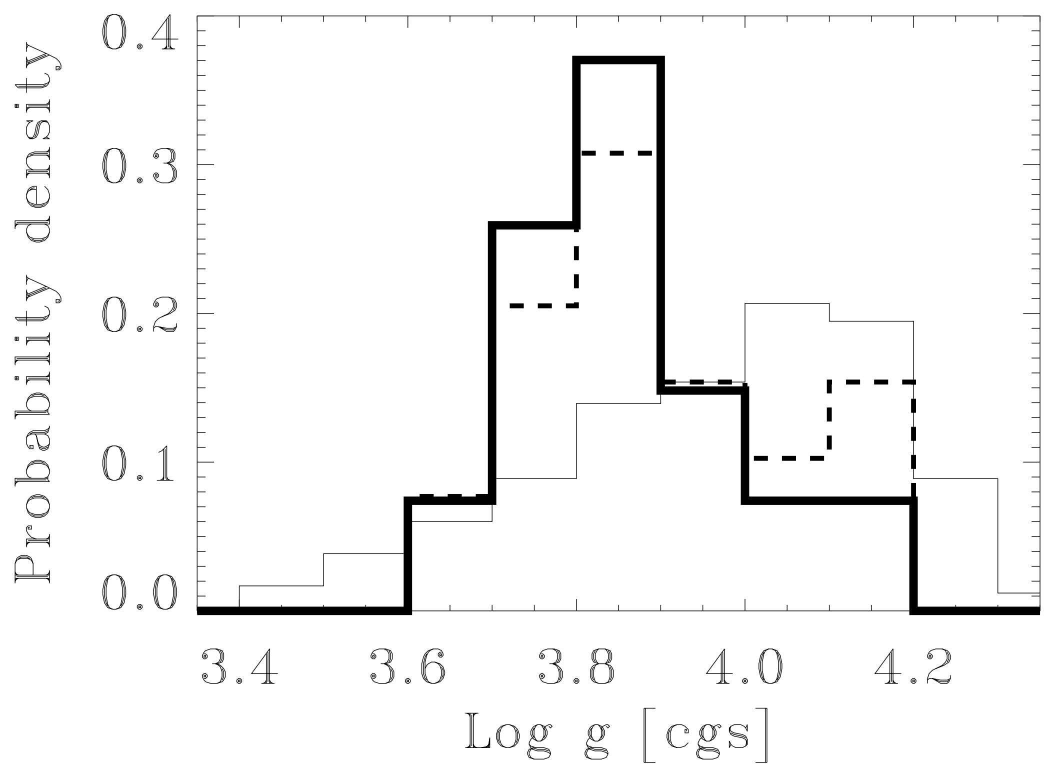

Fig. 4.— Probability density vs. $\log g$ for the Ap stars with resolved magnetically split lines (*thick line*), for the whole sample of magnetic Ap stars (*dashed line*), and for normal B7–F2 main sequence stars (*thin line*)

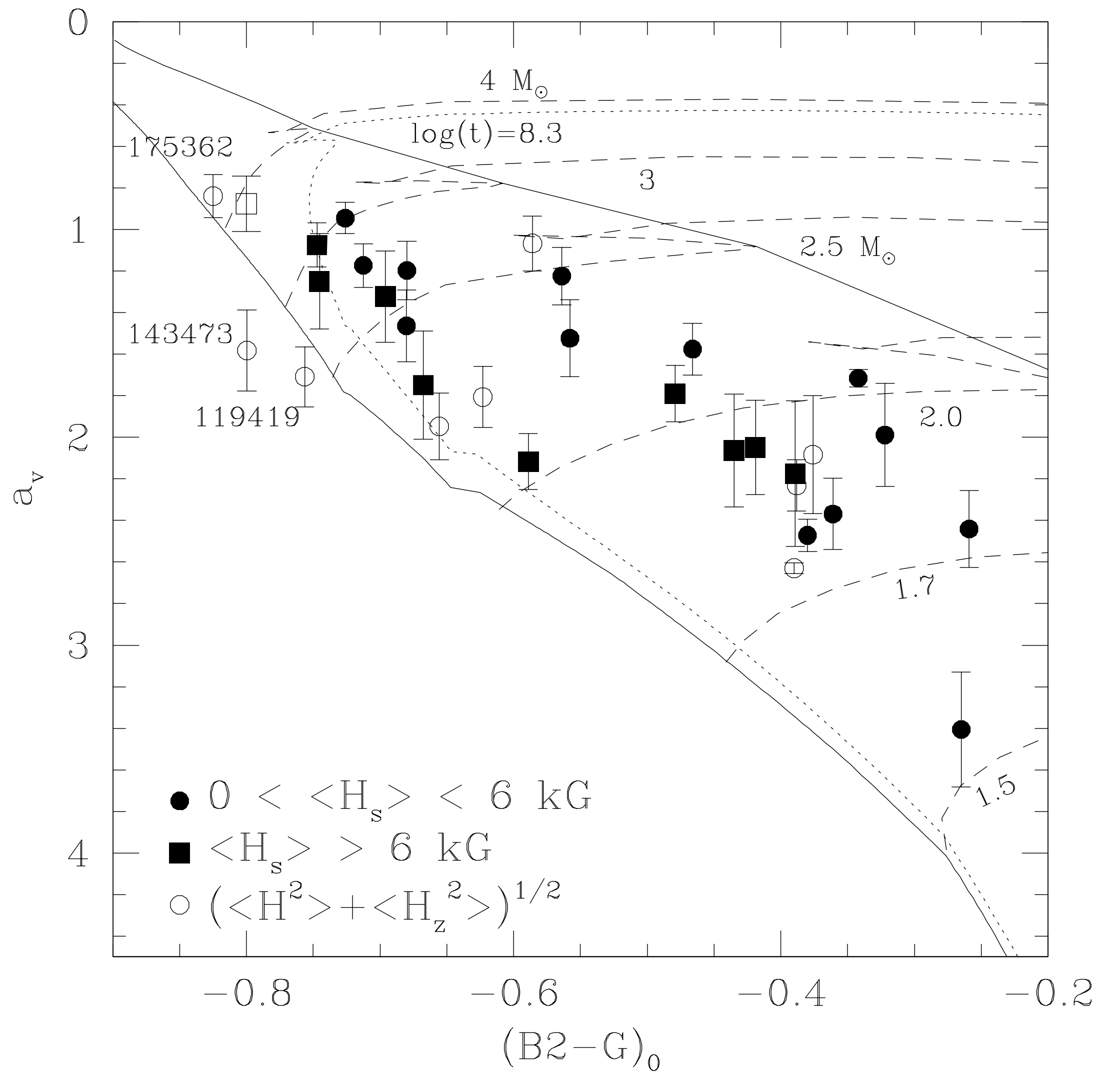

Fig. 5.— Alternative H-R diagram, showing the Astrometry-Based Luminosity a_V vs. the $(B2-G)_0$ index for Ap stars with resolved magnetically split lines (*filled symbols*) and for Ap stars whose mean quadratic magnetic field has been determined (*open symbols*). *Filled squares* correspond to stars with a mean magnetic field modulus larger than 6 kG. The *open square* represents HD 137509, which has an extremely strong field. The other hot stars whose effective temperature has not been derived from photometry (see Appendix A) are identified in the figure. The magnetic field strengths considered in this figure are averages over the phases; in the case of the quadratic field, they are furthermore divided by 1.35 (see text for details)

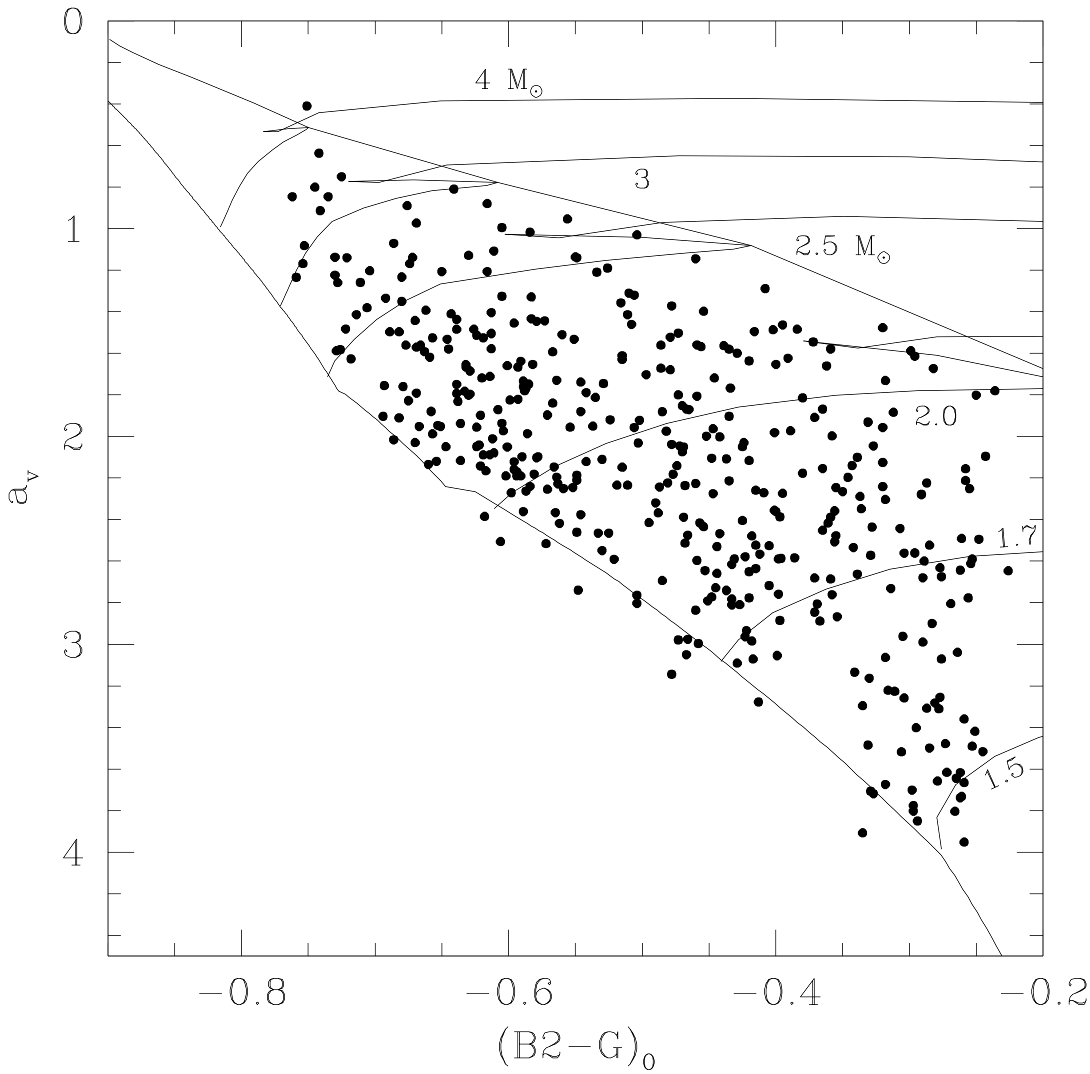

Fig. 6.— Alternative H-R diagram, showing the Astrometry-Based Luminosity (ABL) a_V vs. the $(B2-G)_0$ index for normal, dwarf B7–F2 stars closer than 100 pc. The error bars are not represented, but the relative precision on the parallax is generally better than 10%

they are not so on $\log L$. This removes part of the motivation for applying the LK correction, which is not considered here. Fig. 6 shows the same diagram for the normal stars. The comparison of both figures shows clearly that all Ap stars with magnetically resolved lines lie at some distance from the ZAMS. The same is true for most Ap stars with quadratic field data even though two of them (HD 143473 and HD 119419) lie under the ZAMS. These are two of the stars for which the effective temperatures have been determined from spectroscopy rather than photometry, due to the perceived unreliability of the photometric $T_{\rm eff}$ determinations for them (see Apendix A). Their interstellar reddening was estimated from their X, Y parameters in the Geneva photometry. The reddening estimated in this way is very high for HD 143473 ($A_{\rm V} = 0.95$), while it is negligible ($A_{\rm V} = 0.03$) for HD 119419. In both cases, their $B2 - G$ index does not seem to represent well their effective temperature, but it is important to remember that both stars are extreme photometric Bp stars, with a photometric peculiarity $\Delta(V1 - G) = 0.048$ and 0.056 respectively (Hauck & North 1981).

Note that reddening effects are very small in our context in both forms of the H-R diagram: the reddening line is almost parallel to the ZAMS, so that inaccurate reddening estimation will not affect our conclusions.

Knowing the positions of the magnetic stars in the H-R diagram, it becomes possible to probe the evolution of the magnetic field strength across the main sequence. In Fig. 7, the magnetic field strength H (as given in Tables 1 and 2) is plotted against the age of the stars expressed as a fraction of their total main sequence lifetime. It is clearly seen that magnetic fields become observable in most stars only after they have already completed a significant fraction of their life on the main sequence. Almost one third of the stars of the sample, with derived ages corresponding to 80% and more of the total time to be spent on the main sequence, have almost finished the main sequence part of their evolution. The lowest fraction of main sequence evolution completed, 29%, is shown by the He variable Bp star HD 175362.

In summary, the results presented above support the view that magnetic Ap stars are observed only in a restricted range of evolutionary states. This is in good agreement with the conclusion of Hubrig & Mathys (1994), who had suggested that magnetic Ap stars may be near the end of their main sequence life. From the present study, this conclusion can be regarded as well established only for masses below $3M_\odot$, since all the magnetic stars of the sample considered here but two have masses below that limit. (As a matter of fact, there are some hints that higher-mass magnetic Bp stars may well occupy the whole main sequence width.)

4. Discussion

The sample of magnetic stars studied in this paper suffers from a selection effect, and it is important to assess to which extent this may bias the conclusion drawn about their evolutionary status. Namely, this sample contains a high fraction (about 2/3) of stars with rotation periods longer than 10 days: this fraction is *not* representative of Ap stars in general (the majority of the periods of the latter fall between 2 and 4 days, and some are as short as 0.5 day; see North 1984). However, the present sample also contains at least 12 stars with periods comprised between 2.5 and 10 days. Out of these, 7 at least have periods shorter than 5 days. Two more stars, HD 143473 and HD 165474, whose periods have not been definitely determined, almost certainly belong to this group too. These numbers are sufficient to ensure that any large difference of evolutionary state between the short period stars of the sample and those with slower rotation would show through: yet, we find no hint of such a difference in this study. In Fig. 7, different symbols are used to distinguish stars with rotation periods in three different ranges: less than 10 days (triangles), between

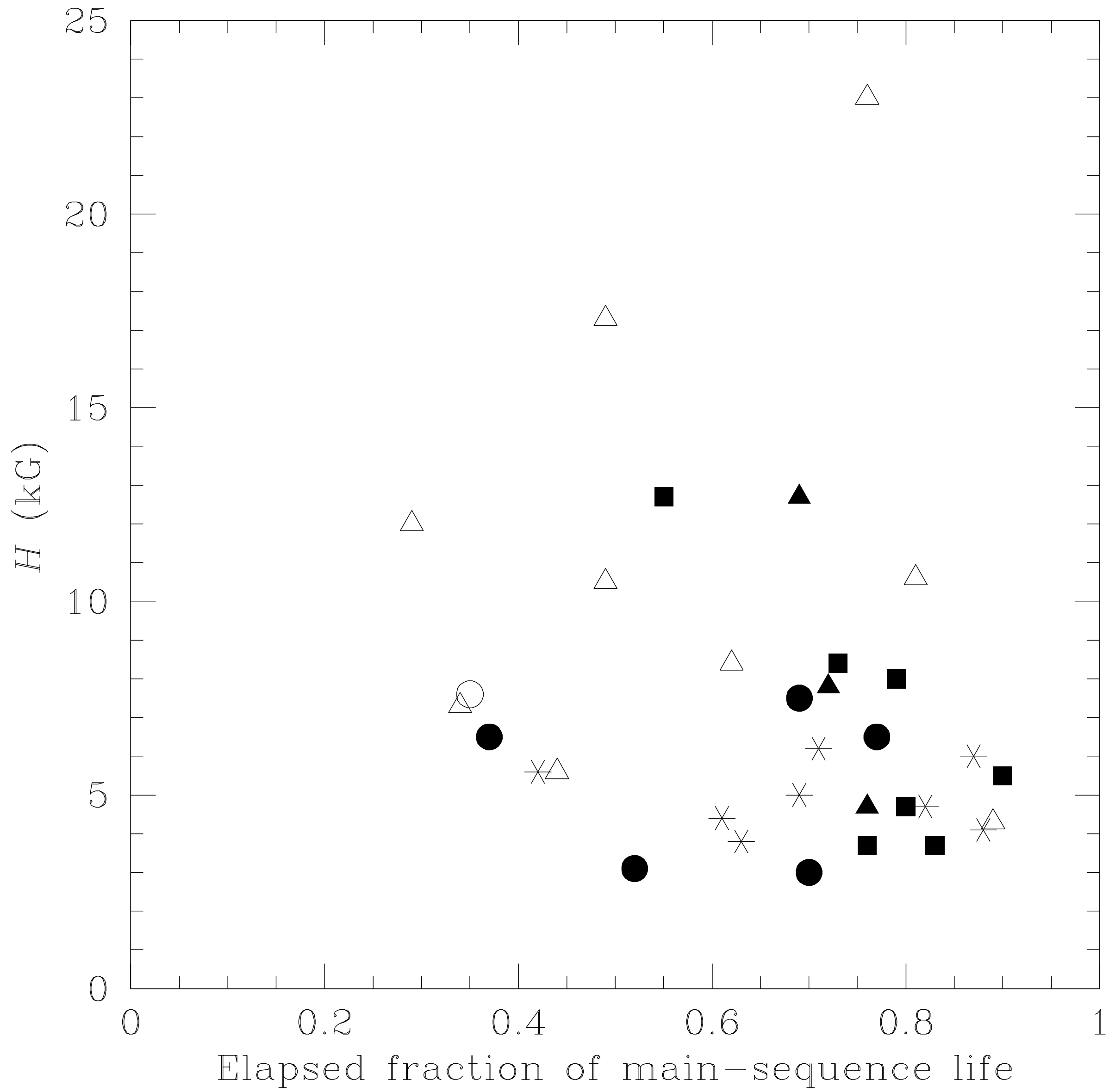

Fig. 7.— Magnetic field strength as a function of the completed fraction of main-sequence life for stars with magnetically resolved lines (*filled symbols and asterisks*) and for stars for which mean quadratic magnetic field determinations are available (*open symbols*). *Triangles* correspond to stars with rotation periods shorter than 10 days, *squares* to periods between 10 and 1000 days, *asterisks* to periods longer than 1000 days, and *circles* to cases where the period has not been determined yet

10 and 1000 days (squares), and longer than 1000 days (asterisks); circles have been used to identify stars with periods still unknown. From the consideration of this figure, the age distribution of the stars with rotation periods shorter than 10 days does not appear to differ from that of the stars with longer periods. On the other hand, the studied sample contains no star with periods between 0.5 and 2.5 days: most techniques of magnetic field determinations cannot be applied to such fast rotators, so that data are currently scarce to study their evolutionary status. Although we cannot rule out the possibility that they might have a different distribution in the H-R diagram than the slower rotating stars, there is no indication suggesting the existence of such a difference. Finally, we also note that, although rotation periods are expected to increase during main sequence lifetime as a result of conservation of the angular momentum (see also below), so that all other things being equal, less evolved stars should rotate faster, this accounts for period changes of much less than one order of magnitude, while the periods of the stars considered here span 4 decades. To summarize, there is no indication that the fact that the distribution of the periods of the stars of the magnetic sample is more skewed towards large values than for Ap stars in general can be held responsible for a significant bias in the distribution of these stars in the H-R diagram.

By contrast, Fig. 7 shows clearly that the strongest fields are found only in the fast-rotating stars; all the stars with rotation periods exceeding 1000 days have fields below 6.5 kG. A similar result had already been obtained by Mathys et al. (1997) from the consideration of the stars with magnetically resolved lines only.

The absence of magnetic Ap stars close to the ZAMS most probably indicates that the appearance of strong magnetic fields is connected to a particular phase of main sequence evolution. Another interpretation might be that there exist indeed A stars which do have magnetic fields from the beginning of their main sequence life, but that these fields have

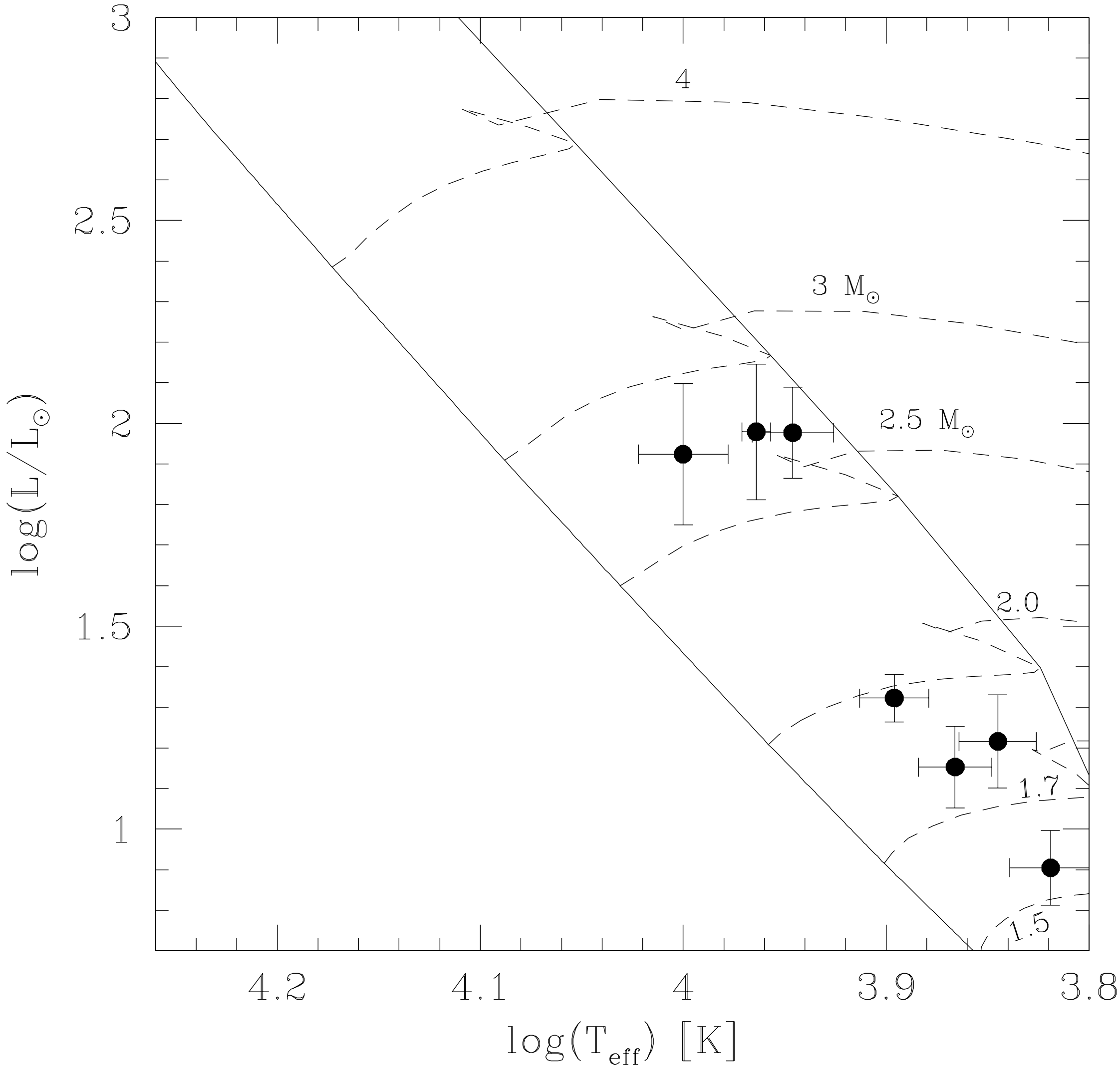

Fig. 8.— H-R diagram for sharp-lined Ap stars showing no evidence of a magnetic field. The mean field moduli of these stars are likely lower than about 1 kG

not been detected, possibly because the stars harbouring them have not yet developed the extreme chemical peculiarities that earmark them as prime candidates for field searches. In relation with this possibility, one can wonder what is the evolutionary state of the chemically peculiar A and B stars with no or very weak magnetic fields. As a by-product of their study, Mathys et al. (1997) have identified a number of such stars, and they argue that their mean field moduli must be lower than about 1 kG.[2] The few of those stars for which good Hipparcos parallaxes are available are represented in Fig. 8. This figure shows that their distribution in the H-R diagram is roughly the same as that of the strongly magnetic stars, yielding some support to the view that chemical peculiarities only become observable after the stars have completed a sufficient fraction of their main sequence evolution. However, the statistical significance of this result is limited, given the small size of the sample on which it is based. By contrast, although searches for magnetic fields have concentrated primarily on Ap (and Bp) stars, there has been a significant number of attempts to detect such fields in normal main-sequence A stars, which have not provided any hint of the presence of fields at any stage during their main-sequence evolution, in spite of the sometimes quite low detection limit achieved.

Thus, in the absence of evidence to the contrary, we shall henceforth assume that the results obtained in the previous section indicate that magnetic fields in A stars appear at a certain stage of their main-sequence evolution. A possible interpretation of this might be that magnetic stars represent a transitory phase in the evolution of A stars across the main sequence. However, since the non-magnetic stars occupy the whole width of the main

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[2]Upper limits to the longitudinal field are more frequently found in the literature but are of little relevance in the present context, since longitudinal fields may escape detection even in strongly magnetic stars as a result of the compensation of fields of opposite polarities from different parts of the stellar surface in spatially unresolved disk-averaged observations.

sequence, without gap, fully overlapping the region of the H-R diagram where the magnetic stars are found, it would then seem that not all A stars pass through this "peculiar" phase.

Unfortunately, no conclusion can be drawn regarding the evolution of magnetic field strength with time. It seems that the strongest magnetic fields appear in the middle of the main-sequence band, but the studied sample of magnetic stars is still too small to provide a really stringent test.

As a by-product, the star sample considered in the present study provides a good basis for the study of possible relations between the magnetic field and other stellar parameters, especially because new, improved determinations of some of the latter have been made possible by the exploitation of astrometric data of unprecedented accuracy. One such parameter is the stellar mass, against which the field strength is plotted in Fig. 9. This gives some hint that stronger fields tend to be found in more massive stars. A somewhat similar trend is reflected in Fig. 10, where there seems to be some loose correlation between field strength and effective temperature. Already, in their study of the stars with magnetically resolved lines, Mathys et al. (1997) had given some hints that the range of possible intensities of the magnetic field for a given temperature increases with temperature. Consideration of the present sample, which includes both stars with magnetically resolved lines and stars with measured quadratic fields, gives the same kind of (somewhat marginal) indication. Finally, in Fig. 11, the magnetic flux ($\Psi = 4\,\pi\,R^2\,H$) is plotted against the stellar rotation period. Here, various symbols are used to differentiate stars according to the fraction of their main-sequence lifetime that they have completed. This figure reveals the possible existence of a loose anticorrelation between magnetic flux and period, or, in other words, of a correlation between magnetic flux and angular rotational velocity Ω.

To conclude, the implications of the new observational results presented in this paper for the understanding of the magnetism of the Ap stars will be briefly discussed.

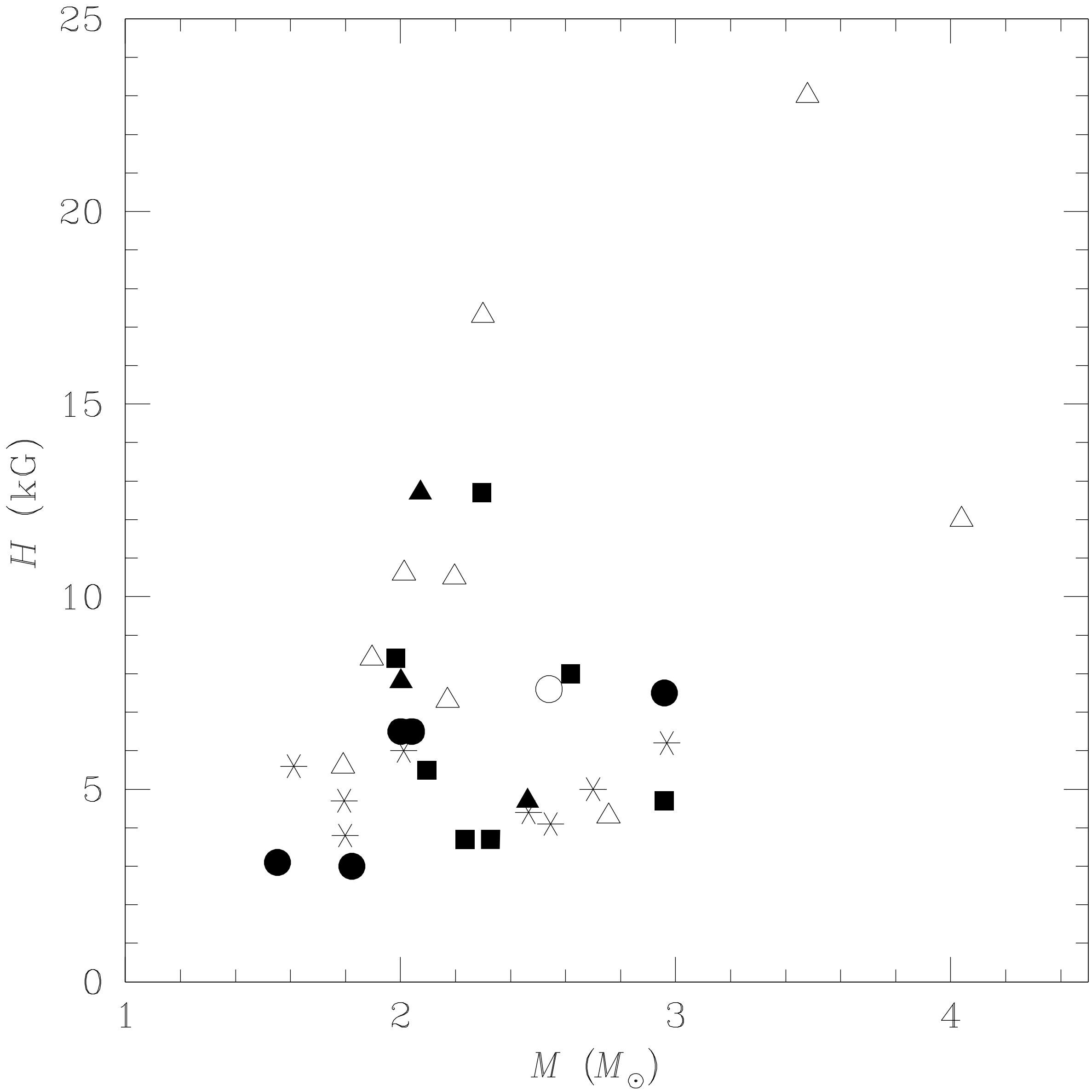

Fig. 9.— Magnetic field strength as a function of mass. Symbols have the same meaning as in Fig. 7

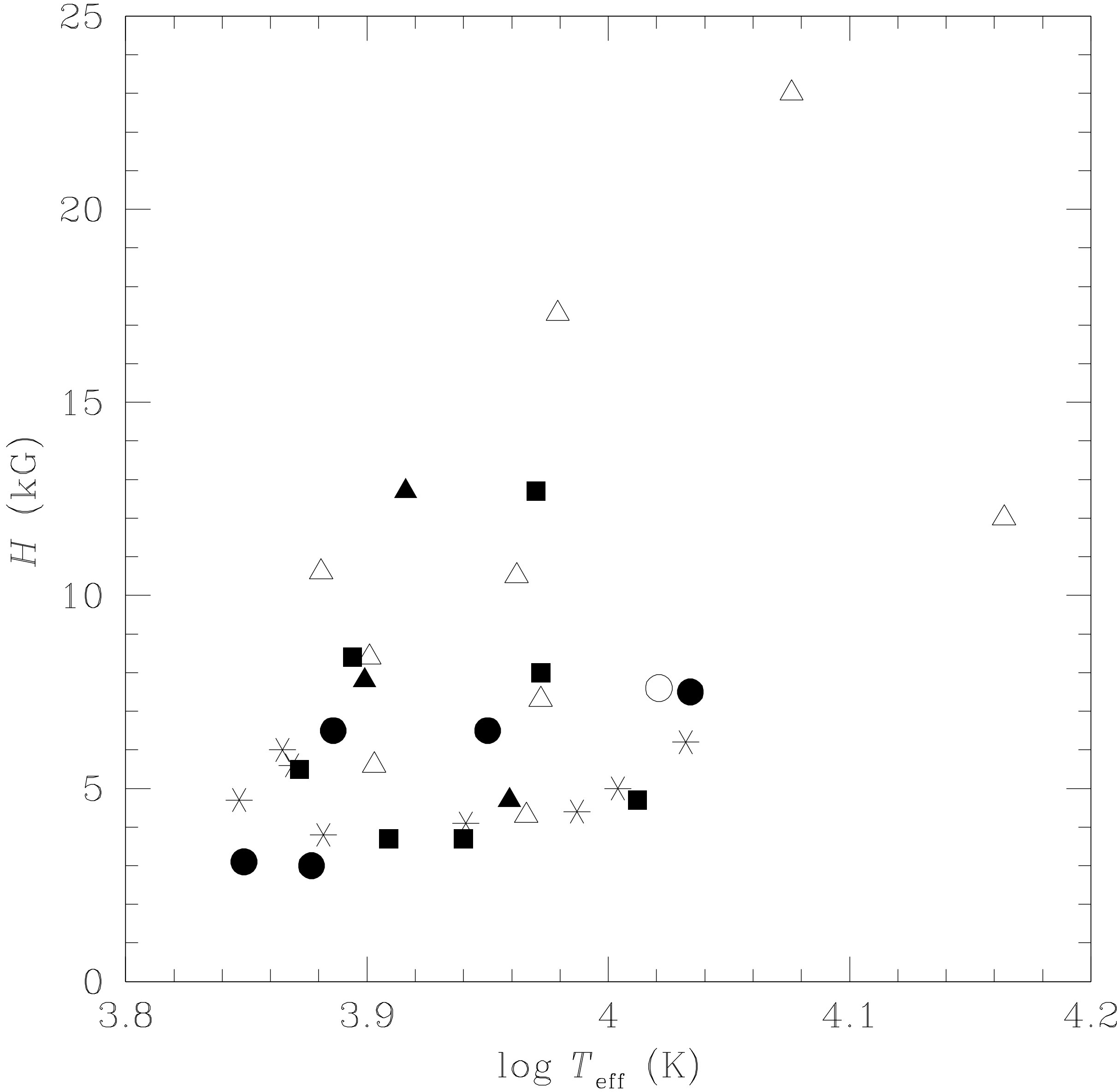

Fig. 10.— Magnetic field strength as a function of effective temperature. Symbols have the same meaning as in Fig. 7

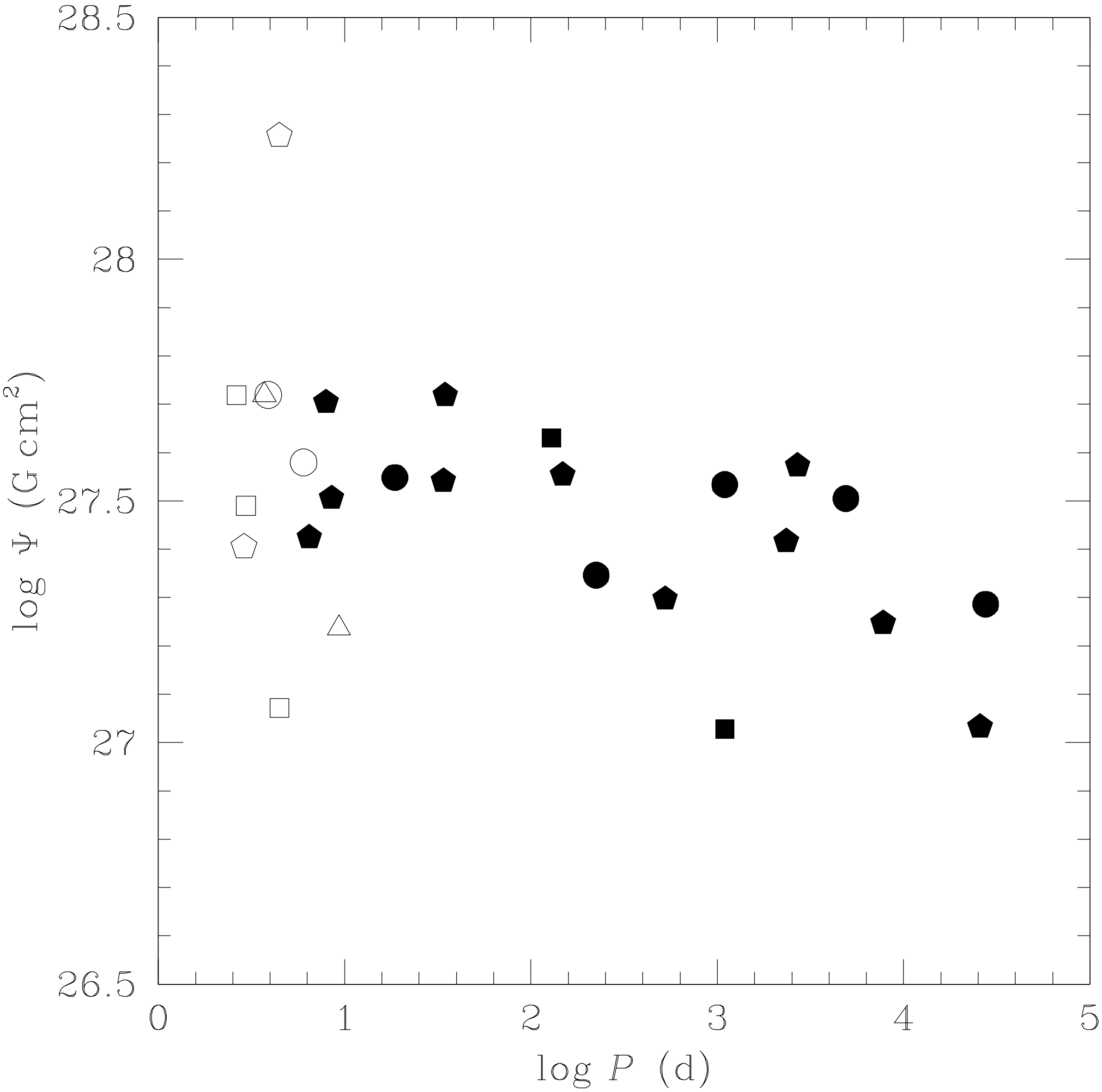

Fig. 11.— Magnetic flux against rotation period for the stars with magnetically resolved lines (*filled symbols*) and for stars for which mean quadratic magnetic field determinations are available (*open symbols*). Different symbols are used according to the fraction of its main-sequence life completed by the star: *triangles*: $f \leq 0.4$; *squares*: $0.4 < f \leq 0.6$; *pentagons*: $0.6 < f \leq 0.8$; *circles*: $f > 0.8$

The origin of magnetic fields in Ap and Bp stars has been the subject of a long debate, which is not closed yet. Two main streams of thought have been followed: one according to which the stars have acquired their field at the time of their formation or early in their evolution (what is currently observed is then a *fossil* field), and the other according to which the field is generated and maintained by a contemporary *dynamo* at work inside the star.

The absence of stars with strong magnetic fields close to the ZAMS might be seen as an argument against the fossil field theories. Nevertheless, internal fossil fields may plausibly be present inside stars with no observable fields (some of which may be found close to the ZAMS), if they do not permeate through to the surface (possibly because that step occurs on a timescale which is a significant fraction of the main-sequence lifetime and has not been completed yet).

The competing dynamo theory proposes that the magnetic field is generated by a turbulent dynamo operating in the star's convective core. As long as it was accepted that strong magnetic fields are observable at all evolutionary states from the ZAMS to the TAMS, one of the difficulties for the dynamo theory was to explain how the field reaches the stellar surface in the rather short time available before the arrival of the star on the main sequence. In view of the result presented here, that magnetic fields become observable only after completion of a significant fraction of main-sequence life, it would be interesting to reconsider the timescales involved in the possible processes of transport of core-generated fields to the surface. In particular, we note that the loose anticorrelation between field strength and rotation period (as seen e.g. in Fig. 7), and the marginal trend of the magnetic flux to be lower in slower rotating stars seen in Fig. 11, are consistent with the usual prediction for the dynamo theory for stars of a given mass (Mestel 1975).

A related issue is that of the slow rotation of the magnetic stars. It is generally assumed that magnetic stars are slow rotators because of magnetic braking. Whether magnetic stars undergo deceleration after arrival on the main sequence or during the pre-main-sequence phase is still a subject of debate. In our sample, the stars with rotational periods longer than 1000 d (identified by asterisks in Fig. 7) are distributed rather uniformly against the fraction of main sequence life completed. This result supports the view that any loss of angular momentum in magnetic Ap and Bp stars must occur either in a pre-main-sequence phase, or at the beginning of the main-sequence life, before the stars become observably magnetic. If it could be shown that no rapidly rotating chemically peculiar star can be found close to the ZAMS, then one could argue that the slow rotation is simply the consequence of braking during the Hayashi phase. The magnetic stars could then be the objects that have managed to retain some of their primeval field and that have undergone braking through interaction with accretion disks and strong thermally driven stellar wind during pre-main-sequence evolution (Mestel 1972; Stepien 1998).

In summary, although they provide new clues, the observational results presented in this work are still inconclusive as to the origin of the magnetic fields of the Ap stars. The study of the magnetic field geometry in stars of different ages and with different rotation rates will provide important additional information to test theoretical predictions. Several mechanisms have been proposed by which the angle between the magnetic and rotation axes might change during the main-sequence lifetime. Therefore, one goal for observers should be to provide theorists with constraints on the distribution of magnetic field geometries. Work on this aspect is in progress.

A. Effective temperatures

Effective temperatures are central to the present discussion of the evolutionary status of the magnetic Ap stars. Possible systematic errors affecting their determination may

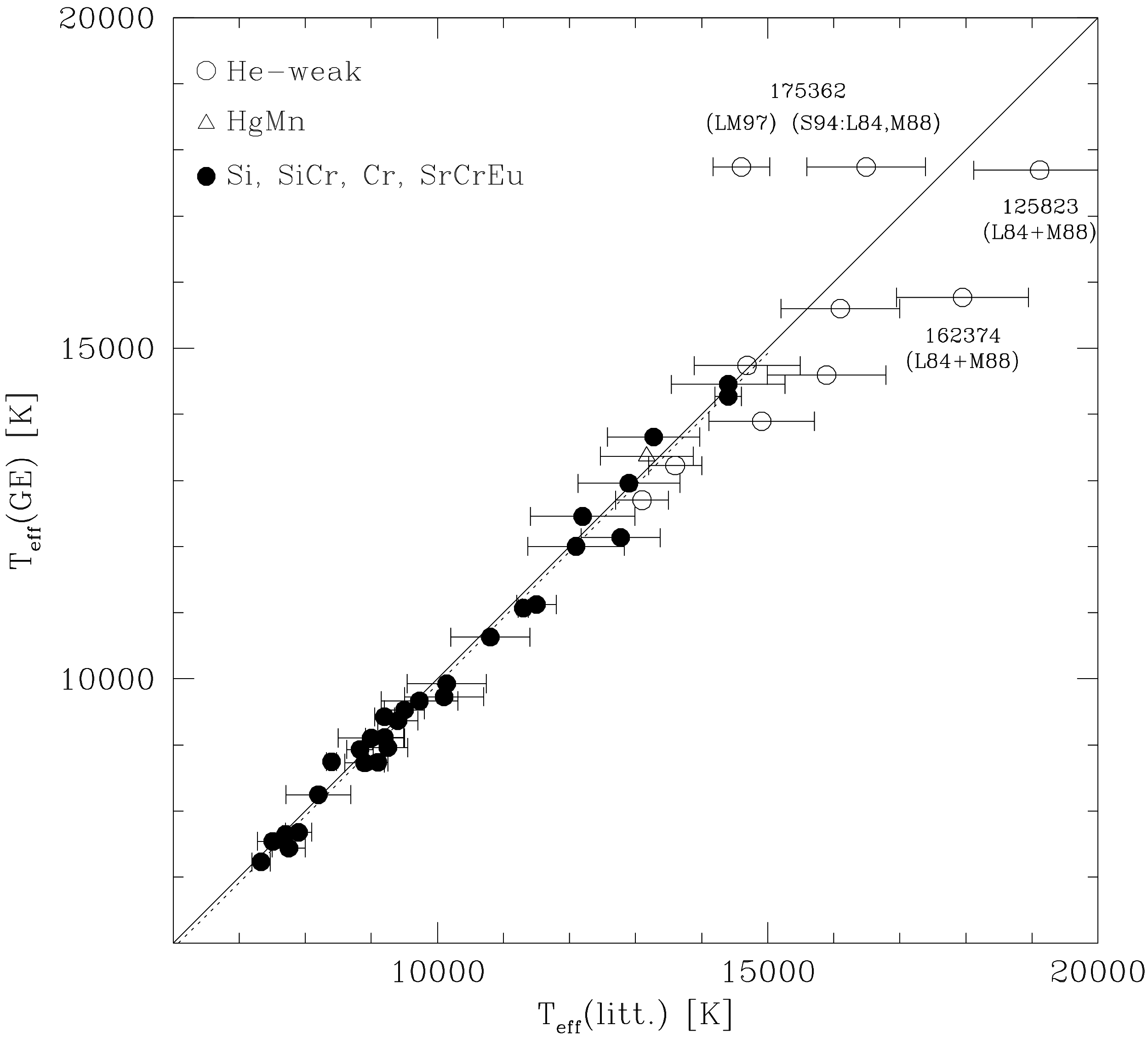

Fig. 12.— Effective temperatures of a sample of Ap and Bp stars: values determined from Geneva photometry vs. values from the literature, derived either through the infrared flux method or through detailed spectroscopic studies. The *dashed line* is the best fit relation between both sets of $T_{\rm eff}$ values, for the stars with effective temperatures below 15000 K. The *solid line* represents equality between both values of $T_{\rm eff}$

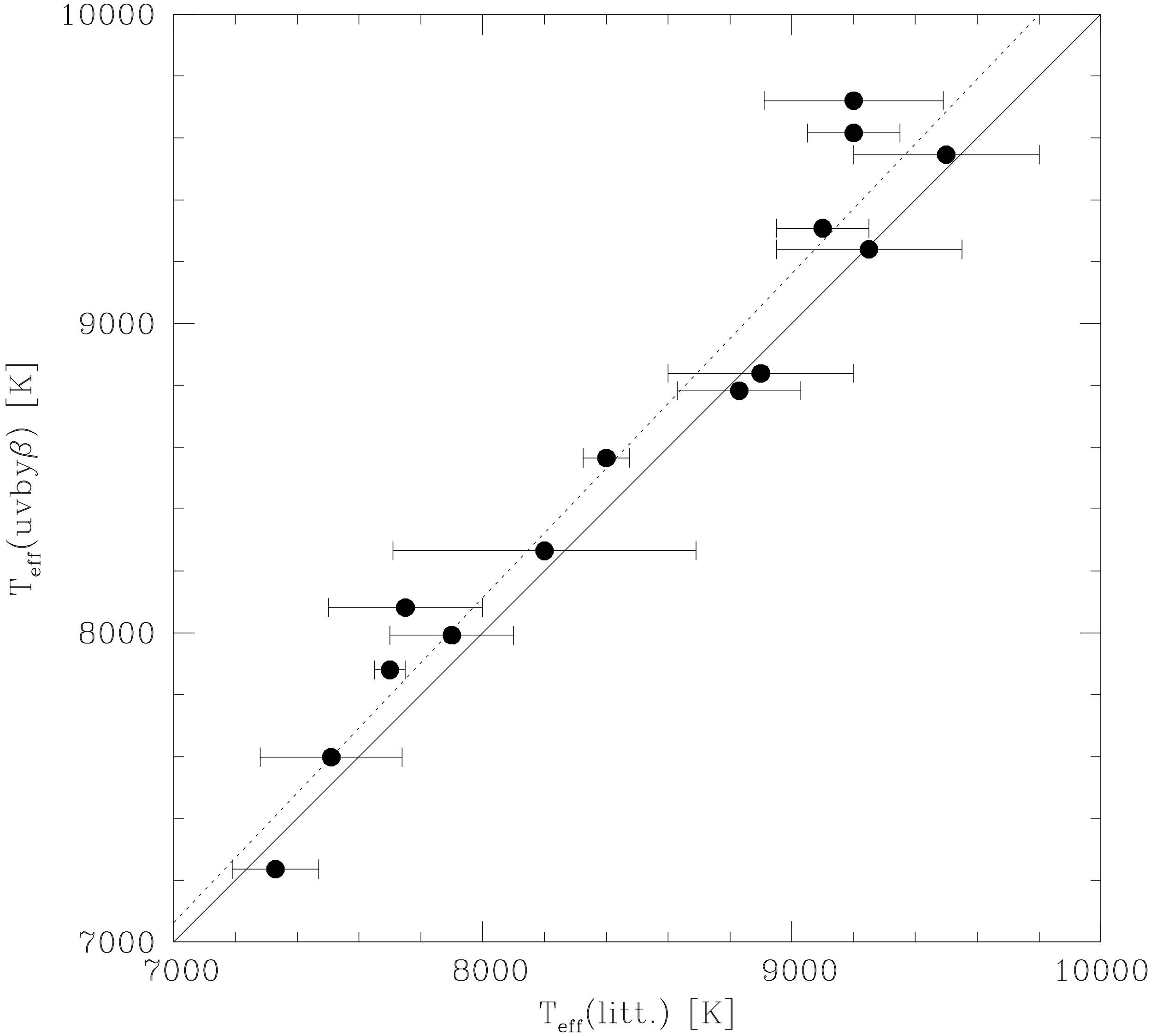

Fig. 13.— Effective temperatures of a sample of Ap and Bp stars: values determined from Strömgren photometry vs. values from the literature, derived either through the infrared flux method or through detailed spectroscopic studies. The *dashed line* is the best fit relation between both sets of $T_{\rm eff}$ values. The *solid line* represents equality between both values of $T_{\rm eff}$

seriously challenge the results of this study. In particular, there would be essentially no evolutionary difference between magnetic and non-magnetic stars if for some reason, the actual temperatures of the former happened to be 500 to 1000 K higher than the values adopted in this work, so that all the points in Fig. 1 would be shifted by roughly the same amount towards the ZAMS. Given the limited size of the sample of magnetic stars, the distribution obtained in such a case, with magnetic Ap stars concentrated towards the ZAMS and absent in the vicinity of the TAMS, would be very nearly as expected for any random sample of main-sequence stars in the considered mass range, since stars move increasingly faster through the main-sequence band as they age. In particular, the evolutionary difference between magnetic Ap and non-magnetic A stars would vanish.

The effective temperatures of the sample stars have been determined from photometric data, preferably in the Strömgren system, applying the calibration of Moon & Dworetsky (1985), or in the Geneva system (Hauck & North 1993; Hauck & Künzli 1996; Künzli et al. 1997). Because of the anomalous energy distribution of the Ap stars, the calibrations of the photometric temperature indicators are frequently questioned. We shall hereafter provide evidence that there is no error or uncertainty in these calibrations that could jeopardize the validity of the conclusions of this paper.

In most cases, the temperatures derived from photometry are in good agreement with the spectral classifications taken from the literature (Renson 1991), except for some of the hottest stars of the sample. For 4 of those (all with mean quadratic field determinations), the discrepancy is rather large, up to a few thousand Kelvin. For some of them, detailed spectroscopic studies were found in the literature, which indicate that the above-mentioned discrepancies find their origin in the inadequacy of the photometric calibrations for effective temperature diagnosis at the hot end of the temperature range of interest. Accordingly, the inconsistencies were resolved by adopting effective temperatures inferred from detailed

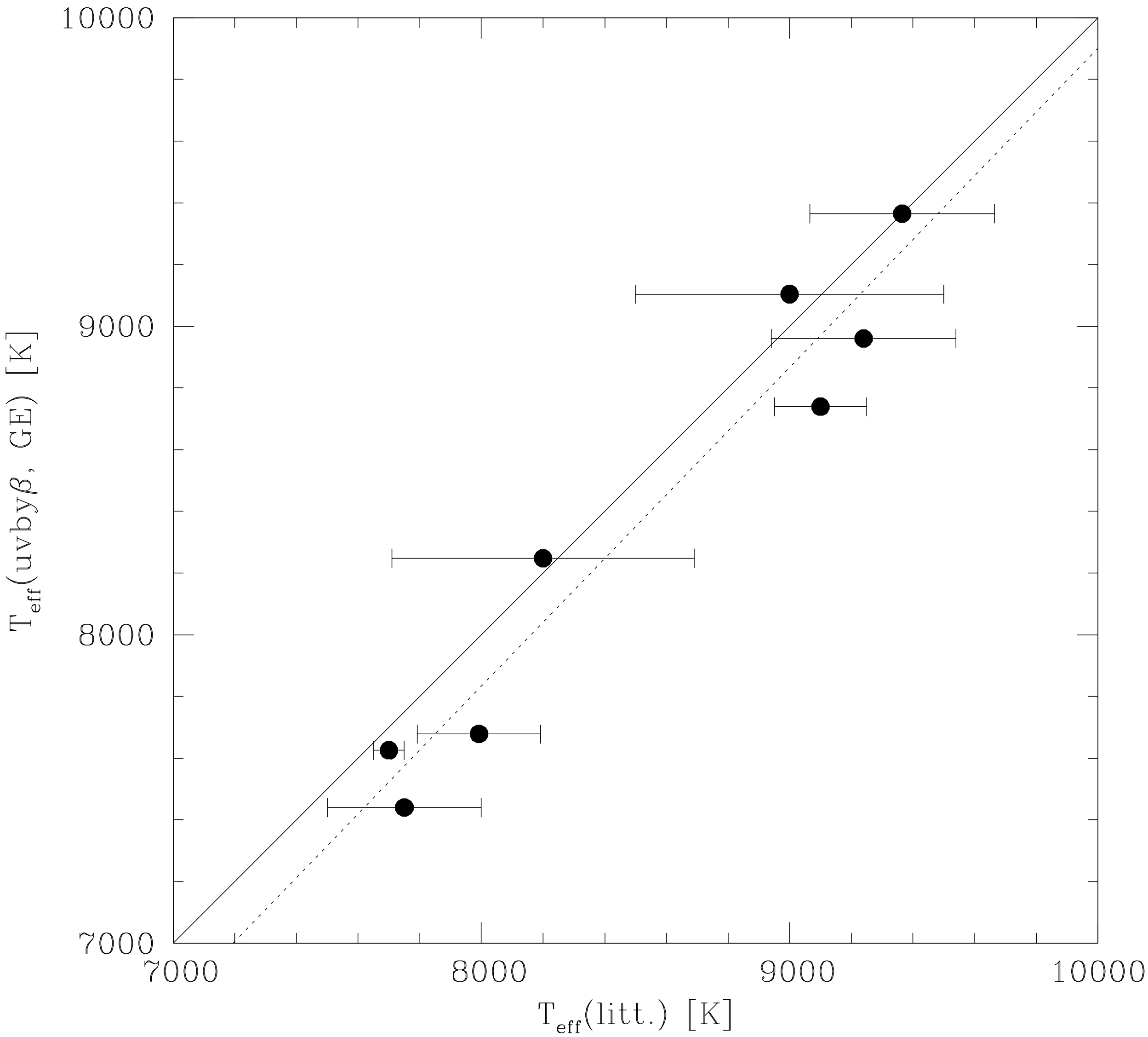

Fig. 14.— Effective temperatures of a subsample of the sample of magnetic Ap and Bp stars studied in this work: photometrically determined values adopted in this paper vs. values from the literature, derived either through the infrared flux method or through detailed spectroscopic studies. The *dashed line* is the best fit relation between both sets of $T_{\rm eff}$ values. The *solid line* represents equality between both values of $T_{\rm eff}$

spectroscopic studies or, when no such study is available, from the published spectral types. These 4 stars are HD 119419 (spectral type A0), HD 137509 (B8), HD 143473 (B9), and HD 175362 (B6). The temperature of the latter is particularly difficult to determine reliably, as a result of the large variations of its spectrum (in particular, of its helium lines).

To assess the correctness of the photometric effective temperature determinations, we have extracted from the literature a set of effective temperatures of Ap and Bp stars, derived through the infrared flux method or detailed spectroscopic studies. In Fig. 12, these literature $T_{\rm eff}$ values are compared with the values derived from Geneva photometry for those stars for which the latter is available. A linear regression of the values obtained through Geneva photometry [$T_{\rm eff}$(Gen)] vs. the literature values [$T_{\rm eff}$(lit)], limited to effective temperatures below 15000 K, gives the following result:

$$T_{\rm eff}({\rm Gen}) = (1.001 \pm 0.021)\, T_{\rm eff}({\rm lit}) - (87 \pm 221)\ {\rm K}\,. \tag{A1}$$

This fit is represented by a dashed line in the figure. Obviously, below 15000 K, the agreement between $T_{\rm eff}$ determinations achieved through Geneva photometry and through more fundamental methods is excellent (the solid line in Fig. 12 corresponds to identical results through both approaches).

In Fig. 13, a similar comparison is shown for determinations based on Strömgren photometry [$T_{\rm eff}$(Str)], for effective temperatures below 10000 K. In this case, the following regression is computed:

$$T_{\rm eff}({\rm Str}) = (1.049 \pm 0.070)\, T_{\rm eff}({\rm lit}) - (277 \pm 594)\ {\rm K}\,. \tag{A2}$$

The accuracy of the determinations based on Strömgren photometry is slightly less good than for Geneva photometry, but systematic effects remain small: at 9000 K, values of $T_{\rm eff}$ derived from Strömgren photometry are overestimated by 164 K in average.

The quality of photometric effective temperature determinations degrades above approx. 15000 K for Geneva photometry, and above approx. 10000 K for Strömgren photometry. This has no significant impact on the present work: the vast majority of the stars of the studied sample have temperatures below or hardly exceeding 10000 K, and for the only stars with significantly higher temperatures, the latter were inferred from published spectroscopic studies, as described above.

Finally, in Fig. 14, a comparison between the values of $T_{\rm eff}$ adopted in this paper [$T_{\rm eff}$(ad)] and those obtained through the infrared flux method or through detailed spectroscopic studies is shown for the stars of our sample for which the relevant information exists in the literature. Again, a linear regression has been computed, yielding

$$T_{\rm eff}({\rm ad}) = (1.034 \pm 0.108)\, T_{\rm eff}({\rm lit}) - (440 \pm 927)\ {\rm K}\,, \qquad \text{(A3)}$$

corresponding to a systematic shift of -134 K of the values of $T_{\rm eff}$ adopted in this work with respect to the results obtained by more fundamental methods.

In summary, the various pieces of evidence gathered above indicate that the effective temperature values adopted in this paper are free from large systematic errors that might lead one to question the validity of the conclusion reached about the location of the magnetic Ap and Bp stars in the H-R diagram.

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