The evolution of Ap stars

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Abstract. The many peculiarities of Ap stars (not only chemical ones, but also magnetic field and slow rotation) may vary during the main-sequence evolution of these stars. We review here briefly the evidences found in the last thirty years for such evolution, with an emphasis on the more recent research. The position in the HR diagram of low mass Ap stars with a significant surface magnetic field (as measured by us) is reviewed as well.

Key words: stars: chemically peculiar – stars: magnetic fields – stars: evolution – stars: rotation – stars: statistics

1. Introduction

We limit this review to the *magnetic* Bp-Ap stars in the traditional sense, i.e. those classified as Si or SrCrEu (hereafter "Ap stars"). Their characteristics are well known in broad outline, even though they may vary a lot from one individual to the next. Many results that were reported in a previous review (North, 1993) will only be briefly mentioned here, if at all.

Every characteristic of Ap stars is likely to change with time: frequency $N(\mathrm{Ap})/[N(\mathrm{A}) + N(\mathrm{Ap})]$, type and strength of peculiarity, rotation ($V \sin i$ and period), strength and geometry of the magnetic field. Any observed change – or lack of it – is expected to put strong constraints on theoretical models and to shed light on the nature and origin of those peculiarities. Ap stars lie on the main sequence (hereafter MS), as has been known for decades, but they may also be in the pre-MS phase, as proposed by (e.g.) Alecian *et al.* (2008). Then, towards the end of an evolutionary track are the white dwarfs, some of which are strongly magnetic. It is tempting to relate the latter to magnetic Ap stars, as did Kawka and Vennes (2004) and Putney (1996). But as those authors have pointed out, should the magnetic flux be conserved, only those white dwarfs with a field $B \gtrsim 10^7$ G can be descendants of Ap stars.

There are two empirical ways of studying the evolution of stars in general:

– **Through galactic open clusters:** This method is the most secure since it allows precise ages to be determined, using the stars lying close to the turn-off. The distance and reddening of open clusters are also well known, as is the bulk metallicity, which is especially interesting since the chemical peculiarities of a single Ap star are sufficiently bizarre to mask that particular property. On

the other hand, membership of Ap stars in the cluster must be well attested, as must also the completeness of their detection down to a given mass.

    – **Through field Ap stars with known surface gravity or age:** This method was employed decades ago by Wolff (1975), who used both $V \sin i$ and the rotation period P to determine $R \sin i$ and to study the evolution of the equatorial velocity with time. Photometric estimates of $\log g$ were used by North (1985; 1986) for BpSi stars, with some success even though such estimates are much less reliable for Ap stars than for normal ones: the rms error is typically 0.3 dex instead of 0.1 dex, but the total range of the $\log g$ values amounts to about 0.6 dex on the MS, so purely photometric estimates may remain interesting when a large enough number of stars is available. The Hipparcos results have allowed more secure estimates of $\log g$: the bolometric luminosity is determined from parallax and $T_{\rm eff}$, and theoretical evolutionary tracks give access to the mass by interpolation. However, since evolution is much slower near the Zero Age Main Sequence (ZAMS) than near the Terminal Age Main Sequence (TAMS), in practice this method does not provide time resolution near the ZAMS, as pointed out by North (1993). Using age directly instead of $\log g$ leads to the same limitation (Kochukhov, Bagnulo 2006; Landstreet *et al.*, 2007 – see especially their Fig. 3). The latter authors also underlined the additional uncertainty introduced by the scatter of bulk metallicities in the solar neighbourhood. One should also keep in mind that this method relies on the assumption that an Ap star with a given mass and metallicity follows the same evolutionary track as a normal A-type star. Nevertheless, it is useful for the late stages of evolution on the MS, so it is perfectly complementary to the cluster method.

2. The evolution of Ap stars

We briefly review the work done and the results obtained so far regarding the evolution of the most conspicuous characteristics of Ap stars.

A. Frequency

In the field: Frequency is a simple concept, but there is some confusion in the literature regarding its exact meaning. Wolff (1968) computed an overall Ap-star "incidence" of about 10% among the bright MS stars in the interval $-0.19 < (B - V) < +0.20$. The sample is magnitude limited ($V < 5.0$), so the above figure can give the expected number of Ap stars that a future survey will yield, but has no direct physical meaning. Note also that this incidence is defined by the ratio $R \equiv \frac{N(Ap)}{N(IV)+N(V)}$, $N(IV)$ and $N(V)$ being the respective numbers of normal A-type stars of luminosity classes IV and V. A better choice would be to define $R \equiv \frac{N(Ap)}{N(Ap)+N(IV)+N(V)}$. In any case, it is not a volume-limited sample, since at the limiting apparent magnitude B5 stars are much more distant than A5 ones. On the other hand, a volume-limited sample such as that defined by Power *et al.* (2008) on the basis of Hipparcos parallaxes, although quite relevant

in principle, is unsatisfactory in practice since there are no Bp stars more massive than about $3.5 M_\odot$ within 100 pc.

The magnitude-limited frequency f_m for a mix of Ap stars of various masses is the mean of the true (volume limited) frequencies f_i, weighted by the total number of stars present in the respective mass bins and corresponding volumes. For example, a mix of ApSi stars with $M = 3.5 M_\odot$, $M_V = -1.2$, $f_\mathrm{Si} = 12\%$ and of ApSrCrEu stars with $M = 2.25\,M_\odot$, $M_V = 1.1$, $f_\mathrm{SrCrEu} = 4\%$ will give $f_\mathrm{m} = 8.2\%$ under the assumption of a Salpeter initial mass function (the limiting apparent magnitude does not matter as long as visual absorption is neglected). The volume-limited overall frequency f_v of the same mix is the mean weighted by the respective stellar number densities, giving $f_\mathrm{v} = 6.1\%$.

In Galactic open clusters: The first studies addressed the simple question whether Ap stars can be found at all in open clusters, and (if so) if their frequency is the same there as in the field. Those studies were in general based on spectral classification (Young, Martin 1973; Hartoog 1976; van Rensbergen *et al.*, 1978). The very first attempt to detect Ap stars in clusters by photometric means was made by a student of B. Hauck, using what became known as the $\Delta(V1 - G)$ parameter of Geneva photometry (Steiger, 1974). Maitzen (1976) then devised the Δa photometric system specifically to detect Ap stars through their $\lambda5200$Å spectral feature, and used it extensively to take a census of Ap stars in Galactic clusters (e.g. Maitzen, Hensberge 1981; Maitzen, Wood 1983). The frequency of Ap stars in clusters was explored independently using the Geneva photometry (North, Cramer 1981). It was generally agreed that the frequency of Ap stars is roughly the same in clusters as in the field, though the relatively small samples did not allow a very definite conclusion.

Does the frequency of Ap stars change with age? That is equivalent to asking: "Do young Ap stars exist at all, or do the peculiarities develop later?". The question was addressed, on the basis of spectral classification, by van Rensbergen *et al.* (1978) and Abt (1979) using clusters, and by Abt and Cardona (1983) using binary stars. The latter authors reported an increasing trend of frequency with age, but independent studies (North, Cramer 1981; North, 1993 and references therein) did not confirm that trend. An interesting study of the Orion and Scorpio-Centaurus associations was undertaken by Joncas and Borra (1981) and Borra *et al.* (1982) by means of the Δa system. They found a deficiency of Ap stars in these young aggregates, and deduced a slow metal enrichment of their atmospheres. On the other hand, they also noticed a few He-weak stars in the Orion association and suggested that those might become BpSi stars through future evolution. That was the first time that the idea that Ap stars could change their peculiarity type as they evolve on the MS was raised. The question has since been addressed by North (1993) on the basis of a compilation of the literature. No clear trend was obtained (except for Am stars) as a function of age, but the frequency of Ap stars as a function of mass was, however, obtained for the first time.

Is the frequency of Ap stars the same in a metal-poor environment?
This is a simple but fundamental question. If one postulates that radiative diffusion in the presence of a magnetic field is the prevailing cause of the chemical peculiarities, one can expect to find "metal-poor" Ap stars (in the sense of their global, not atmospheric, metal content), since there is no 'a priori' reason why that mechanism should not operate at low metallicities. Aurière *et al.* (2007) have shown that all Ap SrCrEu stars with an approximately solar global metallicity have a large-scale magnetic field, so it appears reasonable to expect that similar Ap stars which belong to a metal-poor population will also be magnetic. Therefore, finding Ap stars in a metal-poor environment probably means finding magnetic stars. Since the origin of the magnetic fields remains an open question (although suggestions made in these proceedings may point to an answer) but might depend on metallicity, it is worth exploring the matter.

Paunzen *et al.* (2005; 2006) have explored four clusters and a field in the LMC, the metal content of which ($Z \simeq 0.08$) is about a factor of 2 smaller than that of the Sun. They find an overall frequency $f = 2.2 \pm 0.6\%$, which is at least twice as small as the frequency of $\sim 6\%$ usually quoted for the solar vicinity. However, the volume-limited sample of Power *et al.* (2008) gives a frequency of only 1.5%, which is the same (to within about 1σ) as the frequency obtained for the LMC by Paunzen *et al.* (2005; 2006), whose sample can also be considered volume limited. A reliable comparison should take into account the different ways of defining an Ap star (spectroscopy versus photometry) and the corresponding sample of normal B-A stars, as well as probable biases.

B. Peculiarity type
Analyses routinely attribute chemical abundance anomalies to radiative diffusion in the presence of gravity, with well-substantiated reasons (Michaud, 1970). During evolution on the MS, a typical A-type star will change its T_{eff} by about 27%, e.g. from $T_{\text{eff}} = 10\,000$ K on the ZAMS to $T_{\text{eff}} = 7300$ K on the TAMS, which undoubtedly changes the efficiency of radiative diffusion for a given ion. Similarly, the stellar radius will double, leading to a 0.6 dex decrease of the logarithmic surface gravity. As mentioned above, Joncas and Borra (1981) had suggested the possibility that He-weak stars become BpSi after some evolution on the MS. For the *degree* of the peculiarity, look at Klochkova and Kopylov (1986) and references therein.

C. Evolutionary state within the MS
In clusters: Hubrig and Schwan (1991) and Hubrig and Mathys (1994) tried to answer this question using the proper motion of a few CP members of two superclusters (Hyades and UMa). The five Ap stars studied appeared to be at the end of their evolution on the MS when hydrogen has just been exhausted in the core. Since this short phase was estimated to last for about 10% of the MS lifetime, it was tempting to imagine that Ap stars represent just a quick phase in the evolution of *all* A-type stars, as suggested by Oetken (1986). However, unevolved Ap stars are known to occur in younger clusters (North, 1993), so only a very circumstantial conspiracy of nature could make evolved non-members out

of these (probably unevolved) member CP stars. A more complete and thorough examination of Ap stars in clusters is under way (Landstreet *et al.*, 2008).

In the field: Hubrig *et al.* (2000) used a sample with a majority of narrow-lined and sufficiently strongly magnetic stars, in which the surface field could be estimated from spectra observed in unpolarized light. The sample was therefore biased towards slow rotators. The main result was a slight clustering of Ap stars in the middle of the MS strip, as if they appeared as such only after having spent about 30% of their lifetime, and then disappeared (i.e. became normal A stars) slightly before they reach the core hydrogen-burning phase. The paper became controversial because of its far-reaching implications regarding the origin of magnetic fields. Hubrig *et al.* (2007) rediscussed that point on the basis of a much larger and less biased sample (90 stars with well-defined magnetic curves); they concluded that Ap stars with $M < 3M_\odot$ are more evolved than more massive ones. Kochukhov and Bagnulo (2006) used an even larger sample (literature plus recent FORS1/VLT spectra from the ESO archives), though many stars had only one magnetic measurement. They conclude that Ap stars are, in general, distributed uniformly in age, except for those less massive than about $2M_\odot$. The latter, although not completely absent from the ZAMS, tend to be rare there. Therefore, although Kochukhov and Bagnulo's result contradicts the conclusion of Hubrig *et al.* (2000) that Ap stars become magnetic *only* after spending $\sim 30\%$ of their MS lifetime, it does confirm that the less massive of them are not distributed as expected across the MS.

3. Axial rotation

Projected rotational velocity: Hartoog (1977), Abt (1979), Wolff (1981) and Klochkova and Kopylov (1984) have used the $V \sin i$ of Ap stars in clusters to test whether they undergo any braking during their life on the MS. Klochkova and Kopylov (1986) considered the ratio of the average $V \sin i$ of Ap stars of a given age and of the average $V \sin i$ of normal A stars of the same age, in order to eliminate the effect of conservation of angular momentum, which slows down rotation as a star expands.

Rotational period: When a star expands owing to its evolution, conservation of angular momentum will cause only a slight decrease in equatorial velocity, since the latter increases with radius, partly compensating for the conservation effect. On the other hand, the rotational period is a direct measure of angular velocity, so conservation of angular momentum will imply a significant lengthening of the rotational period. North (1984; 1987) and Borra *et al.* (1985) used the possibility of measuring the rotational period of Ap stars through photometry in clusters and associations, while North (1985; 1998 a, b), Hubrig *et al.* (2007) and Kochukhov and Bagnulo (2006) applied that idea to field Ap stars with known ages or $\log g$. The conclusion was that for Si stars (or stars with $M \gtrsim 3M_\odot$) the period increases with age, but at the rate expected from conservation of angular momentum if the stars are rotating more or less like a solid body. Thus, those
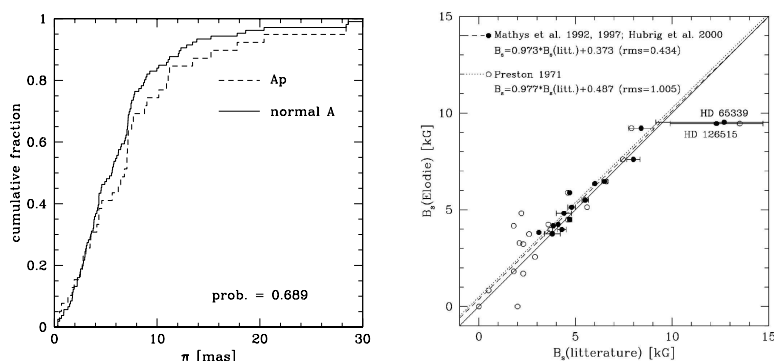
Figure 1. (left): Cumulative distributions of the parallaxes of Ap stars (broken line) and of the normal A-type stars chosen as a reference sample. Note the similar shapes of the distributions. **(right):** Comparison between our magnetic field estimates and those of other authors for Ap stars in common. Very large fields deviate from the regression line because we applied only a simple default method involving the measurement of the quadratic differences of the FWHMs of two cross-correlation functions.

stars must have acquired their slow rotation at the time of formation; there has been no later braking. For cooler and less massive Ap stars, the range of periods is so wide that no conclusion of that kind can safely be drawn.

4. Magnetic field

Intensity and flux: Age will also affect the intensity of the surface magnetic field, if the latter is a fossil of the primordial field. Borra (1981) was the first to find a probable decrease of magnetic field strength with age, on the basis of magnetic field measurements of Ap members of the Orion OB1 association. North and Cramer (1984) made a bold early attempt using a correlation between photometric parameters of peculiarity and surface magnetic field, but this correlation was later found much less significant, if any, than first believed. Nevertheless their (fragile) conclusion, that Ap stars with $M > 3M_{\odot}$ have a field which decreases with time, was the same as that of Borra, itself confirmed by Hubrig *et al.* (2007), Kochukhov and Bagnulo (2006) and Landstreet *et al.* (2007). The magnetic flux (essentially $< B > R^2$ where $< B >$ is the mean value of the surface field or of a proxy for it, and R is the stellar radius) shows little change with age, if any: while Kochukhov and Bagnulo (2006) and Hubrig *et al.* (2007) find it constant for massive Ap stars ($M > 3M_{\odot}$) and marginally increasing for less massive ones ($M < 3M_{\odot}$), Landstreet *et al.* (2007) find a decreasing trend for massive Ap stars and a constant value for less massive ones. The latter conclusions may be more robust than those of the other authors, because they are based on cluster members rather than on field stars.

Geometry: The first attempt to study the evolution of the magnetic field geometry provided rather uncertain conclusions, because of the large errors in the photometric surface gravities (North, 1985). Hubrig *et al.* (2007) reconsidered this matter on the basis of Hipparcos parallaxes, using the ratio $r = B_l^{\min}/B_l^{\max}$ which is negative for large β angles between the rotational and magnetic axes, and positive for small β angles. Interestingly, the evolution of r seems quite different for massive Ap stars compared to less massive ones.

5. The position of cool magnetic stars on the MS

In order to test the robustness of the conclusions of Hubrig *et al.* (2000), I chose a different sample (even though a few Ap stars will be common to both studies), intending that both the sample and its analysis be independant. To take into account the weaknesses pointed out by Landstreet *et al.* (2007), we drop the Lutz-Kelker correction, and we also adopt their bolometric correction (*B.C.*). In addition, we selected our reference sample of normal A stars in a different way: instead of simply taking A stars closer than 100 pc, we selected a sample of A stars *having the same distribution of parallaxes as the Ap stars*, so that any systematics linked with the parallaxes should be the same for both samples (see Fig. 1 left). Indeed, the present sample of Ap stars was not intended for this study: it is not a volume-limited one; it contains Ap stars with $T_{\text{eff}} < 10\,000$ K, $V \sin i < 20$ km s^{-1} and surface magnetic fields determined from echelle spectra taken with the ELODIE spectrograph attached to the 1.93-m telescope at Haute-Provence Observatory. The method of field determination, based on a correlation technique, has been described by Babel *et al.* (1995). Figure 1 right shows how the surface magnetic field thus obtained correlates with other determinations. The typical error is a few hundreds of Gauss, so that in practice we detected fields larger than about 1 kG for stars with $V \sin i \leq 10$ km s^{-1}. This sample is therefore similar to that of Hubrig et al. (2000) in that it contains Ap stars with a confirmed magnetic field, is biased in favour of slow rotators, and contains about the same number of stars.

The T_{eff} was determined from the profile of the H$_\alpha$ line, using Kurucz atmosphere models with $[M/H] = 1.0$ and `synspec` code (Hubeny *et al.*, 1995). Since the profile of this line depends not only on T_{eff} but also on $\log g$ for $T_{\text{eff}} \geq 8000$ K, we also used Geneva or $uvby\beta$ photometry to remove any ambiguity. Most of the stars measured also have Hipparcos parallaxes which allowed us to determine their evolutionary states. We had to eliminate a large number of normal A stars with $T_{\text{eff}} < 9000$ K, which evidently outnumbered the others by a large factor, owing to a bias in the Hipparcos Input Catalogue (had we kept them, a very strong bias in $\log g$ would have appeared). We show the astrometric HR diagram $a_V = \pi \cdot 10^{0.2\,M_V} = \pi \cdot 10^{0.2\,(m_V + 5 - A_V)}$ versus $\log T_{\text{eff}}$ (Arenou, Luri 1999) in Fig. 2 left and right, for Ap and normal A stars respectively. An upper limit to the distance of 200 pc was set, so that both samples are volume limited but are not necessarily complete within that volume. At first sight, one gets the
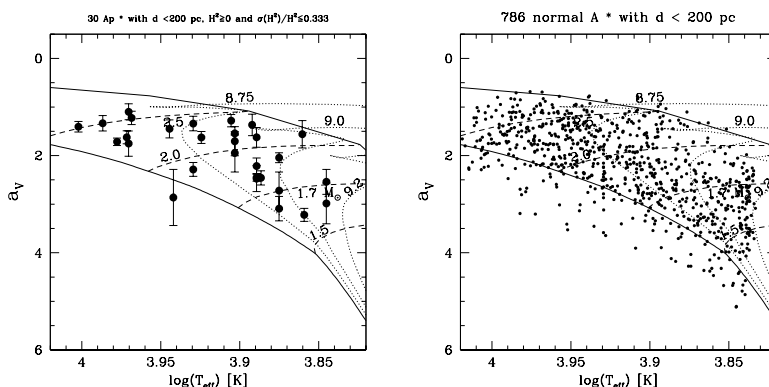
Figure 2. (left): Astrometric HR diagram of Ap stars of our sample with $\pi > 5$ mas. Error bars (chiefly due to parallax errors) are symmetrical in this diagram. **(right):** Same as left, but for normal A-type stars. Note that the way the cutoff at low temperature is defined will affect the comparison between normal A and Ap stars; here, we assume spectral types earlier than F1.

visual impression that Ap stars tend to lie farther from the ZAMS than do the A stars, at least for $M \leq 2\,M_\odot$.

In order to examine the extent to which that may be significant, we built cumulative distributions of $\log g$ and applied the two-sided Kolmogorov-Smirnov test. The results are shown for a limiting distance of 200 pc and of 500 pc in Fig. 3 left and right respectively. Each figure illustrates two pairs of distributions according to stellar mass, the limit being $2.1 M_\odot$. Although for stars less massive than $2.1 M_\odot$ Fig. 3 (left) suggests a result similar to that reported by Hubrig et al. (2000) (with marginal significance), Fig. 3 (right) does not show any significant difference between the distributions of Ap and normal stars.

6. Conclusion

Magnetic fields are being systematically determined for both cluster and field Ap stars, and some evolutionary trends are emerging. Their intriguing dependence on stellar mass is worth investigating further. However, the limited number of Ap stars in clusters or with reliable parallaxes impedes faster progress. Improved Hipparcos parallaxes (van Leeuwen, 2007) already increase the sample of Ap stars with known luminosity, and the Gaia mission should inflate it. But a good age determination of field stars also requires reliable T_{eff} values, which is the next limiting factor. Formation of Ap stars is another promising topic: are magnetic Herbig Ae/Be stars (Alecian *et al.*, 2008) really the progenitors of Ap stars? Do Ap stars form more easily in poor clusters than in rich ones (Maitzen *et al.*, 2008)? Are middle-aged Ap stars with $M < 2\,M_\odot$ really more
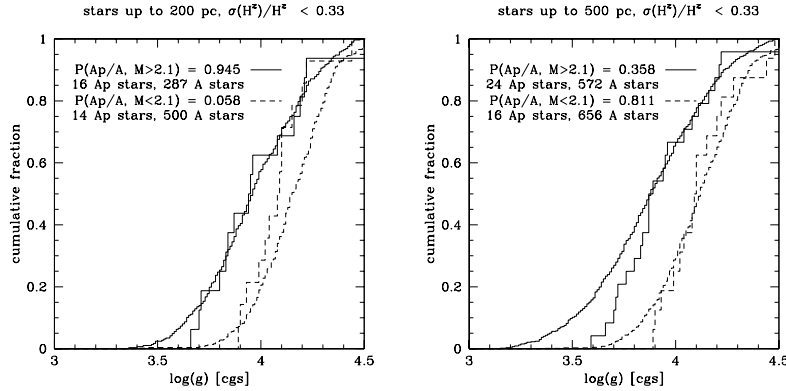
Figure 3. (left): Cumulative distributions of our samples of Ap and A stars with $\pi > 5$ mas. **(right):** Same as left, but for stars with $\pi > 2$ mas.

frequent than young ones, or how can a normal A star become Ap during its MS life? We do not fully confirm the conclusion of Hubrig *et al.* (2000) regarding the position of Ap stars in the HR diagram. There is no clear lack of young objects, and although Fig. 3 seems to show a systematic lack of Ap stars with $\log g < 3.7$ ($M > 2.1\ M_\odot$) and $\log g < 3.9$ ($M < 2.1\ M_\odot$), that result is not significant because of the low sample sizes. Hubrig *et al.* (2007) have cured the latter weakness to some extent, but the incidence of the *B.C.* uncertainty on their conclusions should be assessed.

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