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Rotation and Properties of A- and B-Type Chemically Peculiar Stars

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Abstract. Main-sequence chemically peculiar stars of spectral types A and B, which are characterised by photospheric abundance anomalies resulting from element segregation in the stellar outer layers, rotate slower than normal stars of similar temperatures. The mechanisms by which such slow rotation is achieved are not well understood yet; different processes may be involved for different types of chemical peculiarities, including stellar magnetic fields and multiplicity. Relevant existing observational data are reviewed.

1. Introduction

A considerable fraction of main-sequence (MS) stars of spectral types A and B exhibit atmospheric chemical peculiarities that, apparently, do not have an evolutionary origin, but result from the segregation of chemical elements in the stellar outer layers under the competing actions of various physical processes (see e.g. Michaud, these proceedings). For the purpose of this review, these *chemically peculiar* (CP) stars will be distributed into three main categories: the "magnetic" CP stars (Ap, He weak Si and SrTi, He strong), the Am stars, and the "non-magnetic" Bp stars (HgMn, He weak PGa).

Recently published extensive, systematic studies (Abt & Morrell 1995; Abt, Levato & Grosso 2002; Royer et al. 2002a, 2002b) provide a sample of unprecedented completeness of reliable $v \sin i$ of A and B stars. Equatorial velocity (v) distributions of F0–B8 stars are bimodal, indicating that magnetic CP stars, Am stars, and non-magnetic Bp stars in this spectral type range rotate slower than normal stars of similar temperature (Abt & Morrell 1995; Abt et al. 2002). Abt (2000) even argues that, among A stars, rotational velocity is probably the only parameter that determines whether a star will have a normal or abnormal spectrum. However this argument rests in part on the extension of the definition of CP stars beyond the standard one, encompassing a group of stars in which the line Mg II $\lambda\,4481$ is abnormally weak, but which do not exhibit the spectral anomalies of "classical" CP stars, and it is not supported by the independent work of Royer, Zorec & Frémat (these proceedings). Whether slow rotation suffices or not to make an A star chemically peculiar, it definitely appears to be a pre-requisite for the appearance of abundance anomalies. This is understood as reflecting the fact that segregation of chemical elements can take place in stellar outer layers only provided that they are sufficiently stable (e.g. Charbonneau & Michaud 1991). In summary, there is a close relation between rotation and the appearance of chemical peculiarities in A and B stars: understanding of the ori-

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gin of the latter must involve consideration of the former. In the next sections, current knowledge of the rotation of the various types of CP stars is discussed.

2. "Magnetic" CP Stars

The group of the "magnetic" CP stars includes the "classical" Ap stars, the He weak Si and SrTi stars (He wk), and the He strong stars (He str). The classical Ap stars range in spectral type from early F to late B. They are characterised by overabundances of some elements (e.g., Si, Cr, Sr, rare earths), as well as underabundances of other elements (in particular, He). The abundance anomalies may be quite extreme (up to 5 dex); the abundance pattern varies from star to star. The He wk Si and SrTi stars are intermediate B stars (B2.5–B7), with helium lines abnormally weak for their temperature, where overabundances of Si, or Sr and Ti are observed. The He str stars are early B stars (B1–B2.5), where the helium lines are stronger than in normal stars of similar temperature.

Large-scale organised magnetic fields, with a predominant dipole-like component, are detected through spectropolarimetry in stars of the above-mentioned peculiarity types: this is why we call them, globally, "magnetic" CP stars. The available observational evidence supports the view that the Ap stars, the He wk Si and SrTi stars, and the He str stars all result from similar physical processes. They represent the evolution of the manifestation of these processes along a sequence of increasing temperature. As a matter of fact, the borders between the different groups are not sharply defined, and Ap and Bp stars are often conveniently referred to collectively merely as Ap stars.

Magnetic CP stars generally exhibit periodic variations in photometry, in spectral line intensities, and in magnetic field. Not all observables are detectably variable in all stars. But in a given star, all the observables vary with the same period. The observed periods range from half a day to several decades. The existence of an anticorrelation between them and $v \sin i$ (see Fig. 1 of Preston 1971) leads to the conclusion that the observables in magnetic CP stars vary with the rotation period. The interpretation is that the surface properties of these stars are non-uniform and non-symmetric with respect to their rotation axis. As a result, when the star rotates, the aspect of the hemisphere that the observer sees progressively changes. The non-uniformity of the surface properties is, by and large, determined by the magnetic field. In the first approximation of the latter as a simple dipole, its axis is not aligned with the rotation axis: this is why the interpretation described here was called the *oblique rotator model* (ORM; Deutsch 1956). This model can successfully account for the vast majority of the observations obtained since its introduction. The variations appear to be strictly periodic, repeating themselves exactly from cycle to cycle (but see below). This indicates that the magnetic CP stars rotate rigidly, and that their surface properties are permanent and invariant over timescales of several decades.

For stars of most other types, rotation studies have to rely primarily on the consideration of $v \sin i$, and the ambiguity introduced by the (generally unknown) inclination i of the rotation axis to the line of sight represents a limiting factor. With the availability of the rotation period, the magnetic CP stars comprise one of the few group of stars for which this limitation can be overcome.

A catalogue of the published periods has been compiled by Catalano & Renson (1998), who continue to update it regularly (Renson & Catalano 2001). After critical evaluation of this compilation, I estimate that it contains reliably determined rotation periods for 185 magnetic CP stars, and for 3 more, meaningful lower limits of their (very long) periods. The discussion below is based on this sample of 188 stars, complemented by 7 stars with periods longer than 25 days for which periods (or lower limits) have recently been obtained (Mathys, Manfroid & Wenderoth, in preparation). This sample, in which 140 stars (out of 195) have periods between 1 and 10 days, is by no means a statistically representative sample of the magnetic CP stars. Its selection actually does involve severe biases. Indeed, some periods shorter than 1 day are likely to have been overlooked by observers who did not take more than one observation per night of their programme stars, while the determination of periods much longer than 10 days through photometry (the technique with which most periods have been derived) involves rather severe difficulties (Hensberge 1993), to the extent that these slow variations have often been overlooked (Hensberge et al. 1984). In spite of these biases, it is safe to conclude that the majority of the magnetic CP stars have rotation periods between 1 and 10 days. But the actual rate of occurrence of magnetic CP stars in this period range is almost certainly lower than the value of 72% found in the considered sample.

On the other hand, in recent years, a major systematic effort has been made to identify and study Ap stars showing spectral lines resolved into their magnetically split components (Mathys et al. 1997). A by-product of this project has been the discovery of a sizable population of Ap stars with periods longer than 1 month. This sheds a new light on a long-standing issue. Less than 10 years ago, only 10 Ap stars with periods longer than 100 days were known, so that one could question whether these stars were just odd isolated specimens, resulting from some fortuitous circumstances unrelated with the Ap phenomenon. The sample of 195 stars discussed here contains 22 stars with periods longer than 100 days (more than 10%). This leaves little doubt that these long-period stars are genuinely part of the Ap phenomenon, and that any theory describing how Ap stars form and acquire their properties must be able to account for them. In particular, the very existence of a non-negligible population of long-period Ap stars and the absence of any indication of a discontinuity between this population and the bulk of the Ap stars represent strong evidence that the variations of these stars result from rotation, as in the shorter period stars (a point occasionally questioned in the past; see e.g. Scholz 1984). This view is also supported by more direct evidence, namely the observation in γ Equ (= HD 201601; $P \gtrsim 75$ yr) of the progressive rotation of the direction of the linear polarisation arising from the magnetic field (Leroy et al. 1994).

Admittedly, the systematic search for stars with magnetically resolved lines by Mathys et al. (1997) is prone to picking up a non-representative excess of very slow rotators, so that the fraction of periods longer than 30 days relative to shorter period stars is most likely exaggerated in the sample considered here. By contrast, the distribution of the periods above 30 days in this sample should in first approximation be fairly representative of their actual occurrence in nature. This distribution is consistent with an equipartition of the long periods (say, longer than 100 days) on a logarithmic period scale, or in other words, with a distribution decreasing exponentially with the period. On the other hand, for the two stars 33 Lib (= HD 137949) and γ Equ, one can currently give similar conservative estimates of the lower limit of the period, of the order of 75 year. This represents the largest value derived until now for periods of Ap stars. However, especially for 33 Lib, this value primarily arises from the timebase covered by the observations obtained so far. In on-going magnetic field studies, a couple of Ap stars that have been followed for more than 10 years have only recently started to show hints of some variations, not fully confirmed yet but likely real: it is not implausible that more stars with periods in the century range can be identified in the future.

The extraordinarily slow rotators appear particularly interesting because they represent the most extreme manifestation of the braking process that distinguishes Ap stars from normal A stars. One can hope to gain insight into this process by identifying other properties in which they are different from or more extreme than shorter period stars. This is not trivial, but a few statistical results in that direction have started to emerge in the past few years. Mathys et al. (1997) found that the mean magnetic field modulus (i.e., the line-intensity weighted average over the visible stellar hemisphere of the modulus of the magnetic vector) exceeds 7.5 kG in more than half of the Ap stars with resolved magnetically split lines that have a period shorter than 150 days, while in longer period stars, it is always smaller than 7.5 kG. On the other hand, Stępień & Landstreet (2002) argue that the magnetic fields of slowly rotating Ap stars are in average larger than those of Ap stars with typical rotation periods. This conclusion may be partly skewed, though, because for slow rotating Ap stars, magnetic field determinations have been performed almost exclusively for stars with a field strong enough to produce observable splitting of the spectral lines. A by-product of the study of Mathys et al. (1997), as yet unpublished, has been the identification from high resolution spectra of a subset of Ap stars with very low $v \sin i$ (hence likely to have long rotation periods) with magnetic fields too weak to affect significantly the line profiles in natural light. The magnetic fields of these stars have not been measured, but their inclusion in the statistics would lower the average field strength of the slow rotating Ap stars, bringing it closer to that of the faster rotators. Whether this would be enough to invalidate Stępień & Landstreet's claim or only temper it is unclear: quite possibly, there may be a deficiency of both weak fields and strong fields among stars with periods longer than 150 days.

The geometry of the magnetic fields of the long period Ap stars also appears to differ from that of their shorter period counterparts. Using simple field models consisting of the superposition of collinear dipole, quadrupole and octupole components, Landstreet & Mathys (2000) have shown that slowly rotating magnetic Ap stars tend to have their magnetic and rotation axes aligned to within about 20°, unlike the short period Ap stars, in which the angle between the two axes is usually large. With somewhat more realistic models, involving the superposition of a dipole and a quadrupole with arbitrary orientation, Bagnulo et al. (2002) reached essentially the same conclusion, namely that the angle between the dipole and the rotation axis tends to be small in slow rotators. Furthermore, they reported that the plane of the quadrupole and the plane defined by the dipole and the rotation axis are almost coincident in short-period stars, and preferentially orthogonal in long-period stars.

For the understanding of the origin of the braking mechanism that differentiates Ap stars from normal A stars, an important point that needs to be established is when this braking takes place. Is the slow rotation acquired in the protostellar phase, before the star arrives on the MS, or does braking take place during its MS lifetime? Historically, observational evidence has alternatively favoured one view or the other. An overview of this debate has been given by North (1998), who concluded from a new analysis of Ap Si stars, partly based on Hipparcos data, that there is no indication of any loss of angular momentum on the MS, hence that slow rotation is acquired before these stars arrive on the MS. For strongly magnetic Ap stars with masses below $3\,M_\odot$, that is, a sample that includes a large fraction of non-Si stars, Hubrig, North & Mathys (2000) did not find any correlation between between the rotation period and the fraction of the MS lifetime completed. This indicates that the slow rotation in these stars must already have been achieved before they became observably magnetic. The primary purpose of the latter work was to study the distribution of the Ap stars in the Hertzsprung-Russell diagram. While it is widely accepted that Ap stars are MS objects, it has long been debated whether they occupy the whole width of the MS, or if they are restricted to some part of it. Hubrig et al. (2000), who briefly review the main previous works on this issue, favour the latter view, as they conclude that magnetic Ap stars with masses below $3\,M_\odot$ are concentrated towards the centre of the MS band: they have completed at least 30 % of their MS lifetime. Accordingly, their progenitors should be observable as normal slowly rotating A stars (barring the unlikely existence of a mechanism able to brake them down in a very short time on the MS). Hubrig, North & Medici (2000) showed that unambiguous proof of the existence of these progenitors would require a much larger sample of stars with precise parallaxes than is available today. They found no statistically significant difference between the $v \sin i$ distributions of young and old A stars in the mass range 1.7 to $2.5\,M_\odot$.

Stępień (2000) has proposed a model of the spin down of a magnetic star, based on the assumption that rotational braking of Ap stars takes place during the pre-main sequence (PMS) phase. This assumption may or not be justified, since strongly magnetic stars of mass below $3\,M_\odot$ have not been definitely observed close to the zero-age main sequence (ZAMS). Stępień's model entails that loss of nearly all the angular momentum is only possible for stars with mass below $3\,M_\odot$, and it predicts, for the longest-period Ap stars, a quasi-alignment of the magnetic dipole and of the rotation axis (Stępień & Landstreet 2002).

One aspect that may also be relevant but has so far received little attention in attempts to explain the slow rotation of magnetic CP stars is their occurrence in binaries. The deficiency of short-period binaries (compared to normal A stars) and the lack of circularised orbits among magnetic CP stars, reported by Gerbaldi, Floquet & Hauck (1985), is fully confirmed by more recent studies (Leone & Catanzaro 1999; Carrier et al. 2002). Furthermore, Mathys et al. (1997) suggested that the deficiency of short-period binaries is even more pronounced among very slowly rotating Ap stars: of the 12 Ap stars with rotation period longer than 30 days known to be binaries, only one may have an orbital period (not yet unambiguously determined) shorter than 100 days. In other words, the effectiveness of the achievable rotational braking of Ap stars in binaries appears to be somehow related to the orbital period.

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The various aspects discussed above refer primarily to Ap stars proper. There is no indication that the magnetic He wk Bp stars have a significantly different behaviour than their cooler Ap counterparts, except for the absence of extremely long period stars among them. But the case of He str stars is less clearcut. Contrary to the Ap and He wk stars, in the $v \sin i$ distribution, they do not stand out as a distinct population (Abt et al. 2002). However, this may just reflect the fact that the frequency of occurrence of He str stars among B0–B2 MS stars is very low. This frequency is actually very uncertain.

Walborn's (1983) suggestion of a possible excess of fast rotators among He str stars has recently been dismissed by Zboril & North (1999), on the basis of their improved $v \sin i$ determinations. These authors report that no He str stars have $v \sin i > 130$ km/s, and that most of them have $v \sin i < 100$ km/s. They also show that the distribution of $v \sin i$ in He str stars is different from that in normal B0–B5 dwarfs (that is, He str stars rotate slower) at the 98 % confidence level. This conclusion is based on comparison with the "old" study of rotation in early B stars by Wolff, Edwards & Preston (1982), but there is no indication that it would be challenged if the recent work of Abt et al. (2002) was used as reference instead. Thus in terms of their rotation, the behaviour of the He str stars appears similar to that of the cooler magnetic CP stars. What is intriguing, though, is that the magnetic fields of He str stars either do not show any detectable variations or vary with periods close to 1 day (Bohlender et al. 1987; Matthews & Bohlender 1991). The only exception to this rule (leaving aside the cases of HD 125823 and HD 175362, two stars that are intermediate between He str and He wk) is HD 184927 ($P = 9\overset{\mathrm{d}}{.}53$). Taking into account the revised $v \sin i$ determinations of Zboril & North (1999), if the ~ 1 d variation periods are, like for cooler stars, interpreted as rotation periods, they seem to imply that the geometry of observation of (almost) all known variable He str stars is such that their rotation axis is nearly aligned with the line of sight. Along the same line, one could then assume that the He str stars with a constant field are seen rotation pole-on, and it would be tempting to conclude that the He str phenomenon is the result of a geometrical selection: the He str feature would only be observed in early B stars seen nearly pole-on. This would represent a significant difference between He str stars and cooler magnetic CP stars, since Abt (2001) showed that the rotational axes of the Ap stars proper are distributed randomly. On the other hand, in one case at least, HD 96446, the interpretation of the combination of short period and (very) low $v \sin i$ in terms of an ORM raises inconsistencies difficult to solve between various moments of the magnetic field (Mathys 1994). It may be worth considering critically alternative possibilities for the interpretation of the observed magnetic field variations of He str stars.

Leaving the He str stars aside, the validity of the ORM to interpret the variations of the magnetic CP stars has, with time, received growing support from an impressive amount of observations, and there is no question that this model adequately accounts for the general phenomenology of these stars. However, as observations of improving quality continue to be obtained over an increasing number of rotation cycles for some stars, some subtle, second-order effects start to be detected, which cannot be explained within the standard framework of the ORM. Pyper et al. (1998) reported the occurrence of a sudden, abrupt decrease in the period of CU Vir (= HD 124224) while Adelman et al. (2001) presented evidence that the rotation period of 56 Ari (= HD 19832) steadily increases at a rate of 2 s per 100 years. The interpretation of such changes is still unclear. A tentative explanation of the former in terms of torsional oscillations was proposed by Stępień (1998). Further progress on these novel aspects of the rotation of Ap stars will require additional observational data, on a larger number of stars, so that the systematics of the considered effects can be worked out.

3. Am Stars

Am stars occur between early F and early A spectral types. In their atmospheres, Ca (as well as Sc) is moderately underabundant, while iron-peak elements are slightly overabundant; the abundance anomalies in these stars do not exceed one order of magnitude with respect to the solar values. At the 100 G level, Am stars definitely do not have large-scale organised magnetic fields similar to those of the magnetic CP stars (Shorlin et al. 2002). It cannot be ruled out that they may have fields of kilogauss order with more complex configurations (Lanz & Mathys 1993; Savanov 1995), which would escape detection by spectropolarimetry. But too little is established so far on this matter to be of any use in the context of understanding the rotational properties of Am stars. These stars are not variable: knowledge of their rotation is achieved only through consideration of their $v \sin i$. The latter is always smaller than 120 km/s (Abt & Morrell 1995): Am stars are slow rotators.

Another difference between Am and magnetic CP stars, and possibly one of the keys to understanding their slow rotation, is that a large fraction of the Am stars are binaries, often with short orbital periods. The extensive investigation of binarity in Am stars conducted by Debernardi (2000) is not inconsistent with the view that there exists no single Am star. According to the same reference, the distribution of the orbital periods of Am binaries reaches its maximum at about 7 days, and the vast majority of the observed periods are shorter than 70 days. The eccentricity distribution shows that the circularisation orbital period is of the order of 7 days. It is tempting to ascribe slow rotation in Am stars to tidal braking. Budaj (1996) showed that synchronisation of rotation is a tenable interpretation for sufficiently short orbital periods. However, one can wonder how tidal braking would act in binary systems with periods longer than, say, a month. On the other hand, Budaj also argued that tidal effects may play a significant role in the development of the Am anomalies.

Most available evidence seems to favour the view that Am stars are generally somewhat evolved away from the ZAMS. This is supported by the fact that Am stars tend to appear more frequently in old open clusters than in younger ones (North 1993) as well as by indirect statistical arguments based on the hypothesis of orbital synchronisation in close binaries (Budaj 1996). However, from the consideration of Am stars with well determined Hipparcos parallaxes, North et al. (1997) conclude that Am stars are uniformly distributed across the whole MS width. In other words, the evolutionary status of the Am stars remains debated, so that it is impossible to ascertain if they underwent braking prior to arriving on the MS. There neither seems to have been any attempt to figure out if their rotational velocity changes during their MS life.

4. "Non-Magnetic" Bp Stars

We use the name "non-magnetic" Bp stars to refer to HgMn and He wk PGa stars. The most distinctive features of the former, which belong to spectral types between A0 and B7, are atmospheric overabundances of Hg (sometimes exceeding 5 dex) and of Mn (up to 3 dex). The latter are found between spectral types B6 and B4, and are characterised by a deficiency of helium and overabundances of P and Ga in their atmosphere. A number of arguments support the view that the He wk PGa stars are hotter analogs of the late B HgMn stars (Borra, Landstreet & Thompson 1983). In particular, neither the HgMn stars nor the He wk PGa stars have large-scale organised magnetic fields detectable through spectropolarimetry. For HgMn stars, upper limits for such fields have been brought down below 100 G (Shorlin et al. 2002). Like in the case of the Am stars, this does not definitely rule out the presence of more complex fields of kilogauss order, as suggested by the work of Hubrig and collaborators (see Hubrig & Castelli 2001 and references therein). This implies that HgMn stars may not be strictly non-magnetic: the denomination "non-magnetic Bp stars" should be understood in the "classical" sense, that is, as referring to the fact that these stars do not have fields detectable through spectropolarimetry. Again the evidence for magnetic fields in HgMn stars is currently too thin to allow discussion of a possible link between these fields and rotation. On the basis of indirect arguments, Hubrig & Mathys (1995a) had suggested that at least some chemical elements might be inhomogeneously distributed over the surface of these stars. But no variability had been definitely detected until very recently, when two groups (Wahlgren, Ilyin & Kochukhov 2001; Adelman et al. 2002) reported periodic line profile changes in the Hg II $\lambda\,3984$ line of α And (= HD 358). The mechanism appears to be the same as in magnetic CP stars: the distribution of Hg over the surface of α And is not symmetric about its rotation axis, which induces variations in the spectral lines as the star rotates. This makes α And the first HgMn star whose rotation period can be directly determined. One can hope that, in the future, it will be possible to detect similar variations in other HgMn stars, hence to determine their rotation period, which would allow one to carry out the same kind of analysis as for magnetic CP stars. For the time being, though, studies of the rotational properties of HgMn stars are limited to the consideration of their $v \sin i$. Among the 65 stars with Hg and/or Mn peculiarity for which $v \sin i$ has been determined by Abt & Morrell (1995) and by Abt et al. (2002), only 5 have $v \sin i > 65$ km/s, and only 2 have $v \sin i > 100$ km/s: HgMn stars rotate, in average, considerably more slowly than normal MS stars of similar temperature.

The fraction of spectroscopic binaries among HgMn stars may be as high as 2/3 (Hubrig & Mathys 1995b). About half of these binaries are double-lined systems (SB2). The majority of HgMn binaries have orbital periods shorter than 20 days, while none is known to have an orbital period shorter than 3 days (Hubrig & Mathys 1996). This is all the more remarkable since binary systems with orbital periods shorter than 3 days are common among late B stars. One can speculate that late B binaries with orbital periods shorter than 3 days must be synchronised, which confers to their components a rotation velocity too large to allow the development of abundance peculiarities. On the other hand, among the HgMn spectroscopic binaries studied in detail by Guthrie (1986), about 25 %

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have a HgMn primary rotating subsynchronously. Hubrig & Mathys (1995b) pointed out that several of these binaries in which the HgMn primary rotate subsynchronously are actually part of multiple systems (i.e., systems with more than two components). Hubrig (1998) presented additional evidence that HgMn stars comprise an unusually high fraction of multiple systems (see also Hubrig et al. 2001). She also noticed that every third multiple system with a primary in the spectral type range B6–B9 has a HgMn primary: this is to be compared with the overall fraction of HgMn stars in the same spectral range ($\sim$ 8 % in Abt et al. 2002) It seems unlikely that the association between multiplicity and HgMn stars be purely coincidental: this should be fully taken into account in theoretical efforts to explain the origin of the HgMn peculiarity.

According to North et al. (1997), HgMn stars are uniformly distributed across the whole width of the MS band. Some of the non-magnetic CP stars are definitely very close to the ZAMS: this is, for instance, the case of the HgMn eclipsing binary AR Aur, whose components rotate synchronously (Nordström & Johansen 1994), of the He wk Bp star HR 6000 (Andersen, Jaschek & Cowley 1984), and of a couple of HgMn stars (HD 27376, HD 29589) in the study of Hubrig et al. (2001). Such examples support the view that peculiarity and slow rotation in non-magnetic CP stars are achieved at the PMS stage.

5. Conclusion

The mechanisms by which slow rotation is achieved in A- and B-type CP stars are still poorly understood. While a significant number of relevant observational results have been obtained in recent years, further constraints are still needed to guide theoretical developments. A number of open questions that appear particularly timely and important to address have been identified in this review.

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