Stars and their variability observed from space
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EARLY-TYPE MAGNETIC STARS: THE ROTATION CHALLENGE

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Abstract. Large-scale organised magnetic fields of the order of kG are present in 5–10% of upper main-sequence stars. The rotation periods of those stars span up to five or six orders of magnitude, with no evidence for evolution besides conservation of angular momentum during their main-sequence lifetimes. Explaining how period differentiation over such a wide range is achieved in stars that are effectively at the same evolutionary stage represents a major challenge. To address it, improved knowledge of the distribution of the rotation periods is a pre-requisite. Space missions have already enabled considerable progress to be achieved in the study of periods of days to months, and they will continue to do so in the coming years. They can also contribute usefully to the identification of slowly rotating stars. However, ground-based observations lend themselves better to monitoring the longest periods. The most extreme among the latter, which may reach decades to centuries, are of particular interest, but constraining them is also the most challenging endeavour. Recent progress in this area is reviewed, and future prospects and concerns are discussed.

Keywords: Stars: magnetic field, Stars: rotation, Stars: early-type, Stars: chemically peculiar

1 Introduction

Large-scale organised magnetic fields of ∼100 to a few 10^4 G are present in 5–10% of the early-type stars. To first order, in almost all of them the predominant component of the magnetic field resembles a dipole whose axis is inclined at an angle β to the stellar rotation axis. Periodic magnetic variations are observed as the result of the changing aspect of the visible stellar hemisphere as the start rotates, but the fields do not show any intrinsic variations on time-scales of many stellar rotation periods. The magnetic fields of the early-type stars are generally believed to be fossil fields, that is, fields that were acquired at the time of the formation of the stars, or during their early pre-main-sequence evolution, and frozen in.

The magnetic early-type stars rotate more slowly on average than the non-magnetic stars of the same spectral types. Their rotation periods can be determined directly from consideration of their magnetic variations and/or of related variations of other observables, such as their magnitude in various photometric bands and the intensities of their spectral lines. Indeed, to a large extent, the magnetic field defines inhomogeneities of stellar properties such as brightness and elemental abundances over the stellar surface. These inhomogeneities also have a certain degree of symmetry about the magnetic axis, the magnetic early-type stars are oblique rotators. As a result, the changing aspect of the visible stellar hemisphere as the star rotates manifests itself observationally through strictly periodic photometric, spectroscopic and magnetic variations, whose single common period is the rotation period of the star.

The rotation periods of the magnetic early-type stars range from a fraction of a day to several centuries. To first order, their distribution is similar for the different types of magnetic early-type stars: the Ap and Bp stars, the early-type B stars, and the O-type stars (Shultz et al. 2018). The five to six orders of magnitude spanned by this distribution represent a major challenge for theory: how and when does the period differentiation take place? Answering this question is relevant for the understanding of the formation and evolution of *all* early-type stars.

The Ap (and Bp) stars constitute the best studied group of early-type magnetic stars. They were the first stars, apart from the Sun, in which magnetic fields were detected (Babcock 1947), and for several decades they remained the only non-degenerate stars in which the presence of such fields was definitely established. They still represent, by far, the largest fraction of the magnetic early-type stars that are known to this day, and the number of them whose rotation periods have been determined accurately vastly exceeds the number of other magnetic early-type stars with a known rotation period.

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This review therefore discusses relevant aspects of our current knowledge of the "classical" Ap stars, most of which have spectral types between F0 and B8, in relation to the challenge of understanding the differentiation of their rotation. To a large extent, the insight that is gained from consideration of these stars should be applicable to all magnetic early-type stars.

It has long been known that, as a group, Ap stars rotate more slowly than superficially normal stars with similar temperatures (e.g., Preston 1974, and references therein). The existence of Ap stars with very long periods, from more than 100 d to several years, was also recognised long ago (Preston 1970a). This realisation was made possible by the fact that Ap stars are oblique rotators. The anticorrelation between the variation period and the stellar equatorial velocity was demonstrated convincingly by Preston (1971).

That the rotation rates of the Ap stars can be determined directly from the observation of their periodic variations contrasts with the prevailing situation for most other stellar types, for which the knowledge of rotation is based on the consideration of the projected equatorial velocity, $v\,\sin i$, and is therefore limited by the ambiguity introduced through the inclination (i) of the rotation axis to the line of sight, since it is generally unknown. Furthermore, the lowest value of $v\,\sin i$ that can be determined reliably with a typical high-resolution spectrograph ($R \sim 10^5$) is of the order of $3\,\mathrm{km\,s^{-1}}$. For an Ap star, that corresponds to a rotation period that does not exceed ∼50 d. In what follows, we refer to Ap stars with rotation periods longer than 50 d as the 'super-slowly rotating' Ap (ssrAp) stars.

2 Period distribution

The number of Ap stars for which the rotation period is known has increased dramatically in recent years through the exploitation of the results of various photometric surveys. That includes both ground-based surveys such as ASAS-3 (Bernhard et al. 2015a; Hümmerich et al. 2016) and SuperWASP (Bernhard et al. 2015b), and space surveys such as *STEREO* (Wraight et al. 2012), *Kepler* (Hümmerich et al. 2018), and *TESS* (Sikora et al. 2019), for which data acquisition is still on-going and exploitation of the results is only starting. While the most recent systematic study of the distribution of the rotation periods of Ap stars (Netopil et al. 2017) confirms that the majority have rotation periods between 2 and 10 days, it also clearly shows an extended, nearly flat, tail of super-slow rotators. However, ivestiations of photometric variation are poorly suited to study this long-period tail, which (as explained above) is also beyond the reach of spectroscopic line-broadening studies.

With Doppler broadening below the spectroscopic resolution limit, the spectral lines of stars that have strong enough magnetic fields are resolved observationally into their magnetically split components. The wavelength separation is proportional to the mean magnetic field modulus $\langle B\rangle$, that is, the average over the visible stellar disk of the modulus of the magnetic vector, weighted by the local emergent line intensity. The value, already realised 50 years ago (Preston 1970b), of studying the rotational variation of $\langle B\rangle$ to constrain the geometrical structure of the magnetic fields of Ap stars, motivated the undertaking of systematic efforts to identify Ap stars with resolved magnetically split lines and to study the variations of their mean magnetic field moduli over their rotation periods (Mathys et al. 1997; Mathys 2017, and references therein).

While the existence of ssrAp stars had already been recognised by Preston (1970a), the number of such stars that were known remained small for a long time. Many more have been identified in the past two decades, mostly among the newly found stars with magnetically resolved lines. The majority of the latter are genuine slow rotators (as opposed to faster rotating stars seen at a low inclination angle i). From consideration of the distribution of their periods, Mathys (2017) concluded that several percent of all Ap stars must have rotation periods longer than 1 yr, that the periods of some of them must definitely be of the order of 300 yr, and that there may even exist Ap stars with much longer rotation periods, perhaps ∼1000 yr or more. Since the periods of the fastest rotating Ap stars are of the order of half a day (Netopil et al. 2017), this implies that the rotation periods of the Ap stars span five to six orders of magnitude.

Ap stars lose at most a small amount of their angular momentum on the main sequence (Kochukhov & Bagnulo 2006; Hubrig et al. 2007). The evolutionary changes of their rotation periods during their main-sequence lifetimes do not exceed a factor of 2, so the differentiation of their periods must mostly have been achieved before they arrived on the main sequence, or even before their progenitors become observable as magnetic Herbig Ae/Be stars (Alecian et al. 2013). The way in which this happens is unclear, and more observational constraints are needed to guide the theoretical developments. The differentiation of the rotation in Ap stars is potentially one of the main keys to the understanding of their origin and of the origin of their magnetic fields.

Within this context, the study of the ssrAp stars is particularly valuable, not only to characterise better the long-period tail of the distribution of the rotation periods, but also because, as the most extreme examples of the slow rotation of Ap stars, they have the potential to provide the most valuable insight into the mechanisms responsible for this generic property of the class.

3 The longest periods

The first determination of the period of variation of an Ap star (α^2 CVn = HD 112413, $P_{\mathrm{rot}} = 5.5$ d) was achieved just over one century ago (Belopolsky 1913). Hardly more than 70 years have elapsed since the first detection of a magnetic field in a star of this type (78 Vir = HD 118022, Babcock 1947). It has been almost 50 years since Preston (1970c) compiled the first list of Ap stars that may have long periods, raising the interest in studying such stars. The systematic study of the Ap stars with resolved magnetically split lines led to the conclusion that the ssrAp stars represent a more considerable fraction of the Ap population than was generally believed until then (Mathys 2017). The initiation of this project itself arose from the realisation a little more than 25 years ago of the potential interest of the many Ap stars with magnetically resolved lines that had not been identified yet, much less studied in detail (Mathys & Lanz 1992). These time-scales are longer than the time-bases over which observations have been obtained until now for most ssrAp stars, but still considerably shorter than the rotation periods of many of them. Accordingly, to date only a limited fraction of the super-slow rotators have been observed over a full cycle (or more), making an accurate determination of their rotation periods possible. For the others, still in majority, only lower limits of the periods are currently known, and those must be of the same order as the time-base of the available observations.

More specifically, to the best of our knowledge accurate periods have been determined for 33 ssrAp stars (Mathys 2019). Eight of those periods are longer than 1000 d (Mathys et al. 2019c); the 29 yr period of HD 50169 (Mathys et al. 2019a) is the longest of them. This is at least ten times shorter than the period lengths of 300 yr or more whose occurrence appears inescapable from statistical arguments (Mathys 2017). Among the stars for which only a lower limit of the value of the period is known until now, HD 201601 (= γ Equ) has been monitored for the longest time; the available magnetic measurements span $\sim$70 years. Extrapolating from them suggests that the rotation period of this star cannot be significantly shorter than 97 yr (Bychkov et al. 2016). Consideration of these numbers emphasises the incompleteness of our current knowledge of the distribution of the periods of the most slowly rotating Ap stars. Progress in this area will, by nature, be incremental, because the only way to increase the time base over which relevant observations are available is to await the passage of time. But as observations covering a full rotation cycle are obtained for a growing number of stars, each increase in the value of the longest accurately-determined period will be of the order of a few years. However, in the meantime, it should be possible, and valuable, to improve considerably our knowledge of the distribution of the less extreme rotation periods – say, between 50 days and ten years.

Of the 33 ssrAp stars whose rotation periods have been determined accurately, 18 show resolved magnetically split lines. The spectral lines of another four are definitely very sharp, and do not show any hint of resolution into their magnetic components. We could not find any published measurements of the magnetic field of the remaining 11 stars, nor any high spectral-resolution observation in public observatory archives. The longest rotation period that has been derived to date for an Ap star in which magnetically resolved lines have not been observed (yet) is 236.5 d. The 13 longest periods that have been determined accurately to this day pertain to Ap stars with resolved magnetically split lines. There are different factors that may account for this situation, either individually or in combination with each other.

The vast majority of the known rotation periods of Ap stars have been determined through analyses of their photometric variations. As already stated, this technique is ill-suited for long periods. The latter are best derived from consideration of the variations of the mean magnetic-field modulus, or of the mean longitudinal magnetic field ($\langle B_z \rangle$, the line-intensity weighted average, over the visible stellar disk, of the component of the magnetic vector along the line of sight), or of both. Indeed the ratio of the amplitude of variation of these field moments to the uncertainties affecting their measurements is in general much higher than the ratio of the photometric variation amplitudes to the photometric measurement errors. Furthermore, the magnetic measurements are seldom affected by long-term drifts or other lack of reproducibility that tend to occur frequently in photometric observations. This is especially true for $\langle B \rangle$ determinations, which are obtained from straightforward measurements of relative wavelength shifts of line components in classical high-resolution spectra. As $\langle B_z \rangle$ is diagnosed from the circular polarisation of spectral lines, the derived values may occasionally be affected by systematic instrumental effects, especially when combining observations obtained with different instruments. But for slowly rotating stars, these systematic effects tend to be limited and are often considerably smaller than the variation amplitudes.

Naturally, the stronger the magnetic field, the easier its detection and the higher the relative precision with which it can be measured. Therefore, using magnetic variation curves to constrain the rotation periods of the most strongly magnetic Ap stars is particularly convenient. Conversely, the scientific interest of Ap stars with spectral lines resolved into their magnetically split components and the systematic efforts that were made to identify and study such stars (see Sect. 2) led to the discovery of a large number of super-slow rotators, whose sometimes extremely long periods rather exceeded expectation. Undoubtedly, the combination of these two factors implies that the distribution of the magnetic fields in the ssrAp stars that are currently known is significantly biased towards the stronger ones. However, this does not rule out the possible existence of a difference between strongly and weakly magnetic Ap stars with respect to the rate of occurrence of super-slow rotation. In the course of our systematic search for Ap stars with resolved magnetically split lines, we identified a considerable number of stars whose spectral line profiles hardly differ, if at all, from the instrumental profile of the spectrograph used for their observation. In other words, the spectra of those stars do not show any significant Doppler or magnetic line broadening. If – as appears to be the case for Ap stars with magnetically resolved lines – the inclination angles of the rotation axes of these stars with respect to the line of sight are random, then the majority of them must be super-slow rotators. These stars may potentially represent a significant fraction of the group of ssrAp stars, which has been mostly overlooked until now. The distribution of their rotation periods may or may not be similar to that of their more strongly magnetic counterparts. In particular, the question is open as to whether some of the weakly magnetic stars have periods reaching several hundred years. This question is particularly relevant in relation to the apparent exclusion of very strong magnetic fields in Ap stars whose rotation periods exceed ∼150 d, for which very strong statistical evidence was presented by Mathys et al. (1997) and by Mathys (2017).

More generally, any correlation that may exist between the rotation period and the magnetic properties of the ssrAp stars may potentially provide essential clues for the theoretical understanding of the formation and evolution of these stars. This requires the distribution of the rotation periods to be constrained across the whole range of magnetic field strengths, including the lowest ones. Together with S. Hubrig, we recently recorded circularly polarised HARPS spectra of a number of the above-mentioned Ap stars with very sharp, unresolved lines that we had identified in our systematic search for Ap stars with resolved magnetically split lines. All of them show very definite Stokes V signatures, which confirmed fully the feasibility of using the variations of their mean longitudinal magnetic fields to constrain their rotation periods. We are now preparing to undertake a project to carry out systematic, multi-epoch $\langle B_z \rangle$ determinations of all the known Ap stars with sharp, unresolved spectral lines, with a view to constraining the distribution of their rotation periods.

4 Rate of occurrence of super-slow rotation

Our current knowledge of the overall rate of occurrence of ssrAp stars is limited by the biases affecting the existing studies of the longest period stars, which were discussed in Sect. 3. This has significantly hampered theoretical developments, as a complete and accurate knowledge of the distribution of the rotation periods represents an essential constraint for the models. The *TESS* Mission has presented an opportunity to overcome those biases to a large extent. Indeed, an exhaustive list of Ap stars was proposed for observation by *TESS* during the nominal mission (Cunha et al. 2019). Ultimately not all were observed, but the selection was based on the overall priorities of the mission, not on the properties of the Ap targets, so it is unbiased with respect to those properties. ny inference about the longest-period Ap stars that is derived from the *TESS* observations is representative of their actual rate of occurrence. In particular, all stars are dealt with in the same way, regardless of the strengths of their magnetic fields. This ensures that weakly magnetic stars are duly included in the statistics.

As part of a project in collaboration with D. Kurtz and D. Holdsworth, we have started to identify the Ap stars that do not show evidence of photometric variations of rotational nature in the 27-d-long data sets recorded in each of the *TESS* sectors. The vast majority of these stars very probably have rotation periods considerably longer than 27 d. The main exceptions should be the ones whose rotation axis lies almost exactly along the line of sight. There should be very few such stars; under the assumption that the inclination angles of the rotation axes with respect to the line of sight are random, these angles would be less than 5° for less than 1% of the stars. We checked that the adopted strategy identified successfully almost all the known ssrAp stars present in the fields observed. The rare exceptions all seemed to be cases where apparent variations with periods shorter than 27 d that were detected by *TESS* could plausibly be attributed to contamination by the light of another, unresolved, neighbouring source.

We propose to record high-resolution spectra of all the new long-period candidates identified through the search described above, in order to confirm that they are Ap stars with low projected equatorial velocities. The resulting sample will presumably include a mix of stars with resolved magnetically split lines corresponding to a range of field strengths and of stars showing sharp spectral lines with little or no evidence of a magnetic effect. Further follow-ups of these stars will be carried out to constrain their rotation periods. Ultimately, this study will enable us to characterise the distribution of the ssrAp stars both in terms of period and in terms of magnetic field strength.

5 Final remarks

How the differentiation of the rotation rates of the Ap stars over five to six orders of magnitude is achieved is one of the outstanding unsolved questions of stellar physics. Answering it is essential for understanding the formation of these stars, and the origin of their magnetic fields. More generally, it is relevant for the knowledge of the physical processes that are at play in the formation and evolution of all the early-type stars. This relevance is emphasised by the similarity, recently evidenced, between the distributions of the rotation periods of Ap (and Bp) stars, the magnetic early B-type stars and the magnetic O stars (Shultz et al. 2018).

Knowledge of the distribution of the rotation periods of Ap stars, and in particular of its long-period tail, is essential as input for theoretical developments aimed at explaining the evolution of rotation in these stars. In recent years, the exploitation of the results of several extensive ground- and space-based photometric surveys has led to a considerable increase in the number of well-determined short periods of up to 2–3 weeks. The corresponding part of the distribution is, accordingly, very well defined. By contrast, for more slowly rotating stars the current knowledge of the period distribution remains biased and incomplete.

Some of these shortcomings can now be addressed. This presentation has showed how the “non-variable” Ap stars in the *TESS* database can be exploited to constrain the rate of occurrence of ssrAp stars. In particular, considering them will allow us to identify, and to characterise, the weakly magnetic ssrAp stars, which to date have never been studied systematically. This represents a good illustration of the way in which advantage can be taken of observations from space in order to complement ground-based studies and provide valuable additional scientific insight besides the obvious straightforward exploitation of space-based photometric surveys for systematic determinations of short to intermediate periods for large samples of stars.

However, for the longest periods there is a fundamental limitation that can only be overcome by the passing of time. Namely, no period can be determined accurately that is longer than the time-base over which suitable observations of the star of interest have been obtained. Currently, the longest period that has been determined accurately is that of HD 50169, $P_{\rm rot} = 29\,{\rm yr}$. Most likely, the star that will some day overturn HD 50169 as the longest-period Ap star with full coverage of the variation curve of one of its observables will only have a rotation period a few years longer. Such increments are small compared to the century-scale periods of the most slowly rotating stars. With respect to the latter, we are responsible for ensuring that no gaps are left in the coverage of their variation curves. Decades or centuries may elapse before a critical phase that is missed now can be re-observed.

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