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Periodic Variability on Time-scales of Decades to Centuries in Magnetic Ap Stars: Challenges and Strategies

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Abstract. Recent studies have revealed the existence of a significant population of Ap stars with extremely long rotation periods, and the frequent occurrence of Ap stars in wide binaries. Those results represent new constraints on the understanding of the origin and evolution of Ap stars, and (by extension) of all upper-main-sequence stars. Current knowledge of Ap stars with the longest rotation and orbital periods remains incomplete, on the one hand because in many cases the periods of interest are longer than the time-spans over which relevant observations have been obtained, and on the other hand because some important subsets of Ap stars have been omitted from the studies that have been carried out until now. Additional observations over time-scales of decades to centuries are needed to complement the current incomplete picture. Securing them with the required accuracy and time coverage, and ensuring that their full exploitation will ultimately be possible, represents a unique challenge in time-domain astronomy.

Keywords. Stars: chemically peculiar, stars: rotation, stars: magnetic fields, binaries: general

1. Introduction

Between 5 and 10% of the main-sequence stars between spectral types late-B and early-F are classified as Ap stars, on account of the anomalous strengths of the lines of a number of chemical elements (such as He, Si, Sr, Cr, and the rare earths) in their spectra. The anomalous line strengths reflect under- or over-abundances of those elements in the stellar photospheres, and result from the competing actions of various chemical segregation processes inside those stars, including radiative diffusion and gravitational settling.

The Ap stars host magnetic fields with strengths ranging from several hundred Gauss to several kiloGauss. The fields cover the entire stellar surface and show a significant degree of large-scale organization. They bear some resemblance to a single dipole, and are roughly symmetrical about an axis inclined to the stellar rotation axis. Accordingly, their strength and orientation, averaged over the visible stellar disk, are seen to vary with the rotation period of the star; Ap stars are oblique rotators.

The elemental abundances and the brightness of Ap stars are non-uniform over the surface, with a distribution that mirrors to some extent the structure of the magnetic field. As a result, spectroscopic and photometric variations with the rotation period are also observed in Ap stars.

The magnetic, spectroscopic and photometric variations shown by Ap stars as the result of their rotation are strictly periodic. In particular, no intrinsic variations of the magnetic field have been detected so far in any of them. That stability strongly supports the view that the magnetic fields of Ap stars were acquired or generated during their formation and/or their early evolution: they are frozen-in fossil fields. The mechanisms responsible (and which are still debated) for the acquisition and/or the generation of those fields are important for understanding the formation and evolution of all upper main-sequence stars.

More generally, the origin of Ap stars and the reasons for the existence of this group of stars that are strongly different from the bulk of the main-sequence stars in the same temperature range remain unknown. Solving that enigma requires several open questions about Ap stars to be answered (e.g., Braithwaite & Spruit 2017, and references therein). For example, why do only 5–10% of the main-sequence stars in the late-B to early-F range have large-scale organized magnetic fields and the related non-uniform surface abundance anomalies and brightness just described? Why do Ap stars rotate more slowly on average than normal stars of similar temperatures? Why are there no Ap binaries with orbital periods shorter than 3 days?

2. Ap Star Rotation

The Ap stars are also often referred to as α^2 CVn variables, in acknowledgement of the fact that α^2 CVn was the first star of that class in which variations were detected and characterised, by Belopolsky (1913), who determined its rotation period $P_{\rm rot} = 5.50$ d. That value of the rotation period is typical for an Ap star; the distribution of the values of the rotation periods of those stars peaks abruptly between 1 and 10 days, with a median value of 3–4 d (Mathys 2004).

However, it has been known for almost 50 years that some Ap stars show variations with periods of several years (Preston & Wolff 1970; Wolff & Morrison 1973). By 1975, 11 Ap stars were known to have periods longer than a month, 5 of which appeared to have periods longer than 3 years (Wolff 1975). Nevertheless, for only one of the latter set (HD 187474) was the period (6.4 y) determined exactly. For the other four, only lower limits could be set as the available observations covered a time-span shorter than the periods of variation. In fact, whether the observed long-term variations were periodic at all could even be questioned.

30 years later, 18 Ap stars with periods longer than a month were known, of which 10 appeared to have periods longer than 3 years (Mathys 2004). 3 of those longer periods had also been determined, the longest one reaching 21.7 y. Only lower limits were set for the remaining 7.

At present, the number of Ap stars known to have periods longer than a month reaches 33, and 17 of them appear to have periods longer than three years (Mathys 2017). For 5 of the latter, the exact value of the period has been published, and we expect 2 more to be confirmed soon. That will raise the value of the longest period that is known exactly to ~ 30 y. Of the lower limits that have been set for the other stars, the highest one is 97 y (Bychkov *et al.* 2016), for the star γ Equ. Obviously, the level to which upper limits can be set is defined by the time-span over which suitable observations are collected. While – as mentioned above – the periodic variability of Ap stars was first recognised more than a century ago (in 1913), it was much later before observations lending themselves to long-term variability studies through both their type and quality started to be obtained: a little more than 60 years ago for γ Equ, and ∼20 years ago or less for most Ap stars with extremely long periods.

Early on, when only a handful of Ap stars showing very slow variations was known, one could wonder legitimately if the observed variations, like those of the short-period Ap stars, were due to the changing aspect of the visible hemisphere of the star as it rotated, or if they were of a different nature (e.g., Scholz 1983). It is now beyond question that the stars with extremely long periods are not odd, isolated specimens, but an integral part of the Ap population of which they represent a significant fraction, and that, like

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their shorter-period counterparts, they are oblique rotators whose non-uniform surface properties cause the observed variations (Mathys 2015).

Most of the Ap stars with periods longer than a month that are known today show spectral lines resolved into their magnetically-split components. A systematic study of the stars with magnetically resolved lines suggests that more than 50 of them should have rotation periods longer than a month. It also indicates that several Ap stars must definitely have rotation periods of the order of 300 y, and that some may have periods of 1000 y or more (Mathys 2017).

The frequency of occurrence of extremely long rotation periods among Ap stars is almost certainly underestimated at present, as the known population of such stars is heavily biased towards those that have magnetic fields strong enough to show spectral lines resolved into their magnetically-split components. Only 4 of the 35 stars with rotation periods longer than a month known to date do not show magnetically-resolved lines in their spectra. That is almost certainly a selection effect, as very long periods are best determined from magnetic-field measurements, and as most long-term systematic studies of Ap stars are restricted to stars with strong fields. That bias needs to be addressed in the future, the more so since systematic differences in magnetic properties have been identified between the Ap stars with the longest periods and those that are rotating faster. In particular, magnetic fields stronger than ~ 7.5 kG do not seem to be found in stars with $P_{\rm rot} > 150$ d, while a large fraction of Ap stars with shorter rotation periods have stronger fields (Mathys 2017).

3. Ap Stars in Wide Binaries

Recent studies have identified a dozen Ap binaries with orbital periods of the order of 3 years or longer (Carrier *et al.* 2002; Bailey *et al.* 2015; Mathys 2017). This establishes the existence of a significant population of Ap stars in wide binaries, which had not previously been identified. As for the extremely long rotation periods, several of the long orbital periods have not yet been determined exactly; only lower limits have been set, as the period length exceeds the time-span over which relevant observation have been obtained. Moreover, the sample of Ap stars in wide binaries that are currently known is strongly biased towards the slowly rotating Ap stars. Not only have the latter been the privileged targets of long-term spectroscopic monitoring for the study of their rotational variations, but they also lend themselves better to the very precise radial-velocity measurements required for characterising wide orbits. A systematic investigation of the rate of occurrence of faster-rotating Ap stars in wide binaries is definitely needed, but determining radial velocities with the required precision from spectral lines that are [Doppler] broadened by rotation represents a considerable challenge.

Intriguingly, the rotational and orbital periods of Ap stars appear to be connected. Barring synchronisation, Ap components with 'short' rotation periods ($P_{\rm rot} < 50$ d) are found only in binaries with very long orbital periods ($P_{\rm orb} > 1000$ d), and conversely, when a binary containing an Ap component has a 'short' orbital period ($P_{\rm orb} < 1000$ d), the rotation period of the Ap component is long ($P_{\rm rot} > 50$ d) (Mathys 2017). This connection must be the result of the processes that take place in the formation and early evolution of Ap stars. However, its implications for our understanding of those stages of the stellar life still remain to be worked out.

4. The Time-Domain Challenge

The existence of significant populations of Ap stars with extremely long rotation periods and in wide binaries, and the intriguing correlations found between orbital period, rotation period and magnetic properties in Ap stars are key to our understanding of the

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origins of the chemical peculiarities of those stars, and thence to the eventual elucidation of the manner in which stars evolve through that core stage. To gain that further insight, continued study of the variability of Ap stars with the longest rotation and/or orbital periods is recognised as essential.

The underlying requirement for such studies is that measurements be secured over time-scales of decades to centuries, and that those measurements eventually be combined in a meaningful manner. That implies that the instruments used for such studies achieve a sufficiently high level of stability. Furthermore, as the time-scales of interest may be longer than the lifetimes of many instruments, instruments from different generations need to deliver data that are uniform enough and/or sufficiently well calibrated that they can be compared to, and combined with, each other. In addition, adequate archiving facilities are needed in order to ensure that the relevant data are preserved and remain accessible over the relevant time-scales. However, perhaps the most challenging aspect of all is securing the willingness of observatory directors and Time Allocation Committees to commit small but sufficient continuing observing resources to (very) long-term projects with limited prospects of fast publication of results. Raising awareness of the universal astrophysical value of such projects will translate into the recognition of our responsibility towards future generations to get them started *now* and to ensure their pursuit without undue interruption.

One of the most important, if slightly surprising, take-home messages from this Symposium is the fact that the time domain involves not only the detection of transient variations, however exotic, with very short time-scales, but also the monitoring of very long-term variability in more easily observable objects, and moreover that rich new science can be expected from both types of scale.

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