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Extremely slowly rotating magnetic Ap stars: recent results

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Abstract. I show that the properties of the magnetic fields of Ap stars with extremely long rotation periods are different in several respects from those of shorter period Ap stars.

Key words: stars: chemically peculiar – stars: magnetic field – stars: rotation

1. Introduction

Starting in 1990, together with several collaborators, I undertook a systematic effort to identify and study Ap stars showing spectral lines resolved into their magnetically split components (Mathys, 1990; Mathys, Lanz 1992; 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. Nowadays, more than 10% of the Ap stars with known periods have periods longer than 100 days (Mathys 2004). 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.

The extremely 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 or more extreme than shorter period stars. Here I shall pay particular attention to the relation between some magnetic properties of the Ap stars and their rotation periods.

This study is based on the analysis of 1023 measurements of the mean magnetic field modulus $\langle H \rangle$ of 43 Ap stars with resolved magnetically split lines. This is an augmented version of the data set considered by Mathys *et al.* (1997), based on similar observations, from which the field modulus was determined in the same manner. This data set is complemented by 232 measurements of the mean longitudinal magnetic field $\langle H_z \rangle$ of 34 of these 43 stars. The $\langle H_z \rangle$ determinations are based on spectra recorded in both circular polarisations with the CASPEC spectrograph fed by the ESO 3.6 m telescope, in its post-1995 configuration as described by Mathys and Hubrig (1997), using the same field diagnosis method as these authors. More details about these measurements of

$\langle H_z \rangle$ and the new measurements of $\langle H \rangle$ will be published in a paper currently in preparation.

2. Results

In order to characterise the intensity of the magnetic field of a given star with a single number, I use the average of all the measurements of its mean magnetic field modulus, $\langle H \rangle_{\rm av}$. This is justified by the fact that $\langle H \rangle$ depends little on the geometry of the observation (the angle between the magnetic axis and the line of sight), and that in most cases, its amplitude of variation is fairly small compared to its average value.

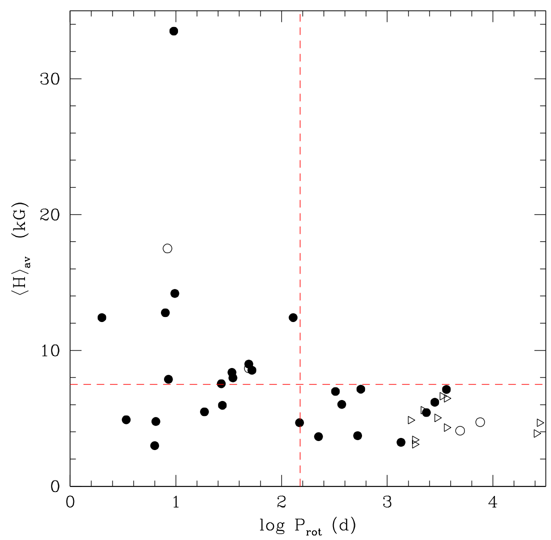

Figure 1. Observed average of the mean magnetic field modulus against rotation period. *Dots*: stars with known rotation periods; *triangles*: stars for which only the lower limit of the period is known. *Open symbols* are used to distinguish those stars for which our measurements do not cover the whole rotation cycle. The horizontal and vertical dashed lines, corresponding resp. to $\langle H \rangle_{\rm av} = 7.5\,$kG and to $P_{\rm rot} = 150\,$d, emphasise the absence of very strong magnetic fields in the stars with the slowest rotation (see text for details).

In Figure 1, $\langle H \rangle_{\rm av}$ is plotted against the rotation period $P_{\rm rot}$ for those stars of the sample for which the latter, or at least a lower limit of it, could be determined. This figure, which is an updated version of Fig. 50 of Mathys *et al.* (1997), fully confirms the result inferred from the latter, that very strong

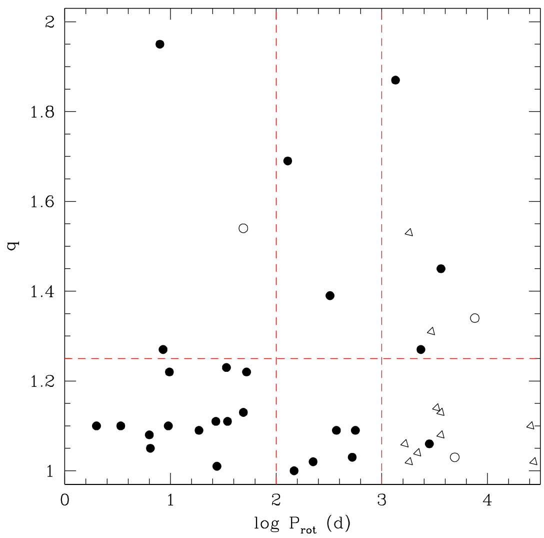

Figure 2. Ratio q of the observed extrema of the mean magnetic field modulus against rotation period. *Dots*: stars with known rotation periods; *triangles*: stars for which only the lower limit of the period is known. *Open symbols* are used to distinguish those stars for which our measurements do not cover the whole rotation cycle. The horizontal and vertical dashed lines emphasise the tendency for larger values of q to have a higher rate of occurrence in the stars with the slowest rotation.

magnetic fields ($\langle H\rangle_{\rm av} \gtrsim 7.5\,$kG) are found only in stars with rotation periods shorter than ~ 150 days. This result is visually emphasised in the figure by the dashed lines: the horizontal one corresponds to $\langle H\rangle_{\rm av} = 7.5\,$kG, and the vertical one to $P_{\rm rot} = 150\,$d. The representative points of 40 stars appear in Fig. 1. 19 of them correspond to stars with $P_{\rm rot} < 150\,$d, of which 13 have $\langle H\rangle_{\rm av} > 7.5\,$kG. By contrast, none of the 21 stars with $P_{\rm rot} > 150\,$d has $\langle H\rangle_{\rm av} > 7.5\,$kG. The difference between the two groups is highly significant.

To characterise the variability of the mean magnetic field modulus, I use the ratio q between its observed extrema. One can find in Fig. 2 some hint that high relative amplitudes of variation of $\langle H\rangle$ are found more frequently in stars with very long periods. In order to help the eye to visualise this, two dashed lines were drawn in Fig. 2: one, horizontal, at $q = 1.25$; the other, vertical at $\log P_{\rm rot} = 2.0$. Among the 17 stars with $P_{\rm rot} < 100\,$d, only 3 have $q > 1.25$. By contrast, 8 of the 16 stars with $P_{\rm rot} > 100\,$d have $q > 1.25$. The evidence is less compelling than for the above-mentioned absence of very strong fields in very slowly rotating stars, but the high rate of occurrence of large relative amplitudes of $\langle H\rangle$ variations among the latter nevertheless seems significant, especially if

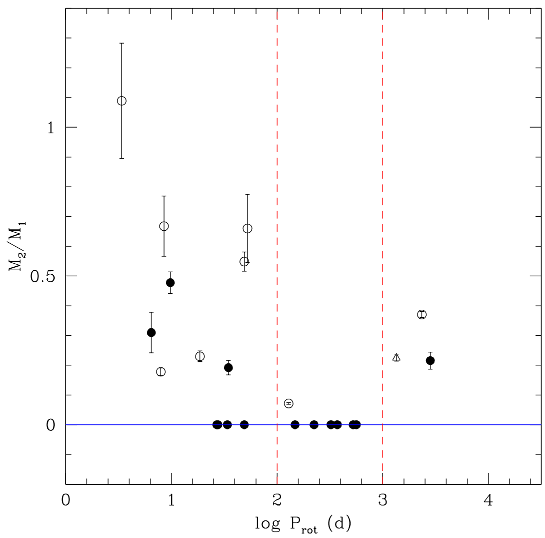

Figure 3. Ratio M_2/M_1 of the fit coefficients of the variations of $\langle H\rangle$ against rotation period. *Open circles*: stars showing $\langle H_z\rangle$ reversal; *dots*: stars in which $\langle H_z\rangle$ has a constant sign; *open triangle*: star for which no $\langle H_z\rangle$ measurements exist.

one considers that for the stars that have not been observed yet throughout a whole rotation cycle, the values of q adopted here are lower limits.

In order to explore the dependency on rotation period not only of the amplitude of the curve of variation of the field modulus, but also of its shape, we have in Fig. 3 plotted against rotation period the ratio M_2/M_1 of the fitted amplitude of the harmonic to that of the fundamental in a fit of the $\langle H\rangle$ data by a function of the form:

$$\langle H\rangle(\phi) = M_0 + M_1\,\cos[2\pi\,(\phi - \phi_1)] + M_2\,\cos[2\pi\,(2\phi - \phi_2)]\,. \qquad (1)$$

Zero values of this ratio correspond to the cases where the measurements are adequately represented by a single sinusoid. The pattern that appears in Fig. 3 is intriguing. The curves of variation of $\langle H\rangle$ show a significant degree of anharmonicity for the majority of the stars with $P_{\rm rot} < 100$ d (but not for all of them). For rotation periods between 100 and 1000 days, the variation curves are mostly sinusoidal. For the three stars with $P_{\rm rot} > 1000$ d for which we have accumulated enough data to fully define the shape of the $\langle H\rangle$ variation curve, a significant first harmonic is present in the fits.

The interpretation of the observed pattern is not straightforward, especially since the observation of a contribution of the first harmonic in the variations of the field modulus may reflect two opposite situations. Let us illustrate this through consideration of the case of the simplest magnetic geometry, a centred dipole. If both poles come alternatively into view as the star rotates (hence if the longitudinal field reverses its sign over the rotation period), the $\langle H \rangle$ variation curve is a perfect double wave, that is, a sinusoid with twice the rotation frequency of the star, with no contribution of the fundamental. By contrast, if the angle between the rotation axis and the line of sight is small, or if the angle between the magnetic and rotation axes of the star is small, so that the same pole remains visible at all times, the shape of the variation of $\langle H \rangle$ is a sinusoid with the rotation period of the star. Therefore, in order to gain further insight, we have used different symbols in Fig. 3 to distinguish those stars where a sign reversal of $\langle H_z \rangle$ is observed (*open circles*) from those where $\langle H_z \rangle$ is found to have always the same sign (*dots*). For one star, HD 59435 (*open triangle*), no longitudinal field determination exists. Then, a clearcut result appears: all the stars in which the field modulus variations show no significant deviation from a sinusoid have a non-reversing longitudinal field. This implies that strong anharmonicity in the $\langle H \rangle$ curve is associated with a large value of the angle β. The pattern apparent in Fig. 3 can accordingly be related to the conclusion reached by Landstreet and Mathys (2000), that magnetic Ap stars with long rotation periods (greater than a month) have their magnetic and rotation axes nearly aligned, unlike shorter period Ap stars, in which the angle between these two axes is usually large. With respect to these earlier results, a hint of a trend that has been unnoticed so far appears in Fig. 3. Namely, while the rate of occurrence of large values of β is higher for rotation periods shorter than 100 days than for periods between 100 and 1000 days, the figure suggest that this rate increases again for periods longer than 1000 days. This suspicion is made considerably stronger if one also takes into account that the following long-period stars, which have not been observed over a full rotation period yet, definitely have reversing longitudinal fields: HD 965 ($P_{\rm rot} \gg 10\,$y; the field modulus variation curve is strongly anharmonic), HD 9996 ($P_{\rm rot} \sim 21\,$y), HD 166473 ($P_{\rm rot} \gtrsim 10\,$y), and HD 201601 ($P_{\rm rot} \geq 70\,$y). Furthermore, it is almost certain that the longitudinal fields of HD 29578 ($P_{\rm rot} \gg 5\,$y) and HD 50169 ($P_{\rm rot} \gg 8\,$y) must also be reversing.

Thus, a revised picture of the relation between the inclination angle of the magnetic axis with respect to the line of sight and the rotation period of magnetic Ap stars emerges: for "short" periods ($P_{\rm rot} \lesssim 100\,$d) and for extremely long periods ($P_{\rm rot} \gtrsim 3\,$y), there is a high rate of occurrence of large values of β, while for intermediate periods ($100\,$d $\lesssim P_{\rm rot} \lesssim 1000\,$d), the magnetic and rotation axes tend to be almost aligned.

Finally, in a significant fraction of the studied stars, the mean magnetic field modulus is observed to show much shallower variation close to the phase of its minimum than around its maximum; actually it is not unusual for the $\langle H \rangle$ variation curves, to have broad, more or less flat minima. By contrast, so far, no star was observed to show a broad, shallow maximum of the field modulus and a narrower, steeper minimum. This probably indicates that it is frequent for Ap stars to have a fairly uniform magnetic field (such as a global dipole) covering the largest part of their surface, with one rather limited region ("large spot") of considerably higher field. In this "spot" the field must have considerably more small-scale structure than in the rest of the star, since its signature is not readily seen in the longitudinal field variation. The opposite topology, a star with a "large spot" that has a lower field than the surroundings, does not seem to occur commonly. If this interpretation is indeed correct, it suggests that models based on low-order multipole expansions are unlikely to provide a very good representation of the actual field geometries.

The frequent occurrence in the $\langle H \rangle$ variation curves of nearly flat minima extending over a broad phase range implies that the probability to observe a star when its field modulus is close to its minimum value is, in general, significantly higher than close to its maximum value.

3. Conclusion

In this study, several relations between the properties of the magnetic fields of the very slowly rotating Ap stars and their rotation periods were identified; some of them confirm or refine the conclusions of previous works. Namely, (i) extremely strong magnetic fields (in excess of 7.5 kG) do not occur in extremely slowly rotating stars (with periods longer than 150 d); (ii) the angle between the rotation axis and the axis of the dipole-like component of the magnetic field is large in "fast" rotators ($P < 100$ d) and in extremely slow rotators ($P > 1000$ d), and small in "intermediate" rotators; (iii) slow-rotating Ap stars frequently seem to have a fairly uniform magnetic field covering the largest part of their surface, with one rather limited region where the field is considerably stronger and has more small-scale structure.

At present the physical implications of these properties, in particular for the understanding of the braking mechanisms responsible for slow rotation in Ap stars, remain to be understood. But the very fact that relations between magnetic properties and rotation are identified in extremely slowly rotating Ap stars suggests that magnetic fields play a significant rôle in the evolution of the rotation of these stars, whose investigation is worth pursuing.

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