A STATISTICAL APPROACH TO THE INVESTIGATION OF MAGNETIC PROPERTIES OF MAIN SEQUENCE STARS

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ABSTRACT. The results of a systematic magnetic survey of the brightest northern MS stars are presented. A homogeneous and representative sample of 30 upper MS stars was observed. Both fast and slow rotating normal and CP stars have been investigated by the same technique. A limit in accuracy of magnetic field measurements at a level of 10 G was reached for the stars with sharp lines in spectra. A statistical analysis of the magnetic field strength distribution of MS stars have been made. In the surface magnetic field range, $B_S = 0.1 \div 100$ kG, the distribution cannot be represented by a single power relation. There is a real break at $B_S \approx 3 - 5$ kG earlier suspected, and which cannot be explained by observational selections only. We discuss a possible mechanism of the break.The distribution of highly magnetic stars is represented by a power law. It was shown that normalization of the high–field part of the distribution could be obtained in the study of the low–field part where the probabilities of finding are much higher. The distribution of weakly magnetic stars is flat. It is very similar to that of magnetic white dwarfs. It has been determined that there are $7.2 \div 8.7$ % of MS stars with surface magnetic fields higher than 1 kG among MS stars of $\mathrm{B8} \div \mathrm{F9}$ spectral classes.

Key words: Stars: Magnetic fields: Magnetic survey: Surface field strength distribution; stars: individual: χ Dra, α Aql.

1. Introduction

Magnetic fields can be found everywhere in the universe. The existence of a field was discovered in many types of stars having different evolutionary status: pre–main sequence stars, main sequence (MS) stars, subdwarfs and degenerate objects such as white dwarfs and neutron stars.

There is evidence that magnetic fields evolve during star's life (Glagolevskij 2001, Hubrig et al. 2000, Valyavin & Fabrika 1999). In studying general magnetic properties of stars which are at different stages one may hope to follow the magnetic fields evolution from protostar to degenerate object. It is believed that when MS star becomes a white dwarf, the field of degenerate remnant are thought to form from the field of its progenitor, MS star, by simple flux conservation. But it is not clear how the field is preserved during the convective giant phase. It can in principle be newly generated by dynamo processes or these processes can amplify initial field. To understand the ways of magnetic fields evolution after MS the general magnetic properties of both MS stars and white dwarfs should be analyzed and compared.

First statistical investigation of white dwarfs has been done by Angel et al. (1981). And latter their methods have been strongly improved by Fabrika et al. (1997) and Fabrika & Valyavin (1999).

Progenitors of white dwarfs, upper MS stars, show the presence of global magnetic fields. They has been definitely and repeatedly detected in two hundred MS stars, mainly chemically peculiar (CP) stars (Romanyuk 2000). Their longitudinal field strength are from a few 10^2 G to 10^4 G. But most of upper MS stars do not seem to have a magnetic field. For a few brightest stars with narrow spectral lines very high precision of measurements was obtained. Example of such data are field measurements of Procyon (Landstreet 1982), for which an uncertainty of 7 G was achieved. Only about 10 upper MS stars have been measured so far with error of less than 50 G (Wade at al. 2000). But for all that stars no field has been detected. Are they distinguished group of stars or their fields simply less than limit of measurements? Or may be they have complex field structure? How frequent are the magnetic stars? How many of stars are weakly magnetic? What is the limit of global field strength that may occur in MS stars? To answer all this questions one should analyse the distribution of magnetic fields of a sample of MS stars.

Based on all available longitudinal magnetic field measurements of upper MS stars Bychkov et al. (1997)

constructed such distribution. It reflects the ratio of stars having surface magnetic field in interval $B_S, B_S + \Delta B$ to the total number of stars. In logarithmic coordinates $\log(P_B) = \alpha \log(B_S) + const$ the distribution has been found to be almost linear in the range of surface fields $\approx 3 \cdot 10^3 - 3 \cdot 10^4$ G, the spectral index is $\alpha \approx -1.9$. Bychkov et al. (1997) pointed out that constant term *const* cannot be determined correctly. It means that the total number of stars in the sample is indefinite and the percentage of magnetic stars is unknown. The magnetic field measurements have so far been made basically in stars which are very likely to possess magnetic fields, sharp lined CP stars. These measurements are not homogeneous both in methods, accuracies and selection criteria. Authors do not always publish null results. Thus the sample cannot be considered as unbiased.

Bychkov et al. (1997) have also noted that the distribution can have a different behavior in the low–field part, where the surface field is less than a couple of kG.

2. The magnetic survey: uncertainties of measurements and promising candidates

We have started systematic magnetic survey of an unbiased sample of upper MS stars with high accuracy of measurements (Monin et al. 2000). The criteria for stars to be included in the sample are as follows:

- stellar magnitude $V \leq 4\overset{m}{.}0$,
- luminosity class V,
- declination $\delta \geq 0°$.

Our sample of 57 stars represents well MS stars in spectral classes B3 ÷ F9. Chemically peculiar stars are included in the list.

The magnetic survey is carried out on the coude echelle spectrograph CEGS of the 1 m telescope of the Special Astrophysical Observatory. The spectra were taken between March 1996 and June 2000. The total number of observed stars is 30. The uncertainty of B_l is varied from star to star and is mainly determined by signal–to–noise ratio, line contrast, and the number of simultaneously measured lines. We used weighted values of B_l. The weighting is made over the signal–to–noise ratio and central depth of lines. It improves the precision of field estimates up to factor 2. The measurements of slow rotating stars with a great number of measurable lines tend to be more precise. It appears that the smallest error which can be reached is 10 ÷ 15 G. The remnant instrumental effects which cannot be removed even by differential measurements lead to the precision limitation at the level of 10 G.

Except for 4 well known magnetic stars, ϵ UMa, θ Aur, α^2 CVn, β CrB, only two stars out of 30, χ Dra (F7V) and α Aql (A7V), have shown a global magnetic field, which is slightly above the 3σ level. Simultaneous analysis of more than 500 metallic lines in the spectra of χ Dra gives $B_l = -45 \div -55 \pm 10 \div 15$ G. The field of the same strength is detected from the Zeeman broadening of the spectral lines. A search for magnetic field in the fast rotating stars is more difficult task. The accuracy is dependant on radial velocity. As compared with slow rotating stars having the same brightness, one needs to get better spectra quality (signal–to–noise ratio) to have similar accuracies. Among fast rotating stars being included in our list α Aql is the brightest one. The most accurate measurement of its field gives $B_l = 122 \pm 35$ G. It has been made using hydrogen lines only. The field is detected at 3.5σ level. Further time resolved spectropolarimetric observations are necessary to ascertain if longitudinal magnetic field variation is occur with a period of rotation. But the detailed study of any star in the list is beyond the scope of the present work. We conclude that χ Dra and α Aql are likely to possess a magnetic field. And they must be considered as promising candidates.

3. The magnetic field function

Using the results of the magnetic survey, all published high-accuracy observations of the brightest MS stars and the published data on highly magnetic stars, the magnetic field strength distribution of MS stars (the magnetic field function) have been constructed (Fig. ??).

The magnetic field function (MFF) is the probability of finding a star with a surface magnetic field in the interval $B_S, B_S + \Delta B$ per one G. Where measurements give B_l rather than surface fields, we take the limit on surface field to be three times of B_l (Angel et al. 1981). The probability can be evaluated as the ratio of the number of magnetic stars to the total number of stars observed with an accuracy which allows a magnetic field to be detected in the interval. And it is supposed to be constant within that interval. That intervals are arbitrary chosen. We propose they should be two–fold.

There is a probability of null detection of a longitudinal field because of the star rotation (Schmidt & Smith 1995; Fabrika & Valyavin 1999). We can miss magnetic star in isolated observation. The probability is independent of the rotational period because an observation falls within a random phase of rotation. It is determined by the accuracy of measurements and the field strength. We take into account the probability of null detection for each star. It reduces the probability of finding a star.

The sample of 57 stars was used to get the MFF in the range 60 G–8 kG. We obtained a field strength in 30 upper MS stars through our survey program. Let recall that two of them are supposed to be magnetic. 27 additional stars were studied by other authors, mainly

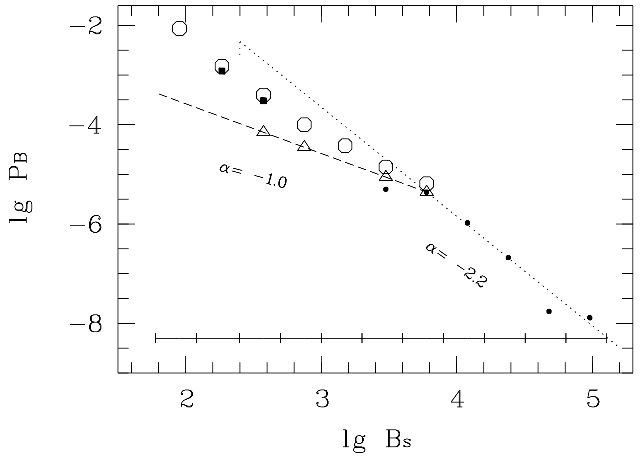

Figure 1: The MFF of the upper MS stars derived in 11 intervals of the surface magnetic fields. Horizontal bars below show the interval boundaries. *Open circles* and *open triangles* represent the upper and lower limits respectively. *Filled circles* correspond to stars whose a mean magnetic field modulus has been derived. The *dotted line* is the best fit power relation to the filled circles with index −2.2. The line bends downwards where the total probability becomes equal to 1 (see text). The *dashed line* is the fit to the lower limits. The index is −1.0. The *Filled squares* represent the probability in the 2nd and 3rd intervals supposing χ Dra and α Aql to be magnetic.

by Landstreet (1982). For the sample we can set the upper limits in the 6 low–field intervals (60 G–4 kG). Not all of stars from the target list of the survey have been studied so far. It may happen that some of them are magnetic. An upper limit value is proportional to $1-\sqrt[n]{1-Q}$, where n is a number of stars in the interval and Q is a significance level. Q was chosen to be 0.75. Such significance level is strong enough. There are 4 stars with well established magnetic fields in the list. They were used to derive the lower limits. The lower and upper limits in intervals 6 and 7 (2–8 kG) are close to each other and, obviously, to the true probability values. It is hardly probable that there are other strongly magnetic stars among brightest MS stars.

Measurements of mean magnetic field modulus of 49 stars with spectral lines resolved into magnetically split components form the high–field part of the distribution (B_S more than two kG). This data was taken from Mathys et al. (1997) and Romanyuk (2000) (filled circles in Fig. ??). We have a poor knowledge of the normalization factor in the high–field part because the way in which the magnetic stars are discovered is far from being systematic. The high and low–field parts are intersected in both the 6th and 7th intervals. Below a few kG the sensitivity of measurements of mean magnetic field modulus is greatly reduced. So, in the 6th interval the frequency of magnetic stars is underestimated. We shifted the high–field part to bring it into coincidence with low–field one in the 7th interval. Thus, normalization factor of the high-field part of the distribution is obtained in the study of the low-field part where the probabilities of finding a magnetic star are much higher. Indeed, below 8 kG the star frequency exceeds 1/50. Therefore, it is necessary to observe a few tens stars to find a magnetic one. In high-field part the probabilities are lesser by two orders. So, one should observe about 1000 stars to discover one with a strong magnetic field. The precise measurements of weak fields in unbiased sample of stars give a possibility to analyse general magnetic properties in a wide range of surface fields.

In the surface magnetic field range, $B_S = 0.1-100$ kG, the magnetic field function cannot be represented by a single power relation. The distribution of highly magnetic stars is represented by a power law with index -2.2 ± 0.2. We confirm the steep slope obtained previously by Bychkov et al. (1997). The distribution of weakly magnetic stars is flat, with index $-1.0 \div -1.3$. It is very similar to that of white dwarfs (Fabrika & Valyavin 1999). There is a real break at 3–5 kG earlier suspected by Preston (1971) and Mathys et al. (1997), and which cannot be explained by observational selections only. Behavior of the MFF in the low– and high–field parts is clearly different. Below a surface field 1 kG the density of motions energy of matter and the density of the thermal energy in the atmosphere of MS stars become higher than the density of energy of magnetic field. The global field configuration can become unstable. And a field can organize more complex structures. Such fields do not detect through Zeeman measurements. As a result the probability of finding a star decreases.

The total probability in whole range must equal to 1. It is not so if the index is -1. We suggest that the incidence of magnetism in the low–field part is somewhat large. In fact, if χ Dra and α Aql are magnetic, the probabilities in 2nd and 3rd intervals are significantly higher (see Fig. ??). With the index -1.3 the limiting field strength (where the total probability becomes 1) is approximately 1 G.

The total probability of finding a star with a field $B_S > 1$ kG among MS stars of B8 through F9 spectral classes is $7.2 \div 8.7\%$. There are about 205 MS stars brighter than $5^{\rm m}\!.0$ on the northern sky. So, one may expect about 18 highly magnetic stars among them. 14 such stars are in the latest catalogue of magnetic chemically peculiar stars by Romanyuk (2000). One may hope to discover some others. Considering the incidence of the weak magnetic fields in MS stars, we find that every 5–6th star is expected to have a magnetic field in the range $B_S = 120-4000$ G.

4. Conclusion

The MFF is a powerful tool to diagnose general properties of stellar magnetism. A principal advantage of this method is a possibility to derive statistics of the data obtained in not systematic manner using measurements (which include null ones) of unbiased sample of stars. The distribution can be compared with those of other type stars, for example, white dwarfs to follow the magnetic field evolution. The essential result is the presence of the break in the MFF of upper MS stars. To understand its nature it is important to continue an extensive study of stars having a weak surface magnetic field. Do most of them really have complex magnetic field geometry?

In the future, we aim at completing the survey of bright upper MS stars of luminosity class V and do the same analysis for a sample of stars of luminosity class IV.

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