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On magnetic fields of Herbig Ae/Be stars

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Abstract. Using standard Zeeman methods, we made an attempt to find dipole magnetic fields in Herbig Ae/Be stars, taking into account that 20 % of these stars with $v\sin i < 100$ km/s, as a result of evolution, have to become magnetic chemically peculiar stars of the upper part of the main sequence. The study of 9 stars of this kind gave negative result. The analysis of all the observed data allowed a preliminary conclusion to be drawn that magnetic field and chemical anomalies arise near the zero-age (ZAMS) line on a time scale of 10^5 years. For the final solution of this problem it is supposed to investigate the slowly rotating stars situated near the ZAMS.

Key words: stars: Herbig Ae-Be stars: magnetic fields

1. Introduction

By the evolutional status stars which we study may be divided roughly into 3 groups:

- magnetic Herbig Ae/Be stars,
- magnetic post-Herbig Ae/Be stars,
- magnetic stars of the main sequence.

Study of the stars of the first group is the main goal. The first results were published by Glagolevskij and Chountonov (1997).

The problem of stellar magnetism is interesting not only in itself, it is linked with studying the processes that take place in the stars at the early stages of evolution. If a field has been formed by a dynamo mechanism, this means that during the early stages there was a period of active convection. If a field is relic this implies that there are processes unknown presently that leave only 10 % of stars magnetic and lead to complex dipole-quadrupole and dipole-quadrupole-hexapole field configurations (Gerth et al., 1997) inherent in many stars. The contemporary theory argues that complex magnetic structures are less steady than dipole ones and dissipate faster, so in due course the number of stars with pure dipole field is expected to increase.

2. Observations

The spectra were obtained on the Main Stellar Spectrograph of the 6 m telescope with Zeeman analyzer and CCD of 1040 × 1160 pixels. The pixel size was 16 × 16 microns. The spectrograph slit width was 0.45 mm, the equivalent width of the slit was 0.27 Å with a reciprocal dispersion of 9 Å/mm or 0.39 Å at 13 Å/mm. Spectra were processed with MIDAS95. Profiles of the measured spectral lines were approximated by a gaussian, and in this way was determined the line centre. The magnetic field B_e was calculated using the well-known formula:

$$\Delta\lambda = 4.67 \cdot 10^{-13} \lambda^2 z B_e,$$

where $\Delta\lambda$ is the line splitting and z is the Lande factor. Sometimes the average Lande factor equal to 1.23 is used. Besides the magnetic fields, we measured MgII λ4481 line width which was then converted to $v\sin i$ (Sletteback et al., 1975). The accuracy of measurements depends strongly on the line widths, their symmetry, signal/noise ratio and the number of spectral lines involved. Often the accuracy of measurements is affected by the rapid profile variations. The variations were observed even within 10-15 min (HD 37022) while the exposure, as a rule, was 30 min. The root-mean-square error of magnetic field measurements was determined from all spectral lines. In the cases when there were few lines in the spectrum, several spectrograms were taken sequentially thus increasing the number of the measured lines. When a single line was measured, the error was estimated from the signal/noise ratio, allowing for sharpness of the line profile.

The data on the magnetic fields and rotation velocities of Herbig Ae/Be stars are listed in Table 1. For the study we selected only the stars with $v\sin i < 100$ km/s since magnetic CP stars are slow rotators. The frequency of occurence of the main sequence magnetic stars among the slow rotators is 20 %. From the data of Table 1, it can be seen that with a probability of 0.9 Herbig Ae/Be stars do not possess strong dipole fields.

HD 190073 has very sharp spectral lines, which

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Table 1: *Results of magnetic field measurements in young stars*

Date	Star	Field B_e (G)	$\sigma(B_e)$, (G)	Spectrum	*vsini* (km/s)	Number of spectral lines	Comments
1991-92	ABAur	no	1000	AOVe	75	-	Catala et al.,1993
18.09.97	31648	<300	300	2/3ep	80	20	
19 08.97	36112	86	700	A3e	70	36	
14.09.97	37022	-630	430	6	123	9	Post Ae/Be
16.01.98	37129	60	230	B2Vp	70	10	Post Ae/Be
7.09.98	”	420	400	”	50	10	”
4.12.82	”	15	290	”	-		Borra et al.,1983
21.11.97	53367	275	870	0III/IVe	30	3	
5.12.95	”	-200	600	”	”	1	He lines
4.01.96	”	-325	190	”	”	22	He+metal lines
29.12.93	100546	?	<100	B9V	65		Donati et al.,1997
”	104237	no	<100	A4V	12		Donati et al.,1997
15.09.97	179218	-230	150	9/AOIV/V	60	10	
13.05.98	”	650	400	”	”	57	
18.09.97	190073	97	174	A0IVep	10	13	
26.05.97	200775	60	440	B2/3eq	60	10	
15.01.98	203024	190	1400	Ae	75	18	complex profiles
15.01.98	250550	-950	770	B9eq	85	14	He+Mg+Si lines
7.12.95	”	-450	430	”	”	12	
8.12.95	”	-800	400	”	”	9	
9.12.95	”	1400	600	”	”	1	Si lines
10.12.95	”	-1700	600	”	”	1	Si lines
18.09.97	283572	+160	550	G2III	120	22	TTau type
21.11.97	53 Cam	6100	400	Ap	-	36	standard near the field maximum

are very likely to belong to its envelope. However the MgII λ4481 line, which is considered (Finkenzeller and Mundt, 1984) to form in the atmosphere of the star, is also sharp, so one can suggest that this star is viewed pole on. The measurement errors of many stars, HD 250550 for instance, are very large due to the asymmetry of spectral lines.

In HD 250550 some Zeeman spectrograms in the silicon short-wave wings reveal a small detail in the right-polarized spectrum, which is absent in the left-polarized spectrum. This fact suggests that on the surface of the star there is a magnetic field, which has probably emerged from the star's limb. Though we selected for the investigation only the slowest rotators, the average *vsini* they have exceeds twice the value for chemically peculiar stars, so the accuracy of the field measurement is appreciably lower.

3. Appearance of magnetic field and chemical anomalies

Table 2 (from top to bottom) shows the basic stages of evolution of magnetic stars: from the stage of Herbig Ae/Be to CP stars of the main sequence. From left to right the stars are divided into 4 groups, relative to the basic chemical anomalies along the temperature scale. CP stars are taken from the catalogue of Egret and Jaschek (1981), and Herbig Ae/Be stars from (Shevchenko, 1989) and (Glagolevskij, 1996). The He-rich chemically peculiar star HD 53367 was found among Ae/Be (Glagolevskij and Chountonov, 1997), but no magnetic field was detected in this star, probably it is beyond the accuracy of measurements. It should be noted that helium absorptions acquire maximum intensity when the envelope influence decreases, the rest of the time the lines are distorted by emission. The post Herbig Ae/Be stars with the known field (Glagolevskij et al., 1986) are shown in Table 3.

Table 2: *The number of chemically peculiar stars, detected at different stages of evolution*

Number of stars				
1	-	-	-	Ae/Be
2	4	-	-	Post Ae/Be
34	58	1000	800	CP
He-rich	He-weak	Si	SrCrEu	Type
22000	15500	11500	9700	T, K

The data of Table 2 may give a rough idea about evolution rate and the formation stage of chemical anomalies and magnetic field. He-rich stars evolve

Table 3: *Root-mean-square error of the magnetic field B_e of post Herbig Ae/Be stars*

HD	$< B_e >$,G	σ, G	Type
36540	470	220 (2.1s)	He-weak
36629	440	270 (1.6s)	He-weak
37058	740	230 (3.1s)	He-rich

very rapidly, but SrCrEu stars very slowly. So, supposing that stars of different types need approximately equal time for chemical anomalies to be formed, it becomes clear why He-rich stars appear at the Ae/Be stage, He-weak at the post-Ae/Be stage, and they are absent at the previous stage; and the Si and SrCrEu-type stars are not present at the first two stages. From this table it can be seen that the number of peculiar stars of the last two types is much larger than of the first two, so the probability of their detection at the Ae/Be and post-Ae/Be stages would be much higher. That is, if they were at those stages they would be surely found. Because of relatively slow evolution they are formed at the stages between the post-Ae/Be and the zero-age main sequence line. Within the bounds of determination accuracy the young stars of the main sequence and late, "old" Ae/Be stars with originating anomalies and magnetic fields may be mixed on the Hertzsprung-Russel diagram.

A rate of a magnetic CP star generation can be estimated on the basis of the known Iben evolution tracks. In Table 4 the average ages of every subgroup of Table 1 are presented. One star of He-rich type (HD 53367), as it seems, is situated on the ZAMS (Finkenzeller and Mundt, 1984), but it has many features of Ae/Be-type stars: the presence of hydrogen in emission, noticeable infrared excess, variability of He lines indicate that most probably HD 53367 is not a He-rich star of the main sequence yet. Therefore the upper value of the absolute magnitude represented in this paper is preferable. The age of HD 53367 according to the Iben tracks is 10^5 years. In Fig. 1 the star on the Hertzsprung-Russel diagram, taken from (Finkenzeller and Mundt, 1984), is marked with the asterisk. The dashed line shows the boundary of Herbig Ae/Be stars birth according to Palla and Stahler (1990). It is well seen to be located near the zero-age line. It is necessary to take into account that the star may evolve to the main sequence below the average line of the ZAMS. The stars with ages different from those in the ZAMS by 10^5 years are represented with the dash-and-dot line. These are the stars of the main sequence. Thus, the incipient magnetic CP stars are to be sought among post Herbig Ae/Be stars.

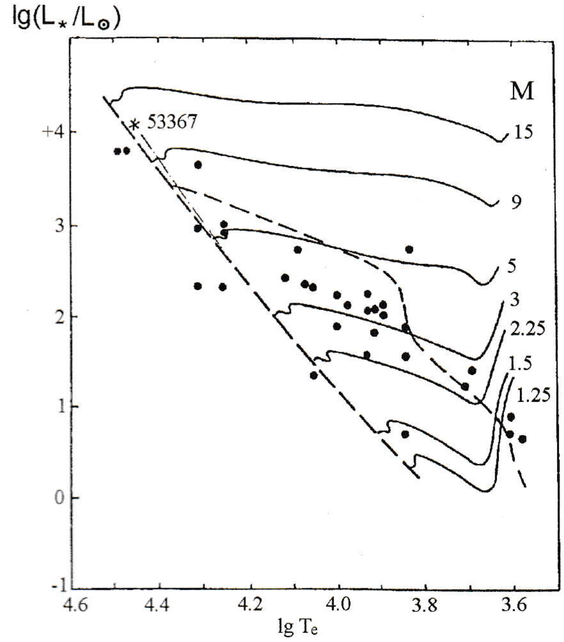

Figure 1: *The position of the He-rich star HD 53367 on the Hertzsprung-Russel diagram. Filled circles are Herbig Ae/Be stars from (Finkenzeller and Mundt, 1984). The position of stars, 10^5 years away from the ZAMS is the dash-and-dot line.*

Table 4: *The average age of chemically peculiar stars at different stages of evolution*

		Age		
10^5	-	-	-	Ae/Be
$2.8 \cdot 10^5$	$1.5 \cdot 10^6$	$6 \cdot 10^6$	$1.1 \cdot 10^7$	Post Ae/Be
$1.0 \cdot 10^6$	$6.3 \cdot 10^6$	$3.2 \cdot 10^7$	$2.5 \cdot 10^8$	CP
He-rich	He-weak	Si	SrCrEu	Type
22000	15500	11500	9700	T, K

For CP stars we took the average age of the V luminosity class stars, for post Herbig Ae/Be stars the age is on the zero-age line (Glagolevskij and Chountonov, 1997). Part of stars do not have a field exceeding the measurement error. We may suppose that stars "without" a field are the youngest with the field still increasing. The average R/R_{ZAMS} for stars with a field is 1.46 ± 0.11, and without a field it is equal to 1.27 ± 0.10. The difference is not large, but nevertheless such a supposition could be taken for a hypothesis. It is interesting that the number of He-rich stars with a field detected is about 41%. This is a large part, though for other types of peculiar stars the number of stars without a field is also very large (see Fig.3). It may be supposed that among all types of stars there are many objects with a complex nondipole structure, besides, the fields probably increase with their age. Thus, for instance, the young star HD 37776 has sectors on its surface with a field of dozens of kG, though a field measured by Zeeman method does not exceed 2 kG (Gerth et al., 1997).

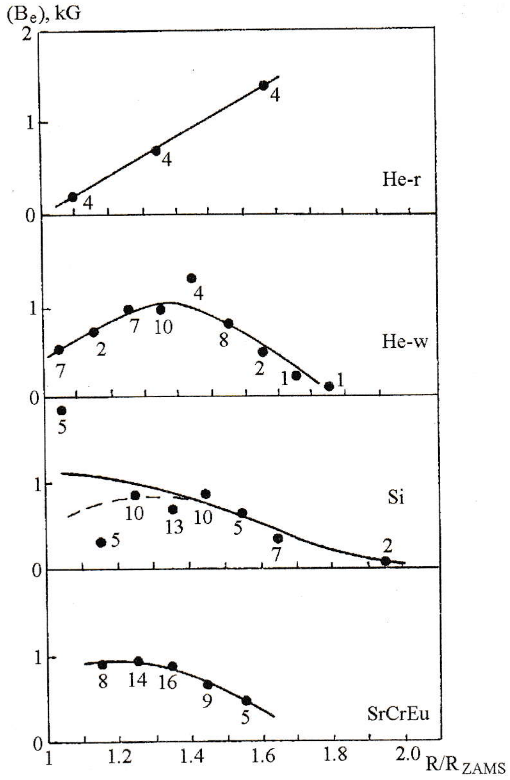

Fig. 2

Figure 2: *Variation of average magnetic field with age in CP stars of different peculiarity types. The numbers of stars averaged are shown.*

Since complex structures of the field are unstable, in due course there left only simple dipole structures of the field, which are easily detected by the Zeeman method. The number of He-weak stars with a field is 48 %. The number of stars with a field for Si type is 60 %, and for SrCrEu stars it is already 82 %. This is apparently an evolutionary effect. Most probably the time the magnetic field increases in stars that evolve slowly is not so long as the time of their stay on the main sequence. Thus, for He-weak stars it also remains to be seen whether they really have weak fields or their fields are strong but of complex structure for measurement of which the Zeeman method is insensitive. We think that a weak field is the main cause, although part of stars, in fact, have complex structure of the field.

Fig. 2 shows relationship between the average value of the field B_e and R/R_{ZAMS}, it is seen that the field of He-rich stars increases with age, possibly, to the upper boundary of the main sequence band, while the field of He-weak stars first increases and then drops. It must fall caused by evolution increase of the star's radius (Glagolevskij, 1988). For silicon stars, $R/R_{ZAMS} < 1.2$ is not reliable because of inadequate quantity of data. However the first point is 10^5 years, so here maximum can be found. Another behaviour of the relationship is shown by the dashed line. It can hardly be supposed on the basis of the contemporary theories that near the zero-age line convection may appear that causes generation of magnetic field, so we may only suppose that the field has appeared earlier and now it reaches the surface and becomes detectable. The field floats up to the surface after the accretion is over and the upper layers are stabilized. Before this moment the accretion masses "covered" the layers with the magnetic force lines and turbulent motions on the surface tangled the force lines which dissipated very quickly. From Fig. 2 (He-r) it can be seen that due to fast evolution, the field does not have time to float up completely during the main sequence stage, so there is no descending branch, and in Fig. 2 (He-w) it is noticeable that the field reaches its maximum and then begins to decrease, which is caused by increase in the radius. The same relationship for Si and SrCrEu-type stars is presented in Fig. 2. It is seen that the magnetic field for Si stars decreases during all the time of their stay on the main sequence, and the maximum is, possibly, near the ZAMS. Assuming that the time of emergence of a magnetic field of all the stars is the same, then, as a result of very slow evolution of Si and SrCrEu stars, the maximum of the relation will be near the ZAMS. Thus, with the adopted scale and insufficient number of the observational data this maximum is not appreciable. For all the relationships in Fig. 2 the numerals near the points indicate the number of B_e values, by which the averaging was done. The B_e values were taken from (Glagolevskij et al., 1986), R/R_{ZAMS} were determined by the parameters β and described in (Glagolevskij et al., 1992).

A possible mechanism of magnetic field generation in the surface convectional layer of a star was discussed by Palla and Stahler (1990). The magnetic field may increase to dozens of kG during the surface burning of deuterium and by the dynamo-mechanism convection, and also it can facilitate the floating of the internal relic field. The calculations (Parker, 1982) show that in the convective medium the velocity of floating of magnetic tubes of force is much larger than in nonconvective. The convection ends as soon as the accretion that delivers deuterium to the surface of the star ceases.

4. Conclusion

From the analysis given above we suggest the following.

1. It is necessary to investigate properly the post-Herbig Ae/Be stars and the stars near the ZAMS, as

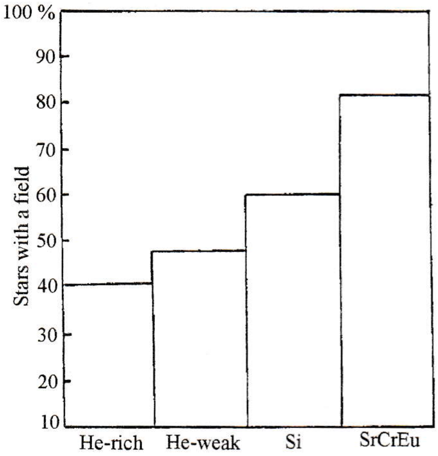

Figure 3: *The proportion of stars of different peculiarity types with detected magnetic field ($B_e > \sigma$).*

at this stage of evolution the appearance of magnetic field and chemical anomalies is possible.

2. Accurate measurements of polarization in profiles at different phases of rotation period of Herbig Ae/Be stars will allow determination of local magnetic fields. Such investigations will also help to ascertain whether the field appearance is due to generation or to the floating up of a relic field.

3. The data show the necessity of further measurements of weak fields B_e of CP stars, since these measurements will give information about the complex structures of the magnetic fields that have just appeared. Investigation of such structures will help to explain the mechanism of magnetic field appearance.

4. A conclusion on the absence of strong magnetic fields in Herbig Ae/Be stars based on measurements of the 9 stars should be considered tentative, as the probability of detecting a field in stars with $v\sin i < 100$ km/s is only 0.2. For a more reliable conclusion to be drawn, at least 15 stars must be measured.

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