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Some notes on the evolution of magnetic fields of CP stars

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Abstract. The magnetic field variations in young Ae/Be Herbig stars show that no strong magnetic field similar to those of chemically peculiar stars are present in them. Evidently, magnetic fields and chemical anomalies in CP stars appear as they arrive on the zero age main sequence when the accretion stops and the surface layers become stable. Magnetic fields are likely to rise to the surface or diffuse from the inner regions of stars. During the period when future magnetic stars were at the stage of emission Herbig stars, they could not decelerate their rotation with the magnetic field involved because of the absence of strong global magnetic fields on their surface. Neither are there data on the braking of magnetic stars on the main sequence. The observed magnetic fields are most likely to remain only in slow rotators in which the differential rotation is absent. Fast rotators with strong differential rotation become normal stars as a consequence of the fact that the magnetic field turns torroidal, which is not detectable by the Zeeman techniques. If the deceleration did partially take place with the magnetic field involved, this could occur only at the earliest stages of star formation, prior to the "birth line" of emission stars of the Hertsprung–Russel diagram. Indirect data show that in different areas of the star's surface at the stage of emission Herbig stars, conditions favouring the appearance of magnetic fields are likely to occasionally arise which are associated by the observers with local matter ejections.

Key words: stars: chemically peculiar — stars:evolution — stars: magnetic fields

1. Introduction

Klochkova, Kopylov (1986) and Glagolevskij (1988 a, b) analysed the problems of chemical anomalies and magnetic fields in CP stars, and it was shown that CP stars occupied the entire main sequence, as normal stars did, and that they had formed during the period of evolution preceding the main sequence. To confirm this conclusion, it was necessary to make a search for magnetic fields in young Ae/Be Herbig stars of the same intensity and structure as those magnetic upper main sequence CP stars had. About 10–15 % of them become magnetic in the future. The second problem consists (as it is currently believed) in that the slow rotation of CP stars is due to magnetic braking at early stages of evolution. However, the presence of strong fields in young stars has not been verified so far.

The third problem is connected with strong local magnetic fields, the presence of which is suggested by some authors to explain jet ejections in young Ae/Be Herbig stars. The fourth problem is related to the final option of the mechanism of magnetic field origin in CP stars — dynamo or relic — which is widely discussed now. Other events bearing on magnetic fields in these stars are also discussed. Thus the problem of direct measurement of fields in young stars appears to be of vital importance.

2. Measurements of magnetic fields in Ae/Be Herbig stars

Ae/Be Herbig stars being at the evolution stage after the "birth line" (Palla, Stahler, 1990) have already pronounced spectral lines convenient for magnetic field measurements (Glagolevskij, Chountonov, 1998). The fields were measured by the standard technique with camera II of the Main stellar spectrograph of the 6 m telescope with a CCD system of 1040 × 1040 pixels. The results of the measurements are listed in Table 1. The measurement accuracy depends on the width of lines, their symmetry, the signal-to-noise ratio and the number of lines used. Sometimes the accuracy decreases as a result of rapid changes in the profiles (for instance HD 37022). The exposure time was normally of about 30 min. The root-mean-square error was determined from all spectral lines. In the cases where there were few lines in the spectrum, several spectrograms were derived sequentially, increas-

Table 1: *Measurements of magnetic fields in young stars*

Star	Field, G	Error, G	Spectrum	v sin i, km/s	Number of sp. lines	Notes
ur	< 1000	–	A0Ve	75	–	1)
HD31648	< 0 >	180	A2/3ep	80	20	
HD36112	86	700	A3e	70	36	
HD37022	−630	430	06p	120	9	Post Ae/Be
HD37129	< 0 >	220	B2p	70	20	Post Ae/Be
KX Ori	340	250	B3V	15	4	Post Ae/Be
V539 Ori	220	350	B3V	15	4	Post Ae/Be
HD45677	−527	1000	B0Ivep	95	6	He, Mg
HD45677	15	290				2)
HD53367	< 0 >	440	B0III/Ive	30	26	He lines, met.
HD53367	−325	190			22	He lines, met
HD100546	–	< 100	B9V	–	65	3)
HD100237	–	< 100	A4V	12		3)
HD144432	−2150	950	A7Ve	80	26	low S/N
HD179218	−230	150	B9/A0IV/Ve	60	10	
HD179218	< 350 >	300		67		
HD190073	97	170	A0Ivep	10	13	
HD200775	60	440	B2/3e	60	10	
HD203024	95	700	Ae	75	18	complex prof.
HD208063	730	460	–	35	4	
HD250550	< 500 >	290	B9eq	85	37	He,Mg,Si lines
γ Equ	−1100	100	F0p	0	21	magnetic star

Notes: 1) Catala et al., 1993; 2) Borra et al., 1983; 3) Donati et al.,1997

ing thus the number of measured lines. If only one measurable line proved to be in the spectrum, the error was then calculated from the signal-to-noise ratio with allowance made for the profile steepness. If several measurements of a star were made on different days, the root-mean-square value of the magnetic field was estimated by the formula (Brown et al., 1981):

$$< B_e >= \sqrt{\sum_{i=1}^{n} \frac{(B_e)_i^2 - (\sigma)_i^2}{n}},$$

where B_e is the measured effective magnetic field value of the star. Apart from the magnetic field, estimates were made of the projection of radial velocity v sin i from the line Mg II λ 4481 Å.

To enhance the probability of finding a magnetic star, only those stars were measured whose rotation velocities v sin $i < 100 - 120$ km/s, since the rotation velocities of magnetic CP stars lie basically within this range. Fig. 1 shows a plot of the portion n/N of magnetic CP stars (constructed from the data of the catalogue of Uesugi, Fukuda (1982)) among normal main sequence stars as a function of rotation velocity. The CP stars with v sin $i < 100 - 120$ km/s account for 20 %. The solid line is drawn by the least-squares method and represents an exponential function of the form $n/N = 36.8 \cdot e^{(-\mathrm{v}\sin i/55.3)}$.

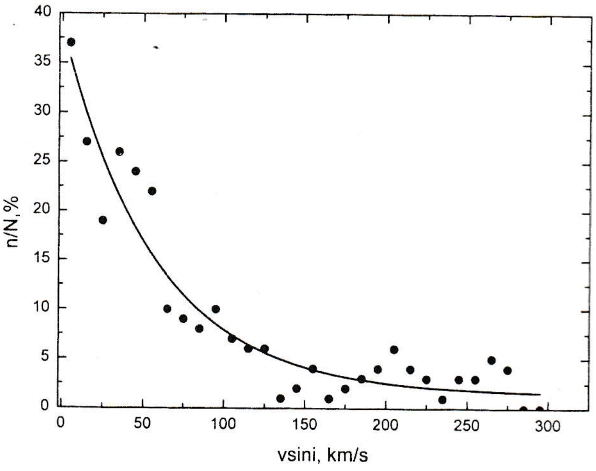


Figure 1: *Relative number of CP stars as a function of rotational velocity.*

From examining the data of Table 1 it can be seen that for none of the stars a magnetic field above 3σ has been found. This implies (taking account of the expected number of magnetic stars of 20 %) that with a probability of 0.96 Ae/Be-type stars have no magnetic fields like those in CP stars. A second conclusion can be drawn from this result: a magnetic field appears in the period between the evolution phases "young emission Herbig stars — main sequence", i.e. at the moment a star arrives on the zero-age main sequence (ZAMS). From Fig. 1, an inference can also be made that the proportion of n/N of peculiar stars depends on their velocity of rotation, it can therefore be suggested that this parameter is one of decisive in formation of magnetic CP stars. If a field was generated by a dynamo with which the field value should be proportional to the rotation velocity, the curve in Fig. 1 would rise with increasing v sin i (see also Fig. 4) and there would be no stars with small v sin i. An impression is created that the smaller the rotation velocity, the better the field is preserved. The most probable cause of such a behaviour may be related to the differential rotation (see further).

One more important consequence of the measurements made consists in that at the phase of emission Herbig stars, the future CP stars could not undergo an additional braking because of the absence of strong magnetic fields in them. Indirect indications are well known (Pogodin, 1992) that in some areas of the surface of young stars a field can appear. Ejections of matter can occur with the local magnetic fields involved. It is hardly probable, however, that the temporary local magnetic fields can have such an effect on the rotational moment as observed in CP stars.

3. The phase of appearance of the magnetic field and chemical anomalies

Klochkova, Kopylov (1986) and Glagolevskij (1988 a, b) reported that magnetic CP stars occupied the whole main sequence as normal stars did. Over the last few years this has been confirmed by the Hipparcos data (Hubrig et al., 1997). In our papers (Glagolevskij, 1996; Glagolevskij, Chountonov, 1998) we also adduced arguments that it was exactly the zero-age main sequence that was the birth place of chemical anomalies and magnetic fields in stars. First, in rapidly evolving He-rich and He-weak stars the magnetic fields show well noticeable tendency to increasing as they evolve from the ZAMS across the main sequence (Glagolevskij, Chountonov, 1998). Second, the investigation of the so-called post-Ae/Be stars (Shevchenko, 1989) has shown that all of them are on the ZAMS, and a few CP stars have already been found among them. Third, in He-rich and He-weak stars helium anomalies tend explicitly to enhance as they evolve away from the ZAMS. In addition, we present the data on variations of the depression parameter Δa at λ5200 Å versus age, the intensity of which is proportional to the metallicity and the magnetic field value (Fig. 2). Here R is the star radius at present, R_z is its ZAMS radius. Experience has shown that the parameter R/R_z characterizes well the star age after the ZAMS and is related to log$g$ in the following manner

$$\log(R/R_z) = 1/2(\log g_z - \log g).$$

To diminish the scatter of points, the relationship in Fig. 2 is plotted by the method of running average over 5 points. One can see well the initial rise of the parameter Δa as the star evolves from the ZAMS. This parameter has a pronounced maximum when the star reaches the location corresponding approximately to luminosity class V. The decrease in the depression intensity is apparently associated with the decrease in the magnetic field intensity as a consequence of increasing star radius.

It is worthwhile to mention here that noticeable chemical anomalies are likely to appear in CP stars earlier than a noticeable magnetic field. It is shown by Glagolexskij, Chountonov (1998) that a magnetic field is found in 48% of He-rich stars. In the rest of the stars it is probably less than the detection threshold. In CP stars of other types this percentage is also high.

4. The problem of braking CP stars

The slow rotation of magnetic CP stars has already been discussed in the literature. Fleck (1980) has developed a theory of gyromagnetic mechanism, Mestel (1975), Strittmatter and Norris (1971) have proposed a mechanism of mass loss in the presence of a magnetic field as a possible source of angular momentum loss, Havnes, Conti (1971) and Mestel (1972) have considered a possibility of braking by interstellar gas accretion in the presence of a magnetic field. A possibility of braking of CP stars by the so-called mechanism "propeller" has also been investigated (Fabrika, Bychkov, 1988). All these mechanisms require sufficiently strong magnetic fields at early stages of evolution which we have failed to detect. This implies that there must be a different braking mechanism, or the rotation velocities of CP stars must be low from the very beginning.

Fig. 3 shows the relationship between v sin i and age for normal and CP stars. For normal stars, v sin i values have been computed from the data of the catalogue of Uesugi, Fukuda (1982) for spectral classes Sp = B 2.5, B 5, B 9 and A 2 corresponding to the mean Sp of the main types of CP stars — He-rich, He-weak, Si, SrCrEu. The rotation velocities for Ae/Be Herbig stars have been borrowed from the papers by Finkenzeller (1985), Grady et al. (1996), van den Ancker et al. (1998) and from Table 1. That Cp stars fall into different luminosity classes has been found from the parameter β of multicolour photometry. It is well seen in Fig. 3 that the relationships for normal and CP stars are alike, only the velocities of the latter have smaller values. Therefore, it can be concluded

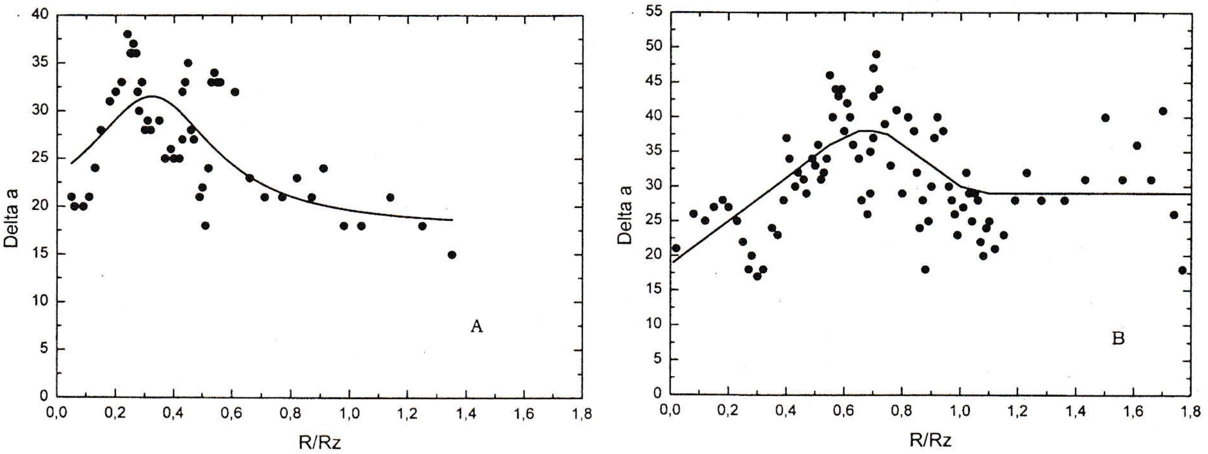


Figure 2: *Depression intensity (in decimal fraction of stellar magnitude) at* $\lambda5200$ *Åin CP stars versus their relative radius* R/R_z*. A —* $T_e > 11000$ *K, B —* $T_e < 11000$ *K.*

that the evolution of rotation of all stars on the main sequence proceeds in a similar manner. Magnetic CP stars probably form either from the slowest rotators or the braking via the magnetic field occurred at the earliest stages of birth.

The absence of strong global magnetic fields in Ae/Be Herbig stars is inconsistent with the assumption that their braking takes place at the pre-main-sequence stage of evolution. Glagolevskij (1988 a, b) shows that the rotation periods of CP stars are larger than those of normal stars; the late CP stars differ from normal ones to a considerably greater degree (they are much slower). This is well visible in Fig. 3. Such a difference could be a reliable indication of braking of stars at the pre-main-sequence phases if it is taken into account that late stars evolve slower and stay longer at this phase, hence the braking is stronger. The absence of the magnetic field effect on the braking has also been discussed in the papers by Glagolevskij (1988 a, b). Therein are presented the mean values of the rotation periods and v sin i for CP stars with a dipole inclination angle with respect to the rotational axis more or less than 45°. In the first case the deceleration was expected to be stronger than in the second. However, the observed relation rather turned out to be the opposite of the expected. For this reason, it can be suggested that the examined relations reflect not the braking effect, but the fact that the differential rotation, depending on the radius, arises at different rotation velocities.

It is quite probable that it is the slowest rotators that can preserve a magnetic field produced at the convective stage of Hayashi by a dynamo (Krauze, Raedler, 1986), or by means of compression of magnetized clouds (Dudorov, Tutukov, 1988, 1990). It is precisely the slow rotators that may have rather slow differential rotation and meridional circulation which would inevitably convert the field into a toroidal one (Raedler, 1986), which is likely to have occurred in normal stars. The Zeeman technique is unable to reveal a torroidal field. It can be supposed that the process of distruction of the poloidal magnetic field in stars of smaller masses comes into play at lower rotation velocities.

If the division of stars into magnetic and normal did take place with the involvement of the differential rotation, a reverse correlation of the field strength and the rotation would then be observed. Such a correlation was noted in the paper by Borra, Landstreet (1980). We present in Fig. 4 the relation between the mean value of $< B_e >$ and v sin i ($< B_e >$ is the root-mean-square value of the star magnetic field) that we have plotted from the data of the catalogue of Uesugi, Fukuda (1982) and from the paper by Glagolevskij et al. (1986) from which it is well seen that slow rotators on the average have stronger fields (the relation is for Si, SrCrEu-type stars, the dots are the result of averaging in the narrow ranges of $< B_e >$ values). The slope of the curve changes dramatically at $< B_e >< 500\,\mathrm{G}$ and v sin $i > 40$ km/s. It can be assumed that this is the boundary where the differential rotation originates.

When discussing Fig. 1, we saw that to explain the larger proportion of CP stars in the region of small v sin i, a mechanism preserving the magnetic field in slow rotators and suppressing it at large v sin i is necessary. The differential rotation could be such a mechanism.

The shape of the relations in Figs. 1 and 4 is at variance with the assumption of the dynamo nature of the magnetic field since the α^2 mechanism (Krauze, Raedler, 1984) capable of generation of a strong poloidal field suggests a magnetic field strength proportional to the rotation velocity. This means that at

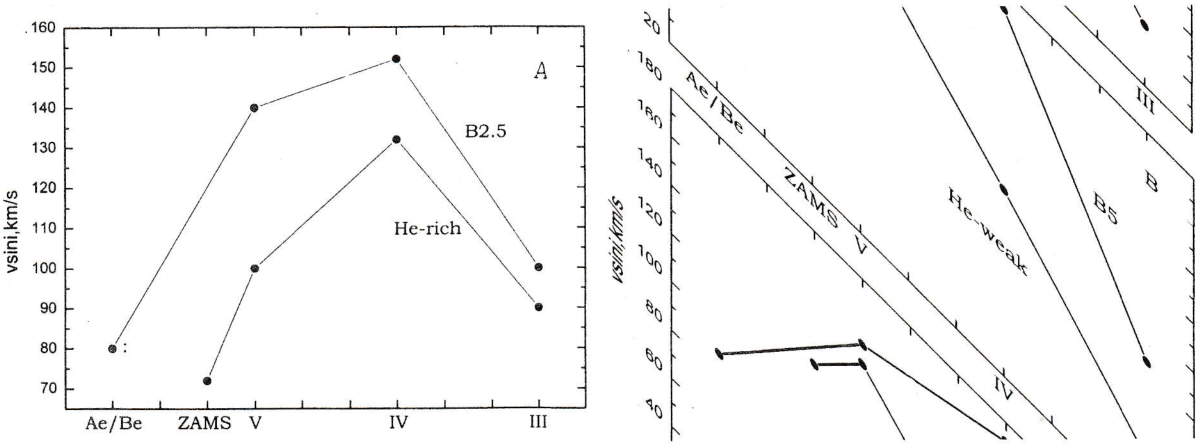


Figure 3: *Relationship of average rotation velocities and age for normal and CP stars*

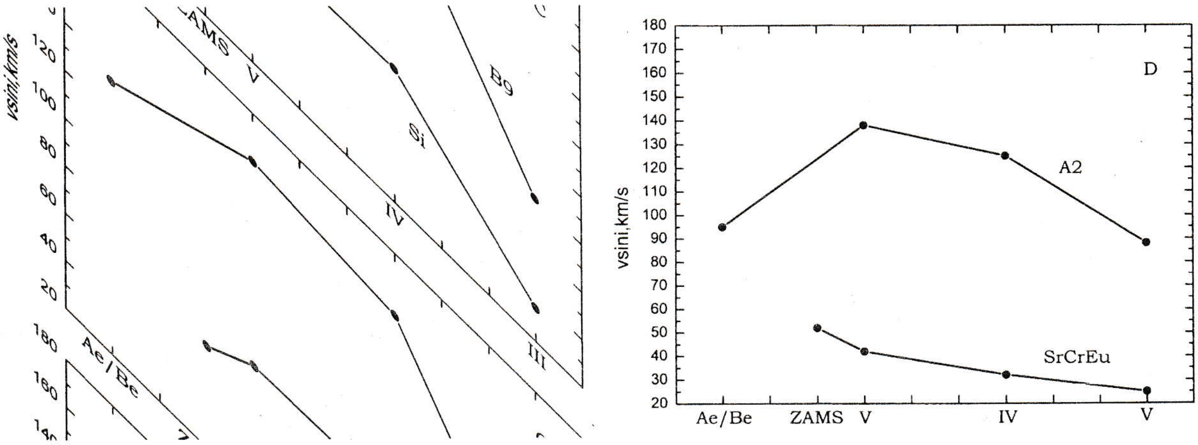


Figure 3: *(continued).*

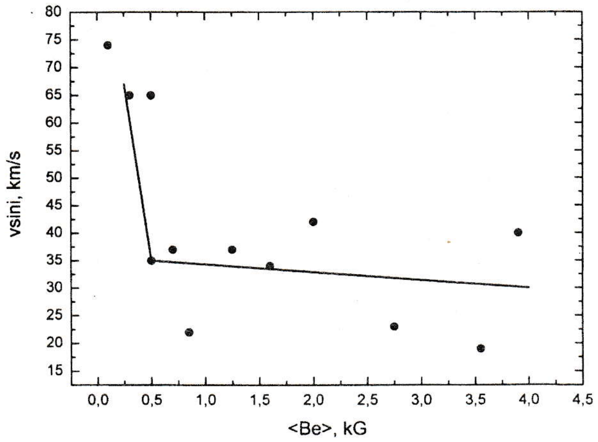


Figure 4: *Relationship between average rotation velocities and their average magnetic fields for CP stars*

low rotation velocities the field must be zero. This is why the field in magnetic stars is most likely to be relic. It is seen from Fig. 4 that extrapolation to the rotation velocity $v \sin i > 90 - 100\,\mathrm{km/s}$, characteristic of normal stars, leads to a zero field.

5. Conclusions

Present the summary of the results of the above analysis of observational data.

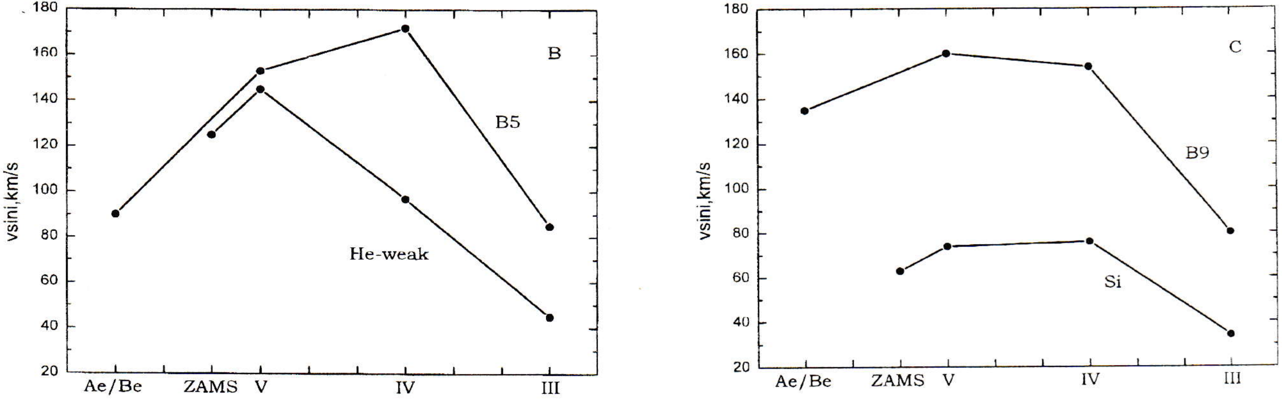
1. Strong global magnetic fields similar to the magnetic fields of CP stars are absent in young stars at the pre-main-sequence stage. They are likely to be hidden in the interior of stars because on the surface they are most likely to be destroyed by non-stationary processes due to the accretion.

2. The data of this paper support the extensively discussed hypothesis (Dudorov, Tutukov, 1990, 1998) of the residual (relic) magnetic field rather than the dynamo hypothesis (Borra, Landstreet, 1980).

3. In view of the absence of strong magnetic fields in young stars, the variation of the rotation velocity takes place without the involvement of the magnetic field. If the mass loss did come about with the magnetic field involved, this could happen only at the earliest stages — prior to the birth line.

Correction

Fig. 3 b), c) on page 92 should be replaced with the following:



4. The conclusion that global magnetic fields are absent in young stars is of particular importance for investigation of physical processes in them. Many phenomena in Ae/Be Herbig stars are presently attempted to be explained by way of assuming the involvement of strong magnetic fields (although the short-time local emergence of magnetic fields to the surface should not be disregarded).

5. It can be supposed that a strong field is preserved only in slow rotators in which the differential rotation is slow or absent. The differential rotation in rapid rotators converts the magnetic fields into a toroidal one and it turns undetectable.

6. As a star approaches the main sequence, when the accretion and the nonstationarity of the upper layers cease and the atmosphere stabilizes, favourable conditions for rising of the magnetic field to the surface and diffusion of chemical elements arise. It is just the zero age main sequence that is the location for the formation of chemically peculiar stars. Apparently a magnetic field forms slower than chemical anomalies.

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