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Conditions of search for magnetic stars at early evolution stages

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Abstract. Conditions which allow the detection of dipole magnetic fields in stars which are at the zero age of the main sequence are analyzed. A preliminary investigation of a sample of young stars with remnants of gaseous–dust structures (the so-called Post–Ae/Be Herbig stars (Shevchenko, 1989)) has shown that they all are located along the zero–age line and a few of them are chemically peculiar He-rich and He-weak–type stars. It is curious that not a single representative of a more numerous group of Si stars has turned out to be among them.

Key words: stars: magnetic field measurements – stars: Ae/Be Herbig stars – stars: polarization measurements

From the modern point of view magnetic fields of chemically peculiar (CP) stars were either generated at the early evolution stages by a magnetic dynamo or preserved after the compression of magnetized protostellar clouds when stars were formed. At the early stages of evolution CP stars lost moment of rotation as a result of interaction between the magnetosphere and the surrounding gaseous–dust envelope. Chemical anomalies could arise, irrespective of the field generating mechanism, only in an extremely stable atmosphere through diffusion of chemical elements due to action of light pressure and gravitation after the termination of accretion process and before or just after a star evolved to the main sequence. Fast–evolving massive magnetic stars with strong helium lines (He – r) probably continue to accumulate helium and other chemical elements during the life–time on the main sequence. In Fig.1 are shown the relations between the helium abundance in stars with strong helium lines and weak helium lines (He–w) (Glagolevskij, Kopylova, 1990), (Glagolevskij et al., 1993), (Zboril et al., 1994) and the relative radius R/R_z, where R is the radius of the star at the present time, R_z is its radius on the Initial main sequence. He–r and He–w stars have already relieved from the gaseous–dust envelope and are in a stable state, however minor mass loss in some He–r still continues in the form of polar flows (Barker et al., 1982). Unfortunately, there are no confident data on the abundance evolution with age of other, except for helium, chemical elements.

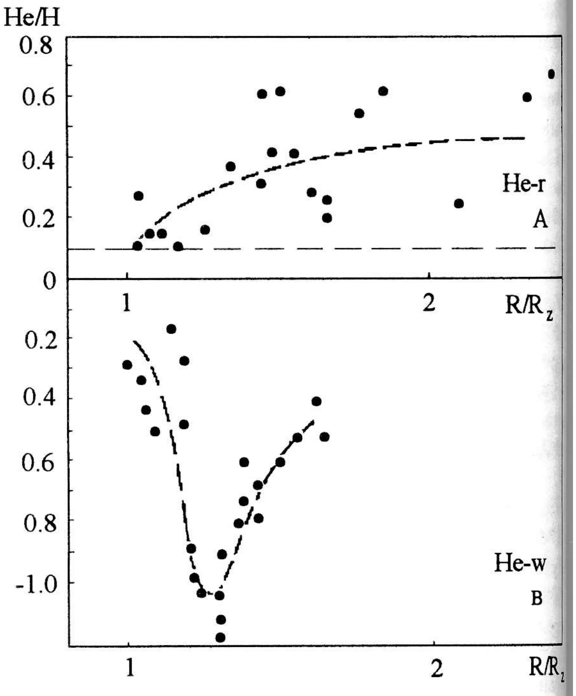

Figure 1: *Helium abundance in He–rich (A) and H weak (B) plotted against the relative radius.*

Slowly evolving low mass CP stars probably have time to be formed “prior to the main sequence” or at the very beginning of their stay on it. Proceeding fro the above said, much attention should be given young Ae/Be Herbig stars, which are at early stag of evolution. It is among them that one should se dipole magnetic fields and initial chemical anom lies, although the anomalies have not yet manag to develop to a degree sufficient for them to be d

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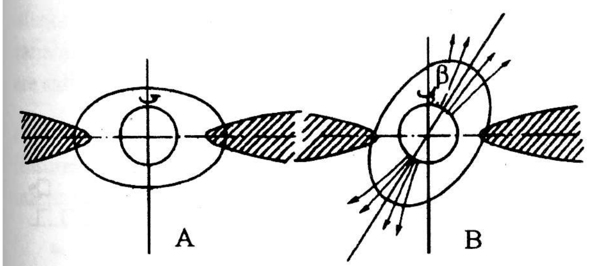

Figure 2: *The shape of the gaseous envelope around the Ae/Be Herbig star; A is the star without a magnetic field; B is a star with a magnetic field which inclined to the axis of rotation at the angle β.*

tected. This requires a time of the order of 10^6 years (Michaud, 1975). This is why the stars which are just approaching the main sequence are especially interesting, although they are rather difficult to separate.

Many stars of the upper part of the main sequence, staying at early stages of evolution, are faint, and inaccessible for magnetic field measurements with the Zeeman analyzer or photoelectric techniques from hydrogen lines. Therefore one has to look for indirect ways of magnetic field detection, for example, by means of polarization study. One of the methods was proposed by Gnedin and Silant'ev (1980), which is used to measure the distribution of linear polarization over the spectrum. Another method is as follows. In accordance with the recent data Ae/Be Herbig stars without magnetic fields are surrounded by a gaseous envelope shaped as a sphere or a spheroid oblate along the equator of rotation, and also by a gaseous–dust accretion disk in the equator plane. In gaseous envelopes powerful flows, associated with the mass loss, and accretion flows are often observed. But if a star is an oblique magnetic rotator (like a magnetic star of the main sequence), the gaseous envelope may then acquire the shape of an elongated ellipsoid of rotation with the large axis coincident with the dipole axis (Dolginov et al., 1979) (Fig.2). A powerful jet stream from the poles arises, which is controlled by the magnetic field. As has already been mentioned, in massive magnetic stars which stay on the main sequence weak polar flows are observed. Polarization of Ae/Be Herbig stars results from the light scatter by atoms, molecules, electrons and dust particles, especially in non–symmetric envelopes. It is constant in the case of unchanged configurations or variable with structural changes and rotation of the non–symmetric structures.

The theory of polarization phenomena has been repeatedly dealt with in literature (e.g. Dolginov et al., 1979). Calculations show that maximum polarization, $p \approx 4\%$, arises in the cases when the relationship between the axes of the ellipsoid is $a = 2.5b$. The electric vector of predominant oscillations of the light wave is normal to the plane run through the axis of symmetry of the ellipsoid and line of sight. With rotation of the star its magnetosphere rotates as well involving in motion the elliptical gaseous envelope, which necessarily results in a variation of polarization and its direction.

Additional polarization is created by the polar jets, the direction of the predominant oscillations of the electric vector being perpendicular to the cone axis, and the maximum polarization may reach 5% (Dolginov et al., 1979).

The gaseous envelope is mainly formed around the star, while the dust is contained in the disk. The scatter of radiation in the gas component occurs in the optical wavelength range, while in the dust component in the infrared. In consequence of the fact that the electric polarization vector of the scattered radiation oscillates perpendicularly to the axis of symmetry in the former case, and in the latter it oscillates along the axis of symmetry, the position angle of linear polarization changes by $\alpha = (90^\circ - \beta)$, when passing from the optical range to infrared. Here β is the angle between the magnetic dipole axis and the axis of rotation of the star. The data presented suggest that in the case of dipole field in an Ae/Be Herbig star one may expect the presence of periodic variability of linear polarization in the optical range and the stability of linear polarization in the infrared range. In such a way one may attempt to define the angle of inclination of the dipole axis.

Taking into account the above–said, let us see which results of the previous investigations can be used to select candidates in the search for magnetic stars. The youngest stars become visible near the line of their appearance shown in Fig.3 and found in the paper by Palla and Stahler (1990), when a star has already lost a considerable part of the surrounding envelope. It is evident that parameters of a star can be investigated from the spectrum when the influence of the envelope becomes insignificant. In rapidly evolving massive stars this will be the period after they evolved to the main sequence. That is why the sample of the stars to be investigated must not contain early B–stars. To reveal the periodicity due to rotation, one should consider polarimetry and photometry most promising.

Polarimetric investigations of Ae/Be Herbig stars have been carried out repeatedly. Linear polarization is known to vary in them in value and direction, however, due to the incidental measurements it is impossible to draw a conclusion on the existence of periodic variability. Only a few searches for periodic light variability have been made. On the basis of the scanty data available so far inferences have been made that in most cases the variability of polarization results from some global processes on the surface of

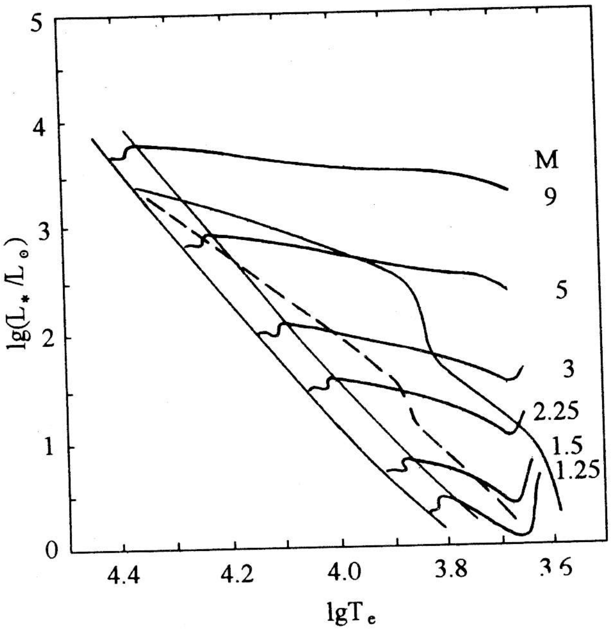

Figure 3: *Evolutionary tracks of Ae/Be Herbig stars. The solid line is the line of "birth" of stars; the dashed line is the average position of stars on the Hertzsprung–Russel diagram.*

stars, in the surrounding envelopes and disks. At the same time powerful gas flows are observed towards and from the star (Pogodin, 1985). The processes occurring in Ae/Be Herbig stars as well as the structure of the formations around them have been poorly studied yet. That is why the observed variability of polarization is difficult to interpret.

Many authors believe that the non–stationary processes in Ae/Be Herbig stars are caused first of all by accretion and/or magnetohydrodynamic activity of solar type due to powerful convection. However the possibility for convection to arise in stars with $M > 1.5M_\odot$ is theoretically argued by many authors (Larsen, 1969; Dudorov, Tutukov, 1988). To overcome this difficulty Palla and Stahler (1990) have assumed layer deuterium burning delivered to the star by accretion matter. In this layer conditions originate which give rise to convection. It disappears when accretion ceases and deuterium burns away. This occurs during the period the star is evolving to the initial main sequence. The presence of convection is necessary not only for explanation of the non–stationarity of Ae/Be stars but also for generation of magnetic field.

Consider the results of investigation of the photometric variability of Ae/Be Herbig stars, which may be expected to have a component associated with rotation. Fig.4 presents histograms of the number of stars N versus the amplitudes Δm of light variations, constructed on the basis of Table 2.1 from the book by Shevchenko (1989). The upper histogram presents all the studied stars, the following one give the data for each type of variability separately in accordance with the classification given in the same work. Examining the histograms the following conclusions can be drawn.

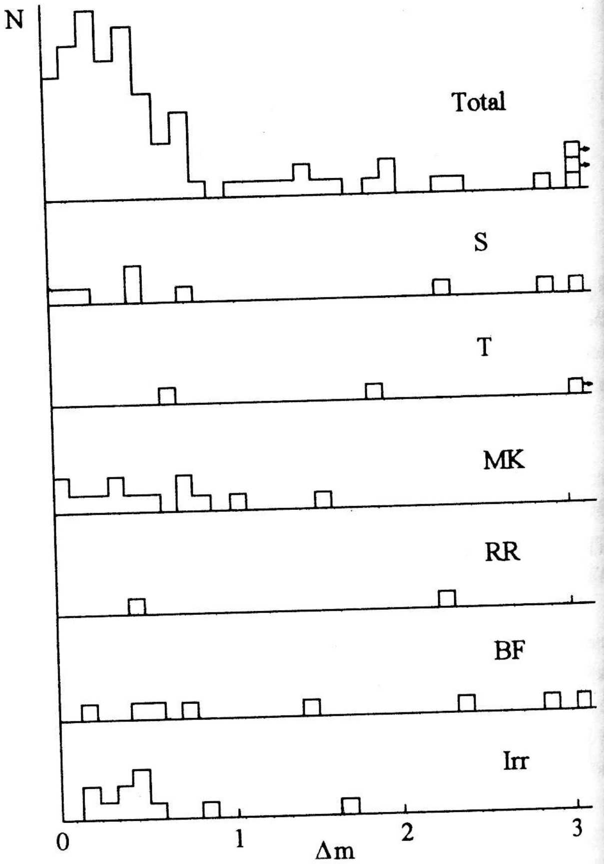

Figure 4: *The distribution of Ae/Be Herbig stars of different types in amplitude of photometric variability. S – fast variables; T – Algol-like periodical variables; MK – variables with smallscale quasiperiodic brightness variations; RR – continuous brightness variations with characteristic times of the order of a month and more rapid variations of the order of days; BF – Algol-like brightness decreasing during several months; Irr – incorrect noise-like brightness variations.*

- The most characteristic amplitudes lie within $\Delta m = 0^m - 0\overset{\mathrm{m}}{.}8$, then a long "tail" up to $\Delta m \approx 3^m$ is observed.

- The division of stars by type of light curves makes probably no physical sense in most cases, since individual types contain only 3–4 stars. In our opinion there are too few data to make a grounded classification. One can speak rather about the great variety of properties of the light curves than about the existence of definite types of variability. Some types of variability, for example Algol–like, do exist and they are sufficiently grounded.

In the cited book of Shevchenko (1989) photometrical features of Ae/Be Herbig stars are analyzed and some inferences are made, which are of interest to us.

- In 1/3 of the stars the light curves are Algol–like.
- Part of the curves show irregular variability.
- There exist large–scale sine–shaped light variations with a characteristic time of over a year.
- In part of the stars a fine–structure quasiperiodic variability is observed.

Apparently, first of all we must be interested in stars with the small–scale quasiperiodic variability, because it is obvious that the large–scale annual variations are not associated with rotation. Since the expected periods of rotation lie (as in magnetic stars) within the limits from fractions of a day to ten days and the character of variability is sinusoidal, we have selected only the objects which comply with these requirements. They are given in Table 1.

In the paper by Walker (1990) more definite data are presented. In four out of six investigated stars a photometric variability with a period expected for these stars, from 0.5 to 3 days, has been found. Thus, there are too few data yet on the photometric light variability associated with rotation. Therefore in the observing program stars of all types should be included. Long series of continuous polarization measurements are needed in order to notice its variability against the background of the considerable irregular variability due to the large–scale events in these stars. In many authors' opinion the irregular polarimetric and photometric variability often occurs as a result of eclipse of a star by inhomogeneities in the disk and global changes in the size of the emitting surface and complex distribution of temperature over it (Shevchenko, 1989). It is of no doubt that an important part is played by the processes of accretion from protoplanetary disks. Pogodin (1985) has revealed fast movement of considerable masses in the envelopes, often at velocities exceeding critical. The reasons for the non–stationary events have not been finally clarified, however it is evident that they are not caused by rotation. The question about the part played by accretion and magnetodynamical processes in the presence of strong dipole fields is very important for the solution of the problem in general and for our task in particular.

In view of the strong non–stationarity in all Ae/Be Herbig stars it becomes unclear how magnetic stars could preserve the relic magnetic field. The photometric data (Table 6.2 in Shevchenko, 1989) show that actually all Ae/Be stars are variable. If the non–stationary processes take place on the star, one can hardly expect the magnetic field to be preserved because of its tangling, which results in fast decay, since the field decays for the time $t \propto l^2$, where l is the characteristic size of magnetic field vortexes (at l equal to the star size $t \approx 10^9 - 10^{10}$ years). Turbulence which is destructive for the relic field may become its generator under certain conditions. For this to happen a stationary convective zone is needed at least before turbulence dies down and before the star evolves to the main sequence. For the generation of a global dipole magnetic field with the help of α^2–mechanism the condition that should be complied with is the absence of differential rotation, which otherwise converts a dipole field into torroidal, and also the absence of meridional circulation (Glagolevskij, 1988). The field had to be generated during the period of existence of rather a powerful gaseous–dust envelopes by interaction with which the star's magnetosphere decelerates the star by a factor of 2–3, as is observed in magnetic stars. Thus, certain contradictory requirements arise: on the one hand the field generation must start before the star evolves to the main sequence when the non–stationarity disappears, on the other hand for the magnetic braking process it is necessary that the field should exist at the early phases when the star is surrounded by sufficiently dense gaseous–dust formations and when it is not stationary.

Ae/Be Herbig stars with magnetic fields, in which atmospheric spectral lines are visible, should have already lost a considerable part of their moment of rotation. Therefore in search for young magnetic stars one should first of all pick out candidates with small vsini. Stars with strong non–stationarity at the surface should be disregarded. The percentage of magnetic CP stars is 10–15% among all stars of the same spectral classes, hence the same number of Ae/Be Herbig stars can be expected to have strong dipole magnetic fields. The problem is posed by the fact that the values of vsini are unknown for most stars.

Probably the sample of stars used in the search for magnetic fields should be limited on the side of high temperatures since the hot stars become free from the surrounding gaseous–dust envelope being already on the main sequence (Palla and Stahler, 1990). Thus, most probably young magnetic stars may be found in spectral classes later than B5. Attention should also be given to the fact that stars near the line of birth are only slightly suitable for studying magnetic fields and chemical anomalies because they have relatively large radii and therefore weak surface magnetic fields and chemical anomalies (Glagolevskij, 1994).

The data presented above allow us to draw the following preliminary conclusions.

1. The program of search for magnetic field stars should not include objects of types earlier than B5.

Table 1: *Periods of quasiperiodical variability of Ae/Be Herbig stars*

Star	period (days)	period probability	variability character
V1057 Cyg	11.1	0.965	Sinusoidal
V1515 Cyg	9.9	0.812	Pseudocyclic
V 380 Ori	4.9	0.821	Pseudocyclic
	10.6	0.776	Sinusoidal
BF Ori	10.0	0.773	Cyclic at minimum light
RR Tau	5.2	0.777	Pseudocyclic at minimum light
VV Ser	3.9	0.865	Sinusoidal
BD+40°4124	0.04	0.903	Sinusoidal
LK H_α234	3.8	0.72	Pseudocyclic
	1.9	0.74	Pseudocyclic
BD+61°154	11.5	0.799	Pseudocyclic

2. Stars with a relatively small vsini should be studied first, since they lose the greater part of its moment of rotation before they get rid of the gaseous envelope.

3. First of all one ought to investigate the stars in which periodic or quasiperiodic light or spectrum variations are of the order of 0.5 t
period of rotation).

4. The observing program should not contain stars which demonstrate considerable atmospheric activity, since in these stars a variable but not constant dipole field may be generated.

5. Probably special attention must be given to young stars that have just evolved to the initial main sequence or stars "approaching" it.

It is seen from the above data that investigation of global and local magnetic fields of young stars is rather a complicated problem which demands a complex solution.

For preliminary investigations we have included in the observing program at the 6 m telescope the so-called Post–Ae/Be Herbig stars (Shevchenko, 1989), which are allied to extremely young groups, immersed into absorbing clouds, have infrared excesses in the region of 1.2–10 μm, and sometimes weak $H\alpha$ emission. By every indication these stars are the objects of Ae/Be Herbig type, which evolutionarily approach the initial main sequence. The stars we have considered are listed in Table 2. Attention is attracted by the presence of well known CP stars of He–r and He–w types. In the table are presented the estimates of effective temperature T_e from the Q–parameter of UBV photometry and X–parameter of multicolour photometry in accordance with the calibration from Cramer (1984). In Fig.5 is displayed the relationship between T_e and spectral classes, the line shows the average relationship for normal stars of the main sequence. It is seen that in Post–Ae/Be Herbig stars there are actually no peculiarities in the spectra.

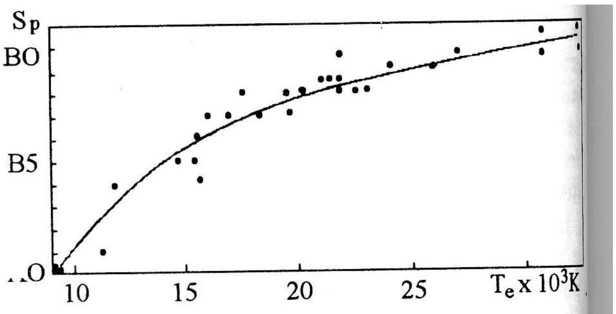

Figure 5: *The relationship between spectral classes of Ae/Be Herbig stars and effective temperature. Th line is a plot of the same relationship for normal star of luminosity class V.*

Let us see how Post–Ae/Be Herbig stars are lo cated on the Hertzsprung–Russel diagram. For deter mination of absolute bolometric magnitudes M_b w employed the method of Crowford, (1979) which w had repeatedly tested, where the relation between β- parameter of multicolour photometry and absolut magnitude M_v was used. To derive M_v we utilize the equivalent widths W_λ of hydrogen lines Hβ, H and $H\delta$ which we reduced into β values with the hel of our graphs. In the cases when β–parameters wer known we also used their $\beta(phot)$ in Table 3. Ha ing defined M_v we made a transition to M_b with th use of the bolometric corrections from the paper b Straizis and Kuriliene (1981).

Equivalent widths of hydrogen lines measured i the spectra taken with the Main Stellar Spectrograp of the 6 m telescope (reciprocal dispersion 9 Å/mm on the plates Kodak IIaO are given in Table 3. I the fourth column are presented the parameters $\beta(H$ obtained from the equivalent widths (the number o measured lines is given in brackets), the next co umn gives $\beta(H^k)$ obtained from the equivalent width $W(H\gamma)$ and $W(H\delta)$ from the catalogue of Klochkov

Table 2: *Effective temperatures* T_e *of Post–Ae/Be Herbig stars*

Star		Sp	$T_e(Q)$,K	$T_e(X)$,K	T_e
HD 594	BD+57°18	B3V	15900	-	15900
HD 236327	BD+57° 19	B5V	14700	-	14700
HD 627	BD+57° 22	B6V	12700	-	12700
HD 36540	-	He-w	-	-	15850*
HD 36629	-	He-w	-	-	20350*
HD 294264	BD-4° 1181	B3V	19900	20600	20250
HD 37129	-	He-w	-	-	18000*
-	KS Ori	A0V	-	10000	10000
HD 36958	KX Ori	He-w	17500	16600	17000
HD 36982	LP Ori	He-r	20300	21300	20800
HD 294263	LZ Ori	AOV	14700	9600	12150
HD 37061	NU Ori	B1V	27800	27000	27400
HD 37058	V359 Ori	He-w	-	-	19200*
HD 37115	V361 Ori	B4V	15600	-	15600
-	V372 Ori	AOV	10000	-	10000
HD 37020	-	B0.5Vp	31200	34000	32600
HD 37022	-	O9.5V	35000:	32000	33500
HD 37023	-	B0.5p	24300	20900	22600
HD 37021	BM Ori	B1.5V	22200	21100	21650
HD 37115	-	B6Ve	15900	15000	15450
HD 41887	-	B2V	23200	-	23200
HD 52942	-	B2IV	22200	24000	23100
-	BD-11° 1761	B2V	17500	-	17500
-	BD-11° 1763	B1.5V	21900	-	21900
HD 53623	-	B0.5IV	28000	28700	28350
-	BD-13° 4928	B0.5V	35000:	32300	33650:
-	BD-13° 4930	O9.5V	35000:	28700	31850:

Notes: calibration for $T_e > 30000$ K is unreliable.

* - Temperatures from Glagolevskij (1995).

Table 3: *Equivalent widths and* β *parameters of hydrogen lines*

Star	W(Hδ)	W(Hγ)	W(Hβ)	β(H)	β(H^k)	β(phot)
HD 36629	5.25	5.82	3.73	2.644(3)	2.650(6)	-
HD 36540	7.85	7.88	-	2.728(2)	2.676(6)	2.711
HD 37020	2.16	1.95	-	2.565(2)	-	-
HD 37021	6.48	5.25	-	2.673(2)	-	-
HD37022	1.69	1.49	3.59	2.573(3)	-	2.701
HD 37023	2.69	2.61	-	2.580(2)	-	2.621
HD 37061	4.59	4.85	4.71	2.637(3)	-	-
HD 37129	6.70	7.82	5.35	2.690(3)	2.660(6)	-
HD 53623	4.17	4.84	4.12	2.629(6)	-	2.657
BD+57°18	7.02	7.15	4.41	2.679(6)	-	2.700
BD+57°19	8.38	8.57	8.38	2.736(6)	-	2.674
BD+57°22	10.00	9.37	10.19	2.731(9)	-	2.765
V361 Ori	8.18	8.29	7.57	2.725(3)	-	-
HD 52942	-	-	-	-	-	2.629

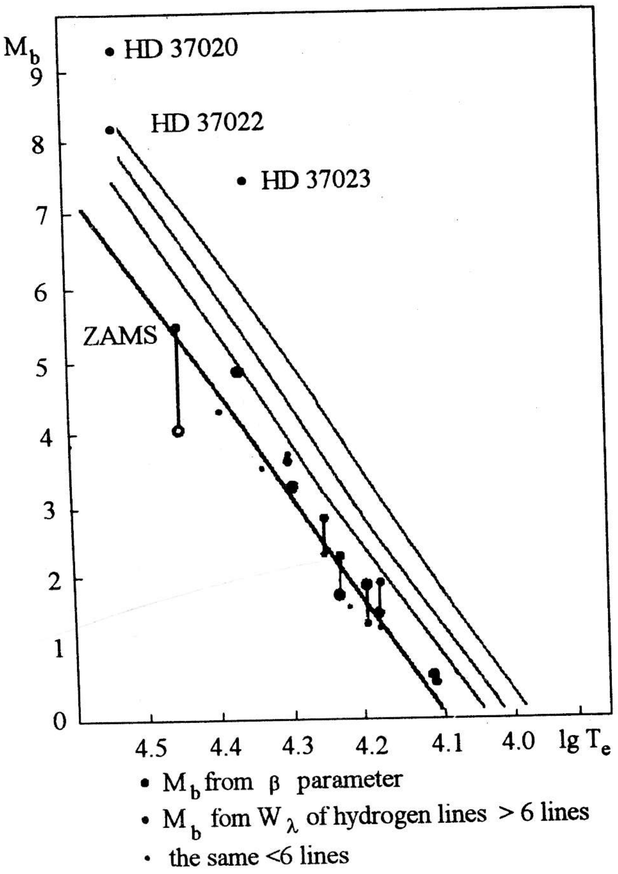

Figure 6: *The Hertzsprung–Russel diagram for the investigation of Post–Ae/Be Herbig stars . The arrows indicate magnetic chemically peculiar stars.* M_b *calculated from the parameter* β *(large circles);* M_b *calculated using more than 6 hydrogen lines (medium circles);* M_b *calculated from less than 6 hydrogen lines (small circles).*

et al. (1987), and then $\beta(phot)$, the photometric parameters from the catalogue of Rufener (1981). In Table 4 are cited the absolute bolometric magnitudes of the stars under investigation, and in Fig.6 the Hertzsprung–Russel diagram based on these data is shown.

Large circles show the data obtained from photoelectric measurements of β, circles of medium size indicate the data obtained from photographic measurements when more than 6 hydrogen lines are used. In the case when less than 6 lines are used the photographic data are marked with small circles.

It is seen in Fig.6 that all the stars are located near the Initial main sequence. This suggests that the stars classified as Post–Ae/Be Herbig are actually young objects. However it is difficult to say which of them are still evolving to the Initial main sequence and which have already started to leave it. Among the Post–Ae/Be Herbig stars which have been studied there are 5 early–type He–r and He–w magnetic chemically peculiar stars with the temperature mo than 16000 K, but there is not a single star of the la type, e.g. Si, although among typical main sequen type, e.g. Si, although among typical main sequen stars late–type stars are much more numerous tha early–type. It is seen on the histogram of Fig.7b.

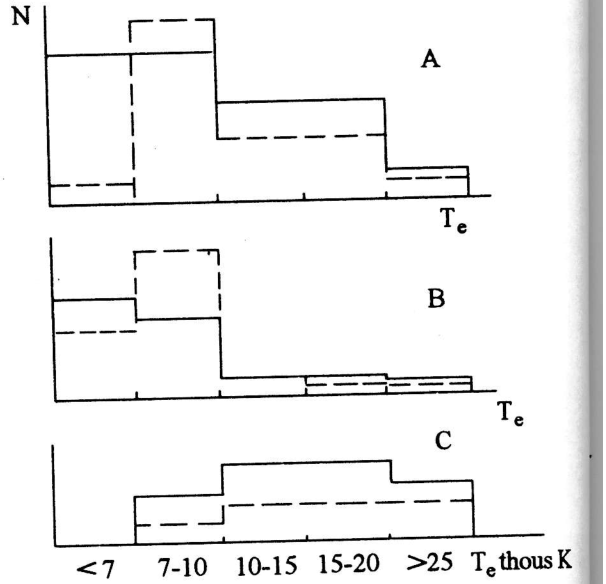

Figure 7: *Temperature distribution of stars. A - Ae/Be Herbig stars (solid line), Post–Ae/Be Herbig stars (dashed line). B – magnetic chemically peculiar stars (solid line), normal stars of luminosity class V (dashed line). C – Post–Ae/Be program stars (solid line), Post–Ae/Be stars plotted on the Hertzsprung–Russel diagram (Fig.6) (dashed line).*

Table 4: *Bolometric magnitudes*

Star	$M_b(\beta(\text{phot}))$	$M_b(\beta(\text{H}))$	$M_b(\beta(\text{H}$
HD 594	-2.01	-2.58	-
HD236327	-2.20	-1.62	-
HD 627	-0.88	-0.73	-
HD 36540	-1.73	-1.60	-2.18
HD 36629	-	-3.99	-3.90
HD 37021	-	-3.80	-
HD 37023	-	-7.84:	-
HD 37061	-	-5.51	-
HD 37129	-	-2.62	-3.17
HD 53623	-4.34:	-5.81	-
V361 Cyg	-	-1.91	-
HD 52942	-	-5.13	-
HD 37020	-	-9.77:	-
HD 37022	-	-8.65:	-

The temperature distribution of Ae/Be Herbi and Post–Ae/Be Herbig stars from the data o Shevchenko (1989) is shown in Fig.7a. The defic of cold Post–Ae/Be–type stars is readily seen, how thousand degrees. In this range one can expect the presense of CP stars among Post–Ae/Be stars. One can assume that their absence is associated with the fact that appearance of helium anomalies occurs more rapidly than those of silicon and others. One can assume also that chemical anomalies in magnetic stars occur near the moment of their evolving to the main sequence.

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