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Express method of search for strong magnetic fields

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Abstract. Possibilities of using the cross-correlation method in search for magnetic stars are considered. For observations with the high resolution echelle spectrometer (Lynx) relationships of limiting magnitude of the technique are plotted versus effective value of a surface magnetic field. Estimates are made using the numerical model. On the basis of test observations a possibility of using the method for magnetic stars with essential values of V sin i is shown.

Key words: stars: spectroscopy – stars: surface magnetic fields – method: cross–correlation technique

1. Introduction

Investigations of stars with surface magnetic fields have been carried out for a number of years at the 6 m telescope (Glagolevskij et al., 1986; Bychkov et al., 1990). These observations can be related to two types. To the first one we refer the works on spectroscopic monitoring of the selected objects, as a result of which we can get variation curves of the effective magnetic field and see its structure. In spite of relatively short characteristic periods of magnetic field variation, the fulfilment of such works with the multiprogram 6 m telescope is being prolonged for years. At photographic registration of spectra the works amounted to the analysis of position measurements of photographic spectrograms, registered with a Zeeman analyzer of circular polarization. Limiting magnitude of the method was determined by penetrating power of photographic registration with the camera F:2.3 of the Main stellar spectrograph, additional losses at analyzer optics being about 2 magnitudes. Fig. 1 presents distributions of the number of stars versus magnitude in which measurements of magnetic fields were done by photographic or photoelectric techniques. Improvements of spectral complexes which combine new achievments in technology of phaseshifting optics and new solid–body light detectors (Najdenov and Panchuk, 1996) extended the possibilities of the first stage. At the 6 m telescope one can obtain the spectra which allow us to restore the total vector of the magnetic field, and to investigate objects with more complicated picture of the field distribution over the star surface than the dipole one.

To the works of the second type we can refer spectroscopic search for magnetic fields in the stars selected preliminary by other features, for instance, by their colours in Geneva photometric system. Si the classical method of search for magnetic field based on the same technology of line shifting m surement on Zeeman spectrograms as in the progra of monitoring, then the limiting magnitude of search method does not differ from that of monito method of magnetic fields. Moreover, the prelimin selection of stars by photometric features is not s ciently effective.

Robinson (1980) suggested a method for magn field measurements which is free from polarizat measurements. The essence of the method is to rive $\pi-$ and $\sigma-$components of the magnetosensit line in Fourier plane. A line with the small La factor which is arised approximately in the same mosphere layers as the studied line, was used a reference non-splitted line. Spectra portions with h S/N ratio were used. This method was improved la by Babel et al. (1995) who detected a magnetic fiel 17.5 kGs in the 9-th magnitude star according to shape of correlation function (the observed and culated spectra were computed). A total time of signal integration on the 2 m telescope didn't exc two hours. This method doesn't require Zeeman sp tra to be registered and is free from measurements positions (or shapes) of separate lines, i.e. opera even at low S/N ratio. Below we discuss possibili of using this method at the echelle spectrometer.

2. Method

To estimate the possibilities of cross–correlat method we made its numerical modeling first. U ing Tsymbal (1994) algorithms for stars with differe values of effective temperature T_e, surface gravity the atmosphere logg and microturbulent velocity

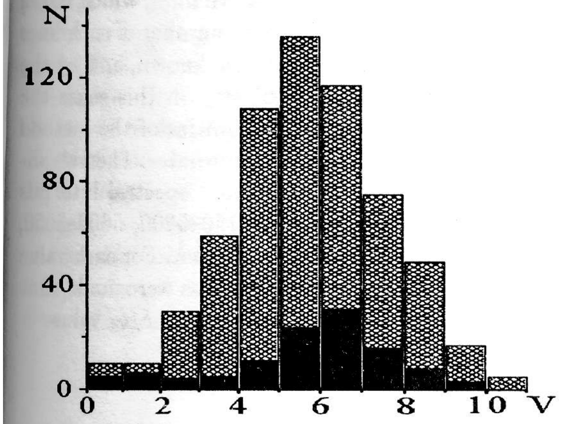

Figure 1: *Distribution of the number of the stars with measured magnetic fields vers magnitude. The 6m telescope observations (Bychkov et al., 1990; Glagolevskij et al., 1986) — filled areas, observations at telescopes of smaller diameter (from the data of Didelon's (1983) catalogue) — shaded areas.*

synthetic spectra were calculated. The solar chemical composition (Grevesse, 1993) was taken. The obtained series of synthetic spectra were gaussian convoluted, which imitate different values of spectral resolution $R = \lambda/\Delta\lambda$. We made calculations for a set of R values in the interval from 10000 to 43000. These spectra will be called as reference ones. Then using the formula

$$\Delta\lambda = 4.67 \cdot 10^{-13} \lambda^2 g_{eff} < H >,$$

(where $\Delta\lambda$ is the shift of σ–component relative π–component; λ (in Å), the line center position; g_{eff}, effective Lande factor; $< H >$, the weighted mean over star disk field in gauss) for a set of values of the effective magnetic field H_0 the positions of π– and σ–components of the lines, for which Romanyuk (1984) collected values of Lande factors, were calculated. Thus, for each H_0 value a list of lines consisted of the shifted σ–components and unshifted π–components was compiled. Using these lists and taking into account intensity difference of π– and σ–components synthetic spectra were calculated. The obtained sets of synthetic spectra were also gaussian convoluted which imitate different values of spectral resolution $R = \lambda/\Delta\lambda$. Then noises of different intensities were added to each synthetic spectrum. The spectra illustrating different stages of calculations are shown in Fig. 2. So we have obtained a set of functional dependences $I_\lambda(T_e;\ lgg;\ \zeta_t;\ H_0;\ R;\ S/N)$. For each of these dependences, from the reference spectra we calculated cross-correlation functions using the algorithms reported by Tonry and Davis (1979).

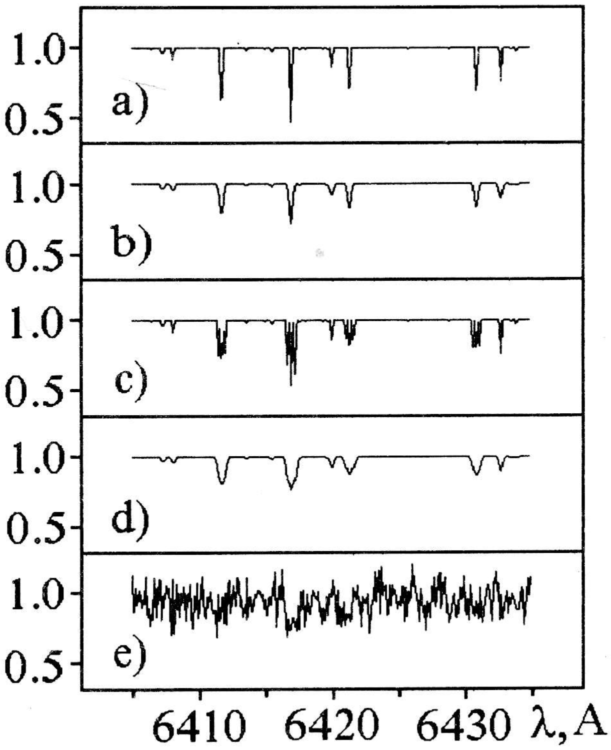

Figure 2: *Specimens of synthetic spectra without and with magnetic field, effect of convolution with spread function, example of noisy spectra. Spectral interval 6400–6450 ÅÅ a) synth without field; b) without field with* $\Delta\lambda = 0.15$; *c) same portion with field,* $H_0 = 10$ kGs, *synth without broadening; d) same as in c), but with broadening* $\Delta\lambda = 0.15$; *e) same as in d), but with noises S/N = 10.*

Synthetic spectra were calculated for the range 3900–7000 ÅÅ and cross-correlation functions were computed for the whole range within intervals as long as 50 Å. This value is a characteristic length of a spectral fragment recorded on a CCD (at observations with the Main stellar spectrograph), or of an individual spectral order (at observations with the echelle spectrometer). The examples of cross–correlation functions are given in Fig. 3. Then it was necessary to formalize the procedure of comparison of cross–correlation functions, calculated for the referense spectra and those under investigation. To do this we measured the widths δ of the central peak of the functions at the levels of its intensity $\delta_{1/2}$, $\delta_{2/3}$, $\delta_{3/4}$ — 1/2, 2/3 and 3/4 from the maximum intensity, respectively.

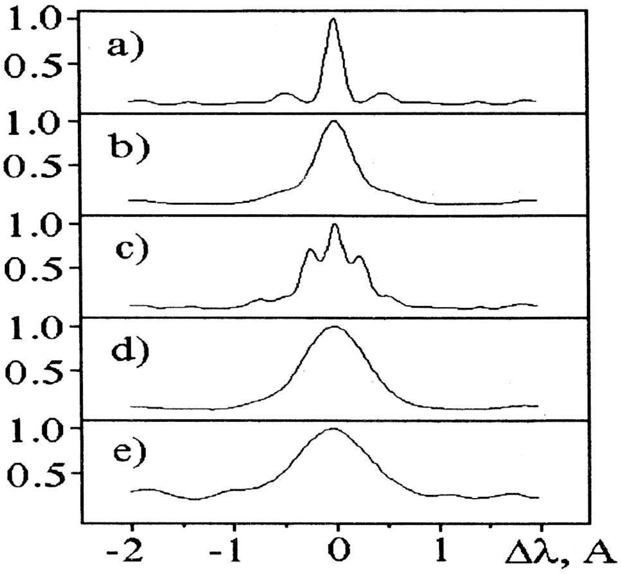

Figure 3: *Examples of cross–correlation functions for the spectra given in Fig. 2: a) autocorrelation function for Fig. 2a; b) autocorrelation function for Fig. 2b; c) cross–correlation function Fig. 2a and 2c; d) cross–correlation function Fig. 2b and 2d; e) cross–correlation function Fig. 2b and 2e.*

Using the relationship between the widths of cross-correlation function peaks, $r = \delta/\delta_0$, and the central wavelength of the spectral interval (Fig. 4), the spectral intervals, for which ratio $r = \delta/\delta_0$ (i.e. sensitivity of the method) is maximum, were chosen.

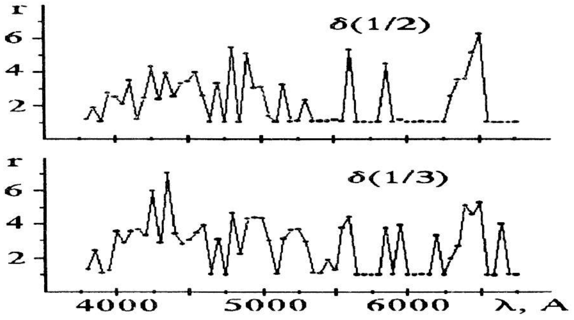

Figure 4: *Width ratios of central peaks of cross–correlation functions against central wavelength of spectral intervals of 50 Å in width. Data are presented for two cross–correlation function peak height values (1/2 and 1/3), in which the widths (δ) of the peaks are measured.*

In the framework of the numerical model the sensitivity of the method is not characterized b whole number of magnetosensitive lines, which f this spectral interval, but by the number of such for which Lande factor values are known, and b degree of their magnetosensibility. In this sens theoretical evaluations of possibilities of the me mentioned below are the lower estimates. Then w alyzed the estimates for 7 selected spectral int only: 4500–4550, 4800–4850, 5150–5200, 5600- 5850–5900, 5950–6000, 6400–6450 ÅÅ. For each of S/N ratio several noise generations were made, allowed us to calculate variance of $r = \delta/\delta_0$ valu

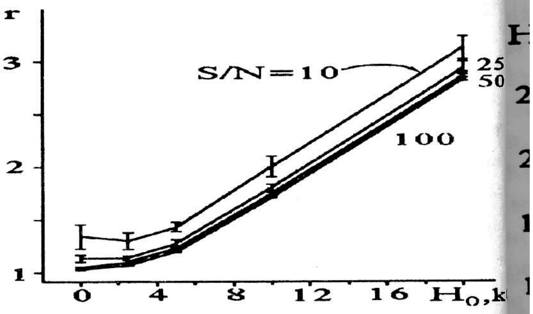

Figure 5: *Relationships between cross–correl function peak widths* $r = \delta/\delta_0$*, measured at the of 1/2 of maximum peak, and effective magnetic Spectral resolution R = 43000.*

Fig. 5 shows an example of relationship betw $r = \delta/\delta_0$, ratios of the widths of cross–correla functions (δ being measured at the half of maxi peak), and effective magnetic field value. The calc tion was done for a set of S/N at the spectral res tion R=43000. Allowing for variance value r = for each S/N we can determine minimum valu the H_0 field yet detectable at this spectral resolu R. Relationships between H_0 and R are presente Fig. 6. It is seen that effective spectroscopic search stars with strong magnetic fields can be fulfilled R not lower than 20000.

To estimate the limiting magnitude of the meth it is necessary for this spectrometer, i.e. for fixed spectral resolution, (for instance, for eche spectrometer Lynx R = 25000), to change from S/N value to magnitude m, recorded at a gi signal integration time t. For this purpose we the curves of m versus S/N obtained for the h resolution echelle–spectrometer of the 6 m telesc (Klochkova, 1995). The relationship between m S/N is obtained by observation with open slit star HD 217086 of known energy distribution. Th calculations were made using the formula

$$S/N = 3600 n_0 t x 10^{-0.4(m-m_0)} \times$$
$$\{3600 n_0 t x 10^{-0.4(m-m_0)} + (w b^{-1} N_r)^2 + w^2 t D\}^{1/}$$

where n_0 is efficiency in electrons per a second by pixel ($e^{-}s^{-1}pixel^{-1}$) from the star of m_0; w is the spectrum height perpendicular to the dispersion, in pixels; N_r – the readout noise, in electrons per pixel; D – dark count, in electrons per pixel for an hour; t – the exposure time in hours; b – binning factor perpendicular to the dispersion; m – stellar magnitude. Using the relationships between m and S/N calculated for different t, we transformed the data of Fig. 6 into relationships between detection threshold of magnetic field in stars of the given magnitude m and different times of signal integration (Fig. 7).

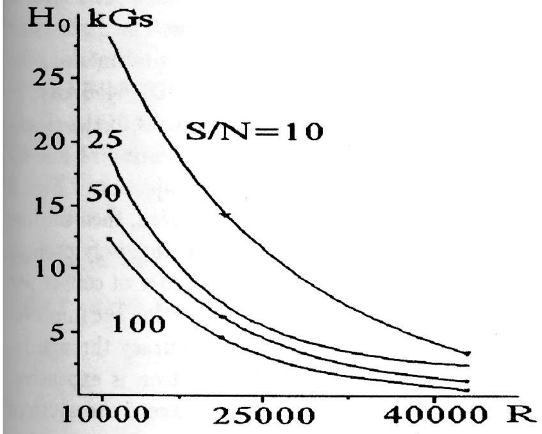

Figure 6: *Minimum field strength* H_0*, which can still be detected, as a function of spectral resolution.*

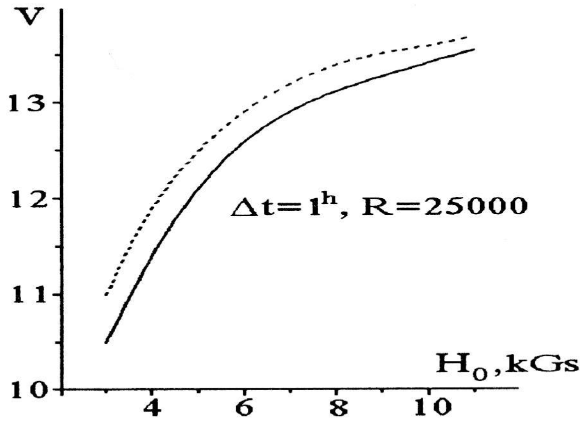

Figure 7: *Magnetic field detectability limit with the signal integration time* $t = 1\,h$*, versus stellar magnitude. Slit width was equal to* $1''$*, seeing –* $2.5''$*. The dashed line is an example of digital masking of spectrum.*

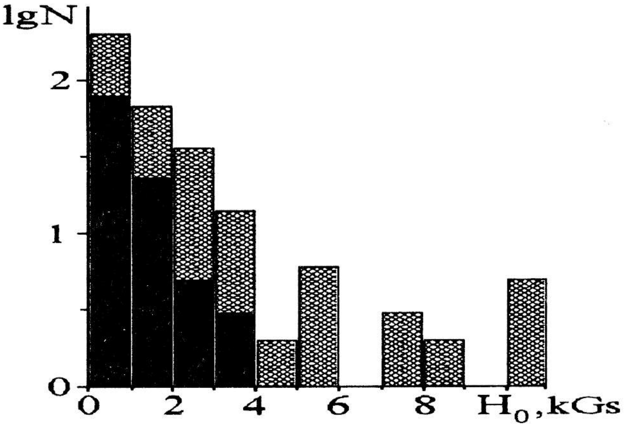

Figure 8: *Distribution of the number of stars on the main sequence with maximum magnetic field recorded by spectropolarimetric or spectroscopic techniques. Filled areas — the 6 m telescope observations (Bychkov et al., 1990; Glagolevskij et al., 1986); shaded area — observations at telescopes of smaller diameter (from the data of Didelon's (1983) catalogue.)*

3. Discussion of results

Above we presented some results of numerical modelling of effective method of search for strong magnetic fields in chemically peculiar stars with narrow lines. It is shown that the method can be used in the range of stellar magnitudes inaccessible for observations with high S/N (> 50). It should be noted that the model does not allow for line broadening due to rotation, therefore this modification of the method can be used for stars in the interval of spectral classes A and F, but in those cases when broadening due to rotation is smaller or exceeds the width of apparatus function, and does not exceed the splitting value (for instance, $V \sin i < 20$ km/s for $H_0 = 5$ kGs). Spectroscopy of peculiar stars, members of open clusters and associations showed that out of 108 peculiar stars investigated, 31 stars have $T_e < 11000$ K, and out of these 31 stars, 6 stars (20 %) have $V \sin i < 20$ km/s (Klochkova, 1985).

Fig. 8 presents distribution of the number of stars on the Main sequence as a function of magnetic field maximum value, recorded by spectropolarimetric or spectroscopic techniques. For plotting Fig. 8 we used Didelon's (1983) catalogue and the data by Glagolevskij et al. (1986), Bychkov et al. (1990). It is seen that the stars of the Main sequence with the effective field $H_0 > 5$ kGs make up less than 5 % of all stars, in which a magnetic field has been either

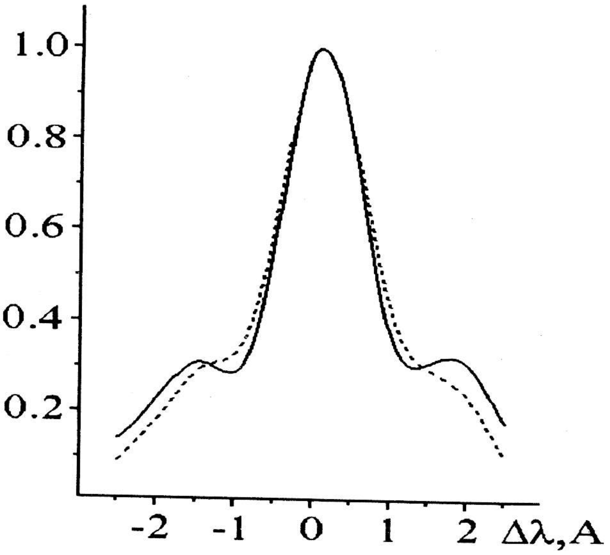

Figure 9: *Example of experimental method testing. Cross–correlation functions of echelle–spectra of HD96707 and α CMi computed for the whole range 5380–6480 ÅÅ using digital masking: solid line — portions containing lines with Lande factor* $0 < g_{eff} < 1$, $\Delta\lambda = 1.36$ Å; *dashed line — lines with* $1 < g_{eff} < 3$ *and* $\Delta\lambda = 1.50$ Å.

found and measured, or its search was undertaken. Note, that among the great number of magnetic stars studied with the 6 m telescope (more than 100 stars for which measurements are carried out for the first time, or specified measurements are made), the objects with the field stronger than 5 kGs have not been detected. From Fig. 8 it follows that to increase twice the number of stars with $H_0 > 5$ kGs field measurements should be carried out for more than 300 stars. It is clear that the searches, using spectropolarimetric techniques characterized by large S/N ratios, are inacceptable at the 6 m telescope. Apparently, search for stars with strong magnetic fields should be carried out in two stages: first, using cross–correlation techniques at spectroscopic observations with the $S/N < 10$, the stars with low values of V sin i are selected, and second, on the basis of observations with $15 < S/N < 30$ magnetic fields are estimated by cross–correlation techniques. Except of the main gain in the limiting magnitude caused by low S/N ratios, excluding from the optical scheme of Zeeman spectrum analyzer increases the limit of the method almost by two magnitudes.

Sensibility of the method considered can be increased using the method of digital masking of the spectrum. By digital masking method one ca tificially remove from the cross–correlation a sis those spectrum fragments which contain n but not magnetosensitive lines. Sensibility ca increased also by increasing the number of trum fragments which contain such lines i.e. by echelle–spectrometer. Here the adjacent spectra ders, if they do not overlap, can be merged form It is essential that the procedure should be care followed for a reference spectrum as well (such a proach is an “off–best” technique of a digital m ing). As it was shown in the tests at the 6 m telesc the presence of observations of a reference spect which is close in T_e to the spectra being exami or calculation of a suitable synthetic spectra wi similar temperature is of importance. The dashed in Fig. 7 shows a gain ensured by digital maskin one and the same spectral range (6400–6450 ÅÅ

Let us now address to the features of the cl cal estimation of magnetic intensification of lin measuring halfwidths. If the slit projection is ov pixels but the line profile is not resolved, then the halfwidth measurement accuracy is inversely pro tional to $(e)^{1/4}$, where e is the number of counts 1 Å (Gustafsson, 1992). In this situation the impr ment of halfwidth measurement accuracy through creasing the time of signal integration is expens When the line halfwidth begins to exceed the widt a pixel, the line halfwidth measurement accuracy comes inversely proportional to $(e)^{1/2}$, and with ther increase of spectral resolution this relation ho Thus, when the effect of line broadening by the m netic field is measured directly (from separate li and the spectral resolution is fixed, for the halfwi measurement accuracy to be raised two times the nal integration time has to be increased by a fac of four. Now consider the advantages of the meth It follows from Fig. 6 that a two–fold decrease of S/N, with a fixed magnetic field detection level, responds to an increase in spectral resolution by than a factor of two (for instance, a change from S $= 50$ to $S/N = 25$ at $H_0 = 4.5$ kGs corresponds an increase in R as low as 1.14 times). As a res of several noise generations we found that the ror of measurement of the cross–correlation functi halfwidth increased by a factor of 1.43. Taking i account that the scale increase transverse the disp sion can be made up for by the binning procedure, find that, with a fixed wide–slit factor, to the ab increase in R corresponds a $2.51 \log(1.14) = 0.1$ loss in magnitude which, as follows from the curve limiting magnitude of the echelle–spectrometer Ly (Klochkova, 1995), corresponds to a 1.2–time loss the exposure time t. Thus, in this method of sear of stars with strong magnetic fields the product is preferable to be increased at the cost of spectr resolution, an additional gain in time of search bei

2/1 2 = 1.67.

The method proposed have been tested by experiment. For this purpose observations of the magnetic star HD 96707 and the standard star α CMi have been performed using the high-resolution echelle-spectrometer Lynx. The spectral range was equal to 5380–6480 ÅÅ, the mean (over the range) signal-to-noise ratio was S/N = 125 and 200, respectively.

In Fig. 9 are displayed examples of cross-correlation functions (spectra of the indicated stars were mutually correlated) computed with the digital masking (in two different masks the portions contain lines with a Lande factor $0 < g_{\rm eff} < 1$ and lines with $1 < g_{\rm eff} < 3$ were taken into account.

It is seen that even in the case of axially rotating magnetic star (for HD 96707 $V \sin i = 45$ km/s) the cross-correlation technique estimates magnetic field even at R = 25000.

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