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Magnetic field variations with pulsational phase in the classical Cepheid star η Aquilae

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Abstract. The presence of the magnetic field on the classical Cepheid η Aquilae is established. The magnetic field shows periodic variations with a reversal of its polarity due to stellar pulsations ($-100 < B_{\rm e} < +50$ G). Two closed values of $B_{\rm e}$ lie out of the magnetic curve at phases $\phi = 0.610$ and $\phi = 0.629$. It was suggested that these recoiled points show that the abrupt change of the magnetic field occurred at the phase of propagation of the shock wave within the stellar atmosphere.

Key words: shock waves – stars: individual: η Aquilae – stars: magnetic fields – stars: oscillations – stars: variables: Cepheids

1. Introduction

Historically, the first investigation of magnetic field on pulsating stars was carried out by Babcock (1958), who published 20 measurements of magnetic field on RR Lyrae for 1955 and 1956 observations. Five measurements out of 20 obtained over five consecutive nights in October 1955 within an error of less than 220 G, showed the variations of the magnetic field from -1580 to 540 G. However a correlation of the magnetic field behaviour with the period of pulsations ($\sim$ 0.567 d) was not found. A similar situation exists for the measurements of the magnetic field over three nights in June 1956. Babcock (1958) wrote, that as for the short-time, so the long-time variations of the magnetic field are present in the RR Lyrae observations, but the character of the variability is vague. This star was studied later by Preston (1967). He carried out 50 photographic observations over two years and failed to record a significant value of the magnetic field. The photographic observations of the magnetic field on RR Lyrae have been published by Romanov et al. (1987). The authors obtained 63 Zeeman spectrograms with the 6m telescope (SAO, Russia) for several nights in 1978, 1982, and 1983 using the achromatic analyzer of circular polarization. The analysis allowed them to conclude that the magnetic field variations vary with the period of stellar pulsations, and one maximum and one minimum are presented without the change of the sign of the field. The mean values (according to Babcock) adopted for the period of pulsations, as well as the magnetic field polarity vary with the 41-day period, determined by the effect of Blazhko. But the problem remains: why Babcock's observations did not show the dependence of the magnetic field variations on the period of pulsations, in contradiction with Romanov's observations, and why the long run of Preston's observations (more than 2 years) has not shown the presence of the magnetic field at all.

The investigation of the magnetic field variation with the period of pulsations for three stars of δ Cephei and one star of W Virginis type using 28 Zeeman photographic spectrograms was carried out by Weiss et al. (1980). The authors constructed a general phase curve for all observations because data for each star were rare. Two maxima (phases $\sim$ 0.55 and $\sim$ 0.0) and two minima were presented on the curve. The validity of such a procedure is not obvious, but the amplitude of variations ($\sim$ 500 G with the change of the sign) and mean error $\sim$ 70 G testify the presence of the magnetic field and its variability in the investigated four Cepheids. These results are inconsistent with the multislit magnetometer observations (Borra et al. 1981; Borra et al. 1984). The measurements of a number of classical Cepheids did not show the magnetic field significantly exceeding the error of the measurements ($\sigma < 20$ G). In the unique observation, a magnetic field was recorded (α UMa: $B_{\rm e} = 15.5 \pm 3.4$ G).

The results of the investigations of the magnetic field behaviour in α Carina (Sp F0Ib-II) using Zeeman photographic spectrograms, was published by Weiss (1986). The period of 6.90 days for the magnetic field variations on Canopus has been reported. The amplitude of the magnetic field variations reaches $\sim$ 700 G with one maximum and one minimum. The found the period is markedly shorter than the computed period of rotation. On the basis of this result the author made an assumption on the probable relation between the identified period and the period of pulsations (not yet established).

The effective longitudinal magnetic field on the supergiant γ Cygni (Sp F8Ib) was measured for the period of 1969–1986 (91 nights in total) using the photoelectric scanner-magnetometer of the 2.6 meter Shajn telescope of the Crimean astrophysical observatory (Severny et al. 1974; Plachinda 1990). In different observing seasons, the intensity of the magnetic field undergoes both the variations in amplitude (from $\sim$ 100 G to $\sim$ 350 G) and in sign, with the characteristic time from 0.78 to 0.92 days. In 1982 the radial velocities were measured using the H_{α} line core and Ca I λ 6499.644 Å line, and periods of the magnetic field oscillation coincide with those of radial velocities periodical variations. The doubled amplitude of radial velocity variations in the H_α core and in the photospheric Ca I line are about 3 $\mathrm{km\,s^{-1}}$ and 1.2 $\mathrm{km\,s^{-1}}$, respectively. It was supposed, that the recorded variations of radial velocity are caused by the perturbation wave crossing the extended atmosphere of the supergiant from the inner layers toward the surface of the star. On the other hand, the investigations of the magnetic field of this star using multislit magnetometers (Borra et al. 1981; Borra et al. 1984) showed the only one significant result out of eight measurements (-18.3 $\pm$ 5.7 G). For other measurements the signal was within the errors, not exceeding a dozen of gauss.

In accordance with the above facts, a clear picture of both nature and behaviour of the magnetic field on cool pulsating stars has not yet been developed. Therefore, additional data are needed which requires further observations using an advanced technique and device.

The aim of this paper is to study the behaviour of the magnetic field variations with time in the classical Cepheid η Aquilae.

2. Observations

The main direct method of detecting a magnetic field in a star is to observe Zeeman splitting of spectral lines. In particular, if the magnetic field is parallel to the line of sight, the π components are not visible, and the two sets of σ components have opposite circular polarizations. The wavelength displacement of σ components from its zero field wavelength, caused by the splitting of atomic energy levels in the magnetic field of a star, produces wavelength shift $\Delta\lambda_{\mathrm{B}}$ equal to

$$\Delta\lambda_{\mathrm{B}} = (e/4\pi m_{\mathrm{e}}c^2)z\lambda^2 B_{\mathrm{e}} = 4.67\times10^{-13}z\lambda^2 B_{\mathrm{e}}, \quad (1)$$

where e is the electronic charge, m_{e} is its mass, c is the velocity of light, z is the effective Lande factor, λ is the wavelength in Å, and B_{e} is the longitudinal magnetic field in gauss.

An advanced technique and appropriate devices have been recently developed for the purpose of high-precision direct spectropolarimetric measurements of stellar magnetic fields (Donati & Semel 1990; Plachinda et al. 1993; Plachinda & Tarasova 1999; Johns-Krull et al. 1999). New direct spectropolarimetric studies show the presence of magnetic fields on solarlike stars, cool giants, and young stars (T Tauri stars) in the pre-main sequence stage of their evolution (Hubrig et al. 1994; Donati et al. 1997; Johns-Krull et al. 1999; Plachinda & Tarasova 2000). The existence of local concentrations of strong magnetic field on the surface of rapidly rotating RS CVn stars was also determined by Donati et al. (1999) using the spectropolarimetric technique of Zeeman-Doppler Imaging.

Our study of the magnetic field on the classical Cepheid η Aquilae was carried out with the same equipment and procedure (*"Flip-Flop" Zeeman Measurement Technique*) discussed in the papers by Plachinda et al. (1993) and Plachinda & Tarasova (1999). Spectropolarimetric measurements were made at the Crimean Astrophysical Observatory using the achromatic Stokesmeter (the working region is 4000–6800 Å) mounted in front of the entrance slit of the coude spectrograph of the 2.6m Shajn telescope. The two orientations of circular polarization are converted to linear polarization by means of an entrance quarter-wave retardation plate. The two modes of linear polarization are then separated into two beams by a plate of Iceland spar. An exit quarter-wave plate converts the linearly polarized light into circularly polarized light that balances differences in the reflectivity of the two light beams from the diffraction grating. The plate of Iceland spar separates the fast and slow linearly polarized beams by $5''$. The entrance slit dimension on the sky is $0.''8$. To avoid some possible instrumental effects, the entrance quarter-wave plate is rotating by 90° between the two exposures, and the positions of the two polarized spectra on the CCD are exchanged. In this way, each magnetic field measurement may consist of two different exposures, and the final value for the mean longitudinal field will be the arithmetic mean of the two individual measurements, in which the instrumental effects are cancelled out to first order:

Table 1. List of spectral lines used in magnetic field measurements

No	λ (Å)	Element	Multiplet	z
1	6154.226	Na I	5	1.333
2	6155.134	Si I	62	0.625
3	6157.728	Fe I	1015	1.250
4	6162.173	Ca I	3	1.250
5	6165.360	Fe I	1018	1.000
6	6166.439	Ca I	20	0.500
7	6173.336	Fe I	62	2.500
8	6175.360	Ni I	217	1.250
9	6176.807	Ni I	228	1.100
10	6180.204	Fe I	269	0.625

$$B_{\mathrm{e}} = (B'_{\mathrm{e}} + B''_{\mathrm{e}})/2, \quad (2)$$

where $B'_{\mathrm{e}} = k(\lambda_{1\mathrm{rcp}} - \lambda_{2\mathrm{lcp}})/2$ and $B''_{\mathrm{e}} = k(\lambda_{1\mathrm{lcp}} - \lambda_{2\mathrm{rcp}})/2$. Here $\lambda_{1\mathrm{rcp}}$ stands for the center of gravity of a line with right circular polarization obtained during the first exposure, and $\lambda_{1\mathrm{lcp}}$ stands for the center of gravity of a line with left circular polarization; the same designations for the second exposure are $\lambda_{2\mathrm{rcp}}$ and $\lambda_{2\mathrm{lcp}}$. The constant $k = 1/(4.67\times10^{-13}z\lambda^2)$.

The spectrograms used here were taken in the spectral region 6150–6180 Å. The reciprocal linear dispersion was 3 Å $\mathrm{mm^{-1}}$ (0.066 Å $\mathrm{pixel^{-1}}$), and the resolving power of spectra was approximately 3×10^4 (3.0 pixel). Signal-to-noise ratios were typically 100–250 for every polarized spectrum. The spectral lines used for magnetic field measurements are listed in Table 1. The columns of this table are, in order, line identification number, wavelength in Å (VALD (Vienna Atomic Line Data-Base): http: //www.astro.univie.ac.at / $\sim$ vald / (Kupka et al. 1999)), element, multiplet, and the effective Lande factor. The Lande values were taken from Beckers (1969). A synthetic spectrum calculated by the program package MERSEN (Cowley 1996 and Tsimbal 1999 (private communication)) have been used to select non-blended lines in the current spectral range. The photospheric line Ni I λ 6175.360 Å is possibly blended by the line of Fe II λ 6175.146 Å with $z = 1.220$.

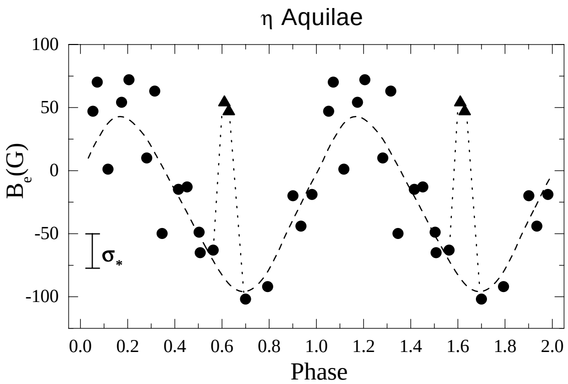

Fig. 1. The variation of the longitudinal magnetic field on η Aquilae with the period of pulsations

3. Discussion

3.1. The results of magnetic field measurements on η Aquilae

The results obtained for magnetic field measurements on η Aquilae are plotted in Fig. 1. Observations were fulfilled over 20 nights between 1991 July 21 and 1991 October 20. The observational run covered 92 days. Magnetic field variations phased with the pulsation period ($P_{\max}$ = 2432926.749 + 7.176641 days (Kiss 1998)) and are in gausses. The total period is shown twice. Filled triangles represent data that lie out of the supposed curve period (dashed curve). The bar is the value of rms error, σ_* = 27 G, of filled circle deviations from the dashed curve. Because the rms error around the arithmetic mean of all magnetic field values (excluding data that are pointed by triangles) is σ_k = 55 G, one can estimate that $(\sigma_k)^2/(\sigma_*)^2 \simeq 4.2$. Using the Fisher test, a confidence level of a statistical assurance of supposed magnetic field variations against phase of pulsations is considerably more than 99%, allowing us to suppose that the variation of the magnetic field with pulsational phase is real.

The obtained results are listed in Table 2. The second column contains the Heliocentric Julian Date (HJD) of the midpoint of the observation (observations per night were lasted two – four hours). In the third column the pulsational phase is given. The next two columns give the observed mean longitudinal magnetic field, $B_{\rm e}$, and the rms errors, σ_i, calculated in a standard manner. In the last column the number of individual measurements, N, responsible for the $B_{\rm e}$ is given, where $N = L(M-1)$, and L is the number of spectral lines, M is the number of exposures.

From this table, one can conclude that the mean value of $\sigma_i > \sigma_*$. This may be caused by an additional source of observational errors which is difficult to estimate: stellar magnetic field is measured using 10 spectral lines formed at different layers of the extended stellar atmosphere with different values of magnetic field. When averaged, different values of longitudinal components of magnetic field strengths, led to an increase of the observational errors at a given phase. More precise additional observations are needed to study the behaviour of stellar magnetic field using every spectral line.

Two values of our data (triangles) lie out of the magnetic curve represented in Fig. 1. These measurements are separated in time by one week (one pulsational cycle). The first point corresponds to $\phi = 0.610$ (HJD = 2448483.321) and the second one corresponds to $\phi = 0.629$ (HJD = 2448476.276). This is a special (singular) phase interval when the magnetic field strength varies abruptly from $\simeq -85$ G to +54 G, and then it falls back down from +47 G to $\simeq -90$ G. At phase $\phi = 0.610$, the discrepancy between the value of the dashed curve (-85 G) and the value of the magnetic field (+54 G) is $5.1\,\sigma_*$. At $\phi = 0.629$, the discrepancy between the value of the dashed curve (-90 G) and the value of the magnetic field (+47 G) is $5.1\,\sigma_*$ also. Moreover, measured values (+47 G and +54 G) are in a very good agreement. Thus we assume that it is a real event. On the other hand, one can see qualitative satisfactory fit in behaviour of the magnetic field strength against phase of a pulsation, between our measurements and Weiss et al. (1980). In both cases two maxima and two minima are presented, and phases of maxima are similar (Weiss et al. (1980): $\phi_{\rm maxima} \sim 0.02$ and ~ 0.55; present paper: $\phi_{\rm maxima} \sim 0.15$ and ~ 0.62).

Therefore, during the observations, magnetic field varied from ~ -100 to $\sim +50$ G versus phase of pulsations. In a very short phase interval $\Delta\phi \leq 0.1$, the magnetic field changes the sign, turns from $\simeq -85$ G to +54 G, and then falls down to a basic value.

Table 2. Measured mean longitudinal magnetic field strengths

No	HJD 2440000+	Phase	$B_{\rm e}$	σ	N
1	8459.431	0.282	10	9	30
2	8460.396	0.416	-15	16	54
3	8461.453	0.563	-63	39	28
4	8462.434	0.700	-102	48	50
5	8464.461	0.982	-19	52	18
6	8465.428	0.117	1	16	45
7	8468.232	0.508	-65	77	16
8	8472.281	0.072	70	30	21
9	8473.243	0.206	72	42	26
10	8474.253	0.347	-50	36	20
11	8475.378	0.504	-49	19	20
12	8476.276	0.629	47	19	20
13	8478.228	0.901	-20	33	18
14	8479.324	0.053	47	42	30
15	8483.321	0.610	54	58	18
16	8523.256	0.175	54	74	32
17	8524.271	0.316	63	30	56
18	8525.243	0.452	-13	23	45
19	8549.231	0.794	-92	41	16
20	8550.237	0.935	-44	36	23

3.2. The photospheric motions

The star η Aquilae (radius = 53.6 $R_\odot$, "evolutionary" mass = 6.4 $M_\odot$ (Fernley et al. 1989), $V_{sini} = 10\ {\rm km\,s^{-1}}$ (Breitfellner & Gillet 1993)) is known to have a bump on the descending branch of its light curve and the radial velocity curve. According to Simon & Schmidt (1976), a bump is caused by a resonance of the fundamental and the second overtone mode. The variations of radial velocity and of FWHM (Full Width of the spectral line at Half of the Magnitude) in the classical cepheid star η Aquilae estimated in our observations, coincided well with those published by Breitfellner & Gillet (1993).

The maximum of the turbulent velocity occurs for η Aquilae at a pulsational phase $\phi \approx 0.85$, when the star has a minimum radius (Breitfellner & Gillet 1993). A larger part of the increasing of turbulence is due to the atmospheric compression, although a shock wave amplification effect is also plausible (Fokin et al. 1996). According to Fokin et al. (1996), during the pulsational cycle a number of compression and shock waves is generated in the atmosphere of δ Cephei, however, only four shock waves are of real importance. The starting phases of these shock waves propagating through the region of Fe I λ 5576.0883 Å line formation are $\phi \sim 0.65$ (S_1), $\phi \sim 0.90$ (S_2), and $\phi \sim 0.40$ (S_3). Shock wave S_4 is formed in the higher part of the atmosphere ($\phi \sim 0.40$) and merges with S_3 at phase ~ 0.50 (see Fig. 3a in the paper by Fokin et al. 1996). First and second waves, S_1 and S_2, are the shocks of largest amplitudes. If we assume that the dynamic structures of atmospheres of both classical Cepheid stars δ Cephei and η Aquilae are qualitatively similar, it is possible to suggest that the starting phase of propagation of the shock wave S_1 coincides well with the phase of observing abrupt change of the magnetic field on η Aquilae. On the other hand, the phase interval of propagation of the S_1 wave $\Delta\phi \sim 0.1$, is also similar to the phase interval of abrupt change of the magnetic field. In the frames of our accuracy of the magnetic field measurements, we cannot pick out another shock wave on the magnetic curve. Additional observations are needed.

The presence of P Cygni type profiles for some metallic lines (Ca I, Fe I, Ni I, Sc II, Ti I) at phases ϕ = 0.060 and 0.072 was detected by Breitfellner & Gillet (1993). These emissions were observed during the same pulsational cycle. However, they have registered no emission at other cycles for these phases. We have also registered no emission at phases 0.053 and 0.072. This suggests that the intensity of the compression or shock waves propagating within the stellar atmosphere varies from cycle to cycle.

Taking into account the above, the two main questions are:

Whether the magnetic field on η Aquilae is varied with a pulsational phase, including the variation of the sign?

To answer this question, the computation of the variability of stellar magnetic field geometry as a function of pulsational phase in frames of magnetohydrodynamic pulsational model is needed.

Whether it is possible to change the sign of the line-of-site component of the magnetic field behind a front of the shock wave propagating within the stellar atmosphere?

As is known, in a conducting gas, magnetic field can strongly interact with the flow. In a simple case, when rotation and gravity are absent, three wave modes are possible. According to their phase speeds, they are classified as slow, intermediate and fast. When the wave amplitude is large, the intermediate mode (i.e., an Alfv́en wave) can propagate without steepening, whereas both the slow and fast magnetoacoustic modes steepen to form slow and fast shock waves, respectively (see, for example, Bazer & Ericson 1959, and Priest 1987).

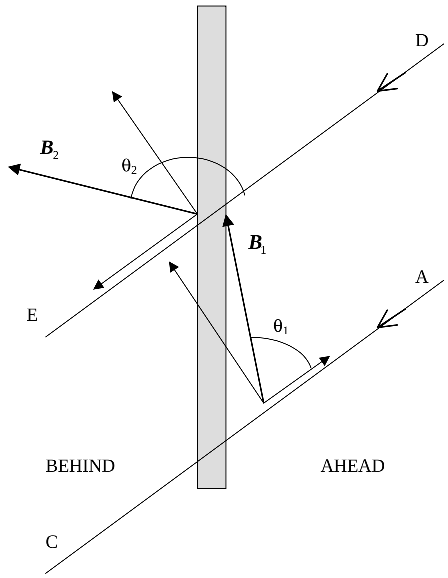

Fig. 2. The changes in magnetic field direction that are caused by oblique slow shock wave. The velocity and magnetic field vectors are assumed to lie in the XY plain. The gray rectangle is the front of the shock wave, $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$ are vectors of the magnetic field ahead and behind of the front, θ_1 is the angle between the line-of-site AC and $\boldsymbol{B}_1$, and θ_2 is the angle between the line-of-site $DE \parallel AC$ and $\boldsymbol{B}_2$

In a case, when magnetic field contains components both parallel and normal to the shock front (oblique shock wave), there are three different solutions for the changes in magnetic field direction, i.e. three types of oblique wave (see Bazer & Ericson 1959). The slow wave is characterized by $v_1^2 < v_{\rm A}^2$, where v_1 is the shock speed and $v_{\rm A}$ is the Alfv́en speed. The magnetic field ahead of the shock is refracted towards the shock normal and its strength decreases as the shock front passes by: $B_2 < B_1$. Here B_1 stands for the magnitude of the magnetic field ahead of the shock, and B_2 stands for the magnitude of the magnetic field behind of the shock (see Fig. 2).

The fast wave is characterized by $v_1^2 > v_{\rm A}^2$. The magnetic field is refracted away from the normal, and its strength increases: $B_2 > B_1$.

In a case of the intermediate wave, $B_2 = B_1$, and the component of the magnetic field along the shock front $B_{2y} = -B_{1y}$ and the component perpendicular to the shock front $B_{2x} = B_{1x}$.

In Fig. 2 we represent the 2-dimensional case for oblique slow shock wave in a frame of reference with axis Y along the shock front (the observer is ahead of the front). One can see, if the angle θ_1 between the line-of-site AC and $\boldsymbol{B}_1$ less than $90°$, and if the angle θ_2 between the line-of-site $DE \parallel AC$ is more than $90°$ (slow shock wave), the longitudinal component $B_{2\|} \parallel DE$ of the magnetic field behind of the shock front will be opposite in sign to $B_{1\|}$. By analog, if $\theta_1 > 90°$ and $\theta_2 < 90°$ (fast shock wave) the longitudinal component of the magnetic field behind of the shock front, $B_{2\|}$, will be opposite in sign to $B_{1\|}$ also.

According to above, we suppose that the sign of the longitudinal component of the magnetic field could be changed behind the shock front within the atmosphere of η Aquilae. Using this qualitative approach, it is possible to interpret the observed change of both magnetic field strength and magnetic field sign at phases 0.61–0.63. The magnetohydrodynamic computation of the shock wave propagation in frames of the magnetohydrodynamic pulsational model, as well as more precise and more detailed observations, are needed to build an actual picture.

4. Summary

Spectropolarimetric measurements of the mean longitudinal magnetic field in the classical Cepheid η Aquilae have been made. The magnetic field shows periodic variations with a reversal of its polarity due to stellar pulsations ($-100 < B_{\rm e} < +50$ G). Two closed values of $B_{\rm e}$ lie out of the magnetic curve ($\phi = 0.610$ and $\phi = 0.629$), and the magnetic field strength varied abruptly from $\simeq -85$ G to +54 G, and then falls back down from +47 G to $\simeq -90$ G. It is suggested that this abrupt change of the magnetic field in η Aquilae is due to the propagation of a strong shock wave within the atmosphere of the star.

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