Secular variability of the longitudinal magnetic field of the Ap star $\gamma$ Equ

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ABSTRACT
We present an analysis of the secular variability of the longitudinal magnetic field $B_\gamma$ in the roAp star $\gamma$ Equ (HD 201601). Measurements of the stellar magnetic field $B_\gamma$ were mostly compiled from the literature, and append also our 33 new $B_\gamma$ measurements which were obtained with the 1-m optical telescope of Special Astrophysical Observatory (Russia). All the available data cover the time period of 58 years, and include both phases of the maximum and minimum $B_\gamma$. We determined that the period of the long-term magnetic $B_\gamma$ variations equals 91.1 ± 3.6 years, with $B_\gamma$(max) = +577 ± 31 G and $B_\gamma$(min) = −1101 ± 31 G.

Key words: Stars: magnetic fields – stars: chemically peculiar – stars: individual: HD 201601

1 INTRODUCTION
The Ap star $\gamma$ Equ (HD 201601, BS 8097) is one of the brightest objects of this class, with the apparent luminosity $V = 4.66$ mag. The exact spectral type of this object is A9p (SrCrEu subclass). The magnetic field of $\gamma$ Equ has been studied for more than 50 years, starting from October 1946 (see Babcock 1958). The longitudinal magnetic field $B_\gamma$ of this star does not exhibit periodic variations in time scales typical of stellar rotation, 0.5 – 30 days. Such a variability of the $B_\gamma$ field was observed in most Ap stars. The above effect is commonly interpreted as the result of stellar rotation (oblique dipole model).

The first measurements by Babcock (1958) showed that the value of the longitudinal magnetic field $B_\gamma$ of $\gamma$ Equ was positive in 1946–52, and approached nine hundred G. From that time on the value of $B_\gamma$ slowly decreased and even changed sign in 1970/71. One could interpret the magnetic behavior of $\gamma$ Equ either as secular variations, or variations caused by extremely slow rotation. If the latter picture is correct, then the corresponding magnetic and rotational periods are in the range from 72 to 110 years (Bonsack & Pilachowski 1974; Leroy et al. 1994; Bychkov & Shtol’ 1997; Scholz et al. 1997).

The behavior of the $B_\gamma$ field in $\gamma$ Equ was investigated by many authors in the second half of the twentieth century. For this research we compiled $B_\gamma$ observations published by Bonsack & Pilachowski (1974), Scholz (1975; 1979), Borra & Landstreet (1980), Zverko et al. (1989), Mathys (1991), Bychkov et al. (1991), Bychkov & Shtol’ (1997), Scholz et al. (1997), Mathys & Hubrig (1997), Hildebrandt et al. (2000), Leone & Kurtz (2003) and Hubrig et al. (2004).

We included in this paper our unpublished magnetic $B_\gamma$ measurements which were obtained during the past seven years. All the new magnetic observations showed, that the slow decrease of the $B_\gamma$ field in $\gamma$ Equ apparently reached the minimum in 1996–2002 and has actually started to increase.

In this paper we determined the accurate parameters of secular variability of $\gamma$ Equ: the period $P_{mag}$, the amplitude and the time of zero phase for $B_\gamma$ variations, which were approximated by a sine wave. We support the hypothesis that the long-term $B_\gamma$ variation in $\gamma$ Equ is a periodic feature. Possible origin of this variation cannot be uniquely determined, see discussion in Section 5 of this paper.

2 OBSERVATIONS AND DATA PROCESSING
We have performed spectropolarimetric observations of Zeeman line splitting for $\gamma$ Equ at the Coude focus of the 1-m optical telescope (Special Astrophysical Observatory, Russian Academy of Sciences). Zeeman spectra were obtained with the echelle spectrograph GECS (Musaev 1996). We have put the achromatic analyser of circularly polarised light in front of the spectrometer slit. Images of the Zeeman echelle spectra were recorded from CCD detectors in standard FITS format. Final reduction of the archived spectra was performed with the standard MIDAS software (Monin 1999).
Effects of instrumental polarisation on \( B_e \) measurements obtained with this instrument were investigated by Bychkov et al. (1998, 2000).

Table 1 presents the full set of our \( B_e \) measurements of \( \gamma \) Equ (total 33 \( B_e \) points). The meaning of the first 3 columns is obvious. The fourth column gives the number \( N \) of spectral lines which were used for the measurement of \( B_e \) for a given exposure. Time length \( \Delta t \) of the exposure (in min) is given in the last column of Table 1.

On average, the value of a single \( B_e \) number listed in Table 1 was obtained after averaging of \( B_e \) measurements obtained in 500-1300 spectral lines. Standard deviation \( \sigma_{B_e} \) for the resulting value of \( B_e \) was computed in the standard manner as the error of an arithmetic mean value.

Errors \( \sigma_{B_e} \) determined in the above way reached rather low values in several observations listed in Table 1. In 2005/2006 we plan to verify the reality of such \( \sigma_{B_e} \) by a special program of \( B_e \) observations. Actually we accept these errors \textit{bona fide} and note the following properties of our \( B_e \) measurements.

The referee pointed out that a few pairs of \( B_e \) measurements of one night in Table 1 differ by only a few G, which is substantially less than the corresponding standard deviation \( \sigma_{B_e} \). We can explain this only as a purely random effect, and do not see any reason for it either in the acquisition of observational data or their reduction.

Secondly, series of measurements taken within a few nights generally show a scatter of the order of 100 G, which is much higher than the standard errors \( \sigma_{B_e} \) in Table 1. The latter are of the order of \( 20-30 \) G, and such a discrepancy suggests that our standard deviations are systematically underestimated, and are in fact of the order of 100 G. On the other hand, such a scatter of \( \approx 100 \) G is not inconsistent with the short-term variability of light and the longitudinal magnetic field \( B_e \) in \( \gamma \) Equ in time scales of minutes or above it.

Leone & Kurtz (2003) recently discovered periodic variations of the longitudinal magnetic field \( B_e \) in \( \gamma \) Equ over the pulsation period of this star, \( P_{\text{puls}} = 12.1 \) min. The estimated amplitude \( \Delta B_e \approx 240 \) G for this period, therefore, these variations at least can contribute to the scatter of our \( B_e \) points collected in Table 1.

Study of the rapid periodic \( B_e \) variations on a time scale of minutes was also presented in Bychkov et al. (2005b) for \( \gamma \) Equ. They did not find conclusive evidence of such variations above the noise level at \( \approx 240 \) G.

We also performed spectral analysis of the full set of 298 \( B_e \) time series from years 1946–2004. We concluded that there are no short-period field variations with periods above ca. 1 day, but were not able to extend our analysis for shorter periods, see Section 4 of this paper.

3 MAGNETIC PERIOD OF \( \gamma \) EQUI

Magnetic observations presented in Table 1 represent completely new data. They cover time span of ca. 7 years and include the phase when the effective magnetic field \( B_e \) in \( \gamma \) Equ apparently reached its minimum value, and then the slow decrease of \( B_e \) observed in the recent \( \approx 50 \) years has been reversed. This fact is of extraordinary importance, because it allows one for a fairly accurate determination of the magnetic period and the amplitude of \( B_e \) variations in \( \gamma \) Equ.

We have compiled the set of 298 observations of the \( B_e \) field in \( \gamma \) Equ, scattered in the literature, and appended our measurements. These data cover the time period 1946–2004 (58 years). They are displayed in Fig. 1. Note, that the \( B_e \) measurements obtained by Babcock (1958) apparently cover the phase of the maximum longitudinal magnetic field in \( \gamma \) Equ.

The set of \( B_e \) measurements analysed in this paper is rather heterogeneous. The data have been obtained by several different observers over a long time period using various instruments and techniques, and it is impossible to estimate or test credibly their systematic and random errors, particularly for the earliest observations of the longitudinal magnetic field in \( \gamma \) Equ.

Therefore, we arbitrarily assumed that systematic errors of the \( B_e \) observations are equal to zero. In other words, all the \( B_e \) points for \( \gamma \) which were found in the literature are fully compatible.

Random errors of individual \( B_e \) points frequently were given in the source papers, and are denoted by vertical bars in Fig. 1. These errors were not directly available for the earliest photographic measurements by H.W. Babcock (1958) and Bonsack & Pilachowski (1974). We adopted here the

| JD | \( B_e \) (G) | \( \sigma_{B_e} \) (G) | \( N \) | \( \Delta t \) (min) |
|----|-----------|----------------|-----|-------------|
| 49648.323 | -1045 | 21 | 706 | 30 |
| 49648.345 | -1315 | 26 | 755 | 30 |
| 49649.229 | -1463 | 37 | 576 | 30 |
| 49649.257 | -1159 | 31 | 656 | 30 |
| 49932.424 | -1317 | 26 | 691 | 60 |
| 49932.469 | -1317 | 26 | 675 | 60 |
| 49933.460 | -1316 | 26 | 700 | 60 |
| 49933.507 | -1317 | 29 | 704 | 60 |
| 50023.158 | -1291 | 22 | 501 | 40 |
| 50023.189 | -1380 | 23 | 650 | 40 |
| 50066.128 | -1539 | 26 | 718 | 40 |
| 50066.157 | -1611 | 62 | 532 | 40 |
| 51533.1229 | -1014 | 16 | 966 | 30 |
| 51533.1451 | -1011 | 14 | 701 | 30 |
| 51535.1847 | -902 | 16 | 955 | 40 |
| 51535.2153 | -901 | 19 | 855 | 40 |
| 51536.1069 | -670 | 18 | 821 | 30 |
| 51536.1285 | -642 | 24 | 508 | 30 |
| 51888.166 | -1069 | 18 | 847 | 30 |
| 51888.190 | -1092 | 20 | 1353 | 30 |
| 51889.103 | -890 | 20 | 847 | 30 |
| 51889.126 | -865 | 20 | 817 | 30 |
| 51890.142 | -742 | 21 | 770 | 30 |
| 52163.3009 | -845 | 19 | 833 | 30 |
| 52163.3201 | -855 | 19 | 732 | 30 |
| 52164.2861 | -956 | 16 | 947 | 30 |
| 52164.3076 | -967 | 16 | 914 | 30 |
| 52165.2812 | -1061 | 17 | 835 | 40 |
| 52165.3111 | -1029 | 16 | 991 | 40 |
| 52186.2229 | -922 | 17 | 1085 | 30 |
| 52186.2451 | -942 | 17 | 1055 | 30 |
| 52187.2673 | -882 | 16 | 1072 | 30 |
| 52188.2395 | -908 | 18 | 838 | 30 |

Table 1. Measurements of \( B_e \) in \( \gamma \) Equ (HD 201601).
estimated error for Babcock’s data equal 238 G, and 151 G for Bonsack & Pilachowski. These numbers were obtained in our thorough reanalysis of the earliest papers dealing with measurements of stellar magnetic fields, cf. Section 3.1 in Bychkov et al. (2003).

Determination of the period and other parameters of the apparent magnetic variability for γ Equ was performed in the following manner. Assuming that the run of the observed longitudinal field $B_e$ with time $T$ can be approximated by a sine wave

$$B_e(T) = B_0 + B_1 \sin \left( \frac{2\pi(T - T_0)}{P} - \frac{\pi}{2} \right),$$  (1)

we determined all four parameters: the period $P$, the average field $B_0$, the amplitude $B_1$, and the time of zero phase $T_0$ using the iterative technique of nonlinear fitting.

Starting values of $P$, $B_0$, $B_1$, $T_0$ and their standard deviations were found by our computer code for the nonlinear least squares method (Bychkov et al. 2003). The final values and their errors were then computed with the public domain code “nlfit.f”, which is designed for curve fitting and surface fitting with the Levenberg-Marquardt procedure (ODRPACK v. 2.01 subroutines). The code is available at the site www.netlib.org.

Fitting of a sine wave to all the 298 $B_e$ points with errors as in Fig. 1 gave very poor results with the $\chi^2$ for a single degree of freedom $\chi^2/\nu = 18.0420$. Such fits are unacceptable, and in case of γ Equ the poor fit is the result of underestimated errors of many $B_e$ points. Many $B_e$ observations presented in Fig. 1 have very low errors, which sometimes are less than 20 G. Our new $B_e$ points, which are collected in Table 1, also are of such a high formal accuracy.

We cannot judge, whether an apparent scatter of $B_e$ points in Fig. 1 is due to unrealistically large errors or the intrinsic short-term variability of the longitudinal magnetic field in γ Equ. The estimated random error of $B_e$ points about the starting sine wave equals to 213 G. For the final fitting of a sine we assumed that all the 298 points have identical errors of 213 G.

Final values of the fitted parameters and their standard deviations $\sigma$ for the sine phase curve are given below.

$$P_{\text{max}} = 33278 \pm 1327 \text{ days} = 91.1 \pm 3.6 \text{ years}$$
$$T_0 = \text{JD } 2417795.0 \pm 1057.$$ $B_0 = -262 \pm 22.4 \text{ G}$
$$B_1 = +839 \pm 22.1 \text{ G}$$
$$r = -0.524 \pm 0.043$$

In other words, a parameter range from $-\sigma$ to $+\sigma$ is just the true 68% confidence interval for this parameter.

The above fit of a sine wave with uniform errors of 213 G is very good, with $\chi^2/\nu = 1.0134$. The effect of inhomogeneity in the $B_e$ time series plus the possible existence of rapid magnetic variability in γ Equ were compensated by the increase of the random error, and neither should influence the above parameters of secular magnetic variability in γ Equ.

The standard parameter $r$ was defined for the oblique rotator model of an Ap star. It is related to the angle $\beta$ between the magnetic dipole axis and the rotational axis,

$$r = \frac{\cos \beta \cos i \sin \beta \sin i}{\cos \beta \cos i + \sin \beta \sin i} = \frac{B_e(\text{min})}{B_e(\text{max})}.$$  (2)

Parameters $B_e(\text{min})$ and $B_e(\text{max})$ of the $B_e$ sine wave for γ Equ are given by

$$B_e(\text{max}) = B_0 + B_1 = +577 \pm 31.4 \text{ G}$$
$$B_e(\text{min}) = B_0 - B_1 = -1101 \pm 31.4 \text{ G}$$

Note, that the meaning of $B_e(\text{max})$ and $B_e(\text{min})$ for use in Eq. 2 is different: $B_e(\text{max})$ denotes there the value of magnetic intensity which has the higher absolute value, and $B_e(\text{min})$ has the lower absolute value. In this way we obtained the value of $r$ for γ Equ equal to $r = 577/(-1101) = -0.524$.

Bychkov et al. (2005a) presented an extensive catalog of the magnetic phase curves and their parameters for 136 stars on the main sequence and above it. We quoted there the previously estimated period for γ Equ, $P_{\text{max}} = 27027^{+3}$, which was obtained on the basis of a shorter series of $B_e$ data. This paper and the new, more accurate $P_{\text{max}} = 33278$ represents a major revision of the previously known magnetic period of γ Equ.

4 SEARCH FOR ADDITIONAL MAGNETIC PERIODS IN γ EQU

Significant scatter of the observed points in the long-term run of $B_e(T)$ in Fig. 1 suggests the search for short-term periodicities. We applied the strategy of prewhitening to the set of available $B_e$ measurements, and removed the principal sine-wave variations from the data. Prewhitened data were then analyzed with the method developed by Kurtz (1985), and with his Fortran code (Kurtz 2004).

Such a search for peaks in the $B_e$ amplitude spectrum of γ Equ in this paper was restricted to trial periods higher than 1 day. This is because many of the earlier magnetic observations for this star either have poorly determined the time of measurement, or have long times of exposure (see
e.g. Babcock 1958). The star \( \gamma \) Equ exhibits rapid nonradial pulsations and the corresponding \( B_e \) with the period \( P_{\text{mag}} = 12.1 \text{ min} \) (Leone & Kurtz 2003) and, possibly, with simultaneous shorter periods (Bychkov et al. 2005b). None of them were analysed in this paper.

We have identified two additional periods of statistically low significance in the range \( P_{\text{mag}} > 1^d \), see Fig. 2.

\[
\begin{align*}
P_1 &= 348.07 \text{ days}, \text{ amplitude } = 122 \text{ G} \\
P_2 &= 23.44 \text{ days}, \text{ amplitude } = 110 \text{ G}
\end{align*}
\]

Both peaks in the amplitude spectrum in Fig. 2 exhibit low signal to noise ratio, with noise level at ca. 80 G. The period \( P_1 \) is close to 1 year. Since most of the existing \( B_e \) observations for \( \gamma \) Equ were performed in months July-November, then the peak \( P_1 \) in the amplitude spectrum represents a false period which most likely reflects the average 1-year repetition time in the acquisition of the existing magnetic measurements.

We believe that the peak \( P_2 \) in the amplitude spectrum of the \( B_e \) field of \( \gamma \) Equ is the random effect of a pure noise. The peak is very narrow, in fact, it only appears in a single bin of a very dense discrete frequency mesh.

Kurtz (1983) discussed the possible existence of the period of \( \approx 38 \) days in his photometric observations of \( \gamma \) Equ in 1981. That period was of low probability, but possibly could be identified with the real rotational period in this star. We do not confirm the existence of the 38 day period in long-term \( B_e \) observations of \( \gamma \) Equ, see Fig. 2.

5 DISCUSSION

There exist three possible explanations for the observed long-term behavior of the longitudinal magnetic field in \( \gamma \) Equ:

1. Precession of the rotational axis (Lehmann 1987).
2. Solar-like magnetic cycle (Krause & Scholz 1981).
3. Rotation with the period of 91.2 years.

The Ap star \( \gamma = \text{HD 201601} \) in fact is a binary system. One can assume, that the gravitational force from the secondary companion can cause precession of the Ap star. As the result, the angle between the rotational axis and the direction towards the Earth varies periodically. Therefore, changes of the aspect can in principle cause apparent variations of the longitudinal magnetic field \( B_e \) or the amplitude of its variations.

Effects of precession in long-period Ap stars were studied by Lehmann (1987), who showed that the oblateness of stars caused by the rotational or magnetic flattening is not adequate to produce observable precession effects. The only exception was 52 Her, where the observed behavior of the star could be interpreted as a precessional motion.

The above considerations indicate that the precession theory does not convincingly explain \( B_e \) variations in this star.

The idea by Krause & Scholz (1981) that we actually observe the solar-like magnetic cycle in \( \gamma \) Equ in which the global magnetic field reverses its polarity, cannot be easily verified by the existing observations of the global longitudinal magnetic field \( B_e \). Moreover, one can note that such an idea requires the existence of a mechanism in the interior of \( \gamma \) Equ which ensures the transfer of huge magnetic energy into electric currents and vice versa. Note that the required efficiency of such a mechanism and the amplitude of magnetic field variations in \( \gamma \) Equ is ca. four orders of magnitude larger than that in the Sun in a similar timescale.

Following the widely accepted picture of an Ap star, we believe that the magnetic field of \( \gamma \) Equ can be approximated by a dipole located in the center of the star. The dipole is inclined to the rotational axis of \( \gamma \) Equ. We assume that the magnetic field is stable and remains frozen in the interior of a rotating star at the time of observations, i.e. during at least of 58 years. Therefore, slow variations of the \( B_e \) field in \( \gamma \) Equ are caused by an extremely slow rotation, in which case our \( P_{\text{mag}} = P_{\text{rot}} = 33278^d \). Such an explanation is supported to some extent by polarimetric measurements by Leroy et al. (1994).

We plan to perform high accuracy polarimetric measurements of \( \gamma \) Equ with the new version of MINIPOL. The device was constructed to measure the angles and the degree of linear polarisation of stellar radiation, and will be operational at the Special Astrophysical Observatory in 2006. We also expect that shall be able to verify the extremely slow rotation of \( \gamma \) Equ measuring the rate of change for the polarisation angle of stellar radiation.

6 SUMMARY

The Ap star \( \gamma = \text{HD 201601} \) exhibited slow and systematic decrease of the longitudinal magnetic field \( B_e \) starting from 1946, when the global magnetic field of this star was discovered (Babcock 1958). We have compiled the full set of 298 existing \( B_e \) measurements, which consists of the \( B_e \) data published in the literature and our observations obtained during recent 7 years. The latter magnetic data (33 \( B_e \) points) were measured with the echelle spectrograph in the Coude focus of the 1-m telescope at the Special Astrophysical Observatory. Our newest observations showed that
the longitudinal magnetic field $B_e$ of γ Equ reached its local minimum and started to rise in 1998-2004.

All the available data cover the time period of 58 years (1946-2004) and include both phases of the maximum and minimum $B_e$. Assuming that the secular variability of the $B_e$ field is a periodic feature, we determined parameters of the magnetic field curve in γ Equ and give the value of its period, $P = 91.1 \pm 3.6$ years, with the zero phase (maximum of $B_e$) at $T_0 = JD 2417795.0 \pm 1057$. Sine-wave fit to the $B_e$ phase curve yields $B_e(\text{max}) = +577 \pm 31$ G and $B_e(\text{min}) = -1101 \pm 31$ G.

Spectral analysis of the 58-year long $B_e$ time series essentially do not show the existence of shorter periods, down to trial periods of $\approx 1$ day. More specifically, there are no real shorter periods in the run of the longitudinal magnetic field $B_e$ with amplitudes exceeding the noise level of 80 G.

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