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Secular variability of the longitudinal magnetic field of the Ap star γ Equ

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ABSTRACT

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

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

1 INTRODUCTION

The Ap star γ 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 γ Equ has been studied for more than 50 yr, starting from 1946 October (see Babcock 1958). The longitudinal magnetic field B_e of this star does not exhibit periodic variations on time-scales typical of stellar rotation, 0.5–30 d. Such a variability of the B_e 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_e of γ Equ was positive in 1946–52, and approached 900 G. From that time on the value of B_e slowly decreased and even changed sign in 1970/71. One could interpret the magnetic behaviour of γ Equ either as secular variations, or as 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 yr (Bonsack & Pilachowski 1974; Leroy et al. 1994; Bychkov & Shtol’ 1997; Scholz et al. 1997).

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

We have included in this paper our unpublished magnetic B_e measurements which were obtained during the past 7 yr. All the new magnetic observations showed that the slow decrease of the B_e field in γ Equ apparently reached minimum in 1996–2002 and has actually started to increase.

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

2 OBSERVATIONS AND DATA PROCESSING

We have performed spectropolarimetric observations of Zeeman line splitting for γ Equ at the Coudé focus of the 1-m optical telescope (Special Astrophysical Observatory, Russian Academy of Sciences). Zeeman spectra were obtained with the Coudé Echelle Grating Spectrometer (Musaev 1996). We put the achromatic analyser of circularly polarized 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 polarization on B_e measurements obtained with this instrument were investigated by Bychkov, Romanenko & Bychkova (1998) and Bychkov, Romanenko & Bychkova (2000).

Table 1 presents the full set of our B_e measurements of γ Equ (total 33 B_e points). The meaning of the first three 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. The time length Δt 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. The standard deviation σ_{B_e} for the resulting value of

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Table 1. Measurements of B_e in γ Equ (HD 201601).

JD 240 0000.+	B_e (G)	σ_{B_e} (G)	N	Δt (min)
496 48.323	−1045	21	706	30
496 48.345	−1315	26	755	30
496 49.229	−1463	37	576	30
496 49.257	−1159	31	656	30
499 32.424	−1317	26	691	60
499 32.469	−1317	26	675	60
499 33.460	−1316	26	700	60
499 33.507	−1317	29	704	60
500 23.158	−1291	22	501	40
500 23.189	−1380	23	650	40
500 66.128	−1539	26	718	40
500 66.157	−1611	62	532	40
515 33.1229	−1014	16	966	30
515 33.1451	−1011	14	701	30
515 35.1847	−902	16	955	40
515 35.2153	−901	19	855	40
515 36.1069	−670	18	821	30
515 36.1285	−642	24	508	30
518 88.166	−1069	18	847	30
518 88.190	−1092	20	1353	30
518 89.103	−890	20	847	30
518 89.126	−865	20	817	30
518 90.142	−742	21	770	30
521 63.3000	−845	19	833	30
521 63.3201	−855	19	732	30
521 64.2861	−956	16	947	30
521 64.3076	−967	16	914	30
521 65.2812	−1061	17	835	40
521 65.3111	−1029	16	991	40
521 86.2229	−922	17	1085	30
521 86.2451	−942	17	1055	30
521 87.2673	−882	16	1072	30
521 88.2395	−908	18	838	30

B_e was computed in the standard manner as the error of an arithmetic mean value.

Errors σ_{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 σ_{B_e} by a special programme of B_e observations. Actually, we accept these errors as 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 σ_{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 in their reduction.

Secondly, a 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 σ_{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 γ Equ on time-scales of minutes or above it.

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

A study of the rapid periodic B_e variations on a time-scale of minutes was also presented in Bychkov et al. (2005b) for γ 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 d, but were not able to extend our analysis for shorter periods, see Section 4 of this paper.

3 MAGNETIC PERIOD OF γ EQU

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

We have compiled the set of 298 observations of the B_e field in γ Equ, scattered in the literature, and appended our measurements. These data cover the time period 1946–2004 (58 yr). 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 γ 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 γ 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 γ Equ 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 Babcock (1958) and Bonsack & Pilachowski (1974). We adopted here an estimated error for Babcock's data of 238 G, and 151 G for Bonsack & Pilachowski (1974). These numbers were obtained in our thorough re-analysis of the earliest papers dealing with measurements of stellar magnetic fields, cf. section 3.1 in Bychkov, Bychkova & Madej (2003).

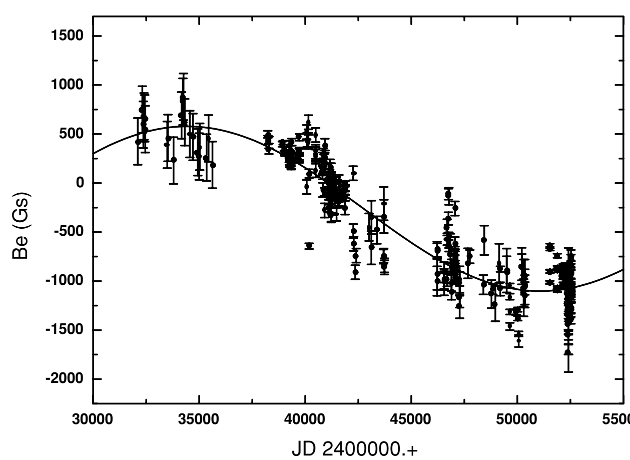

Figure 1. The longitudinal magnetic field B_e for γ Equ in years 1946–2004.

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,

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

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 non-linear fitting.

Starting values of P, B_0, B_1, T_0 and their standard deviations were found by our computer code for the non-linear 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 and surface fitting with the Levenberg–Marquardt procedure (ODRPACK v2.01 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 χ^2 for a single degree of freedom $\chi^2/\nu = 18.0420$. Such fits are unacceptable, and in the 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 unrealistic error estimates 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 213 G. For the final fitting of a sine we assumed that all the 298 B_e points have identical errors of 213 G.

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

$P_{mag} = 33\,278 \pm 1327$ d $= 91.1 \pm 3.6$ yr.

$T_0 =$ JD 241 7795.0 $\pm$ 1057.

$B_0 = -262 \pm 22.4$ G.

$B_1 = +839 \pm 22.1$ G.

$r = -0.524 \pm 0.043$.

In other words, a parameter range from $-\sigma$ to $+\sigma$ is just the true 68 per cent 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 and 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 β between the magnetic dipole axis and the rotational axis, and the angle i between the rotational axis and the line of sight (Preston 1967):

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

Parameters B_e(min) and B_e(max) of the B_e sine wave for γ Equ are given by

$B_e(\max) = B_0 + B_1 = +577 \pm 31.4$ G,

$B_e(\min) = B_0 - B_1 = -1101 \pm 31.4$ G.

Note that the meaning of B_e(max) and B_e(min) for use in equation (2) is different: B_e(max) denotes there the value of magnetic intensity which has the higher absolute value, and B_e(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, Bychkova & Madej (2005a) presented an extensive catalogue 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, $P_{mag} = 27\,027$ d, which was obtained on the basis of a shorter series of B_e data. This paper and the new, more accurate $P_{mag} = 33\,278$ d represent 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 pre-whitening to the set of available B_e measurements, and removed the principal sine-wave variations from the data. Pre-whitened data were then analysed with the method developed by Kurtz (1985), and with his FORTRAN code (Kurtz, private communication).

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 d. This is because many of the earlier magnetic observations for this star either have poorly determined time of measurement, or have long times of exposure (see e.g. Babcock 1958). The star γ Equ exhibits rapid non-radial pulsations and corresponding B_e with period $P_{mag} = 12.1$ min (Leone & Kurtz 2003) and, possibly, with simultaneous shorter periods (Bychkov, Bychkova & Madej 2005b). None of them was analysed in this paper.

We have identified two additional periods of statistically low significance in the range $P_{mag} > 1$ d, see Fig. 2:

$P_1 = 348.07$ d, amplitude = 122 G,

$P_2 = 23.44$ d, amplitude = 110 G.

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

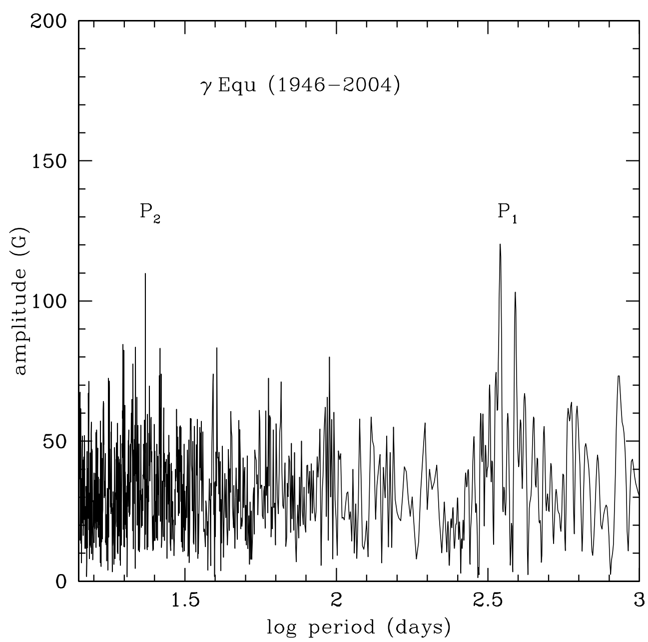

Figure 2. Amplitude spectrum of the B_e time-series for γ Equ, years 1946–2004.

to 1 yr. Since most of the existing B_e observations for γ Equ were performed in the months from July to November, then the peak P_1 in the amplitude spectrum represents a false period which most likely reflects the average 1-yr 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 γ Equ is the random effect of 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 ≈38 d in his photometric observations of γ 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-d period in long-term B_e observations of γ Equ, see Fig. 2.

5 DISCUSSION

There exist three possible explanations for the observed long-term behaviour of the longitudinal magnetic field in γ Equ.

(i) Precession of the rotational axis (Lehmann 1987).
(ii) Solar-like magnetic cycle (Krause & Scholz 1981).
(iii) Rotation with the period of 91.2 yr.

The Ap star γ = 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 behaviour 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 γ 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 γ 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 γ Equ are ca. four orders of magnitude larger than those in the Sun in a similar time-scale.

Following the widely accepted picture of an Ap star, we believe that the magnetic field of γ Equ can be approximated by a dipole located in the centre of the star. The dipole is inclined to the rotational axis of γ Equ. We assume that the magnetic field is stable and remains frozen in the interior of a rotating star at the time of observations, that is, during the recent 58 years. Therefore, slow variations of the B_e field in γ Equ are caused by an extremely slow rotation, in which case our $P_{mag} = P_{rot} = 33\,278$ 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 γ Equ with the new version of MINIPOL. The device was constructed to measure the angles and the degree of linear polarization of stellar radiation, and will be operational at the Special Astrophysical Observatory in 2006. We also expect that we will be able to verify the extremely slow rotation of γ Equ measuring the rate of change for the polarization angle of stellar radiation.

6 SUMMARY

The Ap star γ Equ (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 the recent 7 yr. The latter magnetic data (33 B_e points) were measured with the echelle spectrograph at the Coudé 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 yr (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, $P = 91.1 \pm 3.6$ yr, with the zero phase (maximum of B_e) at T_0 = JD 241 7795.0 ± 1057. A sine-wave fit to the B_e phase curve yields $B_e(\max) = +577 \pm 31$ G and $B_e(\min) = -1101 \pm 31$ G.

Spectral analysis of the 58-yr-long B_e time-series essentially does not show the existence of shorter periods, down to trial periods of ≈1 d. 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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