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Spectroscopic changes of the magnetic CP star γ Equulei*

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Abstract. From an analysis of some new spectroscopic observations of the magnetic CP star γ Equ we derived an effective magnetic field of -930 ± 150 G and a surface magnetic field of 4000 G. The magnitude of the effective field is compatible with a variation of the field on a time scale of a little more than 70 years. The temporal behaviour of the magnetic field is explained by the superposition of a dipole and quadrupole and the model of the oblique rotator. Surprisingly a few radial velocity values differ from the expected ones by about 10 km/s.

Key words: stars: chemically peculiar – stars: individual: γ Equ – stars: magnetic fields – stars: rotation

1. Introduction

The star γ Equ (HR 8097, HD 201601) belonging to the group of the magnetic CP stars is known to show the longest period of the effective magnetic field variation. Corresponding to the observations of Babcock (1958), Bonsack & Pilachowski (1974), Scholz (1979), Borra & Landstreet (1980), and Mathys (1991) the effective magnetic field varies with a period of more than 70 years in the range from about +600 to -1100 G. In the last decade the surface magnetic field has also been repeatedly determined (Mathys & Lanz 1992, Mathys et al. 1996); in all cases it is a little smaller than 4000 G. Linear polarization measurements by Leroy et al. (1994), together with the above mentioned magnetic field data, suggest that the very long period results from the same mechanism as for the other, much shorter period variable magnetic stars namely stellar rotation and the model of the "oblique rotator". The value of the radial velocity (RV hereinafter) of -16 km/s determined for the first time at the beginning of this century does not show significant variations which one could assign to a spotted surface or to the binary nature of γ Equ.

But radial velocity variations were observed, e.g., with an amplitude of about 40 m/s in a period of 12.20 min by Libbrecht (1988) or of about 200 m/s in roughly 11 min by Matthews et al. (1995), confirming the existence of rapid oscillations, as found photometrically in the earlier 1980's and recently again confirmed by Martinez et al. (1996).

2. Observations

In this paper we present some new observations of γ Equ obtained with the newly realized fiber-fed cross-dispersed Cassegrain Echelle Zeeman Spectrograph (TRAFICOS, TRAnsportable FIbre COupled Spectrograph) designed and fabricated by the Astrophysikalisches Institut Potsdam and the Thüringer Landessternwarte Tautenburg and installed at present at the 2 m Telescope in Tautenburg. Furthermore, at our disposal was also one spectrum using the coudé spectrograph of the 2.2 m Telescope on Calar Alto and one spectrum of the coudé spectrograph of the 2 m Telescope in Tautenburg. A detailed description of the Echelle Zeeman Spectrograph will be given elsewhere. Up to now, we have obtained 7 Zeeman spectra of γ Equ with a resolving power of about 25000, a reciprocal linear dispersion of 2.5 Å/mm and a S/N of about 50. The wavelength interval used for the measurements covered the region from about 5400 to 6700 Å.

In addition to these spectra for the determination of the effective magnetic field eight observations with the hydrogen-line magnetometer Hγ equipped with a circular polarization analyser and installed at the 6 m Telescope in the Caucasus are included.

3. Radial velocities

In our observing seasons in 1996 we obtained RVs of γ Equ differing distinctly from all previous measurements. In Table 1 we have collected all RVs which we could find in the literature, together with our values, but not corrected to a common scale and without consideration of the different accuracy. With the

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* Based on spectroscopical observations taken with the 2 m Telescope at the Karl-Schwarzschild-Observatorium Tautenburg, Germany, the 2.2 m Telescope on Calar Alto, Spain, and the 6 m Telescope in SAO, Russia

Table 1. Radial velocities of γ Equ

Jul.Date 2410000+	RV km/s	Author	Jul.Date 2410000+	RV km/s	Author	Jul.Date 2410000+	RV km/s	Author
8450.99	-14.1	Cam	29693.469	-17.5	Sch	31233.374	-16.3	Sch
8491.90	-16.4	”	29696.413	-17.9	”	31234.260	-16.2	”
8504.84	-14.8	”	29697.529	-15.8	”	31234.323	-16.6	”
8510.87	-17.1	”	29711.504	-18.4	”	31592.328	-16.14	”
8947.73	-19.4	”	29712.401	-16.0	”	31593.313	-16.55	”
9336.542	-27.4	Bea_1	30150.309	-16.5	”	32257.397	-16.04	”
9377.460	-17.0	”	30151.278	-15.3	”	32266.497	-16.93	”
9625.751	-18.1	”	30493.281	-15.7	”	32289.465	-16.72	”
9650.724	-19.2	”	30493.391	-16.1	”	32358.354	-16.20	”
12241.71	-19.1	Cam	30811.492	-17.5	”	32405.179	-15.69	”
12968.76	-17.9	”	30812.515	-16.3	”	33691.500	-16.52	”
13718.68	-16.9	”	30837.333	-16.1	”	33700.488	-16.44	”
23790.5	-18.2	Bab	30911.303	-15.9	”	33739.458	-15.95	”
24171.5	-16.9	”	30929.210	-16.9	”	33740.541	-16.34	”
24233.5	-17.1	”	30933.214	-16.9	”	34444.827	-14.5	Bea_2
24261.5	-16.9	”	31171.546	-16.7	”	35863.519	-15.9	Byc mean of 7 spectra
24319.5	-16.9	”	31172.471	-17.0	”	35863.530	-16.6	” 6
24554.5	-16.4	”	31215.372	-16.4	”	35863.540	-16.2	” 6
24707.5	-16.0	”	31216.397	-16.8	”	37059.188	-16.2	Zve mean of 6 spectra
24933.5	-16.1	”	31226.424	-16.4	”	37059.200	-16.7	” 5
24998.5	-16.8	”	31227.426	-16.8	”	37637.917	-17.0	Mat
25025.5	-16.7	”	31229.473	-17.0	”	39608.417	-15.43	this paper
25348.5	-17.0	”	31230.427	-15.5	”	40297.540	-12.25	”
25442.5	-14.3	”	31231.256	-14.7	”	40299.519	-12.88	”
25624.5	-17.2	”	31231.340	-16.1	”	40301.481	-12.78	”
29684.472	-18.0	Sch	31232.249	-15.0	”	40353.431	-5.50	”
29685.542	-18.2	”	31232.311	-16.3	”	40354.429	-4.89	”
29690.526	-18.1	”	31232.379	-16.4	”	40355.426	-5.28	”
29691.517	-18.4	”	31233.249	-16.3	”	40356.439	-4.28	”
29692.544	-18.4	”	31233.311	-16.1	”	40391.285	-12.80	”
						40410.191	-14.80	”

Abbreviations:

Cam	Campbell W.W., Moore J.H., 1928, Publ. Lick Obs. 16, 1
Bea_1	Beardsley W.R., 1969, Publ. Allegheny Obs., Univ. Pittsburgh, Vol.8, No.7
Bab	Babcock H.W., 1958, ApJS 3, 141
Sch	Scholz G., 1979, Astron. Nachr. 300, 213
Byc	Bychkov V.D., 1987, Pisma AZh 13, 773
Zve	Zverko J., Bychkov V.D., Ziznovsky J., Hric L., 1989, Contr. Astron. Obs. Skalnate Pleso 17, 71
Mat	Mathys G., 1990, A&A 232, 151
Bea_2	Beavers W.I., Eitter J.J., 1986, ApJS 62, 147

exception of the RVs of this paper and of one value (-27.4 km/s) no hint of a RV variation can be seen. We should mention, however, a remark by Beardsley (1969) that a series of spectra at Allegheny in the 1960s suggests a variation in RVs in the range from -6 to -26 km/s. Unfortunately, we are not able to find the publication including the individual values. So as to demonstrate that we can exclude an instrumental cause for the deviation of our RVs of γ Equ (especially for the values of about -5 km/s) from the other ones we give in Table 2 the RVs of two late-type stars observed at the same time. Comparing the mean of the GCRV and our result for both stars there is no doubt about the correctness of the RVs of γ Equ.

Considering in Table 1 the conspicuous small dispersion of the RVs in the observational interval between 1909 and 1994 (the mean is -16.81 km/s and the standard deviation is ± 1.57 km/s) there are no significant variations that would indicate binary motion. The extraordinary values of the RV in 1996 indicate a double star with a very long period and high eccentricity. Taking into account the above-mentioned mean and the standard deviation the RVs derived in this paper obviously lie just over the threshold of 3 σ with a "peak-width" of about 100 days.

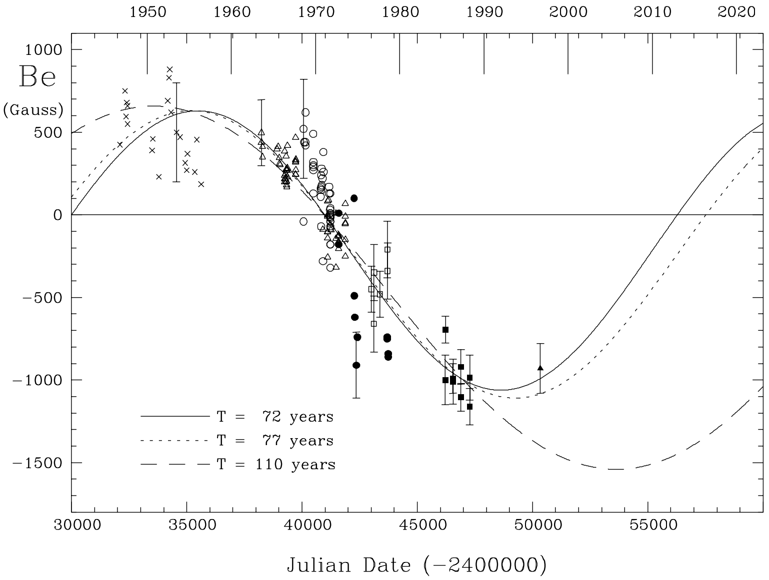

Fig. 1. Time variation of the longitudinal magnetic field. Crosses: Babcock (1958); triangles: Bonsack & Pilachowski (1974); circles: Scholz (1979), measurements with uncertainty ±300 G (open circles) and ±200 G (solid circles); open squares: Borra & Landstreet (1980); solid squares: Mathys (1991). The curves are the best sinusoidal fit, and correspond to a period T = 72 years (solid), 77 years (dotted), and 110 years (dashed). The filled triangle corresponds to the mean value of this paper, (−930 ± 150 G).

Table 2. Radial velocities of comparison stars

Comp. star	Source	Jul.Date	RV
		2450000+	km/s
ι Per			
	GCRV (mean)		+49.41 ± 0.46
	Tautenburg	353.56	+48.19 ± 0.17
γ Tau			
	GCRV (mean)		+38.69 ± 0.23
	Tautenburg	353.61	+38.59 ± 0.09

The probability of detecting an equivalent "peak" in the distribution of the RVs of Table 1 is for a period of 1000 days about 95 %, for a period of 5000 days about 55 %, and for a period of 25000 days about 10 %. Consequently, only a period smaller than about 1000 days can be excluded with some certainty. With the present data it is in fact impossible to detect a longer period or a connection between the magnetic field and the RV. By chance a period of 77 years as it is proposed in the magnetic field variation (see next section) should be detectable in the RVs.

4. Magnetic field

All spectra of this paper (see Table 1) except the last two have been used in order to determine the magnetic field of γ Equ. In detail, the first spectrum has been measured for an estimation of the surface magnetic field and the other ones have been reduced for the determination of the effective magnetic field. The last two spectra are only suitable for RV measurements.

4.1. Effective magnetic field

The Zeeman échelle spectra have been reduced with a program developed specifically for TRAFICOS in combination with the ESO-MIDAS95 Echelle-Context. The determination of the line centers of the selected lines, lying mainly in the wavelength region between 5400 and 6700 Å has been done manually with the MIDAS routine "Gaussian fit" and stored in tables. For the determination of the field strength the displacements of the spectral lines of each spectrum have been measured and subsequently the data of the individual Zeeman spectra have been superposed. This procedure is justified by the extremly long magnetic period of γ Equ. For the four best spectra a mean value of the magnetic field strength $B_{\mathrm{eff}} = -990$ G follows. Furthermore, in addition to the échelle spectra eight observations with the magnetometer at the 6 m Telescope in Zelenchuk were received. The average of the measurements is $B_{\mathrm{eff}} = -870$ G showing a sufficient agreement of both observational methods.

All magnetic field measurements of the effective field existing in 1993 are collected in the paper by Leroy et al. (1994) and are represented by two periods, 77 and 110 years. Using these diagrams of Leroy's paper (we are much obliged to the authors that we have the permission to use their collection of data and especially S. Bagnulo who has produced our Fig. 1) the filled triangle in Fig. 1 corresponds to the mean value of the effective field determined from our observations. The dashed curve corresponds to the fit of the measurements with a period of 110 years and the solid and dotted curves to respectively 72 and 77 years. It can be seen that with the present measurements a period of little more than 70 years gives the best fit.

4.2. Surface magnetic field

In 1994 we obtained a CCD spectrum of γ Equ using the coudé spectrograph of the 2.2 m telescope on Calar Alto. The high resolution spectrum (dispersion 2 Å/mm, resolution 51 mÅ/pixel, S/N 200) is suitable to determine the surface magnetic field directly from the resolved magnetically split line Fe II 6149 Å and for testing an empirical relation given by Mathys & Lanz (1992), (ML hereinafter), between the magnetic surface field strength of

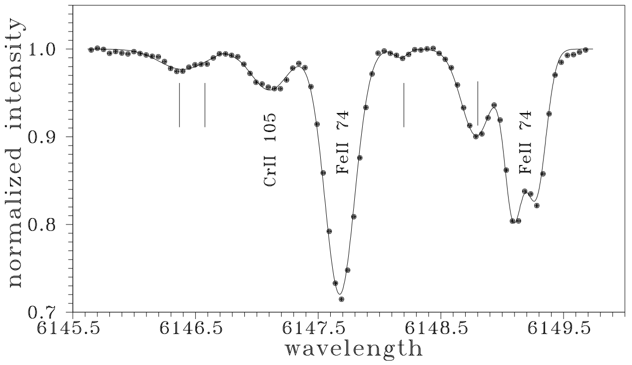

Fig. 2. Multi-Gaussian fit around the FeII line pair including several additional lines. Dots: measured spectrum, solid: fitted curve.

Table 3. Line parameters resulting from multi-Gaussian fit.

Line [Å]	R	$FWHM$ [mÅ]	W [mÅ]
6147	0.283±0.002	284.1±2.5	85.6±1.4
6149_{blue}	0.196±0.003	162.7±6.1	66.4±3.5
6149_{red}	0.174±0.003	175.4±6.6	

Ap stars and the ratio of the equivalent widths of the FeII line pair 6147/6149 Å. Whereas the 6147 Å line is a Zeeman quadruplet not resolved in our spectrum, the 6149 Å line is a doublet, and its Zeeman pattern is clearly resolved. Both lines are affected by the partial Paschen-Back effect which is responsible for the relative magnetic intensification of the line strengths. The line transitions and the splitting patterns for different field strengths were given by Mathys (1990).

Fig. 3 shows the spectral region around the FeII line pair. The strong blends in the blue wings of both FeII lines do not permit a determination of line centers or equivalent widths by direct integration. So we used a multi-Gaussian fit including eight lines, four of which could not be identified unambiguously. Table 3 gives the resulting parameters for the two FeII lines. The MIDAS routine used for the fitting procedure (Newton-Raphson iteration) also gives the errors of the parameters obtained. The fit was originally done on a pixel scale and then converted into a wavelength scale.

The value of the shift between the centers of the split 6149 Å line is (190 ± 6) mÅ . With g_{eff} = 1.35 calculated from the line transitions this shift corresponds to a magnetic surface field of
$B_{\mathrm{res}} = (3990 \pm 130)$ G.
Here the definition of B_{res} directly corresponds to the definition of H_g in ML.

For the relative magnetic intensification of the line strength of the two FeII lines ML gives the relation
$B_{\mathrm{emp}} = (1.59 \pm 0.24) + (13.3 \pm 1.3) \cdot V$,
where
$V = 2 \cdot (W_{6147} - W_{6149})/(W_{6147} + W_{6149})$
is a measure for the ratio of the equivalent widths of the two lines. The relation was obtained by ML empirically for a $3000 \leq B_{\mathrm{emp}} \leq 5000$ G range. From Table 3 we calculate
$B_{\mathrm{emp}} = (5000 \pm 2400)$ G.
The large error of B_{emp} results both from the error of measurement of V as well as from the scatter in the empirical relation of ML. A further estimation of B_{emp} of a spectrum received on JD 2450300 in Tautenburg, but with an unresolved 6149 Å line, caused by a very moderate S/N and lower resolution, yields 4800 G.

Table 4. Surface magnetic field strength of γ Equ obtained from resolved lines and by using the empirical relation of ML.

Jul.Date 2440000+	B_{res} [kG]	B_{emp} [kG]	Reference
7283	3.70	4.7	ML
7638	3.73	-	M
8169	3.82	-	M
8479	3.83	-	M
8790	3.79	-	M
8925	3.89	-	M
9102	3.83	-	M
9216	3.84	-	M
9457	3.87	-	M
9577	3.86	-	M
9608	3.99	5.0	this paper
9696	3.90	-	M
9829	3.87	-	M
9909	3.84	-	M
10300	-	4.8	this paper

Table 4 gives a comparison between our and some previous results. The values denoted by the reference M are taken from a list in the paper by Mathys et al. (1996). Possibly, our values of the surface magnetic field coincide with the end of a long-term increase (or possible maximum) of the surface field strength of γ Equ. As the comparison of the values B_{emp} and B_{res} in Table 4 shows in the case of γ Equ the result derived from the empirical relation of ML is too large by a factor of about 1.3 compared to the surface field derived directly from the magnetic splitting.

4.3. A model of the magnetic field

To investigate the magnetic field of γ Equ in more detail we assume that its variation is produced by the same mechanism as it is usually accepted for the short-time variations of the Ap stars: the model of the rigid rotator. Such a model is preferable to that of an oscillatory dynamo proposed by Krause and Scholz (1981). Comparing the present data of B_{s} and B_{eff} the small ratio of both values during the minimum passage of B_{eff} indicates that the magnetic field should penetrate a layer with a thickness of more than 1/3 of the stellar radius. For the generation of a dynamo there is no other way than to identify this layer with the convective zone, but such a thickness of the layer is atypical for an F0 star like γ Equ.

The study of the structure of the magnetic field of γ Equ is essentially restricted by the existence of the incomplete mag-

netic curve as well for B_{eff} as especially for B_{s}. For the analysis the following notation and assumptions are adopted:
i, angle between the rotation axis and the line of sight,
β, angle between the rotation axis and the magnetic axis, and furthermore
-the period of the magnetic field variation is 77 years with a symmetry axis in 1995/1996 coinciding possibly with the passage of the effective magnetic field through the minimum. We choose Leroy's et al. value of the period though our measured value indicates a little smaller period, but for the further analysis this is not of importance.

In our investigation of the magnetic field distribution at the surface we try to represent the field by the superposition of a dipole with a higher multipole. The magnetic field vector consists of three components with the unity-vectors in direction of the radius of the star, and along lines of longitude and latitude. A fourth component is added for a scalar magnitude, which can be used for different purposes (e. g. brightness). The calculation of the magnetic field components makes use of the fact that the sums of the potentials of pointlike field sources add linearly, which holds also for the derivatives. Thus, the potential of a single source will be calculated by the transform from rectangular to spherical coordinates. Then the field vector is easily derived by the spherical gradient of the potential. The advantage of the linear superposition of potentials and vectorial fields is obvious. The calculation is not limited to special source configurations, say to the dipole or to the quadrupole, which formerly were derived by complicated analytical treatments, e.g. using Legendre functions. The individual treatment of 'monopoles' allows an arbitrary composition of configurations up to higher multipoles. In principle, any field desired can be represented by a row of 'monopole' fields (a well known lemma of the potential theory). The arrangement of the sources may be anywhere in the interior of the star and specified by their spherical coordinates. On physical grounds the sum of positive and negative magnetic sources should be zero. By a trial and error method the fitting of the model to the observational curve can be realized - assuming a reasonable magnitude of the field strength at the magnetic pole, B_{p}, - by changing the distance r of the position of the "monopoles" from the center of the star and by varying the angle between the rotation axis and the line of sight, i, and the angle β. A description of the program will be given by Gerth et al. (1997).

In order to compare the present magnetic data of γ Equ (given in Fig. 1) with the calculated shape of a magnetic curve the annual mean values of B_{eff} of the individual authors are plotted in Fig. 3, in which asterisks correspond to data where the number of measurements exceeds 5 and triangles are those with a number smaller than 5. The mean error of a value represented by a asterisk is about ±50 G (max. ±138 G in 1974) and ±65 G (max. ±122 G in 1988) for a triangle respectively. Babcock's first observation in 1946 was adopted as the phase 0.2. Although the shape of the magnetic curve in the negative extremum is nearly unknown the measurements seem to indicate the existence of different amplitudes of the extrema, which immediately excludes, that the magnetic field is produced by a central dipole field. The dot-dashed curve in Fig.3 demonstrates this fact. It is the best fit and has the following parameters:
$B_{\mathrm{p}} = 3.4$ kG, $i = 100°$, $\beta = 130°$, $r = 0.063$.

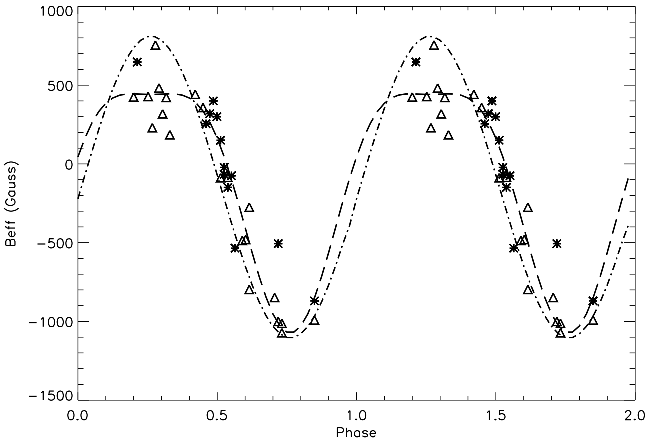

Fig. 3. Variation of the longitudinal magnetic field. The asterisks correspond to annual means with the number of measurements larger than 5 and triangles are those with smaller than 5. The dot-dashed curve represents a central dipole field and the dashed curve represents the superposition of a dipole and quadrupole. The period is 77 years and the parameters of both curves are given in the text.

Table 5. Strength and position of the dipole and quadrupole.

No.	Longitude [°]	Latidude [°]	B_{p} [kG]
1	0	0	3.8
2	90	40	-3.8
3	180	0	3.8
4	270	-40	-3.8
5	90	40	1.6
6	270	-40	-1.6

Our experience with model magnetic fields of other magnetic Ap stars with distinctly non-sinusoidal magnetic curves like HD 32633, HD 37776 or 53 Cam suggests that a dipole-quadrupole field structure is the best configuration to represent the course of the present magnetic data of γ Equ. Assuming the following parameters $i = 103°$, $\beta = 130°$, $r = 0.10$ and the values of Table 5 we obtained as a result of the calculations the dashed curve in Fig. 3.

Considering Table 5 it can be noted that one of the axes of the quadrupole coincides with the axis of the dipole. The "monopoles" are located in the same plane and are inclined to the rotational axis at the angle $\beta = 50°$ (or 130°). This result and the magnetic field strengths at the poles are summarized in Table 6. The average magnetic field of 3.8 kG is very close to the above-mentioned values determined for B_{s}.

The map of the magnetic field distribution at the surface of γ Equ is represented in Fig. 4. This map of the topographical arrangement of the magnetic field with its vectorial character

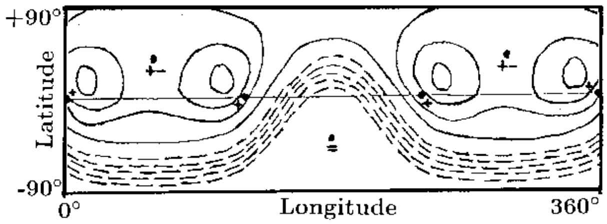

Fig. 4. Cylindrical-projection of the magnetic field distribution at the stellar surface. The solid lines correspond to the positive and the dashed lines the negative field.

Table 6. Field magnitude at the magnetic poles

Longitude [°]	Latitude [°]	B_p [kG]
0	0	3.8
90	40	2.2
180	0	3.8
270	-40	5.4

on the surface of the star is constructed by matrices. The matrix elements are defined by the usual spherical coordinates of the longitude and the latitude. By this method of cartographical projection as a rectangular matrix, the areas of the elements become narrower from the equator to the poles. Therefore, all topographical structures in this representation of the map appear broader in direction to the poles.

The positive magnetic field is shown by solid lines and the negative one by dashed lines. It should be realized that in the upper part of the map there are two maxima of the positive field. Therefore it could be possible that these areas are also "spots" with anomalous chemical abundance.

5. Discussion

The statements concerning the behaviour of the RV and the magnetic field of the extraordinary Ap star γ Equ are incomplete in many aspects, mainly for the very long time scale of the variations. However, the reason of the observed changes, the rotation of the star, should not be a subject of doubt. The choice of the magnetic model proposed in this paper is caused by our intention to investigate the connection between the strength and structure of a simple magnetic field configuration with the chemical element concentration at the surface of some sufficiently researched Ap stars. If our assumption about the character of the model would be correct an important hint about the origin of the magnetic fields can be drawn, namely the fields should be produced by a dynamo process in the past.

The value of the effective magnetic field of -990 G given in section 4.1. for the échelle spectra of Tautenburg is the mean of the best four spectra. But, if we include also the other échelle Zeeman spectra of Table 1 in the determination of B_{eff} a value of about -1100 G follows, indicating a period longer than 80 years. This would agree with a similar finding by Leroy (1995) if he adds to the previous polarimetric observations the two more recent measurements. Comparing the angles $i = 80°$ and $\beta = 150°$ following from all of Leroy's measurements of the linear polarization with the values $i = 103°$ and $\beta = 130°$ characterizing our model, the agreement seems to be quite good, if we consider the different derivations and the incomplete data sets for the construction of both magnetic models.

Concerning our modelling we would like to make a comment on the value of r. The investigations of magnetic field models of other Ap stars show that the "monopoles" which form dipole, quadrupole or sextupole structures of magnetic field are always located symmetrically about the center of the stars. The models of 9 stars that we constructed give the best fit of the calculated and observed curves if we adopt $r = 0.063$ in case of the dipole structure, $r = 0.10$ for the dipole plus quadrupole structure, and 0.18 for the dipole plus quadrupole plus sextupole structure. At present we are not able to give a reasonable explanation for this finding.

Finally we want to repeat the concluding remark containing in Leroy's et al. paper that observations of B_{eff} and B_{s} in the next few years are of crucial importance to confirm or refute the period and model adopted.

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