Magnetic fields of supergiant stars

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Abstract. Magnetic fields of supergiants have been observed scarcely and sporadically. The results are not convincing because of the weakness of the measured field strengths and the complexity of the physical phenomena in evolved stars at all. Hitherto only the supergiant ν Cep exhibits periodically (every 4.8 year) a strong magnetic field of about +2000 G, which has been proved by superposing the measuring values of individual lines of several spectrograms. Continued and cooperative observations of this star have secured 118 measurements covering a time interval of 12 years. To answer the question whether magnetism might be typical for the state of evolution as we observe in ν Cep, other supergiants of similar spectral and luminosity class as ν Cep are due to be observed systematically. A search program for magnetic fields of supergiants has already started in 1986 rendering first preliminary results given in the present paper.[1]

Key words: Magnetic stars, supergiants, search for magnetic fields, observation, measurement. Stars: ν Cep, 9i Per, 4 Lac

1. Introduction

Notices in literature on magnetic field measurements at supergiants are very scanty. Referring to C. de JAGER's comprehensive book "The brightest stars" (de JAGER, 1980), we find on only half a page (p. 45) entirely 4 examples of magnetic supergiants, that we list up in the order of spectral class:

Table l

β Ori	B8 Ib	–100 to +260 Gauss	(Severny et al., 1974)
α Car	F0 Ib	–100 to +600 Gauss	(Rakos et al., 1977)
γ Cyg	F8 Ib	–170 to +200 Gauss	(Severny et al., 1974)
VV Cep	M2 Iab	–360 to +850 Gauss	(Ledoux and Renson, 1966)

Particularly the star α Car (Canopus) has been investigated to more extend by W. W. Weiss (1986), who corroborated the occurrence of a magnetic field varying from -150 to +600 Gauss.

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To the list (Table 1) of supergiants investigated for magnetic fields we are authorized by our measurements to add the star ν Cep A2Ia (-400 to +2400 Gauss) (Scholz and Gerth, 1980, 1981). Obviously, the magnetic field strength of about 2400 Gauss, which occurred first in 1978, surpasses that of all other stars in the list, thus deserving more interest.

Some questions immediately arise and should be answered:

1. Can we rely on the measurements and believe in the occurrence of magnetism in supergiants at all?

   – Then the magnetic field measurements ought to be proved by reliable significance criteria!

2. Should ν Cep be taken as a special representant of magnetic supergiants?

   – Then it has to be investigated more intensively and extensively than others!

3. Is the occurrence of magnetism bound to a concrete state of evolution?

   – Then more supergiants of similar spectral and luminosity classes should be investigated!

2. The problematic of strong magnetic fields in supergiants

We start our considerations from the first question that demands a critical view, having in mind that the occurrence of magnetic fields in supergiants at all has been taken sceptical by many workers in the field of stellar magnetism. Undoubtedly, since BABCOCK's pioneer work, started in 1944, the domain of stellar magnetic fields is occupied overwhelmingly by the peculiar A stars, leading to the commonly accepted opinion that the peculiarity and the spectral class A might be correlated to the occurrence of appreciable magnetism in these stars. However, we have to admit that technical measuring conditions decidedly gave a rise to prefer the Ap stars because of the availability of sufficient, not severely blended, narrow metallic lines in the spectra of these slowly rotating A stars. The Ap stars represent a relative stable physical configuration of a main sequence star, the magnetic field being – obviously – topographically fixed to the figure of the star, leaving the question about the origin of a magnetic field open. Whether we observe either a relic field frozen in the plasma of the star since earlier states of evolution or an actually generated one by a dynamo mechanism will be subject of further research. Quite another situation we meet at supergiant stars of the spectral class A. Having been started after condensation and ignition of thermonuclear reactions on the ZAMS as an early B star with an initial mass of the order of 20 $M_\odot$ and a radius of about 6 $R_\odot$, a vigorous development on a very shorter time scale than in Ap stars sets in, followed by depletion and exhaustion of the thermonuclear fuel, then contraction, heating, and convection of the core, mass-loss of about 5 $M_\odot$ and retardation because of removal of angular momentum, expansion and semiconvection of the mantle – and the migration apart from the main-sequence up to luminosity classes Ia,b. The whole star being in motion, nobody can expect that any ancient magnetic structure could have been preserved.

But above all any primordial field, if such one had existed at the time of the star's setting on the ZAMS, would have been diluted very much and slowed down in the course of evolution; because - as Krause and Scholz (1986) argue in the case of ν Cep – the star has expanded its size from $6R_\odot$ to $90R_\odot$, which corresponds to an enlargement of the surface by the factor 225. Therefore, when we observe a magnetic field of 2400 Gauss at present, the recalculation to the ZAMS state would yield nearly $5{\cdot}10^5$ Gauss – in clear contradiction to all our knowledge on B stars, so that any plausible explanation of the origin of the magnetic field by relic fails and has to be refuted.

Similar conditions we may assume for other supergiants. Any former magnetism must have been destroyed by inner motion of the star or/and has vanished by dilution. Therefore, in the case of supergiants we can be sure to have at hand a "tabula rasa" regarding conserved magnetism.

If we observe, indeed, strong magnetic fields at supergiants, then those may have been generated only recently – on the time scale of cosmical development – thus making the supergiants well-suited candidates for proving observationally the dynamo theory.

3. The reality of the measurements

But do we observe, indeed, magnetic fields or some kind of a measuring artifact? When we overlook Table 1 above we see that the spectral classes from B to M are present, but in no case the magnetic field strength exceeds absolutely 1000 Gauss. The accuracies dealt with by the authors are $\approx$ 40 Gauss for the photoelectric and $\approx$ 300 Gauss for the photographic measurements (averaging). Certainly, there may be some difference in accuracy between photographic and photoelectric observations. Moreover, we have to distinguish between inner and outer accuracies. Nevertheless, such accuracies can hardly be believed. Whoever knows the tedious task of determining stellar magnetic fields has good reasons to be sceptical. The Zeeman-displacement in the spectra undergoes a lot of disturbing influences, some of them changing unforeseenably from one observation to the other, so that the inner accuracy never can give a correct measure of the quality. This assessment concerns also the measurements of the magnetic field at Canopus by W. W. Weiss (1986) – despite of his sophisticated correlation method, by which the inner accuracy is extremely improved. But, because of neglecting the relation of the Zeeman-displacement to the Landé-factor this method fails to be free from disturbing asymmetries.

4. The observation of the supergiant ν Cep

Let us report on our experience of measuring magnetic fields of supergiants, which is connected with the observation of ν Cep. At the Central Institute of Astrophysics in Potsdam the investigation of magnetic stars has been established since 1966. Hitherto there have been measured more than 700 Zeeman spectrograms of various stars on a modified Abbe-comparator (Gerth et al., 1977) evaluated by means of a set of special computer-software programs.

In the search program for magnetic fields in A stars also the supergiant ν Cep (HD 207260) of the spectral type A2 Ia was included following a hint at a possible magnetic field given by Stokes et al. (1974), who found this star to be eventually circularly polarized.

In 1975 21 Zeeman spectrograms of ν Cep were secured with the 2m-telescope in connection with the coudé- spectrograph in Tautenburg and measured on the Abbe-comparator in Potsdam. The obtained values of the magnetic field strength are spread from -600 to +650 Gauss with a mean value near zero (Fig. 1). The scattering proved to be a normal statistical one. After eluding two years ν Cep was observed once more. The measurements showed obviously a positive magnetic field of about +800 Gauss, which was not taken too seriously because of the poor statistical significance (4 plates).
But one year later, in 1978, a magnetic field strength in ν Cep of $\approx$ +2000 Gauss could be established; one plate even reached up to 2800 Gauss, marking thus the highest value of a magnetic field strength at supergiants hitherto measured.

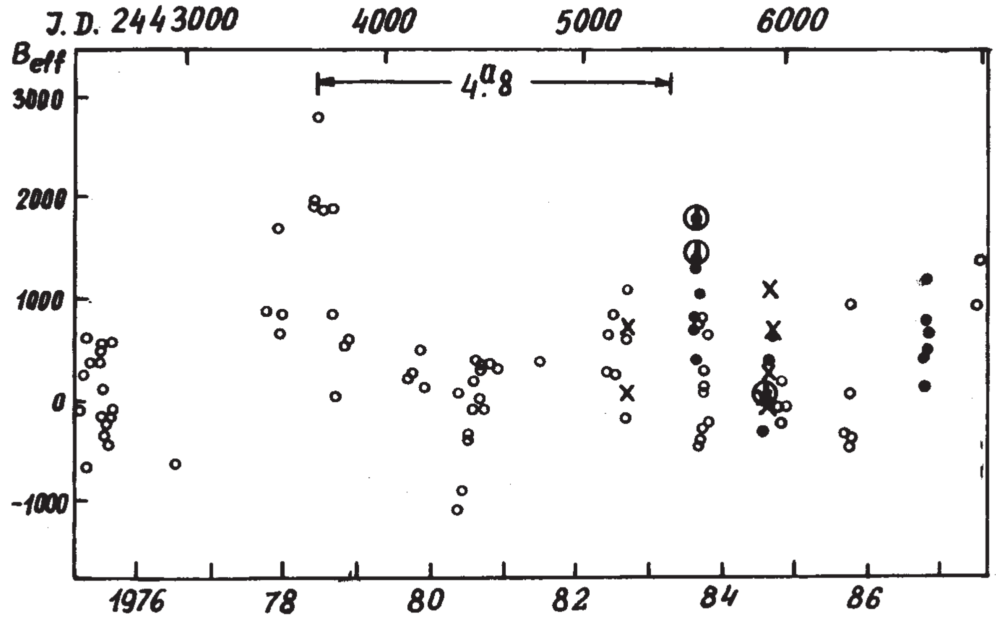

Fig. 1. Measuring values of the magnetic field strength of the supergiant ν Cep in progress of time.
Circles: photographic observations from Tautenburg; crosses: photographic observations from Rozhen; dots: photographic observations from Zelenchuk; triangles in circles: photoelectric observations (magnetometer measurements)

The first observed maximum occurred in 1978. From the curvature a period of 5 years was derived. The second maximum in 1983 is not sufficiently secured by observation. A third maximum is expected for 1987/1988.

However, experience and therefore caution suggested to keep reserve concerning this detection. Maybe, some kind of a measuring artifact could not have been perceived, making the observed field a spurious one.

4.1. A significance test for magnetic fields

In order to secure the reliability of the occurrence of a magnetic field a significance test (similar to the procedure after Babcock) was used that we relate to. Having not been described elsewhere, it should be shortly sketched and inserted here. This test uses the physically founded condition for the occurrence of a magnetic field reduced from the line displacements of Zeeman spectrograms, i.e., the linear relation between $\triangle\lambda/\lambda^2$ and the (effective) Landé factor z:

$$\frac{\triangle\lambda}{\lambda^2} \sim z$$

If there is a systematic displacement on account of any asymmetry caused by the spectrograph and/or the measuring device, then that cannot be related to the z-value. In the case of the existence of a magnetic field, at the diagram for $\triangle\lambda/\lambda^2 = f(z)$ the linear function will be shifted to the ordinate, the gradient being the magnetic field strength and the ordinate section – the spurious field. Unfortunately, the measuring points are usually spread from $z \approx 1$ to $z \approx 2$, scattered and crowded around a mean value of about $z \approx 1.5$, so that by visual inspection on such a diagram no slope is to be detected. A linear regression computation renders the determination of the coefficients of the linear function objective. However, the straight line is very sensible to torsion around the center of the cloud of points introducing therefore still more inaccuracy. Only a line-to-line superposition of the measuring data of several spectrograms, performed by a coordination program, diminishes the scattering, whereas the intrinsic linear function is preserved. The ratio of the resultant value to its mean square deviation gives a suitable criterion for the significance[2].

The application of this significance test to the data sets of the 6 plates of ν Cep from 1978 clearly proved the presence of a magnetic field at the star by a ratio of more than 3σ (Scholz and Gerth, 1980).

4.2. Continuation of observations

In the following years the magnetic field strength returned to the previous value near zero (Fig. 1). But from the curvature one could already derive a long-term variation exhibiting a period of approximately 5 years. In 1982 the mean field increased again, but the expected maximum in 1983 was left out because of technical conditions at the observatory in Tautenburg. Fortunately, in this year the cooperation among the Academies of Sciences of the socialist countries gave the possibility to use the 6m-telescope of the Special Astrophysical Observatory in Zelenchuk. The measurements contributed values up to +1600 Gauss (magnetometer measurements). Besides of this the measurements allowed to compare the photographic and photoelectric observations and further the results obtained from Tautenburg and Zelenchuk which were in good agreement regardless of the natural scattering. The results of these cooperative observations are given by Scholz et al. (1984).

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[2] The method of the significance test is described and demonstrated by Scholz and Gerth (1980, page 214, Fig. 2) – available via INTERNET by the address `www.ewald-gerth.de/53.pdf`.

In the later years from 1984 to 1986 the field strength measured in Tautenburg, Zelenchuk and Rozhen, traversed the third observed minimum. Unfortunately, the scattering had an appreciable amount, so that without the '83 observations from Zelenchuk the existence of the field would be newly uncertain. Therefore, observations of the next maximum expected to the end of 1987, will be of the greatest importance to get a final conclusion about the magnetic field of ν Cep.

The last search for periods using all the data available up to now yields
P = 4.79 a.

5. Explanation of the observed phenomena

As ν Cep in respect of magnetic fields has been investigated more intensively and extensively than others by about 120 measurements, it would be worthwhile to continue the observation series. In particular further parameters of the star have to be taken into account, e. g. the radial velocity, the rotational velocity, line broadening by micro- and macroturbulence, luminosity variations, etc. The full consideration of all phenomena could give some hope for a conclusive explanation of the observed long-time variation of the magnetic field strength, which Krause and Scholz (1986) relate to a manifestation of an oblique rotator leading to a dynamo mechanism. Thus, with a magnetic dipole fixed to the figure of the star, the long-time variation is interpreted as a kinematic effect, presumably as the rotation of the star possessing a non-rotational symmetric magnetic field. But, if rotation is taken into consideration, the extraordinarily slow rotational velocity has to be proved. With a period of 5 years and a star radius of 90 $R_\odot$ the equatorial velocity would amount to 2.5 km/s. The measured value of $v \sin i$ for ν Cep, however, is 38 km/s (Scholz and Gerth, 1980). Despite accounting for the uncertainty of the inclination angle i, there will be left a large difference, which immediately becomes explicable regarding micro- and macroturbulence as the main cause for line broadening. Moreover, the slow rotation is quite plausible considering the expansion of the star accompanied by conservation of the angular momentum and, conversely, the mass loss accompanied by removal of angular momentum – both taking place in the course of evolution and acting in the same direction.

6. A search program for other magnetic supergiants

Returning to the third question of the introduction we ask for whether the occurrence of appreciable magnetism might be typical for the state of evolution of a supergiant like ν Cep. Therefore, it is necessary to look for other magnetic supergiants of similar spectral type. In 1986 a program for a systematic search for magnetic fields in supergiants has started, which will be performed in the framework of the multilateral cooperation at different observatories.

Fig. 2 shows the distribution of the supergiant stars over the HR-diagram (taken from de Jager, 1980), the location of ν Cep (Scholz et al., 1981) and the stars (Table II, designated by figures) set onto the observational program, which were elected with respect to the spectral class, the brightness, and the line width (using basically the catalogue of E. L. Chentsov, 1978).

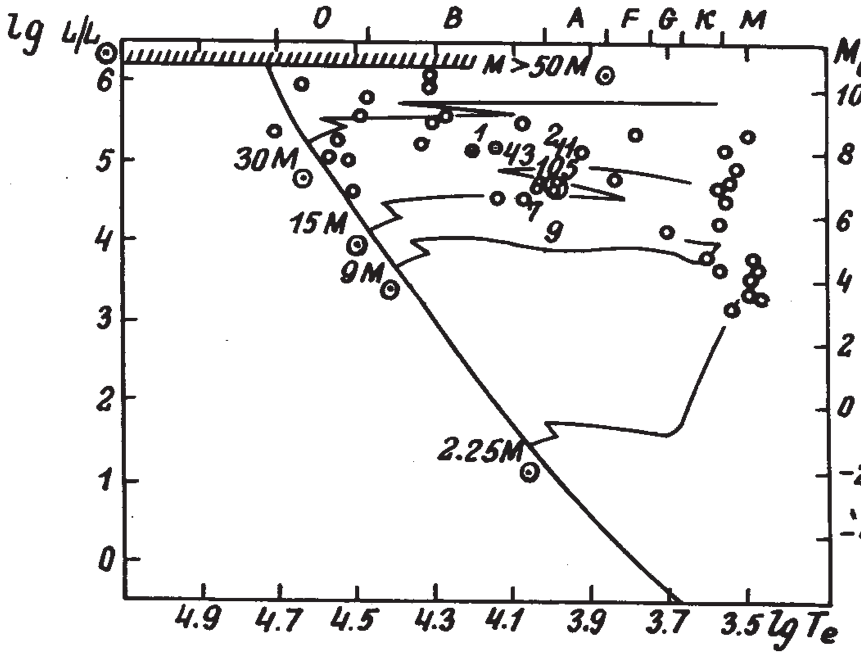

Fig. 2. Distribution of supergiants over the HR diagram.
Figures: Stars in the vicinity of ν Cep (SCHOLZ and GERTH, 1981) set on the observational program according to Table 2. Evolutionary tracks for different initial masses on the ZAMS traverse the conglomerations of supergiants on a zig-zag path (DE JAGER, 1980).

The list remains open to add further candidates of magnetic supergiants. Conversely, the investigation of special stars must not be broken off after having not found significantly magnetic fields by a few observations, for magnetic fields could occur later if long-time variations – as in ν Cep – are present.

Table 2

	Star	Spectral Class	M_δ	B_e	Date
1	χ Aur	B5 Iab	-7.9		
2	α Cyg	A2 Ia	-7.8		
3	β Ori	B8 Ia	-8.1		
4	η CMa	B5 Ia	-8.2		
5	9i Per	A1 Ia	-7.7	-200 ± 430 Gauss	18.10.1987
6	σ Cyg	B9 Iab	-6.9	-110 ± 900 Gauss	18.10.1987
7	4 Lac	B9 Iab	-6.5	-200 ± 430 Gauss	18.10.1987
8	ν Cep	A2 Ia	-6.8		
9	η Leo	A0 Ib	-5.4		
10	2H Cam	B9 Ia	-7.2		
11	3H Cam	A0 Ib	-7.3		

The first three supergiants (9i Per, 4 Lac, and σ Cyg) have already been observed in 1986 at the 6m-telescope in Zelenchuk. For each star 4 spectra were taken consecutively, in order to be sure to have approximately the same physical conditions in the star and, above all, to realize the earlier mentioned significance test, which requires several spectrograms to perform the superposition of the line-coordinated values.

The first preliminary results of this search for magnetic fields of supergiants obtained by the superposition procedure from 4 plates in each case are given in Table 2 at the right side. Regarding the accuracy calculated from the linear regression treatment of the measuring data, one can see that convincing field strengths could not be detected yet. But, because these first results cannot be regarded already as conclusive ones, search and research in the field of magnetism in supergiants have to continue.

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