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The magnetic field of β Cep and the Be phenomenon

H.F. Henrichs, J.A. de Jong

Astronomical Institute, University of Amsterdam, Kruislaan 403, 1098SJ Amsterdam, Netherlands

J.-F. Donati, C. Catala

Observatoire Midi-Pyrénées, Toulouse, France

G.A. Wade

Dept. of Astronomy, Univ. of Toronto at Mississauga, Ontario, Canada

S.L.S. Shorlin

Physics and Astronomy Dept., Univ. of Western Ontario, Canada

P.M. Veen

Sterrewacht Leiden, Leiden University, Netherlands

J.S. Nichols

Harvard/Smithsonian Center for Astrophysics, Cambridge, U.S.A.

L. Kaper

Astronomical Institute, University of Amsterdam

Abstract. New circular spectropolarimetric observations of the B1 IIIe star β Cep ($v\sin i$ = 25 km s^{-1}) show a sinusoidally varying weak longitudinal magnetic field ($\sim$ 200 G peak-to-peak). The period corresponds to the 12 day period in the stellar wind variations observed in ultraviolet spectral lines. Maximum field occurs at maximum emission in the UV wind lines. This gives compelling evidence for a magnetic-rotator model for this star, with an unambiguous rotation period of 12 days.

The similarity between the Hα emission phases in β Cep and in Be stars suggests that the origin of the Be phenomenon does not have to be rapid rotation: we propose that in β Cep the velocity to bring material in (Keplerian) orbit is provided by the high corotation velocity at the Alfvén radius ($\sim$10 R_*), whereas in Be stars this is done by the rapid rotation of the surface. In both cases the cause of the emission phases has still to be found. Weak temporary magnetic fields remain the strongest candidate.

A full paper, with results including additional measurements in June and July 1999, will appear in A & A.

1. Introduction

Besides the well-studied pulsation period of 4^h34^m and episodes of Hα emission, the star β Cep (B1 III, $v\sin i = 25$ km/s) shows a very significant period of 12 d in the UV wind lines, which was discovered by Fishel & Sparks (1972) from OAO-2 data. Henrichs et al. (1993) proposed that this periodicity has to be identified with the rotational period of the star and suggested that the stellar wind is modulated by an oblique dipolar magnetic field. Such a rotation period would match a radius between 6 and 10 $R_\odot$.

To verify this hypothesis Henrichs et al. (1993) presented magnetic field measurements obtained with the University of Western Ontario photoelectric Pockels cell polarimeter and 1.2 m telescope, simultaneously with UV spectroscopy with the IUE satellite, but no periodic magnetic field variations were found, which remained unexplained. The 1σ error bars were about 150 G, comparable to the measured field strength. It was suggested that perhaps the new Be phase of the star, discovered in July 1990 by Mathias et al. (1991), see also Kaper et al. (1992) and Kaper & Mathias (1995), might have been related to the decrease in magnetic field strength, but this could not be tested.

Here we give the first results of new, much more accurate, magnetic measurements of β Cep. We also consider the significance of this discovery for understanding the Be phenomenon.

2. Observations and data reduction

During December 1998 and January 1999 we have obtained 15 circularly polarized (Stokes V) and unpolarized spectra (Stokes I) of β Cep, using the the 2 m Télescope Bernard Lyot at the Observatoire du Pic du Midi, France, with the MuSiCoS fiber-fed cross dispersed échelle spectrograph with a dedicated polarimetric unit (described by Donati et al. 1999) at the Cassegrain focus.

The data reduction was done with the dedicated ESpRIT reduction package, described by Donati et al. (1997). Because the radial-velocity amplitude as a consequence of the pulsation of β Cep is considerable, we shifted the minima of the I profiles to zero velocity before calculating the field strength. The mean longitudinal field (B_ℓ) is calculated from the Least-Square Deconvolved spectra with the formulae presented by Mathys (1989) and Donati et al. (1997).

3. Period analysis

3.1. Pulsation period and binary orbit

A sine fit through the radial velocities with the known period kept fixed yields 19±1 km s^{-1} for the semi amplitude and −20 ±1 km s^{-1} for the average system velocity. The phase-shift difference between the observed and calculated (O−C) radial velocity maximum values, using the ephemeris from Pigulski & Boratyn (1992), equals −0.112±0.002 d, in good agreement with the expected phase delay caused by the light-time effect in the orbit near periastron. The system velocity is also in good agreement with the extrapolated value. Our observed values are in fact very close to the predicted values at periastron itself. If in fact our data were taken at periastron, it would imply from their figures that the binary period is 85 y (from the phase delay) or 88 y (from the system velocity), in good agreement with the derived orbit of 91.6±3.7 y derived in 1990. New speckle interferometry may confirm the orbital phase.

3.2. UV stellar wind period

From IUE spectra it is known that the UV stellar wind lines of C IV, Si III, Si IV, N V and Al III show a very clear 12 day periodicity. See Henrichs et al. (1998) for sample C IV doublet UV profiles. The outflow velocity exceeds −600 km s^{-1}. We note that this type of variability is very unlike what is observed in O stars (e.g. Kaper et al. 1996), but is very similar to profile variations of other magnetic B stars (Henrichs et al. 1998). We measured the equivalent width (EW) of this line in the velocity range [−680, 945] km s^{-1} after normalizing all 88 available IUE spectra between 1979 and 1995 to the same continuum around the C IV line and dividing each spectrum by the average of the normalized spectra. The error bars are calculated following Chalabaev & Maillard (1983). The EW values are plotted as a function of phase in Fig. 1 (upper panel), in which we separated the early and more recent UV data to visualize the compatibility. We derived the following ephemeris for the deepest minimum, i.e. maximum emission: $T(\mathrm{EW_{min}}) = \mathrm{BJD}\ 2445621.722\pm0.011 + N\times(12.00106\pm0.00006)$, with N the number of UV cycles.

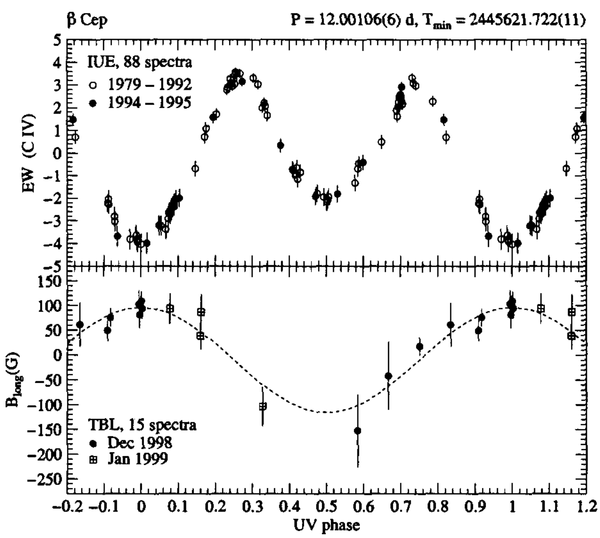

Figure 1. *Upper panel:* Equivalent width of the C IV stellar wind line measured in IUE spectra as a function of 12 d phase. Phase 0 corresponds to maximum emission. *Lower panel:* Magnetic data as a function of the UV phase, with best sine fit overplotted. No significant difference in zero phase between the UV and magnetic data is found.

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3.3. Magnetic period

The best-fit sine function to the 15 B_ℓ measurements yielded $B_0 = -10\pm11$ G, $B_{\rm max} = 106\pm16$ G. with a reduced $\chi^2 = 0.7$. Maximum field strength occurs at $T(\rm B_{max})$ = BJD 2451238.34±0.12 + $N\times$12.00106, with N the number of magnetic cycles. In the lower panel of Fig. 1 we have drawn a dashed sine curve with this period and phase through the magnetic measurements. The deep EW minimum coincides, within the uncertainties, with maximum magnetic field.

4. Hα behavior

By current definition β Cep is a Be star. For earlier Hα emission-phase histories see Mathias et al. (1991) and Panko & Tarasov (1997). During our observations of β Cep there was no emission, as shown in Fig. 2, compared with earlier data taken at the Observatoire de Haute Provence (OHP). The emission phase has presently declined beyond detectability, as predicted by Kaper & Mathias (1995). The question arises whether during future emission phases the magnetic field structure will remain unaltered.

5. Conclusions and discussion

We have found a varying weak magnetic field in β Cep, consistent with an oblique dipolar magnetic rotator model (rotation period 12 d), in which outflow (causing wind emission) occurs along the magnetic poles, similar to models by Brown et al. (1985), Shore et al. (1990a) and Shore et al. (1990b). In these

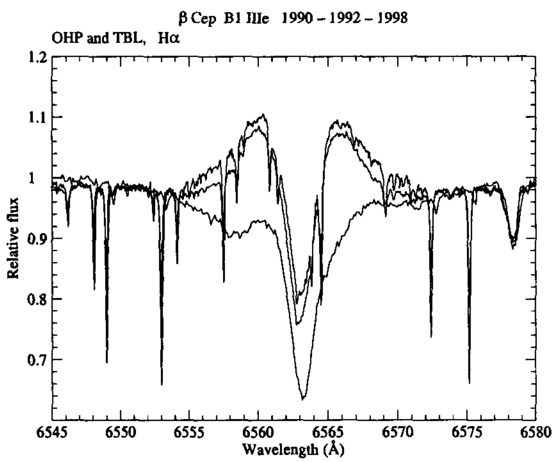

Figure 2. Hα profiles in 1990, 1992 (OHP, terrestrial lines not removed) and December 1998 (TBL). The emission has presently declined beyond detectability, in agreement with the predicted decay.

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models the C^{+3} production in the jet-like mass loss is presumably due to the dissipation of shear-generated Alfvén waves near the polar cones.

The symmetry between the magnetic extremes is consistent with an equator-on inclination angle, and with the magnetic axis perpendicular to the rotation axis. If we adopt an inclination angle of 60° (Telting et al. 1997) and $v\sin i$=25±3 km s^{-1}, the rotation period requires a radius of 6.9±0.8 $R_\odot$, in rather good agreement with the radius of the B1 III star ϵ Cen of $5.9^{+1.2}_{-0.6}$ $R_\odot$, based on interferometric and parallax measurements.

The polar field of a perpendicular magnetic dipole rotator is $3.2\times B_\ell$, i.e. about 300 G. Such a configuration causes magnetic braking, which might explain the low rotational velocity of this (evolved) Be star. For a star rotating with angular velocity Ω and rate of change $\dot{\Omega}$, the spindown timescale is equal to $\tau_{sd} = \Omega/\dot{\Omega}$, caused by the amount of angular momentum carried away by the corotating stellar wind, with mass-loss rate $\dot{M}$, at the Alfvén radius r_A. This can be calculated from $\dot{M} v_w r_A = I\dot{\Omega}$. The Alfvén radius is given by

$$r_A \approx 12.5 R_* \frac{B_{300}^{1/2}(R_*/7R_\odot)^{1/2}}{(v_{600})^{1/4}(\dot{M}_{-10})^{1/4}} \tag{1}$$

where the polar field strength B is in units of 300 G, the wind velocity v_{600} is given in units of 600 km s^{-1} and the mass-loss rate $\dot{M}$ is in units of $10^{-10}M_\odot y^{-1}$. For the typical parameters of β Cep given above $\tau_{sd} = 1.6\times10^7$ y, which is shorter than the main-sequence lifetime of a 15 $M_\odot$ star. This is a conservative estimate, because the field was assumed te be constant, whereas on the main sequence the star most likely had a stronger field, at least because of its smaller radius. This explains the presently observed slow rotation rate.

This conclusion has an interesting consequence in the light of the well documented Hα emission history of β Cep, which is similar to that of the usually more rapidly rotating Be stars. Because of this similarity we presume that the (unknown) primary mechanism causing this phenomenon is the same in Be stars as in the magnetic slow rotator β Cep. The role of the rapid rotation in Be stars is to give the temporary excess of outflowing matter sufficient angular momentum to stay in a Keplerian disk around the star. In β Cep such matter would leave the star not with angular momentum corresponding to the rotation velocity at the surface, but to the corotating velocity at the about 10 times larger Alfvén radius, which is comparable to the surface rotation velocity of the rapidly rotating Be stars. This suggests that the primary origin of the Be phenomenon is not necessarily rapid rotation. We note that temporarily emerging magnetic field structures, smaller than measured here, could cause the outflowing matter to go into orbit, and may be responsible for the Be phenomenon, but this hypothesis cannot be (dis)proven as yet because of instrumental limitations. Spindown will only occur when the magnetic pressure is stronger than the pressure of the outflowing wind. This implies for a star like β Cep a field of at least 15 G, with a spindown timescale of 5×10^7 y. Such small fields cannot be presently detected, but should be searched for in future investigations.

The role of variable pulsation behavior with respect to the hydrogen emission episodes, if such a role exists, is probably different from rapidly rotating Be stars, in which equatorial confined non-radial modes are usually acting.

Finally, it should be noted that the star β Cep appears to be one of the very few stars in its class which shows this type of strong wind variability and in this respect β Cep is an exceptional β Cep star.

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Discussion

Tarasov: Our few years patrol of the star did not confirm rapid (hours) variability of the Hα emission and showed no day-to-day variability. The emission was always blue-shifted and could therefore be caused by the companion.

Henrichs: The companion is about 5 magnitudes fainter, so I doubt that it can cause the Hα emission. I would not expect rapid variability in the Hα emission on the pulsation timescale because the emission likely originates at many stellar radii by the magnetically confined wind. The predominantly blue-shifted emission is consistent with an outflow. It would be indeed interesting to search for a 12 d periodicity in the Hα emission.

Dudorov: Do you plan to investigate the magnetic field of other Be stars?

Henrichs: We have observed γ Cas and a few other Be stars, but the analysis is still underway. We expect much larger error bars than for β Cep.