THE NATURE AND EVOLUTION OF DISKS AROUND HOT STARS
ASP Conference Series, Vol. 337, 2005
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The Polarization of Achernar

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Abstract. Recent near-infrared measurements of the angular diameter of Achernar (the bright Be star alpha Eridani) with the ESO VLT interferometer have been interpreted as the detection of an extremely oblate photosphere, with a ratio of equatorial to polar radius of at least 1.56 ± 0.05 and a minor axis orientation of $39° \pm 1°$ (from North to East). The optical linear polarization of this star during an emission phase in 1995 September was $0.12 \pm 0.02\%$ at position angle $37° \pm 8°$ (in equatorial coordinates), which is the direction of the projection of the rotation axis on the plane of the sky according to the theory of polarization by electron scattering in an equatorially flattened circumstellar disk. These two independent determinations of the orientation of the rotation axis are therefore in agreement. The observational history of correlations between Hα emission and polarization as found in the literature is that of a typical Be star, with the exception of an interesting question raised by the contrast between Schröder's measurement of a small polarization perpendicular to the projected rotation axis in 1969–70 and Tinbergen's measurement of zero polarization in 1974.5, both at times when emission was reportedly absent.

1. Introduction

The interferometric observations of Quirrenbach et al. (1997) directly verified the hypothesis that the emission lines of Be stars are produced in an equatorially flattened circumstellar envelope or disk. The related hypothesis of the linear polarization of Be stars as due to scattering of the starlight by free electrons in the disk was also verified by confirmation of the prediction that the polarization position angle should be perpendicular to the direction of elongation of the disk as projected onto the plane of the sky.

Domiciano de Souza et al. (2003, hereafter DKJ) studied the bright Be star Achernar (α Eridani, HD 10144, B3V pe) by Earth-rotation synthesis on the Very Large Telescope Interferometer (VLTI) from 11 September to 12 November 2002. They concluded that the ratio $2a/2b = 1.56 \pm 0.05$ of the major to minor axis of the elliptical fit to the observed distribution of equivalent uniform disk angular diameters reflects the true projected photospheric distortion of the star itself, with a negligible contribution from circumstellar material. The minor-axis orientation on the plane of the sky was found to be $39° \pm 1°$.

Achernar has not been studied as extensively by polarimetry as many other bright Be stars. The published optical continuum measurements from original sources are summarized in Table 1, albeit with no guarantee of completeness. According to the spectroscopic history given by Balona, Engelbrecht, & Marang (1987), no Hα emission was present in 1963, Hα emission was strong in 1965, several observers failed to see emission during the late 1960s and early 1970s, and the Hα line profile developed from pure absorption to strong emission between 1974 and 1978. Presumably Serkowski's observations recorded the dissipation of an equatorial disk in 1968, and Tinbergen's observations showed the absence of a disk before the beginning of an emission episode, but with this interpretation it is hard to understand Schröder's detection of a small polarization perpendicular to the direction of the projected rotation axis.

Table 1. Polarimetric observations of α Eri.

Epoch	p (%)	θ (degrees)	Reference
1968.1	0.03 ± 0.01	26 ± 10	Serkowski (1970)
1968.9	0.02 ± 0.01	46 ± 14	Serkowski (1970)
1969–70	0.011 ± 0.004	136.2 ± 10.4	Schröder (1976)
1974.5	0.001 ± 0.005	...	Tinbergen (1979)

2. New Observations

2.1. Polarimetry

Achernar was observed polarimetrically during 1995 September 1–14 with Any-Pol (McDavid 1999) on the 0.6 m telescope at Cerro Tololo Inter-American Observatory (CTIO). Table 2 gives the results obtained by averaging the normalized Stokes parameters from a total of 18 individual measurements in each of the Johnson-Cousins *UBVRI* passbands (6 repetitions on each of 3 different nights). At the Hipparcos distance of 44.1 ± 1.1 pc (Perryman et al. 1997) no significant interstellar polarization is expected, so these data represent intrinsic polarization.

Table 2. CTIO Polarimetry of α Eri (1995 September 1–14).

Filter	p (%)	θ (degrees)
U	0.12 ± 0.05	40 ± 12
B	0.14 ± 0.04	41 ± 8
V	0.11 ± 0.05	45 ± 13
R	0.10 ± 0.06	25 ± 17
I	0.13 ± 0.06	34 ± 13

A neutral density filter was used together with the bandpass filters, and the normalized Stokes parameters were corrected for a constant instrumental polarization on the order of 0.1% determined by repeated observations of the unpolarized standard star α Piscis Austrini (Serkowski 1974) made on the same nights and in the same sequence as described above for α Eri. The position angle was calibrated on the polarized standard star η Aquilae (Hsu & Breger 1982). The bright Be star α Arae was observed 6 times in the V passband on one night with the neutral density filter as a check on the instrumental system, yielding $p = 0.50 \pm 0.06\%$ and $\theta = 175° \pm 4°$, in agreement with the values $p = 0.56 \pm 0.03\%$ and $\theta = 176° \pm 2°$ obtained by McLean & Clarke (1979) during 1976 using an interference filter centered on 510.0 nm with *fwhm* 5.1 nm. This is not an ideal check star since the degree of polarization is known to be variable, with a nonzero interstellar component. The observed position angle, however, should always be the same for any given observed degree of polarization, as is seen in this case.

The wavelength dependence of the polarization is formally undefined by these observations. However, combining the 90 individual measurements of q and u yields $p = 0.12 \pm 0.02\%$ over the visual band. Since the 99% confidence interval is equivalent to 3σ at this signal-to-noise level (Clarke & Stewart 1986), or 0.06% in this specific case, the polarization is almost certainly nonzero.

2.2. Simultaneous spectroscopy

The polarimetry of Achernar at CTIO in 1995 was obtained simultaneously with ultraviolet spectroscopy from the orbiting International Ultraviolet Explorer (*IUE*) and ground-based optical spectroscopy. Peters & Gies (2000) found a periodicity of 1.27 ± 0.05 days in the ultraviolet flux at 145 nm which they attribute to nonradial pulsation, based on analysis of cross-correlation functions of a set of selected ultraviolet photospheric line profiles using the Fourier-time series methods of Gies & Kullavanijaya (1988). The pulsation period of $1.26 \pm .09$ days, which is consistent with the period of the flux variability, is tentatively identified as a low-order sectoral mode with $\ell = 1$–2. The same periodicity was found in optical photometry by Balona & Engelbrecht (1986), who attributed it to rotational modulation of the photospheric flux by a starspot.

3. Discussion

At 44.1 ± 1.1 pc distance, the interferometric measurements of DKJ correspond to an equatorial radius $R_{\rm eq} = 12.0 \pm 0.4\, R_\odot$ and a maximum polar radius $R_{\rm pol}^{\rm max} = 7.7 \pm 0.2\, R_\odot$. For a spectral type of B3 Vpe, as given in the *Bright Star Catalog* (Hoffleit & Warren 1991), the mass of Achernar is expected to be about $6\, M_\odot$ and its radius about 3.5–4.0 $R_\odot$ (Harmanec 1988). The rotating B3V model sequence of Collins, Truax, & Cranmer (1991) has polar radius $R_{\rm pol} = 4.6\, R_\odot$ and maximum equatorial radius $R_{\rm eq}^{\rm max} = 6.9\, R_\odot$. The VLTI radius thus appears surprisingly large, and the rotational distortion greater than the maximum possible in a conventional Roche model.

The photospheric dimensions determined by DKJ were based on a first-order approximation, using an elliptical fit to equivalent uniform disk angular diameters derived from a set of squared fringe visibilities obtained by Earth-rotation synthesis with two ground baselines. As emphasized by Tango & Davis (2002), the visibility functions of stars with extended atmospheres are qualitatively different from those of a uniform disk. The addition of rapid rotation and the resulting gravity darkening to the unusual limb darkening profile which might be expected for a Be star could make the interpretation of the basic visibility data very difficult. Furthermore, the two baselines for the Achernar VLTI observations, which happened to be nearly aligned with the major and minor axes of the best-fit ellipse, were calibrated on different stars.

The small polarization perpendicular to the projected rotation axis reported by Schröder (1976) at a time when emission was absent could be the signature of electron scattering in an oblate extended photosphere, given the right combination of conditions for scattering from electrons in the outer atmosphere of the bright pole to dominate the polarization from the equator, where the flux is lower and the radiation field is not so strongly forward peaked (Collins 1970; Cassinelli & Haisch 1974). Tinbergen's measurement of zero polarization in 1974 might then be understood as the cancellation of this photospheric contribution by scattering from a small equatorial disk which was only beginning to grow, with the net polarization involving also the effects of stellar oblateness on polarization from the disk, as explored by Bjorkman & Bjorkman (1994).

Acknowledgments. The author was a Visiting Astronomer at Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation. Thanks to Stan Owocki for suggesting the explanation given herein for the polarization history of Achernar.

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