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Polarimetric study of the RV Tauri star AC Herculis

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Abstract. BVRI polarimetry of AC Her shows that the wavelength dependence of polarization is weak with a marginal increase towards blue and that the position angle is nearly independent of wavelength. We argue that the interstellar component of polarization in the direction of AC Her is negligible ($< 0.1\%$). The polarization observed in AC Her most probably results from a combination of pulsation related asymmetry in the star and circumstellar grain scattering; and its variation during a light cycle is not caused by changes in the circumstellar dust envelope but rather by the changes in asymmetry in the star.

Key words : RV Tauri star—circumstellar dust—intrinsic polarization—interstellar polarization—AC Herculis

1. Introduction

RV Tauri stars, which are variable yellow supergiants, constitute an interesting and rather poorly understood class of pulsating variables. The anomalous excesses in infrared radiation observed in these rare objects are attributed to the cool and extended dust thermospheres condensed from the material ejected by them (Gehrz 1972). AC Her, recognized as an RV Tauri star, is a metal-poor and carbon-rich star (Baird 1981).

Polarimetric observations of AC Her in B band obtained by Henson, Kemp & Kraus (1985) indicate that the light and polarization changes are strongly correlated, with the maximum of polarization occurring just after the primary light minimum. Though their observations clearly demonstrated how polarization varies over a light cycle, information on the wavelength dependence was lacking. A knowledge of the wavelength dependence of polarization would be of help in identifying the mechanism responsible for it. At low polarization levels, the contribution by the interstellar component may mask the real variation in the intrinsic polarization. Information on the wavelength dependence of polarization may also give some indication about the interstellar contribution.

In this paper we present BVRI polarimetry of AC Her and estimate the interstellar contribution to the observed polarization. We also discuss the possible mechanism which produces the polarization changes in AC Her.

2. Observations

AC Her was observed polarimetrically on 1985 April 24 (JD 2446180.40) in BVRI bands with the 102 cm telescope of Uttar Pradesh State Observatory, Naini Tal. The polarimeter used consists of a half-wave retarder rotated at 10.41 Hz acting as the polarizer and a Wollaston prism acting as the analyser. A microcomputer system built around a Z-80 microprocessor was employed for the acquisition and on-line processing of the data. The integration time used was 60s and the observations were repeated a few times to bring down the errors due to photon statistics. A detailed description of the polarimeter and the method of calibration are given in Deshpande *et al.* (1985).

3. Results

The values of linear polarization ($P\%$) and position angle (θ°) obtained by us are given in table 1 along with their measurement errors and are plotted in figure 1 against the corresponding inverse of the effective wavelength of observation. We find from the figure that the dependence of polarization of wavelength is rather weak; there is only a marginal increase towards blue. This is consistent with the results which Henson, Kemp & Kraus (1985) obtained from the very limited simultaneous measurements they had in B and V bands. From figure 1, we also find that the position angle of polarization is essentially independent of wavelength; however, there is an indication of a shallow dip (2–3°) in the $V - R$ region.

Table 1. Polarimetric observations of AC Her

Wavelength band	Linear polarization ($p\%$)	Position angle (θ°)
B	0.67 ± 0.06	37 ± 3
V	0.48 ± 0.05	32 ± 3
R	0.47 ± 0.06	33 ± 4
I	0.40 ± 0.05	40 ± 4

The RV Tauri variables R Sct, U Mon (Serkowski 1970), RU Cen and SX Cen (Raveendran 1989, in preparation) show similar wavelength dependences of polarization; the polarization is always larger in ultraviolet than in yellow, but the dependence is very weak. The amplitude of polarization variation (~ 1.5%) of AC Her is also similar to that observed in the above mentioned objects.

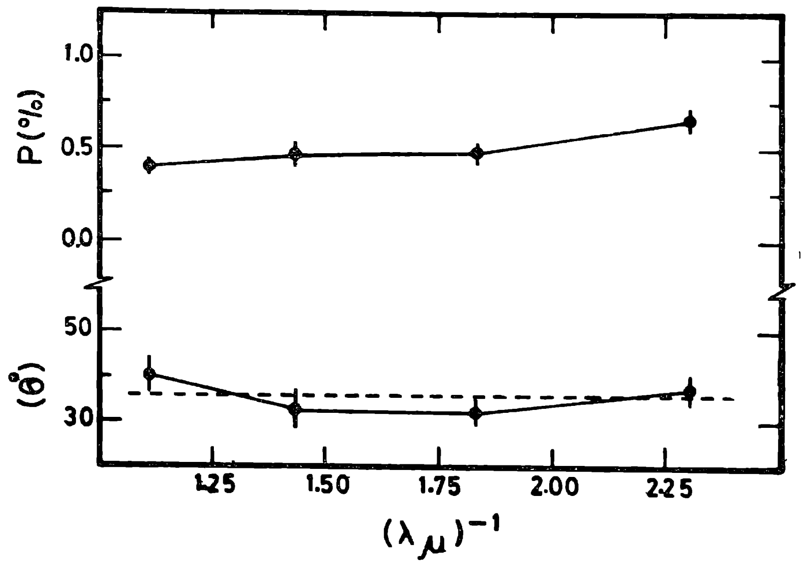

Figure 1. Plot of linear polarization (P%) and position angle (θ°) against the inverse of the effective wavelength of observation. The dashed line represents the mean position angle.

4. Discussion

4.1. Regularity in the polarimetric behaviour

Most probably, there are not many RV Tauri stars like AC Her with regular periods of light variation. One of the classification criteria for the membership of RV Tauri group is the interchange of the primary and secondary minima present in their light curves (Payne-Gaposchkin, Brenton & Gaposchkin 1943). From an analysis of 587 primary and secondary minima, Erleksova (1984) finds that no shallow minima were found at the expected phases of primary minima and that the deepest secondary minima never reached the depth of the primary ones, contrary to the general belief (Payne-Gaposchkin, Brenton & Gaposchkin 1943; Kukarkin *et al.* 1969; Baird 1981).

The times of primary minima estimated from the American Association of Variable Star Observers' visual data (Mattei 1986, personal communication), obtained around the times of polarimetric observations plotted in figure 1, are found to satisfy the ephemeris,

$$\text{Min } I = \text{JD } 2445231.7 + 75.^{d}46\, E \qquad \ldots(1)$$

given by Henson, Kemp & Kraus (1985). According to this ephemeris, the polarimetric observations listed in table 1 fall on the ascending branch ($\phi = 0.^{p}57$) of the light curve after the secondary minimum. A plot of the AAVSO data, shown in figure 2, confirms this; the time of polarimetric observations is indicated in the figure by an arrow.

The values of P% and θ° in B band estimated from the plots of Henson, Kemp & Kraus (1985) are 0.45 ± 0.1 and 25 ± 6. These values are only marginally

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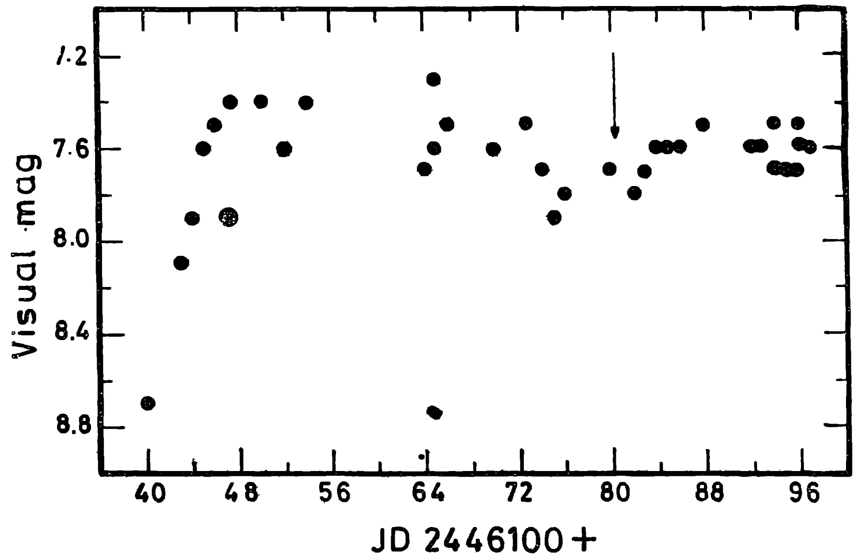

Figure 2. Plot of the AAVSO visual data against the corresponding Julian day of observation. The arrow indicates the time of polarimetric observations.

different from that obtained by us when we consider the fact that θ varies from 22° to 56° and P reaches as high as 1.4%. Shawl (1975a) has reported a set of observations at inverse effective wavelengths, 2.17 μm^{-1} (B band) and 1.87 μm^{-1} (V band) obtained on JD 2440699 (1970 April 22). The phase computed using equation (1) is $\phi = 0.^p93$. From a revision of the photographic observations of AC Her presented by Payne-Gaposchkin, Brenton & Gaposchkin (1943), Erleksova (1984) has given the following ephemeris :

$$\text{Min } I = \text{JD } 2435052 + 75.^d439\, E \qquad ...(2)$$

which gives a phase $\phi = 0.^p86$ at JD 2440699. From the plots given by Henson, Kemp & Kraus (1985), we find that in the phase interval $0.^p86 - 0.^p93$, $P\%$ and θ° are 0.55 ± 0.1 and 45 ± 5, very close to the values of 0.40 ± 0.04 and 41 ± 3 given by shawl (1975a).

The agreement in the values of polarization and position angle obtained at such largely separated epochs indicates that the behaviour of polarization of AC Her is probably regular; however, small changes in the amount of polarization from cycle to cycle are reported by Henson, Kemp and Kraus (1985). Here we mention that the V light curve of AC Her shows large cycle to cycle variation whereas the $(B-V)$ colour curve does not (Cardelli 1985).

4.2. *Interstellar component of polarization*

Polarimetric observations of several stars in UBVRI bands by Coyne, Gehrels & Serkowski (1974) and Serkowski, Mathewson & Ford (1975) show that for each direction the interstellar linear polarization reaches a maximum $P_{\max}$ at some wavelength $\lambda_{\max}$; but the scaled down polarization $(P/P_{\max})$ is a well defined function of the scaled down wavelength $(\lambda/\lambda_{\max})$.

The normalized Stokes parameters of interstellar and intrinsic palorization add linearly (Dyck, Forbes & Shawl 1971), and hence when the intrinsic and interstellar components are comparable, the modulation of the intrinsic component by the interstellar component should be easily seen in the observed polarization. An upper limit on the interstellar component can be put from the colour excess $E(B-V)$, since reddening is an essential condition for the production of interstellar polarization (Schmidt 1958). Though the value of $P_{\max}$ is poorly correlated with $E(B-V)$, the maximum possible value for the interstellar component is given by (Serkowski, Mathewson & Ford 1975)

$$P_{\max} \leqslant 9.0\, E(B-V).$$

Cardelli's (1985) estimate of interstellar reddening $E(B-V) = 0.1$ mag gives a value of $P_{\max} \leqslant 0.9\%$, larger than the observed value. By the arguments presented above, we should observe either a rotation of the plane of polarization with wavelength or a maximum in the $P(\lambda)$ curve that is characteristic of the interstellar polarization or both. The only exception to this would be when the intrinsic polarization has the same position angle as the interstellar component and the particular wavelength dependence required to cancel the modulation by the interstellar component; this possibility, we believe, is very unlikely.

An indirect indication of an insignificant contribution by the interstellar component to the observed polarization in AC Her is the near-identical wavelength dependences seen in AC Her and RU Cen, a similar carbon-rich RV Tauri star with negligible reddening (Raveendran 1989, in preparation).

Although the value of $\lambda_{\max}$ shows a large range, in the direction where there are no dense clouds it is fairly represented by the empirical relation (Serkowski, Mathewson & Ford 1975),

$$\lambda_{\max}(\mu\mathrm{m}) = 0.555 - 0.03\, E(B-V).$$

With $E(B-V) = 0.1$, the above relation gives $\lambda_{\max} = 0.552$ μm, i.e., the maximum effect of interstellar component will be felt in the V band. Hence, the shallow dip (2–3°) in the position angle in the $V-R$ region seen in figure 1 may be the effect of the interstellar component. The position angles at B and I bands are essentially the same, indicating that the interstellar contribution at these wavelength bands is negligible. If we assume that the effects of interstellar component in P and θ in I band are of the order of observational errors, the maximum possible value for the interstellar component at this band turns out to be P(I band) $\sim 0.07\%$, and using the empirical relation (Serkowski, Mathewson & Ford 1975),

$$(P/P_{\max}) = \exp\left(-1.15 \ln^2 (\lambda/\lambda_{\max})\right),$$

we get $P_{\max} \sim 0.1\%$ peaking in V band. Most probably, the amount of observed polarization is not affected by this much amount; otherwise, we would have seen a hump or dip in the $P(\lambda)$ curve at V band. But it could cause a decrease of $\sim 3°$ in θ if the position angle of interstellar polarization is $\sim 170°$.

Accurate polarimetry over a still longer wavelength base line is needed to assess the contribution of the interstellar component to the observed quantities more exactly.

4.3. Polarization mechanism

There are two main mechanisms that have been proposed to explain the continuum polarization in late-type stars in general. Harrington (1969) has shown that the light emerging from the limb of star would be highly polarized due to Rayleigh scattering by molecules and atoms if the Planck function has a steep gradient. The other mechanism proposed to explain the observed linear polarization is scattering by molecules or dust in an extended asymmetric circumstellar envelope (Kruszewski, Gehrels & Serkowski 1968; Shawl 1975b; Daniel 1978). In some cases a combination of both the photospheric effects and grain scattering is invoked to account for the observed linear polarization (Daniel 1982, Magalhaes *et al.* 1986).

There is no general agreement in the models which are suggested to explain the intrinsic polarization observed in RV Tauri stars. The polarization in U Mon and R Sct has been ascribed to their non-radially pulsating photospheres (Serkowski 1970). U Mon exhibits a systematic pattern in the variation of the direction of polarization, whereas R Sct does not show any such behaviour. Landstreet & Angel (1977) could not detect any change in either the amount or direction of polarization across the spectral lines in R Sct, thus ruling out the photospheric effects as proposed by Harrington (1969). In AR Pup it is suggested that a major portion of polarization arises from grain scattering in more localized transient regions close to the photosphere and not in the extended infrared emitting circumstellar envelope (Raveendran & Kameswara Rao 1988).

In the case of red variables, a correlation between the average intrinsic polarization and (11–3.5 μm) colour is found to exist (Dyck *et al.* 1971). While AR Pup follows the same mean relationship, the amount of polarization shown by U Mon and AC Her is too small for their observed infrared excesses.

Henson, Kemp & Kraus (1985) have found that in AC Her, the phases of the most rapid and extreme polarization change coincide with the phases where Baird (1981) has observed blue-shifted radial velocities that suggest an outward passage of atmospheric shock waves. Hence they suggested that polarization most likely arises in the region upon which the shock waves are acting.

The position angle of polarization always lies in a narrow range (22–55°), indicating the existence of a fundamental plane of symmetry. The near-regular cycle-to-cycle behaviour of $\theta°$ implies a regular variation in the geometry involved over the light cycle. The possibility of the observed variation in θ arising from a variation in the geometry of the extended infrared emitting envelope coupled with the pulsation of the star is very remote. Ultraviolet observations of the 0.22 μm absorption feature of circumstellar dust obtained at two different phases of light cycle do not show any major changes indicating that changes in the dust shells do not produce the changes in polarization (Baird & Cardelli 1985).

The near flat wavelength dependence (figure 1) seen in AC Her rules out the possibility of the origin of polarization due to scattering by molecules or atoms. The path of polarization on the equatorial (Q, U) plane (Henson, Kemp & Kraus 1985) suggests a possible relation between the position angle (i.e., geometry) and amount of polarization. We feel that the polarization observed in AC Her, most probably, results from a combination of pulsation related asymmetry in the star (non-radial pulsation ?) and circumstellar grain scattering and its variation during the light is caused by the changes in the asymmetry in the star.

A detailed study of the wavelength dependence of polarization over a few light cycles is necessary for a better understanding of the polarization mechanism operating.

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