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Polarimetric observations of the RV Tauri star AR Puppis

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Summary. *UBVRI* polarimetry of AR Pup is presented. Large variations are seen both in the amount and direction of polarisation. On one occasion, the polarisation in *U* was found to be as high as 14.6%. Polarisation level increases rapidly near about the times of primary minima and decreases comparatively slowly afterwards. The $P(\lambda)$ curve is found to exhibit a wide range of shapes. The stokes parameters Q and U in *UBVR* filter bands observed during JD 2446471 – 508 are found to lie on separate straight lines. Circumstantial evidences suggest that the origin of a major portion of polarisation observed in AR Pup is due to grain scattering in more localised transient regions probably close to the photosphere and not in the infrared emitting extended circumstellar dust envelope. The regular changes seen in the $P(\lambda)$ curve during JD 2446471 – 508 indicate that changes in the grain size distribution are systematic.

Key words: RV Tauri stars – AR Pup – polarisation – stellar atmospheres – circumstellar matter

1. Introduction

AR Pup is recognised as a member of RV Tauri type stars. These are variable supergiants (Luminosity classes Ib or Ia), with only a few dozen known members. The main photometric characteristic of these variables is that they exhibit alternating deep and shallow minima which may interchange occasionally. AR Pup has a period around 75 days between two consecutive deep minima and its mean brightness varies with a period around 1200 days (Payne-Gaposchkin et al., 1943). The spectral types of RV Tauri stars lie in the range F-K and vary over their light cycles appreciably (Preston et al., 1963). During a spectroscopic survey of RV Tauri and yellow semi-regular variables, Rosino (1951) obtained a single spectrum of AR Pup and pointed out the presence of strong CH bands. Because the infrared spectrum showed the double silicate emission features at 10 μm and 18 μm Gehrz and Ney (1972) suggested that AR Pup is very similar to that of oxygen-rich RV Tauri stars. Later, Lloyd Evans (1974) confirmed the presence of strong CH and CN bands in the optical spectrum of AR Pup and classified it as a group B star on the system of Preston et al. (1963). Stars belonging to group B, which are considered to be carbon-rich show strong CH and CN bands between secondary and primary maxima and exhibit a discrepancy between the spectal type based on Ca II lines and that based on hydrogen lines.

The anomalous excess in infrared radiation observed in RV Tauri stars has been attributed to the cool and extended dust thermospheres formed from the matter ejected by atmospheric shocks (Gehrz, 1972). Intrinsic polarisation observed in several cool stars is found to be related to their corresponding infrared excess indicating that polarisation may be partly due to dust scattering in the circumstellar envelope (Dyck et al., 1971). RV Tauri objects, in general, have received comparatively less attention polarimetrically. In the literature polarimetric data is available only for three RV Tauri objects, namely U Mon, R Sct and AC Her, and all of them are found to possess variable linear polarisation (Serkowski, 1970; Henson et al., 1985). Polarimertric observations of RV Tauri stars would be very much useful in understanding the properties of circumstellar dust around these objects if dust scattering is the main mechanism for producing the observed polarisation.

During a programme of broad band polarimetric observations of carbon variables, AR Pup was found to exhibit a large and highly time-dependent linear polarisation (Raveendran et al., 1985, 1986). In this paper we present the results of polarisation measurements of AR Pup and discuss the implications of the results on the origin of polarisation.

2. Observations

AR Pup was observed polarimetrically on one night each in November and December 1984 and February 1985 in UBVRI bands and on 7 nights during February-March 1986 in UBVR bands with the 102 cm telescope of the Kavalur Observatory. The polarimeter used consists of a halfwave retarder rotated at 10.41 Hz acting as the polariser and a wollaston prism as the analyser. A microcomputer system built around a Z-80 microprocessor was employed for the acquisition and on-line processing of the data. Depending on the sky conditions and faintness of the object in each wavelength band, the integration times were varied between 60 s to 120 s and the observations were repeated 3–6 times to bring down the errors. A detailed description of the polarimeter and the method of calibration are given in Deshpande et al. (1985).

In Table 1, linear polarisation (P%), position angle ($\theta°$), and the errors in their measurements are given along with the corresponding Julian day of observation. The V magnitudes and the various broad band colours are given in Table 2. The uncertainty in V is ~ 0.1 mag and that in the colours is ~ 0.06 mag. The

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Table 1. UBVRI polarimetry of AR Pup

JD	*U*		*B*		*V*		*R*		*I*	
2446000+	*P*%	*θ*°	*P*%	*θ*°	*P*%	*θ*°	*P*%	*θ*°	*P*%	*θ*°
007.44	0.5 ± 0.4	68 ± 23	0.7 ± 0.1	130 ± 5	1.5 ± 0.1	123 ± 2	2.1 ± 0.1	127 ± 2	2.6 ± 0.1	131 ± 1
053.35	6.5 ± 0.3	95 ± 1	5.6 ± 0.1	104 ± 1	5.1 ± 0.1	107 ± 0	4.6 ± 0.1	112 ± 1	4.2 ± 0.1	119 ± 1
114.28	4.7 ± 0.4	116 ± 2	5.4 ± 0.2	118 ± 1	5.2 ± 0.1	122 ± 1	5.2 ± 0.1	118 ± 1	5.0 ± 0.1	118 ± 1
471.27	9.9 ± 0.4	92 ± 1	8.7 ± 0.2	97 ± 1	7.1 ± 0.1	98 ± 0	6.3 ± 0.1	101 ± 0	—	—
472.27	10.8 ± 0.2	94 ± 1	9.0 ± 0.1	97 ± 0	7.5 ± 0.1	100 ± 0	—	—	—	—
478.17	14.6 ± 0.3	98 ± 1	12.2 ± 0.1	100 ± 0	9.5 ± 0.1	101 ± 0	8.3 ± 0.1	105 ± 0	—	—
503.20	6.4 ± 0.2	80 ± 1	5.9 ± 0.1	87 ± 0	5.3 ± 0.1	96 ± 0	4.6 ± 0.1	99 ± 1	—	
504.20	5.9 ± 0.2	77 ± 1	6.0 ± 0.1	86 ± 0	5.5 ± 0.1	95 ± 0	4.9 ± 0.1	98 ± 1	—	—
505.18	5.9 ± 0.2	75 ± 1	5.8 ± 0.1	84 ± 0	5.6 ± 0.1	90 ± 0	4.9 ± 0.1	95 ± 1	—	—
508.16	6.1 ± 0.6	75 ± 3	5.8 ± 0.1	85 ± 1	5.6 ± 0.1	93 ± 0	5.1 ± 0.2	100 ± 2	—	—

Table 2. UBVRI photometry of AR Pup

JD 2446000+	*V*	*U-B*	*B-V*	*V-R*	*R-I*
007.44	9.17	—	0.51	0.54	0.42
052.43	9.25	0.32	0.82	0.64	0.50
053.35	9.30	0.46	0.78	0.55	0.56
114.28	9.29	0.20	0.73	0.60	0.61
471.27	10.01	—	—	0.68	—
472.27	—	0.58	—	—	—
478.17	10.06	0.52	0.88	0.60	—
503.20	9.45	0.62	0.82	0.48	—
504.20	9.48	0.62	0.88	0.54	—
505.18	9.51	0.66	0.84	0.52	—
508.16	—	0.76	1.00	0.64	—

large errors in the measurements are mainly due to the prevalent poor sky conditions.

3. Results

3.1. Photometric behaviour

Intrinsic polarisation in many late type stars has been found to be closely tied up with the light variation (Serkowski, 1970; Shawl, 1975). A knowledge of the photometric behaviour at the times of polarimetric observations would be more useful for a meaningful interpretation of the polarimetric data.

AR Pup shows significant irregularities both in the period and shape of light curve (Payne-Gaposchkin et al., 1943). This makes the prediction of the light curves based on photometry done at earlier epochs difficult. The only available information on the light variation around the times of the polarimetric observations is the visual estimates of brightness by the American Association of Variable Star Observers (Mattei, 1986, private communication). Because of the limited observations and the scatter in the individual estimates, the data do not define the particular photometric cycles during which the polarimetric measurements were made. The times of minima estimated from the AAVSO data for the interval JD 2445999–6253 satisfy a 75 ± 1 day period. Further, photometry obtained by us during January-March 1987 also indicate a similar period. So we assumed a 75.0 day period and computed separate mean light curves by fitting first and second harmonics to the AAVSO data obtained during JD 2445999–6253 and JD 2446352–568. Since the visual estimates show a large spread, the observations were arranged in order of increasing phases and three point running averages were taken before plotting in Figs. 1 and 2 along with the computed mean light curves. The *V* magnitudes given in Table 2, also plotted in Figs. 1 and 2, lie systematically above the computed mean light curves. JD 2446000 was taken as the initial epoch.

From Fig. 1, we find that the deeper minimum occurs at $0^{\mathrm{p}}.33$ and the polarimetric observations obtained on JD 2446007.44, 053.44 and 114.28 fall respectively at $0^{\mathrm{p}}.10$, $0^{\mathrm{p}}.71$ and $1^{\mathrm{p}}.52$. The *V* magnitudes at these epochs were roughly the same (~ 9.25). The AAVSO visual estimates are few in number during the interval JD 2446352–568 resulting in a larger uncertainty in the mean

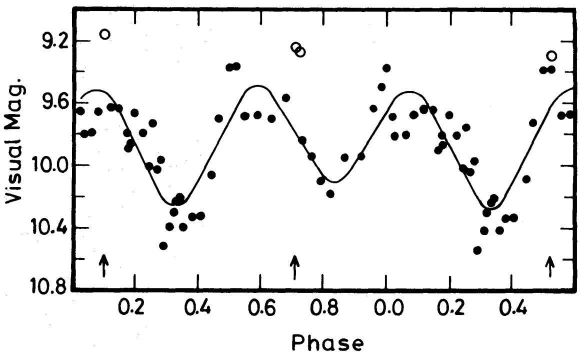


Fig. 1. Plot of the mean light curve and running averages (filled circles) computed from the AAVSO data for the interval JD 2445999–6253. Open circles are the *V* magnitudes given in Table 2. The arrows indicate the phases of polarimetric observations

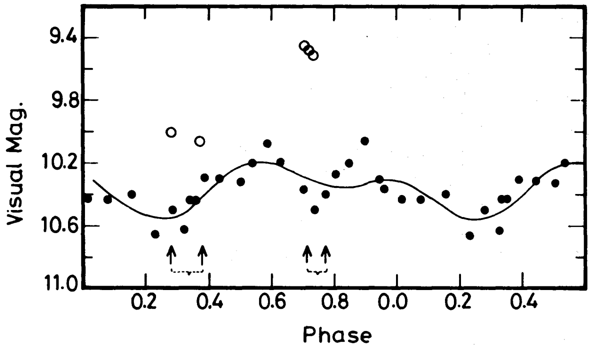


Fig. 2. Same as Fig. 1 for the interval JD 2446352–568

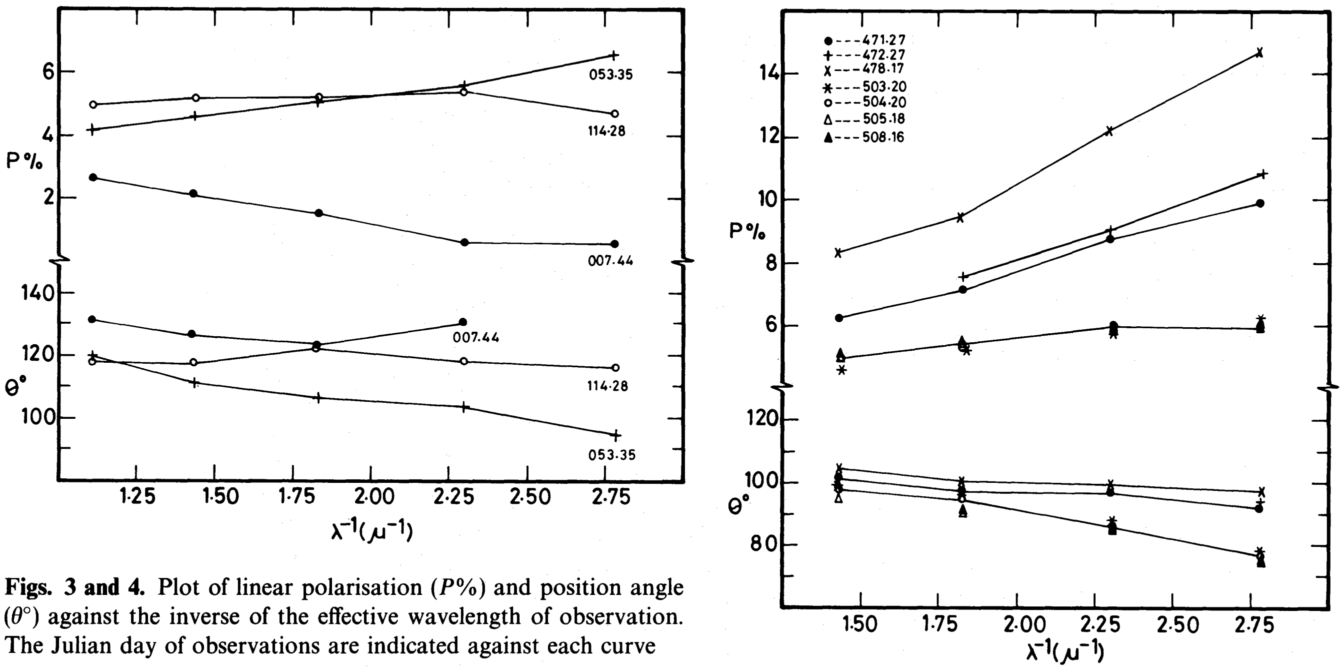
light curve plotted in Fig. 2. The deeper minimum occurs around $0^p.25$. The polarimetric data of JD 2446471–8 fall at $0^p.28-0^p.38$, during the ascending branch of the light curve close to the minimum. The measurements of JD 2446503–8 lie in the range $0^p.71-0^p.78$, on the descending branch close to the secondary minimum. The epochs of the deep minima in Figs. 1 and 2 satisfy a 74 day period. It is evident from Figs. 1 and 2 that the mean brightness of AR Pup is variable and the amplitude of the 75 day period light variation is larger when the star has a higher mean brightness. These characteristics are typical of an RV Tauri star of group b (Tsesevich, 1975).

3.2. *Polarimetric behaviour*

Values of $P\%$ and $\theta°$ given in Table 1 are plotted in Figs. 3 and 4 against the respective inverse of the effective wavelength of observation. The Julian day of observation is also mentioned against each curve. It is evident from these figures that large changes occur both in the amount and wavelength dependence of polarisation even over very short time-scales. The linear polarisation observed in U on JD 2446471.27 was ~ 9.9%, whereas that observed after a mere 7 days' interval was as high as 14.6%. Larger changes in polarisation and position angle are found to occur in ultraviolet (~ 14% and ~ 55° in U) than in red (~ 6% and ~ 30° in R). During JD 2446503–8, there was a suggestion of a slight increase in polarisation in R while that in U monotonously decreased (Fig. 4).

The available polarimetric data is limited. Still, from the changes seen in polarisation close to and after light minima, it is possible to conclude that significant increases in polarisation level occur only close to the epochs of primary minima. The most striking characteristic evident from Fig. 4 is the apparent dependence of the shape of the polarisation curve on the polarisation level as it changes. We find that as polarisation increased from JD 2446471.27 onwards, the $P(\lambda)$ curve became steeper towards ultraviolet and became nearly flat when the polarisation decreased later. Unfortunately, we could not follow up the variation. But the observations obtained on JD 2446007.44 may be indicative of the fact that $P(\lambda)$ curve might change direction if polarisation level decreased further. We know that polarisation was low just before the minimum that occurred around JD 2446024.8. Hence the qualitative agreement of the nature of the wavelength dependence seen on JD 2446053.35 and during JD 2446471–8 suggests that most probably just before the primary minimum of JD 2446468.8 also the polarisation level was low. The observations of JD 2446114.28 are more close to a light minimum than that of JD 2446053.35. Hence from the behaviour of $P(\lambda)$ curve seen during JD 2446471–508, we would expect a wavelength dependence that monotonously increases towards ultraviolet, contrary to what is actually observed. It is possible that the polarisation level and the peculiar nature of dependence of polarisation and position angle on wavelength observed on JD 2446114.28 may be the result of modification of existing polarisation by the changes that occurred close to the primary minimum of JD 2446199.8.

An inspection of Fig. 4 reveals that for a particular wavelength a possible correlation between the amount of polarisation



Figs. 3 and 4. Plot of linear polarisation ($P\%$) and position angle ($\theta°$) against the inverse of the effective wavelength of observation. The Julian day of observations are indicated against each curve

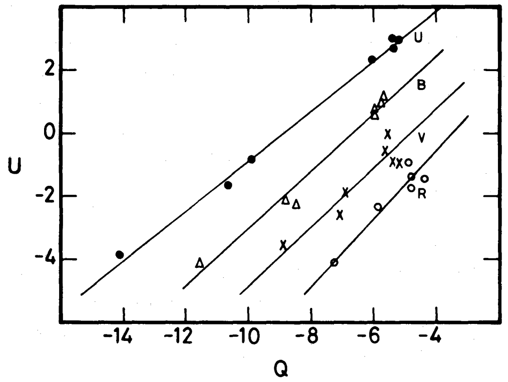


Fig. 5. The path of polarisation observed during JD 2446471–508 in the (Q, U) plane. Note that the first set of observations fall nearly in the middle of each line

and position angle exists; the more the position angle departs from ~ 100°, the less the percentage polarisation is. The apparent correlation becomes very clear when the (P, θ) measurements are transformed to the equatorial stokes parameters $Q=P\cos 2\theta$ and $U=P\sin 2\theta$. Figure 5 represents such a transformation and we find that the observations in each wavelength band fall on separate near straight lines. Here it is worth noting that the first set of observations, namely that obtained on JD 2446471.27, fall in the middle of each line. The straight lines drawn in Fig. 5 are the least square fits for the observed (Q, U) values for each of the filters used. The slopes of the lines for U,B,V and R are 0.78 ± 0.02, 0.91 ± 0.05, 0.85 ± 0.12, and 1.0 ± 0.11 respectively.

4. Discussion

4.1. *Interstellar component of polarisation*

We did not attempt to derive the interstellar component of polarisation by observing nearby stars. But, an upper limit on the interstellar component can be put from the colour excess $E(B\text{-}V)$, since reddening is an essential condition for the production of interstellar polarisation (Schmidt, 1958). The maximum possible value for the interstellar component is given by $P_{\max}\leqslant 9.0\,E(B\text{-}V)$ with the maximum occurring at $\lambda_{\max}=0.555\text{–}0.03\;E(B\text{-}V)$ (Serkowski et al., 1975). The $E(B\text{-}V)=0^{m}.04$ quoted by Dawson (1979) for AR Pup gives a value of $P_{\max}\leqslant 0.34\%$ peaking in V band and is comparable to the errors of observations. The above estimation agrees with the fact that on one occasion, namely JD 2446007.44, the polarisation observed in U band was very close to zero. Hence, we conclude that the contribution from the interstellar component is negligible and the observed quantities are intrinsic to the star.

4.2. *Polarisation mechanism in AR Pup*

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

There is no general agreement in the models which are suggested to explain the intrinsic polarisation observed in RV Tauri stars. The origins of polarisation in U Mon and R Sct have been ascribed to their non-radially pulsating photospheres (Serkowski, 1970). U Mon exhibits a systematic pattern in the variation of the direction of polarisation, whereas R Sct does not show any such behaviour. Landstreet and Angel (1977) could not detect any change in either polarisation or direction across the spectral features in R Sct, thus ruling out the photospheric effects as proposed by Harrington (1969). Henson et al. (1985) have attributed the origin of polarisation observed in AC Her to the circumstellar gas shell surrounding it.

The position angle is expected to be wavelength independent for polarisation produced by photospheric effects caused by asymmetries due to either non-radial stellar pulsations or temperature distributions across the disc. From Figs. 3 and 4, we find that AR Pup shows a variable and a strong wavelength dependent direction of polarisation.

The nature of wavelength dependence seen in AR Pup rules out the possibility of the origin of polarisation due to the scattering by molecules or atoms. We feel that polarimetric observations of AR Pup can be understood better in terms of scattering by grains in an asymmetric cloud around the star. The amplitudes of polarisation variation seen in U Mon, R Sct, and AC Her are similar (1.0 – 1.5%) and are much smaller than that is observed in AR Pup. Photospheric effects similar to those suggested for the other RV Tau objects may be operative in AR Pup, but the contribution to the observed polarisation is probably negligible.

4.3. *Place of origin of polarisation*

Among the known RV Tauri stars, AR Pup is one of the few objects in which a very large infrared excess is observed (Gehrz and Ney, 1972; Lloyd Evans, 1985). The infrared emission in RV Tau stars are ascribed to the extended cool dust envelopes surrounding them. Computational models of extended circumstellar scattering envelopes using Mie theory (Shawl, 1975; Daniel, 1978, 1982) do not predict the high intrinsic polarisation (~ 14.6%) observed in AR Pup. Kruszewski, et al. (1968) and Daniel (1980) have suggested that preferential attenuation of direct star light by thick material present in the line of sight might be invoked in order to increase the polarisation produced by axisymmetric envelopes. But the sudden changes observed in the polarisation in AR Pup during JD 2446471–478 may not be caused by variations in the obscuration of direct star light by thick condensations in the line of sight because in such a case one would expect a very large change in the brightness and no change in the direction of polarisation. In the case of red variables, a correlation between the average intrinsic polarisation and (11 μm – 3.5 μm) colour is found to exist (Dyck et al., 1971). It is interesting to note that AR Pup also follows the same mean relationship. Forrest et al. (1975) find no definite changes in infrared flux in stars which show large polarisation variation. Hence they attribute the infrared emission to the total abundance of dust in the envelope which does not change substantially with time while intrinsic polarisation is attributed to scattering and absorption effects from more localised transient regions.

The regular behaviour of P and θ observed during JD 2446471–508 appears to be as a result of some systematic variation in the several parameters which determine the level, direction and wavelength dependence of polarisation produced. It is difficult to conceive that the whole extended infrared emitting circumstellar envelope is involved to produce such a regular variation. But it is much more probable that transient localised regions such as those suggested by Forrest et al. (1975) for red variables were largely responsible for the observed polarimetric behaviour. Here we would like to mention that Bastien and Landstreet (1979) have attributed the changes in position angles observed in RY Tau, a T Tauri star, to scattering from blobs of material moving about. Localised condensations if situated preferentially and closer to the photosphere might scatter a larger portion of light in the line of sight giving rise to a higher percentage of polarisation. A variation in the projected geometry would lead to a variation in the direction of polarisation and the change in the observed brightness would be only marginal. In Fig. 5 we find that at low polarisation levels the scatter in V and R is larger. The extended circumstellar envelope might be contributing to the observed polarisation at longer wavelengths which becomes significant at low polarisation levels.

Baird (1981) has observed blue-shifted radial velocities in AC Her during the rising light after primary minimum suggestive of an outward passage of shock. Such detailed radial velocity studies are lacking for AR Pup. But it is reasonable to expect a similar behaviour in this object also. The nature of the rapid and regular changes in the polarisation observed in AR Pup after the primary minimum (Fig. 4) indicates a possible relation to the outward passage of a shock. The pressure increase due to shock might help to form small solid particles (Shawl, 1975). The conditions existing close to the primary minima may be favouring the formation of more localised condensations which are responsible for the observed polarisation. It is possible that the life times of such condensations may be longer than the period of light variation. Hence the contribution from different regions might produce the peculiar wavelength dependence of P and θ of the type observed on JD 2446114.28. The varying size of the star as it pulsates might also modify significantly the observed polarisation. More polarimetric observations extending to infrared are required to sort out the polarimetric behaviour of AR Pup before any meaningful model could be constructed.

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