Mon. Not. R. Astron. Soc. **303,** 595–602 (1999)

Linear polarization in the RV Tauri star AR Puppis

A. V. Raveendran★
Indian Institute of Astrophysics, Bangalore 560034, India

Accepted 1998 November 2. Received 1998 October 26; in original form 1998 July 31

ABSTRACT
The *UBVR* polarimetry of AR Pup obtained on 14 nights during 1990–93 shows a large variation in both the amount ($\sim$ 6 per cent in the *U* band) and the wavelength dependence of polarization. The simultaneous photometry (20 nights) and polarimetry (30 nights) in the *V* band during 1997 December–1998 April, which cover about one and a half pulsational cycles, clearly establish the polarization–light curve connection in AR Pup: both go through the maximum and minimum at about the same time. We interpret the observed near-straight line locus of polarization between any two consecutive minima in the *Q*, *U* plane as resulting from the simultaneous presence of two independently varying polarization components, one slowly and the other relatively rapidly. We suggest that the mechanism that produces the exceptionally large polarization in AR Pup is, most likely, selective absorption by non-spherical grains, which condense with a certain amount of alignment after each light minimum during a pulsational cycle. *BV* photometry was also obtained on 44 nights about the times of *UBVR* polarimetry for information on the contemporaneous light variation. The position angle of polarization in AR Pup does not show any correlation with its mean light level which is found to vary nearly sinusoidally with a 1165$\pm$4 d period.

Key words: polarization – stars: AGB and post-AGB – circumstellar matter – stars: individual: AR Pup – stars: variables: other.

1 INTRODUCTION

RV Tauri stars are low-mass, yellow supergiant pulsators (luminosity class Ib or Ia) with periods in the range 40–140 d. They have been identified as objects undergoing post-AGB evolution towards white dwarf stage by Jura (1986) and Alcolea & Bujarrabal (1991) from studies of their circumstellar dust and gas envelopes. In spite of their high intrinsic luminosities, the number of RV Tauri stars known is very small, only $\sim$ 120, implying a short lifetime for the RV Tauri phase of evolution. However, the lifetimes of 200–500 yr estimated by the above authors seem to be unreasonably short (Zsoldos 1995). From detailed high-resolution spectral analyses of a sample of field RV Tauri stars, Gonzalez, Lambert & Giridhar (1997a,b) find that the abundance anomalies observed in these stars are very similar to those seen in peculiar, high-latitude A–F supergiants that have been identified as post-AGB stars. Detailed accounts of the photometric and spectroscopic properties of RV Tauri stars are given in Pollard et al. (1996, 1997).

AR Puppis is classified as an RVb Tauri star because of the variation in its mean light level. It has a period of $\sim$ 38 d between two consecutive minima. Lloyd Evans (1974) has assigned AR Pup to the spectroscopic group B, defined by Preston et al. (1963), on the basis of the presence of strong CN and CH bands in its spectrum in the optical region. AR Pup, which has exceptionally large infrared excesses in the *JHKL* bands (Lloyd Evans 1985), has been detected at 12-, 25-, 60- and 100-μm *IRAS* passbands (Beichman et al. 1985). The anomalous infrared excesses observed in RV Tau stars have been attributed to the extensive circumstellar dust envelopes surrounding them (Gehrz 1972; Gehrz & Ney 1972; Lloyd Evans 1985; Goldsmith et al. 1987). As dust scattering produces linear polarization, it is quite natural to expect RV Tauri stars to be intrinsically polarized, and indeed almost all objects that have been observed polarimetrically, even though they constitute only a small fraction of the known stars, are found to possess variable linear polarization, correlated with the pulsational light modulation. All of them, except AR Pup, show, typically, an amplitude of 1–2 per cent over the light cycle (Serkowski 1970; Henson, Kemp & Kraus 1985; Nook, Cardelli & Nordsieck 1990; Polyakova 1992). AR Pup shows the most remarkable time- and wavelength-dependent polarization variation (Raveendran & Kameswara Rao 1988; Raveendran, Kameswara Rao & Anandaram 1989). On one occasion it was found to show $\sim$ 14 per cent in *U*, which is the highest so far observed in a single star not associated with any known nebulosity.

The limited data available only indicate broadly that the polarization rapidly increases after a light minimum and circumstellar dust scattering is perhaps the main mechanism responsible for the observed polarization in AR Pup (Raveendran et al. 1989). In this paper we report more extensive polarimetry and near-simultaneous photometry of AR Pup, which clearly bring out the polarization–light curve connection. We present an analysis of both the short- and

★E-mail: avr@iiap.ernet.in

Table 1. *BV* photometry of AR Pup.

JD 244 0000+	*V*	*B* − *V*	JD 244 0000+	*V*	*B* − *V*
7853.376	9.773	0.659	7854.361	9.738	0.646
7855.369	9.705	0.613	7856.365	9.629	0.626
7867.367	9.613		7869.328	9.611	0.802
7870.319	9.615	0.793	7878.352	9.671	0.863
7881.281	9.876	0.896	7882.274	9.895	
7913.237	9.513	0.792	7915.230	9.573	0.826
7916.212	9.609	0.804	7917.248	9.629	0.815
7918.273	9.602	0.834			
9012.328	9.794	0.622	9018.268	9.595	0.586
9019.253	9.609	0.643	9020.221	9.614	0.657
9021.202	9.630		9034.235	9.748	0.887
9035.231	9.783	0.871	9036.268	9.775	0.875
9037.219	9.838		9047.171	10.087	
9048.152	10.044		9050.128	9.961	0.756
9059.134	9.699	0.691	9060.145	9.676	0.701
9064.108	9.563	0.693	9065.122	9.538	0.709
9358.342	9.488	0.721	9360.239	9.370	
9362.299	9.284	0.613	9363.300	9.235	
9368.264	9.179	0.723	9398.240	9.237	0.648
9415.289	9.224	0.858	9416.272	9.250	0.866
9417.247	9.281	0.877	9418.203	9.331	0.864
9419.252	9.321	0.892	9420.262	9.373	0.882
9421.251	9.398	0.881			

long-term polarimetric behaviour of the star and discuss the implications of the observations on the possible mechanism(s) involved in producing the unusually large polarization variation.

2 OBSERVATIONS

AR Pup was observed photometrically in the *BV* bands on 15 nights during 1989 November–1990 January, 16 nights during 1993 January–March and 13 nights during the corresponding period in 1994 with the 0.34-m telescope at Vainu Bappu Observatory (VBO), Kavalur. During 1997 December–1998 March it was observed in the *V* band on 20 nights with the 1-m telescope at VBO. All observations were made differentially with respect to HD 66559 (CD−35°4134). The differential magnitudes and colours were converted to *V* and *B* − *V* using $V = 8.373$ and $B - V = 0.924$ for HD 66559 (Raveendran et al. 1989), and are given in Tables 1 and 2. The *V* and *B* − *V* values used for the comparison star are essentially the same as those given by Pollard et al. (1996). Each value given in the tables is an average of 3–4 independent measurements. To convert the *V*-band observations obtained during 1997 December–1998 March to standard *V* values, the differential *B* − *V* curves of AR Pup obtained earlier were made

Table 2. *V* photometry of AR Pup.

JD 245 0000+	*V*	JD 245 0000+	*V*	JD 245 0000+	*V*
806.406	9.676	807.392	9.652	808.368	9.633
813.366	9.554	814.297	9.502	822.261	9.509
823.281	9.521	824.230	9.588	831.220	9.586
840.236	10.004	852.169	9.525	853.198	9.573
864.180	9.351	865.186	9.339	877.113	9.718
878.153	9.750	891.169	9.635	893.132	9.646
901.097	9.549	902.091	9.553		

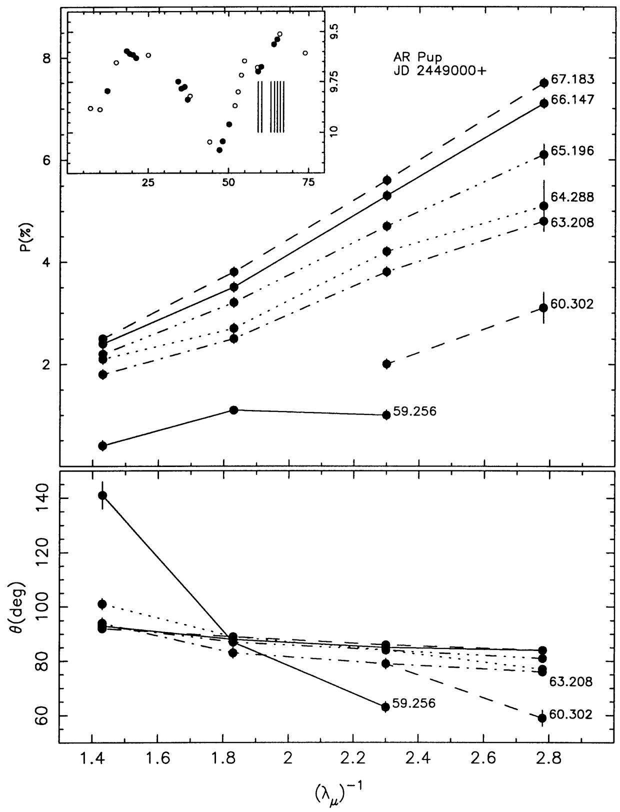

Figure 1. Plots of linear polarization and position angle against the inverse of the effective wavelength of the photometric band. The numbers against the curves identify the Julian days of observation. Inset: Light curve in the *V* band. Filled circles indicate the present observations and open circles those obtained by Pollard et al. (1996). The vertical lines show the times of polarimetry.

use of. The uncertainty in *V* and *B* − *V* given in Table 1 is typically ∼ 0.012 mag, and that in *V* given in Table 2 is slightly larger.

The linear polarization measurements of AR Pup were made in the *UBVR* bands on 15 nights during 1990–96 with the PRL polarimeter (Deshpande et al. 1985). All observations, except those corresponding to JD 245 0198.180, which were made using the 1.2-m Gurushikar telescope at Mount Abu, were obtained with the 2.34-m telescope at VBO. During 1997 December–1998 April AR Pup was observed on 30 nights in the *V* band with the IIA polarimeter (Jain & Srinivasalu 1991) attached to the 1-m telescope. The same instrument was used to obtain the differential *V* magnitudes mentioned above. On nine nights at the beginning of the observing run AR Pup was observed in the *B* band also. The results of the polarimetric observations are given in Tables 3 and 4. Several standard unpolarized and polarized stars were observed along with AR Pup to determine the instrumental polarization and zero-points of position angles.

3 DISCUSSION

3.1 Polarization–light curve connection

The linear polarization and position angle obtained during JD 244 9059–67 are plotted against the corresponding inverse of the effective wavelength of the photometric band in Fig. 1. The Julian days of observation are indicated against the respective plots. The inset shows the *V*-band light curve corresponding to the

Table 3. *UBVR* polarimetry of AR Pup.

JD	*U*		*B*		*V*		*R*	
240 0000+	*P*(%)	*θ*(°)	*P*(%)	*θ*(°)	*P*(%)	*θ*(°)	*P*(%)	*θ*(°)
47914.223	7.0 ± 0.4	90 ± 2	5.4 ± 0.2	90 ± 1	3.9 ± 0.1	89 ± 1	2.9 ± 0.1	102 ± 1
47941.220	3.8 ± 0.5	89 ± 4	2.9 ± 0.2	94 ± 2	1.8 ± 0.1	109 ± 3	1.0 ± 0.2	109 ± 6
48297.238	1.9 ± 0.2	11 ± 2	1.4 ± 0.1	7 ± 2	1.4 ± 0.1	166 ± 1	1.6 ± 0.1	157 ± 1
48301.269	4.0 ± 0.2	13 ± 2	2.8 ± 0.1	6 ± 2	2.3 ± 0.1	175 ± 1	2.2 ± 0.1	172 ± 2
48325.226	3.4 ± 0.3	98 ± 2	1.6 ± 0.1	106 ± 1	1.4 ± 0.1	122 ± 1	1.8 ± 0.1	135 ± 2
48665.350	2.9 ± 0.8	76 ± 8						
48706.263	5.0 ± 0.9	105 ± 5	3.9 ± 0.2	90 ± 1	2.7 ± 0.1	99 ± 1	2.6 ± 0.1	103 ± 2
49059.256			1.0 ± 0.1	63 ± 2	1.1 ± 0.0	87 ± 1	0.4 ± 0.1	141 ± 5
49060.302	3.1 ± 0.3	59 ± 3	2.0 ± 0.1	79 ± 2				
49063.208	4.8 ± 0.2	76 ± 1	3.8 ± 0.1	79 ± 1	2.5 ± 0.1	83 ± 2	1.8 ± 0.1	94 ± 2
49064.288	5.1 ± 0.5	77 ± 1	4.2 ± 0.1	84 ± 1	2.7 ± 0.1	89 ± 1	2.1 ± 0.1	101 ± 2
49065.196	6.1 ± 0.2	81 ± 1	4.7 ± 0.1	84 ± 1	3.2 ± 0.1	87 ± 1	2.2 ± 0.1	93 ± 1
49066.147	7.1 ± 0.1	84 ± 1	5.3 ± 0.1	85 ± 1	3.5 ± 0.1	88 ± 1	2.4 ± 0.1	93 ± 1
49067.183	7.5 ± 0.1	84 ± 1	5.6 ± 0.1	86 ± 1	3.8 ± 0.1	89 ± 1	2.5 ± 0.0	92 ± 1
50198.180			2.2 ± 0.6	65 ± 8	1.9 ± 0.1	62 ± 3		

pulsational cycle during which the polarimetry was made; the vertical lines indicate the times of polarimetry. The light curve exhibits a shallow minimum of short duration of the type reported earlier by Raveendran et al. (1989). Such short-term fluctuations, which may be a regular feature of AR Pup, and probably of RV Tauri stars in general, may often miss detection because of the common occurrence of large gaps in the light curves. When the observations were begun, the polarization was low at all wavelength bands, and the position angle showed a strong rotation with the wavelength. During the following days, the polarization level steadily increased with the wavelength dependence becoming steeper towards the ultraviolet, in a way similar to that reported by Raveendran & Kameswara Rao (1988). The light minimum just preceding the polarimetry was the deeper one, as indicated by the maxima, which are well-defined by the photometry, on either side. The polarization,

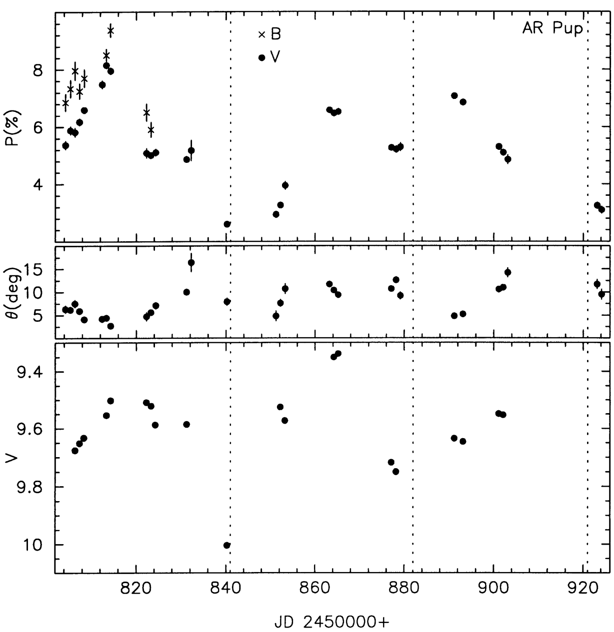

Figure 2. Plots of linear polarizations in the *B* and *V* bands, and position angle and magnitude in the *V* band against the Julian day of observation. The vertical dotted lines indicate the times of light minima.

which was probably low (< 1 per cent), started increasing 6–8 d after the minimum.

The observations listed in Table 4 and plotted in Fig. 2 are spread over approximately one and a half light cycles, starting immediately after a secondary minimum, which occurred ~ JD 245 0802, and ending after a primary minimum. The vertical dotted lines indicate the times of minima estimated from the light curve plotted in the bottom panel of the figure. The data do not permit the estimation of the exact light phases at which the polarization became maximum and minimum. However, it appears that the polarization attained a maximum very close to a light maximum and a minimum very close to or slightly after a light minimum. The polarization did not start increasing immediately after a primary minimum, while it did start increasing immediately after a secondary minimum, as indicated clearly by the observations at the beginning. The most striking characteristic of the polarization curve plotted in Fig. 2 is that before a primary minimum the polarization dropped to a lower level than before a secondary minimum; the exact levels to which it dropped were probably different for the two minima covered. Even though the polarization and light curves look similar, the rise and fall in the former are not well-correlated with those in the latter. This is evident from the observations obtained during the two secondary maxima, which show that the polarization decreased much faster than the brightness. The position angle of polarization, though varied over the light cycle, showed only a small range, and there was no significant difference between its values close to the primary and secondary light minima.

3.2 Multiple polarization components

It is clearly evident from the results presented above that the variations in polarization and brightness are strongly coupled in AR Pup, with both reaching either a maximum or a minimum at about the same time. However, the time of onset of the rapid increase in polarization relative to the light minimum is not always the same. There is apparently no definite relationship between the amount of polarization and the time elapsed after a minimum. The maximum level reached by the polarization does not depend on the maximum brightness reached during a pulsational cycle; however, there is an indication that the deeper the light minimum, the lower the level to which the polarization drops.

Table 4. *BV* polarimetry of AR Pup.

JD 245 0000+	P(%)	θ(°)
V band		
804.272	5.4 ± 0.1	6.3 ± 0.8
805.369	5.9 ± 0.1	6.2 ± 0.6
806.376	5.8 ± 0.2	7.5 ± 0.8
807.359	6.2 ± 0.1	5.9 ± 0.6
808.412	6.6 ± 0.1	4.1 ± 0.3
812.406	7.5 ± 0.1	4.2 ± 0.5
813.338	8.2 ± 0.1	4.4 ± 0.4
814.275	7.9 ± 0.1	2.7 ± 0.4
822.274	5.1 ± 0.2	4.7 ± 0.9
823.256	5.0 ± 0.1	5.6 ± 0.6
824.331	5.1 ± 0.1	7.1 ± 0.7
831.200	4.9 ± 0.1	10.0 ± 0.6
832.235	5.2 ± 0.3	16.4 ± 2.0
840.230	2.6 ± 0.1	7.9 ± 0.8
851.214	2.9 ± 0.1	4.8 ± 1.1
852.196	3.3 ± 0.1	7.6 ± 0.8
853.283	3.9 ± 0.1	10.7 ± 1.1
863.224	6.6 ± 0.1	11.7 ± 0.4
864.206	6.5 ± 0.1	10.4 ± 0.5
865.188	6.5 ± 0.1	9.4 ± 0.5
877.107	5.3 ± 0.1	10.7 ± 0.5
878.174	5.2 ± 0.1	12.6 ± 0.6
879.135	5.3 ± 0.1	9.2 ± 0.8
891.169	7.1 ± 0.1	4.8 ± 0.4
893.112	6.8 ± 0.1	5.2 ± 0.4
901.130	5.3 ± 0.1	10.6 ± 0.6
902.109	5.1 ± 0.1	11.0 ± 0.6
903.121	4.8 ± 0.2	14.2 ± 1.0
923.111	3.2 ± 0.1	11.7 ± 1.0
924.114	3.1 ± 0.1	9.5 ± 1.1
B band		
804.272	6.8 ± 0.3	13.8 ± 1.2
805.369	7.3 ± 0.3	11.5 ± 1.2
806.376	8.0 ± 0.3	11.4 ± 1.1
807.359	7.2 ± 0.3	8.6 ± 1.0
808.412	7.7 ± 0.3	10.0 ± 1.1
813.338	8.5 ± 0.2	3.0 ± 0.7
814.275	9.4 ± 0.2	3.6 ± 0.7
822.274	6.5 ± 0.3	8.0 ± 1.3
823.256	5.9 ± 0.3	11.5 ± 1.2

The polarization measurements in V between two successive light minima, which constitute a polarization cycle, are grouped together and plotted in Fig. 3 against the corresponding times elapsed after the first minimum; the data obtained earlier (Raveendran & Kameswara Rao 1988; Raveendran et al. 1989) are also included. Before plotting, the observations in each group were laterally shifted along the time axis by the number of days indicated in the figure. As the time of minimum preceding the observations during JD 244 6471–508 is uncertain, they were shifted by an arbitrary number of days along the time axis to align them with the other observations during the increasing phase. It is interesting to see that all the observations during the increasing phase of polarization lie on a near-straight line, implying that, irrespective of the maximum level reached, the rate of increase in polarization was almost the same during the different cycles considered. Although the decline phase of polarization shows a larger scatter, the average rate of decay, which is significantly smaller than that during the increasing phase, was also the same during different cycles. This indicates that the level to which the polarization drops before the onset of the next increase will depend upon the level to which the polarization increased during the current cycle. Hence, it is quite possible that a residual polarization component, which decreases comparatively slowly, is superposed on that produced during the rise in the subsequent cycle, making the observed polarization a resultant of these two independently varying components. Further, it is possible that the slow varying component itself could be composed of two or more independently varying components.

Fig. 4 shows the V-band observations obtained during JD 245 0804–903 in the Q, U plane. The different symbols denote observations between two different sets of successive minima. We find from the figure that the three sets of observations that were obtained fall on separate near-straight lines. In each case, as the polarization increased, the locus in the Q, U plane moved in one direction and later when decreased moved in the opposite direction. The straight lines in Fig. 4 represent least-squares fits to the data in the respective intervals considered. We would expect the observed polarization to show such a pattern in the Q, U plane if there were two components independently varying in magnitude, one slowly and the other relatively rapidly, while the position angles of both remained nearly constant. We conclude that the observed polarization comprises independently varying multiple components. Even though they fall on the declining branch, the data obtained during JD 245 8031–2 show almost the same amount of polarization as that obtained one week before, but with significantly different position angles (Fig. 2). In the Q, U plane these observations largely deviate from the near-straight line path (Fig. 4), and probably indicate the contribution from a very short-lived component.

The observations obtained during JD 244 8297–325 do not conform to the pattern in the evolution of polarization seen during a pulsational cycle on other occasions. On JD 244 8301, which is close to a light minimum according to the photometry by Pollard et al. (1996), the polarization at all wavelength bands was significantly larger than that on JD 244 8325, which is close to a light maximum, contrary to what is expected. Similarly, the position angle showed a strong rotation with wavelength even though the amount of polarization was around 2 per cent or more. The peculiar behaviour in the variations of polarization and position angle during JD 244 8297–325 also will result if there are independently varying multiple components with significantly different position angles. Even before the light minimum of JD 244 8304, apparently there were two components with a large difference in their position angles, as indicated by an increase in polarization before the light minimum instead of a decrease. In the U and B bands the residual polarization components and those produced after the minimum were nearly mutually perpendicular, as indicated by the flip in the position angle in those bands. In all other cases considered both the residual and the new polarization components were mutually aligned within 10–20°.

3.3 Long-term behaviour

The long-term light modulations exhibited by RVb Tauri stars have been attributed to the quasi-periodic eclipses of the pulsating star by dark matter present as it moves in a binary orbit (Fokin 1994). Pollard et al. (1996) find that such a model cannot account for a number of observed features, such as the damping of the amplitude of the short-period light variation during the long-term minimum

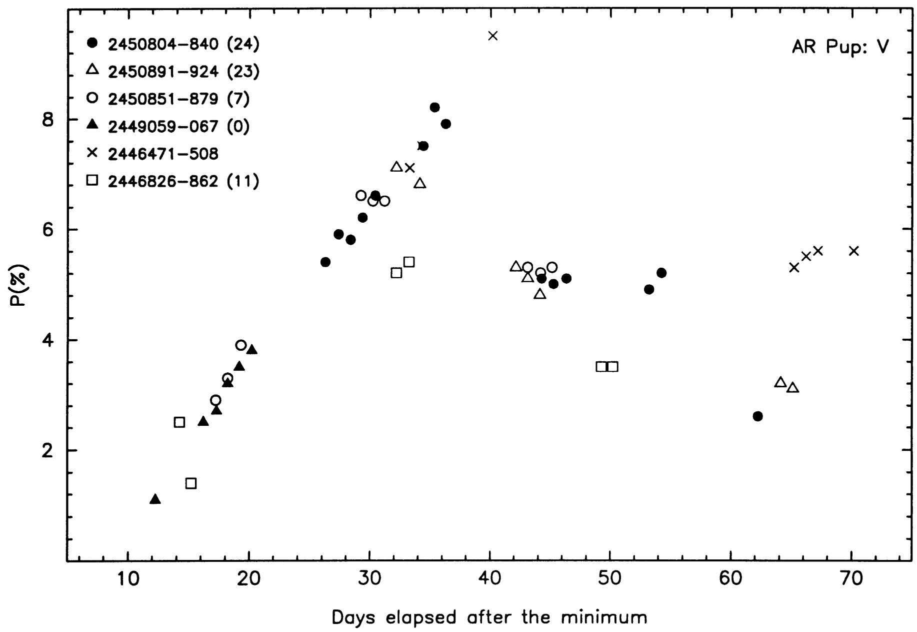

Figure 3. Plot of linear polarization in V against the number of days elapsed after a minimum. The observations obtained between two consecutive light minima are grouped together and shifted along the time axis by the number of days indicated in the brackets.

and the phase-dependent colour variation accompanying the long-term light modulation. They prefer the model of a binary eclipsed periodically by a circumbinary dust torus which interacts with the pulsating star at some phase in the orbit. As there is very little colour variation during the long-term cycle, they suggest that AR Pup is interacting less with the circumbinary dust torus.

Pollard et al. (1996) have derived a 1389±30 d period for the long-term light modulation using their data, which show a reasonably sinusoidal shape. This period is comparable to the time base covered by their observation. In Fig. 5 we have plotted all the available V magnitudes of AR Pup. The data in the JD 244 7850–9450 interval clearly define the modulation in the mean light level, and indicate a period around 1200 d. It is difficult to be sure whether the long-term modulation persisted with the same period over the entire time span (1982–98) covered in the figure because of the large number of gaps in the data. Assuming a sinusoidal variation, a least-squares solution yields a 1165±4 d period for the entire data set. The measurements listed by Raveendran & Kameswara Rao (1988) were not included in the analysis because they are affected by large errors. The smooth continuous curve in the figure, which represents the computed light modulation, shows that the available data is consistent with a persistent, regular modulation with the above period. If the circumbinary dust torus is really responsible for the long-term modulation in AR Pup, such a regular variation implies that there is little interaction between the star and the dust torus.

A power spectrum analysis of the entire V-band data set consisting of 283 values, after the removal of the assumed long-term sinusoidal variation, shows a peak around 39.1 d, which is close to that found by Pollard et al. (1996) from their data, and another of slightly smaller amplitude around 37.0 d. A piecewise analysis of the data shows that the shorter period peak arises because of the inclusion of the photometry by Eggen (1986) and Raveendran et al. (1989), which satisfies a shorter period of 37.8 d between two consecutive light minima.

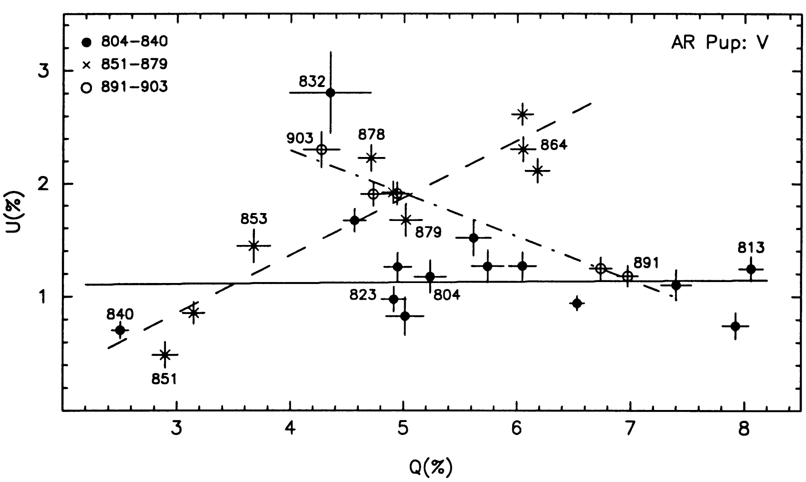

Figure 4. Paths of the polarization in the V band observed during JD 245 0804-903 in the Q, U plane. The observation obtained on JD 245 0832 was not included in the least-squares solution because it shows a large deviation (see text). Some of the observations are identified by the last three digits of their Julian days.

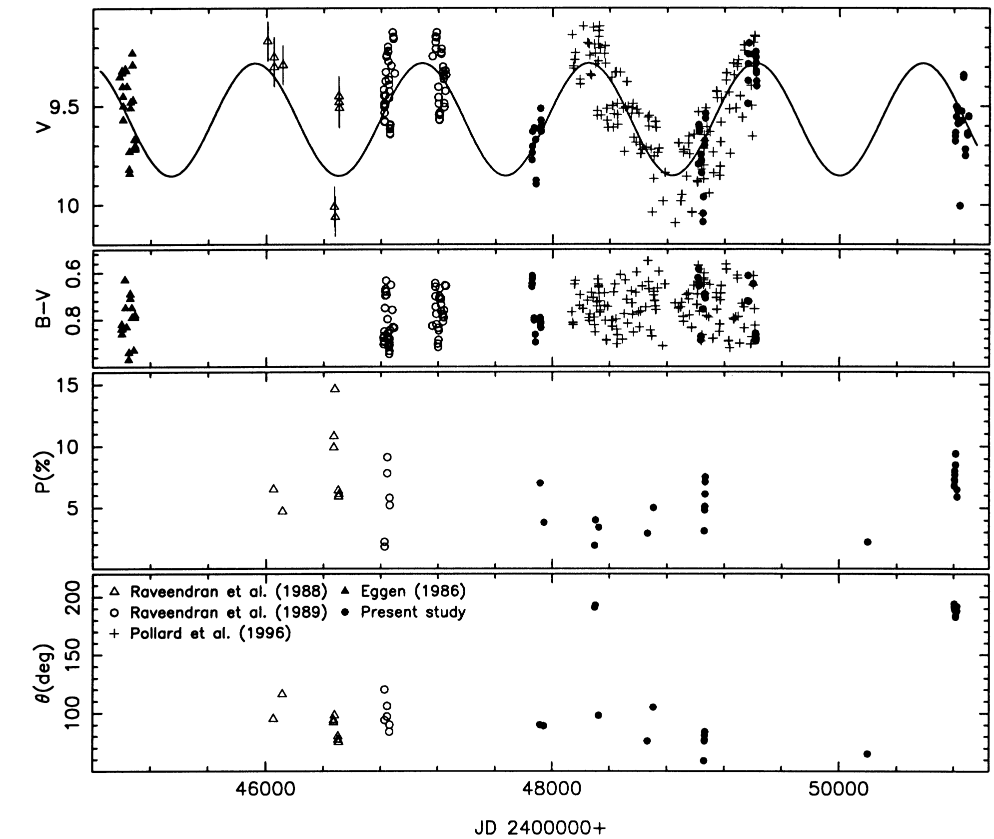

Figure 5. Long-term photometric and polarimetric behaviour of AR Pup. The linear polarization and the position angle are those in the *U* band, except for the last two sets where the quantities are those in the *B* band.

The damping of the amplitude of short-period variation during the minimum of the long-term modulation of the mean light level, as seen in AI Sco and U Mon (Pollard et al. 1996), is absent in AR Pup. Therefore, the conclusion by Pollard et al. (1996) that in RVb stars the amplitudes of short-period light variation change periodically and in correlation with the long-term light modulation may not be true in general. Raveendran et al. (1989) have pointed out that the large, short-term variability seen in the shape of the *V* light curve during different pulsational cycles is not reflected in the $B-V$ variation. It is clear from Fig. 5 that the long-term variation in the mean light level of AR Pup is also not reflected in the $B-V$ colour, as reported by Pollard et al. (1996).

Fig. 5 also shows the long-term behaviour of the linear polarization and position angle in the *U* band observed in AR Pup. In a few cases where measurements are not available in *U* those in the *B* band are plotted. As can be seen from the figure, neither the variation in polarization nor that in position angle shows any correlation with the long-term light modulation. To observe a net polarization integrated over the visible disc of the star there should be some asymmetry present. If the 1165-d period corresponds to the binary period, it should be reflected in the position angle of polarization in case the companion or the dust torus is producing the required asymmetry. We find, however, that most of the position angles lie in two distinct bands, centered around 100° and 10°, which are mutually perpendicular to each other. Apparently, there is no correlation between the occasional flip in the position angle band and the phase of the long-term light modulation. If AR Pup is a binary, there is no evidence that its polarimetric properties are affected by the presence of its companion.

3.4 Polarization mechanism

The nature of polarization variation in the RV Tauri stars, U Mon, R Sct and AC Her, for which the polarization–light curve connection is well established (Serkowski 1970; Henson et al. 1985; Polyakova 1992), is both qualitatively and quantitatively completely different from that in AR Pup. In the above three objects the amount of polarization varies by 1–2 per cent and its maximum coincides with the light minimum. Serkowski (1970) has attributed the polarization variation in U Mon to the non-radial oscillations of the star. As the polarization in AC Her changes rapidly close to the phases where Baird (1981) has reported the passage of a strong atmospheric shock, Henson et al. (1985) suggest that the polarization most likely arises in the region upon which the shocks are acting, and a net polarization results because of either the non-radial pulsations in the star or a radial pulsation propagating into an asymmetrical circumstellar medium. Nook et al. (1990) argue that both an asymmetric radiation field, caused either by the pulsational distortions of the photosphere or by the presence of spots, and an extended circumstellar dust envelope are involved in producing the polarization observed in RV Tauri stars.

The case for non-radial pulsation in RV Tauri stars has not been well established. Shenton et al. (1992) argue that the optical and infrared light curves can be understood only if the star embedded in an extended circumstellar envelope undergoes strong non-radial pulsations, with the shape of the star oscillating between prolate and oblate spheroids at successive minima. Fokin (1994) favours a strictly radially pulsating status for the RV Tauri stars. The position angle of polarization should change both significantly and systematically with the light curve phase if a non-radial pulsation is causing the asymmetry required for net polarization. From Fig. 2 it is evident that the position angle varies only marginally, and there is no difference between its values close to the primary and secondary minima, ruling out the possibility that an asymmetric radiation field has any major role in producing the observed polarization in AR Pup. The presence of a residual component of polarization and the sudden flip in the position angle also exclude the possibility of an asymmetric radiation field causing the observed polarization. The observations clearly establish that the drastic changes that occur in the wavelength dependence of polarization are cyclic in nature. It is not likely that the extended infrared-emitting circumstellar dust envelope is involved in such a cyclic phenomenon. The systematic behaviour of the polarization in the *Q*, *U* plane in Fig. 4, and the rapid and regular changes of polarization during the increasing phase after each minimum, indicate rather more localized effects and rule out any direct role of the extended circumstellar envelope in producing the observed polarization in AR Pup. The simultaneous presence of independently varying multiple polarization components and the flip in the position angle over short time-scales (Fig. 5) also imply more localized effects. Based on a single set of observations which showed a regular behaviour of polarization in the *Q*, *U* plane, Raveendran & Kameswara Rao (1988) suggested that polarization in AR Pup results from scattering by localized transient regions, preferentially located close to the photosphere. A linear polarization of 10 per cent would require that a substantial fraction of starlight is reflected along the line of sight and this would definitely be felt in the brightness observed. From Fig. 2 we find that during the first secondary maximum observed there was little change in the brightness even when the polarization changed by about 4 per cent, making the above possibility quite unlikely.

We suggest that the polarization in AR Pup, most likely, arises from selective absorption (and scattering) by non-spherical aligned grains along the line of sight. An increase in the number of aligned grains, which results in an increase in polarization, could be caused by either the condensation of fresh grains or the alignment of the grains already existing. The latter possibility is less likely because it requires a constant supply of dust grains close to the star and a mechanism for aligning them during each polarization cycle. The rapid increase and the slow decline in the polarization seen in Fig. 3 strongly suggest the occurrence of rapid condensation of grains and their subsequent slow dispersal (or destruction). The systematic changes in the wavelength dependence of polarization as it increases after a minima (Fig. 1) also support the grain-condensation view. During the rapidly increasing phase grains condense with a certain amount of alignment. The presence of multiple components of polarization indicates that the grains are not dispersed or destroyed completely before the onset of the next increase. The position angle of polarization is determined by the direction of alignment of the majority of the grains, which is not expected to change drastically between two consecutive minima; the near-straight line paths in the *Q*, *U* plane of the polarization imply this. The different slopes seen on different occasions indicate slightly different directions of alignments during different polarization cycles. As seen from Fig. 3, during each minimum the new component of polarization, which is added to the already-existing declining component, has an amplitude of 3–5 per cent in the *V* band. The maximum amount of polarization observed during each cycle would depend on the magnitude of the residual component and the relative alignment of the two components.

The main difficulty encountered in the mechanism suggested above is the requirement that the dust condensation should occur in a region where the density is sufficiently high for the grains to condense and the cyclic effects of the pulsation are felt; these require the place of origin to be relatively close to the star. The presence of strong absorption bands and lines of CN, CH, TiO and H_2O in the spectra of RV Tauri stars during minima (Preston et al. 1963; Lloyd Evans 1974; Mozurkewich et al. 1987; Pollard et al. 1997) clearly shows the existence of cooler regions around RV Tauri stars. The spectroscopic observations by Pollard et al. (1997) establish the occurrence of two shock waves per luminosity period in AR Pup; the Hα emission, which is present throughout the pulsational cycle, shows enhancement in its equivalent width around phases 0.1 and 0.65. One of the main effects of periodic shock waves is to extend greatly the steady-state dynamic atmosphere, increasing the density at large radii by many orders of magnitudes over that in static atmospheres (Bowen 1988). Gonzalez et al. (1997a,b) have reported that the atmospheres of RV Tauri stars have undergone depletion of elements that are easily condensed into grains. The phenomenon of depletion of certain elements from the photosphere requires the selective removal of grains after condensation from gas. The above authors have further reported that the depletion–condensation temperature curve of AR Pup shows a sudden change of slope around $T_{\rm cond} = 1000$ K, suggesting the condensation of dust relatively near the photosphere.

4 CONCLUSIONS

The photometry of AR Pup available during 1982–98 is consistent with a near-sinusoidal modulation of its mean brightness with a 1165-d period. If the long-term modulation arises because of the presence of a circumbinary dust torus, which periodically causes obscuration, both photometry and polarimetry suggest that there is little interaction between the pulsating star and the dust torus. The exceptionally large amount of polarization seen in AR Pup can be accounted for only by assuming selective absorption by aligned grains in the line of sight. The observed polarization is probably a resultant of multiple, independent components, which requires that the grains that condense are not completely dispersed or destroyed during each pulsational cycle. The position angles of polarization, although they show significant variations, are found to lie in two mutually perpendicular bands. It is not clear what causes the underlying symmetry. The polarimetric behaviour of AR Pup is completely different from that of other RV Tauri stars, but, as pointed out earlier (Raveendran et al. 1989), qualitatively it is very similar to that reported for *o* Cet by Shawl (1975). AR Pup has the highest infrared excess in the *JHKL* bands among the 35 RV Tauri stars and related objects observed by Lloyd Evans (1985); probably, it is still in an active mass-losing phase. The passage of shocks always occurs about 7 d after a minimum in AR Pup (Pollard et al. 1997), but the onset of the sudden increase in polarization does not occur at any definite phase of the pulsational cycle. AR Pup definitely deserves more attention observationally.

ACKNOWLEDGMENTS

I thank Dr K. E. Rangarajan for a critical reading of the manuscript, and Professors U. C. Joshi, M. R. Deshpande, N. Kameswara Rao and Mr G. Srinivasalu for their help in acquiring the polarimetric data.

REFERENCES

Alcolea J., Bujarrabal V., 1991, A&A, 245, 499

Baird S. R., 1981, ApJ, 245, 208
Beichman C. A., Neugebauer G., Habing H. J., Clegg P. E., Chester T. J., 1985, *IRAS* point source catalogue. Jet Propulsion Laboratory, Pasadena, CA
Bowen G. H., 1988, ApJ, 329, 299
Deshpande M. R., Joshi U. C., Kulshrestha A. K., Bansidhar, Vadher N. M., Mazumdar H. S., Pradhan S. N., Shah C. R., 1985, Bull. Astron. Soc. India, 13, 157
Eggen O. J., 1986, AJ, 91, 890
Fokin A. B., 1994, A&A, 292, 133
Gehrz R. D., 1972, ApJ, 178, 715
Gehrz R. D., Ney E. P., 1972, PASP, 84, 768
Goldsmith M. J., Evans A., Albinson J. S., Bode M. F., 1987, MNRAS, 227, 143
Gonzalez G., Lambert D. L., Giridhar S., 1997a, ApJ, 479, 427
Gonzalez G., Lambert D. L., Giridhar S., 1997b, ApJ, 481, 452
Henson G. D., Kemp J. C., Kraus D. J., 1985, PASP, 97, 1192
Jain S. K., Srinivasalu G., 1991, Opt. Eng., 30, 1415
Jura M., 1986, ApJ, 309, 732
Lloyd Evans T., 1974, MNRAS, 167, 17P
Lloyd Evans T., 1985, MNRAS, 217, 493
Mozurkewich D., Gehrz R. D., Hinkle K. H., Lambert D. L., 1987, ApJ, 314, 242
Nook M. A., Cardelli J. A., Nordsieck K. H., 1990, AJ, 100, 2004
Pollard K. R., Cottrell P. L., Kilmartin P. M., Gilmore A. C., 1996, MNRAS, 279, 949
Pollard K. R., Cottrell P. L., Lawson W. A., Albrow D. M., Tobin W., 1997, MNRAS, 286, 1
Polyakova T. A., 1992, SvA, 36, 52
Preston G. W., Krezeminski W., Smak J., Williams J. A., 1963, ApJ, 137, 401
Raveendran A. V., Kameswara Rao N., 1988, A&A, 192, 259
Raveendran A. V., Kameswara Rao N., Anandaram M.N., 1989, MNRAS, 240, 823
Serkowski K., 1970, ApJ, 160, 1107
Shawl S. J., 1975, AJ, 80, 602
Shenton M. et al., 1992, A&A, 262, 138
Zsoldos E., 1995, A&A, 296, 122

This paper has been typeset from a TEX/LATEX file prepared by the author.