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Fading of light maximum and linear polarization variation in the carbon Mira R Leporis

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ABSTRACT

Polarimetry of R Lep obtained over the years 1991–2002 is presented. During this period the star underwent an episode of fading of the brightness at light maximum, after an interval of about 35 yr. An analysis of the data shows that the percentage linear polarization increased as the fading progressed, attained a maximum of slightly over 3 per cent in the *V* band close to the epoch of minimum, and remained more or less at the same level during and well after the recovery to normal brightness. The polarization, apparently, originated from the circumstellar envelope above the region where the dust that caused the fading in the star condensed. The physical mechanism that causes the rather large polarization during fadings is perhaps selective extinction by aligned foreground grains produced by the passage of shocks through the circumstellar envelope. The small-amplitude, short-term fluctuations in polarization observed in R Lep, which appear to be superposed on the fading-related large-amplitude variation, are probably pulsation-related and arise from the inner zones of the circumstellar envelope.

Key words: polarization – stars: carbon – circumstellar matter – stars: individual: R Lep – stars: variables: other.

1 INTRODUCTION

Miras are large-amplitude (>2.5 mag in the visual region) variable red giants evolving through the tip of the asymptotic giant branch (AGB) in the Hertzsprung–Russell diagram. They form a subgroup of the population of long-period variables having large ranges in ages and initial masses (Mennessier et al. 2001). R Lep, which is classified as a carbon-rich Mira variable, has a late spectral type of C (7,4e) and a pulsation period of 432 d (Kukarkin et al. 1969). From the extensive visual observations available for this star, Mattei & Foster (2000) find that its period of pulsation is slowly increasing. Polarimetric observations by Serkowski (1966), Kruszewski, Gehrels & Serkowski (1968) and Serkowski (1971) clearly established the intrinsic polarization and its variability in R Lep. Recently, Serkowski & Shawl (2001) have presented polarimetry of 167 cool red variables which includes the data on R Lep obtained during 1966 March–1974 November. Most of the *V*-band data on R Lep listed in the paper were published earlier (Kruszewski et al. 1968; Serkowski 1971). Raveendran & Kameswara Rao (1989), who made additional multiband polarimetric observations, have pointed out that the *V*-band data of R Lep available during the years 1966–87 strongly suggested the existence of a long-term polarization component, the amplitude of which monotonically decreased from about 2.7 per cent in 1966 to about 0.5 per cent in 1987, and that the trend in the data indicated a still higher value for the polarization prior to 1966; these data (Serkowski 1966; Dyck & Sanford 1971; Landstreet & Angel 1977; Boyle et al. 1986; Serkowski & Shawl 2001) are replotted in Fig. 1 along with the American Association of Variable Star Observers (AAVSO) observations (Mattei, private communication) for the period 1960–84 to facilitate easy comparison with the present data. The average brightness at the maximum of the 432 d period variation of R Lep is about 6.7 mag, and during 1959–60 it was fainter than 9.7 mag (Mayall 1963). Therefore the above authors proposed that the large value of polarization observed in 1966 was directly connected to the faint light maximum of R Lep in 1959–60, and that the long-term component which secularly decreased was the result of an episodic mass ejection and its subsequent dissipation in the circumstellar envelope. Mayall (1963) has listed another three more stars, all of them carbon Miras, which show long-term modulation in light maximum. Based on the AAVSO data from 1900–75, Percy et al. (1990) have presented an extended list of Miras, most of them again carbon-rich, which show long-term changes in brightness at light maximum, and suggested that obscuration by carbon grains as in the case of R Coronae Borealis (RCB) stars may be causing the occasional fadings in these objects.

Polarimetric data on R Lep before the 1959–60 fading are not available. It was observed for the first time in 1966 by Serkowski (1966) as part of a programme on high Galactic latitude Mira and red variables to look for intrinsic polarization. During 1995, after a period of about 35 yr, the light maximum in the visual region was again close to 9.5 mag. The possibility of a period around 40 yr for the modulation of the light maximum in R Lep has already been pointed out by Mayall (1963).

From 1984 onwards we have been following up R Lep polarimetrically, mostly in the *V* band, whenever possible. In this paper

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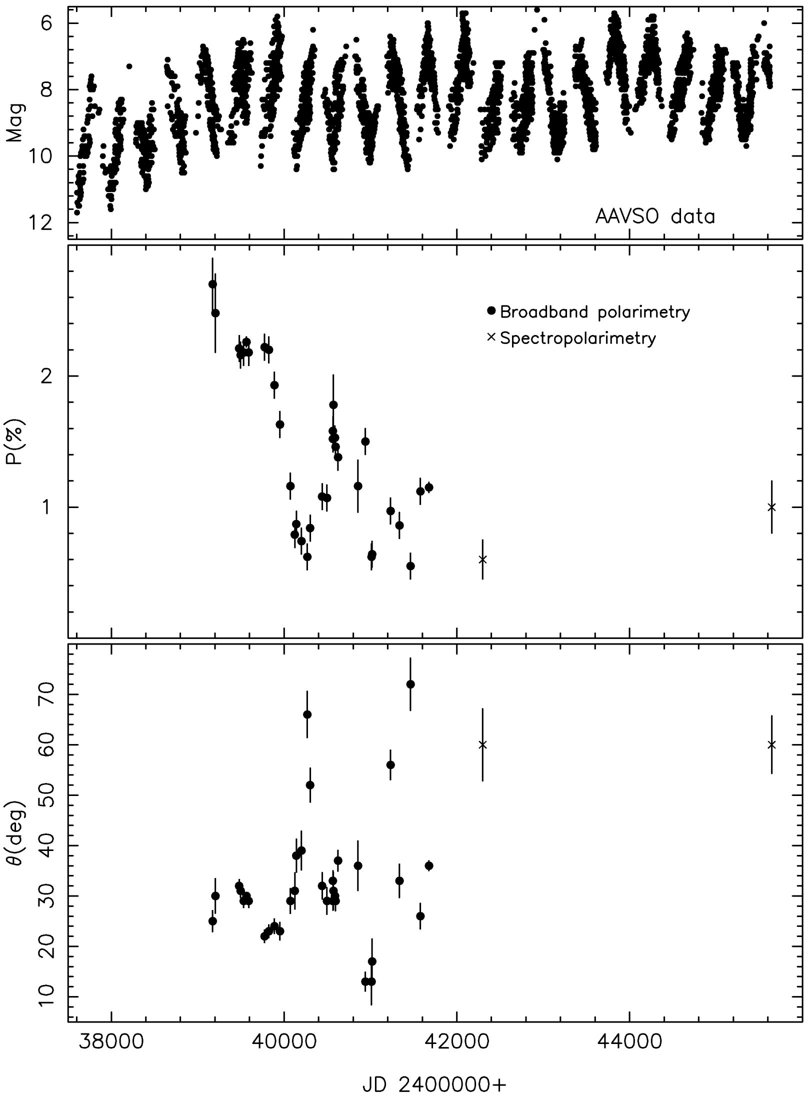

Figure 1. R Lep: plots of AAVSO data (top panel), and linear polarization (middle panel) and position angle (bottom panel) in the visual band for the period 1960–84.

we present new polarimetric observations of this star, and discuss its polarimetric behaviour during the recent fading in brightness at light maximum and the likely mechanism that causes the fairly large linear polarization during fadings.

2 OBSERVATIONS

R Lep was observed during 1991–93 on five nights in the *BVR* bands with the Physical Research Laboratory (PRL) polarimeter (Deshpande et al. 1985) attached to the 234-cm telescope at Vainu Bappu Observatory, Kavalur. The polarimeter consists of a superachromatic half-wave plate rotated at 10.41 Hz as the modulator and a Wollaston prism as the analyser. Both of the emergent beams are detected by separate photomultiplier tubes. The star was again observed in the *V* band on 28 nights during 1997–2002 with the fast star–sky chopping polarimeter (Jain & Srinivasalu 1991) attached to the 1-m telescope at the same observatory. This comparatively simple polarimeter had a high-grade HNP'B sheet as the analyser until 2001 January; it has since been replaced by a Glan–Taylor prism procured from Karl Lambrecht Corporation.[1] Since the sky subtraction was found to be inexact, the background brightness was removed from the data by observing it separately. Both unpolarized and polarized objects were observed on every night of programme star observation to monitor the performance of the polarimeters, and to determine the instrumental polarization and the zero offset in the position angle. The results of the measurements are given in Tables 1 and 2. The errors in linear polarization P (per cent) and θ (degrees) include the uncertainty in the determination of the instrumental polarization and zero offset of the position angle.

3 RESULTS

3.1 Fading-related variation in polarization

The polarization measurements in the *V* band given in Tables 1 and 2, and those reported by Raveendran & Kameswara Rao (1989),

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Table 1. *BVR*-band polarimetry of R Lep.

JD	*B*		*V*		*R*	
240 0000+	*P* (per cent)	$\theta(°)$	*P* (per cent)	$\theta(°)$	*P* (per cent)	$\theta(°)$
48303.235	1.20 ± 0.22	59 ± 5	1.08 ± 0.06	46 ± 1	1.74 ± 0.04	49 ± 1
48696.123			1.22 ± 0.04	48 ± 1	1.73 ± 0.03	39 ± 1
48697.151			1.94 ± 0.21	47 ± 3	1.74 ± 0.04	40 ± 1
49062.168					1.65 ± 0.12	16 ± 2
49063.169	3.00 ± 0.63	37 ± 3	1.92 ± 0.03	28 ± 1	1.75 ± 0.04	19 ± 1

Table 2. *V*-band polarimetry of R Lep.

JD 240 0000+	*P* (per cent)	$\theta(°)$	JD 240 0000+	*P* (per cent)	$\theta(°)$
50793.182	3.26 ± 0.14	24.0 ± 1.2	50804.192	3.32 ± 0.10	29.0 ± 0.8
50805.321	3.33 ± 0.08	28.0 ± 0.7	50808.233	3.03 ± 0.10	25.6 ± 0.9
50812.226	2.73 ± 0.08	30.0 ± 0.8	50823.092	2.95 ± 0.07	26.9 ± 0.7
50831.183	2.78 ± 0.06	26.8 ± 0.7	50840.285	2.73 ± 0.10	26.9 ± 1.0
50851.242	2.79 ± 0.10	31.0 ± 1.1	50852.094	2.52 ± 0.61	27.0 ± 0.7
50864.093	2.78 ± 0.09	29.0 ± 0.9	50877.141	2.82 ± 0.09	27.8 ± 0.9
50891.133	2.56 ± 0.07	27.3 ± 0.8	50893.086	2.94 ± 0.06	30.0 ± 0.6
50901.081	2.87 ± 0.07	28.4 ± 0.7	50903.091	3.03 ± 0.08	28.6 ± 0.7
51202.090	2.65 ± 0.06	22.6 ± 0.7	51221.215	2.36 ± 0.07	23.5 ± 0.9
51260.085	2.43 ± 0.07	28.9 ± 0.8	51261.092	2.09 ± 0.07	24.6 ± 1.0
51548.222	2.88 ± 0.09	27.1 ± 0.9	51585.220	2.81 ± 0.10	29.1 ± 1.0
51586.213	3.32 ± 0.09	30.5 ± 0.8	51604.148	2.93 ± 0.09	30.1 ± 0.9
52285.225	1.48 ± 0.11	23.3 ± 2.0	52313.123	1.36 ± 0.16	18.5 ± 3.4
52314.125	1.59 ± 0.08	17.7 ± 1.4	52316.117	1.70 ± 0.09	17.8 ± 1.6

are plotted in Fig. 2. The latter set of observations provides the necessary baseline to isolate the polarization changes associated with the fading of the light maximum. The AAVSO data for the same period (Mattei, private communication), plotted in the top panel of the figure, clearly show the modulation in the brightness at light maximum; the decline to the minimum and recovery back to the normal brightness were fairly rapid, as observed during the previous occasion (Mayall 1970). The fading phenomenon, which lasted for 6–7 yr, does not seem to be part of a slow and smooth long-term variation; it appears to be rather episodic in nature. The connection between the long-term changes in polarization and the fading of light maximum, pointed out earlier by Raveendran & Kameswara Rao (1989), is quite apparent from the figure. Both linear polarization and position angle showed remarkable variations associated with the fading of light maximum.

It is evident from Fig. 2 that appreciable changes in linear polarization began to occur simultaneously with the onset of fading, which occurred sometime around JD 244 9000. As the fading progressed in R Lep, the percentage linear polarization continuously increased and reached a maximum close to the epoch of minimum brightness for the light maximum and continued to remain more or less at the same level even well after the recovery of the light maximum back to its normal brightness. Polarimetric observations are lacking around JD 245 0000, the epoch of minimum. The available data, however, suggest that during the minimum of long-term modulation in brightness the linear polarization was not very much different from a little over 3 per cent.

As seen in Fig. 1, the linear polarization in the *V* band 6–7 yr after the minimum of previous fading in R Lep was about 2.5 per cent. Fig. 2 shows that the value of polarization around JD 245 2000, which is about 6 yr after the recent minimum, was also probably around 2.5 per cent.

From the bottom panel of Fig. 2 we find that the average value of position angle during JD 244 6000–244 8700 (1984–92) was 45°, while during JD 244 9000–245 1700 (1993–2000) it was 28°. It is remarkable that the change in position angle of polarization occurred abruptly. The position angle flipped from its pre-fading value to the new value as soon as noticeable changes occurred in the brightness at light maximum; there was no significant change in the position angle either during the fading when the linear polarization increased from about 1 per cent to slightly more than 3 per cent, or during the recovery. Even well after the recovery of the light maximum, the position angle continued to remain almost at the same value. Appreciable changes began to occur in it only recently when the polarization began to decrease substantially.

The observations of R Lep by Serkowski (1966) obtained in 1966 February show the position angle to be 25°, indicating that during the previous fading also the position angle of polarization in the *V* band was not very much different from 28°. However, the changes in the position angle as polarization decreased are different during the two fadings: in the present case it decreased while it increased in the previous case.

The behaviour of the position angle during the fading implies the following. (i) The polarization observed in R Lep is entirely of stellar or circumstellar origin, as already suggested by Serkowski (1966) because of its high Galactic latitude. We would have seen the position angle slowly rotate as the polarization increased if the interstellar component of polarization in the direction of R Lep were significant. Fig. 2 shows that there was little change in the position angle when the linear polarization increased from about 2 per cent

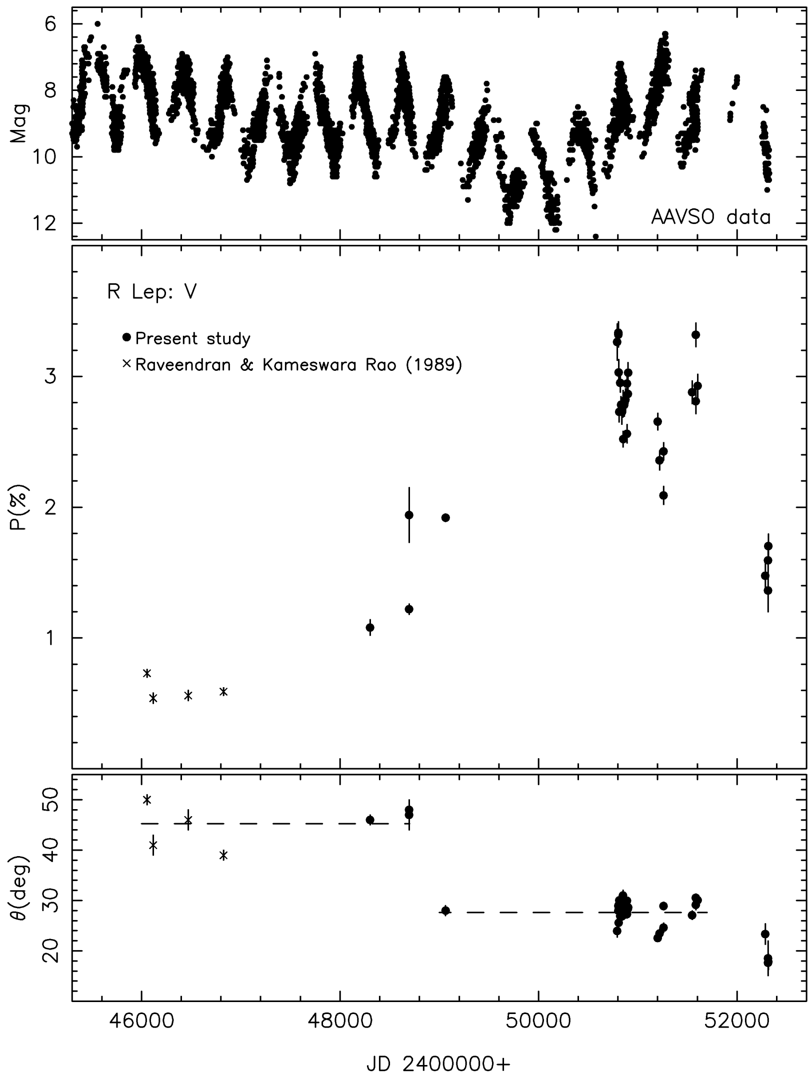

Figure 2. R Lep: plots of AAVSO data (top panel), and linear polarization (middle panel) and position angle (bottom panel) in the *V* band. The dashed horizontal lines in the bottom panel represent the average values during the corresponding periods.

to slightly more than 3 per cent. The Galactic latitude of R Lep is −31°. Polarimetric observations are available for two stars within 1°.2 of R Lep in the sky (Heiles 2000); the listed values of polarization for the objects are 0.234 ± 0.024 per cent at a position angle of 10°.3 and 0.0 ± 0.2 per cent. (ii) There was only a single component for the polarization after the onset of fading. If the observed polarization were a resultant of two independently varying components with different time-scales, the slowly varying pre-fading component and the fast changing new component associated with the fading, the change in position angle would have been continuous and not abrupt as observed. The fact that the position angle did not show continuous rotation as the fading progressed indicates that whatever caused the fading possibly destroyed the prevailing slowly varying polarization component, resulting in a single polarization component. The continuous rotation of the observed position angle in R Lep produced by the superposition of two independently varying polarization components, which has already been clearly demonstrated by the plots given in Serkowski (1971) and Raveendran & Kameswara Rao (1989), can be seen in Fig. 1. The fact that the position angle did not return towards its pre-decline value (∼50°) as the polarization associated with the fading decreased also supports the idea that there was only a single, dominant component for the polarization after the onset of the fading.

3.2 Pulsation-related variation in polarization

The information available on changes in polarization in Miras over the pulsation cycle is generally very poor. Fairly sufficient observations exist only for the oxygen-rich prototype *o* Cet. These observations, made about 30 years ago by Serkowski (1971) and Shawl (1975b), have well established the existence of cyclic changes in the polarization associated with the pulsation of the star. The amplitude of polarization variation in the *V* band over the pulsation cycle is about 1 per cent and sharply increases towards the blue–ultraviolet region (Serkowski 1971). In the case of R Lep, which is the next polarimetrically well-observed Mira variable, the data available in the literature (Serkowski 1971; Dyck & Sanford 1971; Raveendran & Kameswara Rao 1989), although clearly establishing the existence

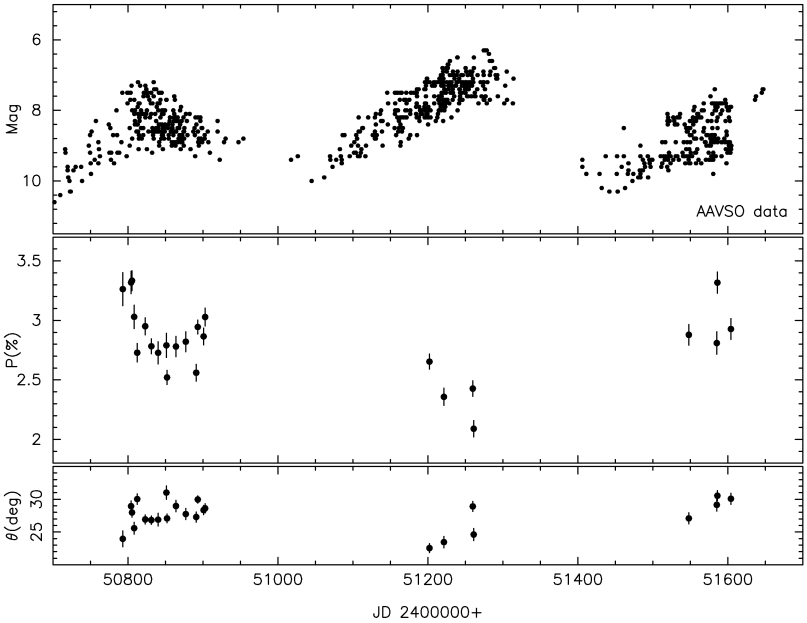

Figure 3. R Lep: plots of AAVSO data (top panel), and linear polarization (middle panel) and position angle (bottom panel) in the *V* band obtained close to the maximum of the long-term modulation in polarization.

of short-term fluctuations in both linear polarization and position angle, are inadequate to confirm or rule out the existence of any cyclic variations in polarization associated with its 432-d pulsation period. The presence of the large-amplitude long-term component probably causes difficulty in isolating any small-amplitude cyclic component that is possibly present.

In Fig. 3 we have plotted the polarization measurements obtained close to the maximum of the long-term modulation along with the AAVSO data (Mattei, private communication) for the corresponding period. The figure shows that the observed polarization has a component that undergoes short-term variations. The data obtained during the first light cycle plotted in the figure, where the phase coverage is better, indicate that the polarization changed during a small fraction of the pulsation period centred about the light maximum with a total amplitude of 0.5 per cent or less. There is a slight indication that the position angle also varied in anticorrelation with the variation in polarization. The nature of polarization variation observed implies that the fading-related polarization component was not affected much by these short-term changes. As during the first light cycle plotted in Fig. 3, the polarization was anticorrelated with the brightness during the second cycle also. It is difficult to comment on the variation during the third cycle because of the large scatter and small number of observations; there is a likelihood that the polarization increased as the brightness increased. Apparently, these short-term polarization changes are superposed on the long-term component associated with the fading and both of them vary nearly independently of each other. The net polarization, which is the resultant of these two components, may increase or decrease as the short-term component increases depending on their relative position angles. The slight wavelength dependence of position angle seen in Table 1 may result from the superposition of components of different magnitudes. The short-term variations seen Fig. 3 are possibly pulsation-related; their low amplitudes and poor phase coverage coupled with comparatively large observational errors make it difficult to connect them definitely with the pulsation of the star. More accurate multiband polarimetry, well distributed over a few pulsation cycles, is definitely needed for this purpose.

4 DISCUSSION AND CONCLUSIONS

Percy et al. (1990) and Whitelock (2000) have called attention to the possibility that the physical mechanisms responsible for fadings in carbon Miras and RCB objects are the same, namely obscuration by carbon grains. *JHKL* photometry of the three carbon Miras R For, V Hya and R Lep, both outside and during fadings, by Lloyd Evans (1997) indicates that the fadings in these objects are essentially caused by obscuration by dust consequent to its condensation, as in the case of RCB objects. However, the geometries of dust clouds in the two cases are vastly different. Dust condensation in the case of RCB objects is highly localized (Feast 1996), while in carbon Miras it has a rough spherical symmetry about the star (Lloyd Evans 1997). Since the above three objects during their minima fall on the general trend of carbon Miras in the $J-K$, $K-L$ diagram, Lloyd Evans (1997) has suggested that the main effect involved during fadings in these objects is increased circumstellar dust absorption. High-resolution spectra of the prototype R CrB obtained by Kameswara Rao et al. (1999) over a fortnight beginning with the onset of the 1995–96 decline show transient emission lines and high-excitation weak lines that are blueshifted relative to strong lines, leading the above authors to conclude that the dust condensation in the star is triggered by the passage of an atmospheric shock. Based on spectral evolution and dispersal times of dust implied by light curves observed in RCB stars, Clayton et al. (1992) have advanced arguments which favour dust formation within a few stellar radii. In spite of the high effective temperatures of these objects, shock-induced dust condensation can occur even at $(1.5–3)R_*$ (Woitke, Goeres & Sedlmayr 1996). It is not clear what triggers dust condensation in the circumstellar envelopes around the carbon Miras, or gas ejection from the objects and subsequent dust condensation as suggested by Lloyd Evans (1997). The existence of strong outward-moving shocks in the atmospheres of long-period variables has been well established (Bowen 1988). Probably the atmospheric shocks play a major role in dust condensation activity in carbon Miras also.

Sufficient polarimetry exists only for three RCB objects, V854 Cen, RY Sgr and the prototype R CrB. V854 Cen did not show any change in linear polarization in the *V* band from its value during maximum even when the star declined in brightness by about 4 mag (Kameswara Rao & Raveendran 1993). During the minimum of the same decline when the brightness dropped by more than 8 mag, the polarization observed in the *V* band was about 10 per cent (Whitney et al. 1992). When the object recovered from the minimum the percentage linear polarization in the *V* band returned almost to its pre-decline value (Kameswara Rao & Raveendran 1993). Both RY Sgr and R CrB are found to show similar behaviour during declines (Serkowski & Kruszewski 1969; Coyne & Shawl 1973; Stanford et al. 1988). The position angles observed during light maximum and deep minimum differ drastically in V854 Cen, indicating that the polarized flux seen at light minimum is not the attenuated polarized flux observed at light maximum. The polarization late in the decline arises from clouds ejected at earlier epochs or dust particles distributed asymmetrically and more extensively about the star (Whitney et al. 1992; Kameswara Rao & Raveendran 1993).

R Lep is the only carbon Mira that has been observed polarimetrically before, during and after a fading. From the results presented in the previous section it is evident that its polarimetric behaviour during fadings is completely different from that of the above three RCB objects. The differences in the polarimetric behaviours of the two classes of variables arise mainly from the differences in the geometry of dust condensation and the place of origin of polarization.

In order to observe a net polarization in light integrated over the stellar disc, there should be an overall departure from spherical symmetry. The polarization associated with the fading definitely did not arise from the dust that caused the light fading in R Lep. If the condensed dust, either in the circumstellar envelope or in the ejected gas, had caused the observed polarization as a result of an asymmetry in its density distribution, we would have seen appreciable changes in the polarization when the material later dispersed, as a consequence of expansion or otherwise, and caused changes in the scattered and direct light. As suggested by Lloyd Evans (1997), the dust formation probably had a rough spherical symmetry about the star. The fact that the percentage polarization in R Lep did not depend on its brightness during and even well after recovery also implies that the polarization did not originate from regions below the region of dust condensation. The polarization, therefore, originated from the portions of the circumstellar envelope above the region where the dust that caused the fading condensed.

The data strongly suggest that the small-amplitude, short-term fluctuations are superposed on the fading-related large-amplitude polarization variation, indicating that the asymmetry that caused the latter is left approximately undisturbed by the changes that cause the former. Hence, the most likely place of origin of the short-term component of polarization, which is possibly associated with the pulsation of the star, is the inner zones of the circumstellar envelope. R Lep has a thick circumstellar envelope (Mennessier et al. 2001). Probably during the pulsation cycle only the inner zones of the envelope are affected significantly, while the entire envelope is affected during fadings.

The carbon-rich RV Tau star AR Pup shows pulsation-related large-amplitude polarization variation (Raveendran 1999). On one occasion the polarization in the *U* band was ∼14 per cent, which is the highest so far observed in a single star not associated with any known nebulosity (Raveendran & Kameswara Rao 1988). Raveendran (1999) has suggested that the mechanism operating in AR Pup is, most likely, selective extinction by aligned non-spherical grains, produced by the passage of atmospheric shocks.

If the dust particles are spherically shaped, or non-aligned if elongated, it is imperative that the mechanism which caused the fading in R Lep also produced a highly asymmetrical dust distribution in the outer regions of the circumstellar envelope. The observed polarimetric properties can then be accounted for only if the following conditions are met. A continuous increase in percentage polarization without any change in the position angle as the fading progressed requires a continuous increase in either the number of scatterers or the asymmetry in the distribution without any change in the effective geometry, because the position angle is determined only by the geometry of distribution of the scatterers (Simmons 1982). For the percentage linear polarization to be nearly the same during the recovery phases, it is essential that the transparencies of both the direct light and the light illuminating the scatterers should increase by the same factor as the dust that produced the fading disperses. Further, the resulting change in the column density of dust particles in the envelope along the line of sight during the fading should be negligible so as not to cause any additional absorption of the direct starlight. The possibility that the above conditions are satisfied during the fading episode of R Lep is remote. It is also less likely that the polarization associated with the fading is caused by the presence of increased dust not in the line of sight, as in the case of a bipolar geometry. The possibility that the ratio of the scattered light to the direct light did not change during the dispersal of the obscuring dust and thereby produced a nearly constant degree of polarization, when the brightness of the star increased by more than 2 mag, is also remote. Numerical computations by Shawl (1975a) and Raveendran (1991) show that when the direct starlight dominates it is extremely difficult to produce linear polarization exceeding 1 per cent in the *V* band with spherical particles, even under the most favourable geometry. We suggest that the physical mechanism that produced the fairly large polarization connected with the fading in R Lep is selective extinction by aligned non-spherical grains present along the line of sight, and that the degree of alignment of these foreground grains, which continually increased during the decline phases, did not change appreciably during the recovery phases or well after the return to the maximum. Such a model can account for all the observed polarimetric peculiarities of the star, especially the nearly constant percentage polarization during the recovery phases and well after. Selective absorption of vibrations parallel to the long axis of the net-aligned grains producing a polarization of 3 per cent in the *V* band is expected to produce only negligible changes in the extinction and reddening by the circumstellar envelope. It is fairly certain that non-spherical grains do exist in circumstellar envelopes, because we know that they constitute one of the components of the interstellar medium and circumstellar environments are the potential sites for their production. The only uncertainty is about an efficient physical process that leads to a net alignment in them. An increase in polarization requires an increase in the number of aligned grains either by condensation of fresh grains or by alignment of grains already present in the envelope. Lloyd Evans (1997) has reported that, as the decline in brightness at light maximum progressed in R Lep, emission in the (0, 0) band at 5165 Å of C_2, which is usually not observed during pulsation cycles unlike the emission in the (1, 0) band at 4737 Å, gradually strengthened and peaked close to the deep minimum. He has suggested that the intense emission at 5165 Å, which is probably shown by all carbon Miras during their fadings in varying degrees at some phases, possibly resulted from a great increase in the density of gas immediately above the condensed dust. The increase in gas density and creation of a net alignment in the non-spherical grains were probably the consequences of the passage of shock waves in the circumstellar envelope around R Lep. The Gold-type mechanism of grain alignment, which involves purely mechanical processes, like the interaction of gaseous flows with grains, can lead to a net alignment of the latter (Lazarian 2000).

The agreement in the position angles of polarization during fadings in R Lep indicates the existence of a preferred geometry. The position angles of polarization close to the epochs of maximum polarization in AR Pup also lie in two distinct bands that are mutually perpendicular (Raveendran 1999). Apparently, the physical mechanism that causes the high linear polarization in R Lep during fading is the same as that which produces the exceptionally high polarization in AR Pup.

The large interval between successive fadings in R Lep is a serious disadvantage in studying in detail the fading-related changes in the star. However, by studying the group of carbon Miras that show fadings as a whole, we can improve the data required to understand better the occasional fadings that these stars undergo.

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