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Polarization measurements of the luminous blue variable HR Carinae*

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Abstract. We have made BVRI polarization measurements of HR Car on ten occasions during the period JD 2447919 to JD 2449014. All our observations are on the rising part of the light curve. We find the presence of intrinsic variable polarization in HR Car. This result implies that the scattering material situated close to the star is not spherically symmetric and it varies with time. The observations are consistent with the bi-polar geometry of the nebula. The variations in intrinsic polarization in HR Car may be due to temporal variations in the structure of the circumstellar material. The observed variations in the position angle of the intrinsic polarization indicate that even though the nebula is bipolar on a large scale, on a smaller scale, the variations in the distribution of the scattering material are not axisymmetric. The geometry of the dust shell and the nebula around HR Car appears to be similar to that observed in bi-polar Type I planetary nebulae.

Key words: stars: early-type – stars: supergiants – stars: variables: general – polarization – stars: individual: HR Car

1. Introduction

Luminous blue variables (LBVs) are very massive and hot stars that display large irregular spectroscopic, photometric and polarimetric variations (Humphreys & Davidson 1994; Nota et al. 1995). LBVs have been found in the Milky Way, in the LMC, M31 and M33. In the HR diagram, they are located close to the instability limit to the evolution of very massive (more than 40 solar masses) stars. From an evolutionary point of view, LBVs are believed to represent a short lived transition phase in the evolution of massive O stars into WR stars. Some of the LBVs have cold detached dust shells and also low excitation nebulae.

HR Car (≡ HD 90177, V = 7.6 to 8.6, (B-V) = 0.88, B2I, l = 285^o, b = -2^o) like many LBVs has undergone slow and irregular spectrophotometric variations of about 1.5 mag over timescales of months (Carlson & Henize 1979). Recent studies indicate a distance of 5 kpc (van Genderen et al. 1991) or 5.4 kpc (Hutsemekers & van Drom 1991) which are based on reddening-distance method and kinematics respectively. The error in this distance is estimated to be about 1 kpc. HR Car is an IRAS source (IRAS 10211-5922) with far-infrared colours similar to that of planetary nebulae. The IRAS fluxes (12μm = 11Jy, 25μm = 53.5Jy, and 60μm = 37.1Jy) and flux ratios indicate the presence of significant amount of cold dust in the form of a circumstellar dust shell formed as a result of mass loss from the star.

HR Car is associated with a circumstellar filamentary nebula. There is also a bright inner nebula from which the filaments seemed to emanate (Hutsmekers & van Drom 1991; Clampin et al. 1995; Nota et al. 1997). From a recent set of high resolution coronographic images Nota et al. (1995) confirm that the nebula around HR Carinae is truly bipolar and very reminiscent of the Eta Carinae nebula.

Despite detailed polarimetric investigations of other LBVs such as AG Carinae (Schulte-Ladbeck et al. 1994; Leitherer et al. 1994) and R 127 (Schulte-Ladbeck et al. 1993), the only polarimetric observations of HR Car made are those reported by Serkowski et al. (1975) during a study of interstellar polarization. More recently, Clampin et al. (1995) found evidence of intrinsic polarization in HR Car from the change in polarization at the Hα emission line with respect to the continuum. Serkowski et al. (1975) and Clampin et al. (1995) suspected that HR Car perhaps has a component of polarization that is variable.

We have carried out BVRI polarization measurements of HR Car to probe the geometry of the circumstellar material and to study the variation in polarization. An analysis of our observations is presented in this paper. Our measurements confirm that HR Car is a polarimetric variable.

2. Observations

Optical linear polarization measurements were made with the 1-m telescope at the Vainu Bappu Observatory, Kavalur, India. We used a fast star-and-sky chopping polarimeter (Jain & Srinivasulu 1991) to make polarization measurements of HR Car through BVRI filters. The instrument and the data reduction method were described by Jain & Srinivasulu (1991). The mean instrumental ploarization determined by observing several of the unpolarized standards (Serkowski et al. 1975) was

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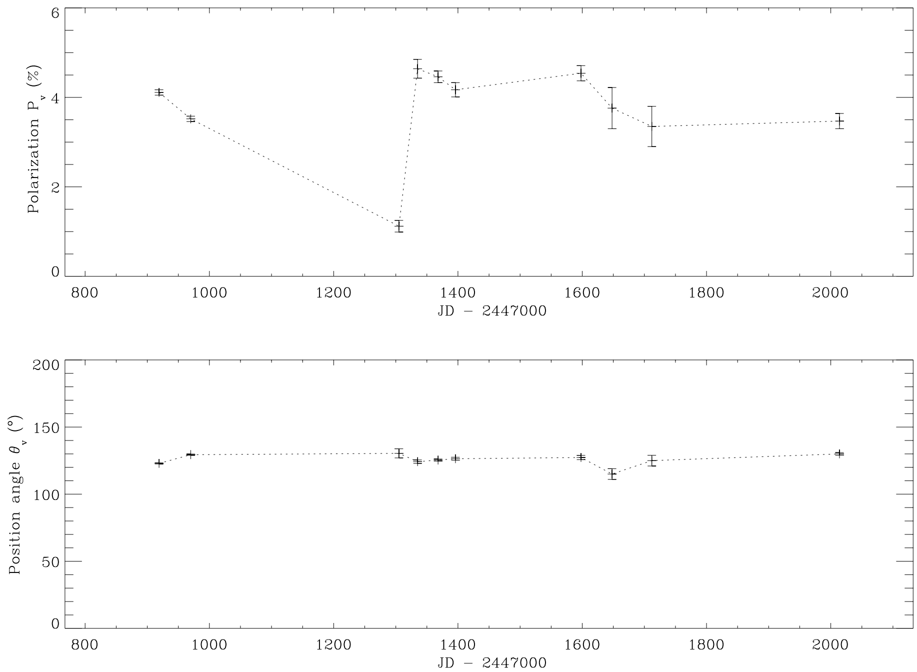

Fig. 1. Plots showing the variation of the V band polarization P and position angle θ with time (in Julian Day)

found to be $\simeq 0.10$% and has been subtracted vectorially from the measurements. The zero of the polarization position angles was determined by observing the polarized standards of Hsu & Breger (1982). HR Car was observed on ten nights during the period JD 2447919 to JD 2449014 (27th January 1990 to 26th January 1993).

3. Analysis

The BVRI polarization measurements of HR Car are given in Table 1. The errors in the percentage of polarization (P) and position angle (θ) are also listed in Table 1.

Our polarization measurements of HR Car are in good agreement with the polarization measurements made by Serkowski et al. (1975) and more recent measurements made by Clampin et al. (1995). From these observations we find clear evidence that HR Car displays very large variations in its linear polarization with time indicating significant variations in the distribution of scattering material in the envelope and a clumpy axisymmetric outflow.

Fig. 1 shows a plot of the V band polarization P and position angle θ as a function of time. It can be seen that while the polarization P undergoes large variation (ranging from 1.12% to 4.64%, with mean $\langle P \rangle$ = 3.17%, dispersion $\sigma_p = 1.02\%$), the position angle θ stays roughly constant (mean $\langle \theta \rangle = 125.6^o$, standard deviation σ_θ = 4.5^o). It is interesting to note that even on JD 2448305 when the percent polarization (1.12$\pm 0.13\%$) shows the largest deviation from the mean value (3.71%), the position angle (130.4$\pm 3.4^o$) is close to its mean value (125.6^o). The wavelength dependence of P and θ at various epochs is shown in Fig. 2. Again, the percent polarization is found to show significant changes in the wavelength dependence as a function of time, but the position angles do not show large variation with wavelength and time. Our polarimetric measurements are also displayed in the Q-U plane in Fig. 3, where Q(=P cos2θ) and U(=P sin2θ) are the Stokes parameters. It can be seen that the points in the Q-U plane are not colinear. This indicates that the intrinsic component in the polarization of HR Car varies with time both in the degree of polarization P and in position angle θ.

Table 1. BVRI polarization measurements of HR Car

JD	B	V	R	I
	P (%) $\theta(^o)$	P (%) $\theta(^o)$	P(%) $\theta(^o)$	P(%) $\theta(^o)$
2447919	4.59 ±0.14 120.1±0.9	4.11 ±0.06 122.9±0.4	3.87 ±0.07 127.2±0.5	3.53 ±0.09 121.8±0.7
2447970	3.82 ±0.13 129.6±1.0	3.52 ±0.06 129.4±0.5	3.86 ±0.08 127.6±0.6	3.94 ±0.09 134.2±0.6
2448305	0.76 ±0.26 124.3±9.6	1.12 ±0.13 130.4±3.4	1.17 ±0.12 123.4±2.8	0.80 ±0.14 146.4±4.0
2448335		4.64 ±0.21 124.2±1.3	3.69 ±0.29 122.7±2.2	4.17 ±0.21 131.3±1.4
2448368	3.10 ±0.42 125.2±3.9	4.46 ±0.13 125.4±0.8	4.05 ±0.12 125.1±0.8	3.88 ±0.14 127.4±1.0
2448396	2.63 ±0.39 124.9±4.2	4.17 ±0.16 126.4±1.1	3.13 ±0.11 125.9±1.0	3.39 ±0.18 136.6±1.6
2448598	4.19 ±0.25 125.3±2.5	4.54 ±0.17 127.3±1.6	3.89 ±0.16 127.7±1.7	
2448648	2.95 ±0.53 130 ±4	3.76 ±0.46 115 ±4	3.80 ±0.17 128 ±1	2.95 ±0.21 129 ±2
2448712		3.35 ±0.45 125 ±4	3.54 ±0.34 124 ±3	2.27 ±0.39 123 ±5
2449014	3.48 ±0.36 127 ±3	3.47 ±0.17 130 ±1	3.44 ±0.16 132 ±1	2.30 ±0.23 128 ±3

A single U band measurement on JD 2447970 gave: P(%) =1.57±0.91, θ^o =108 ±17

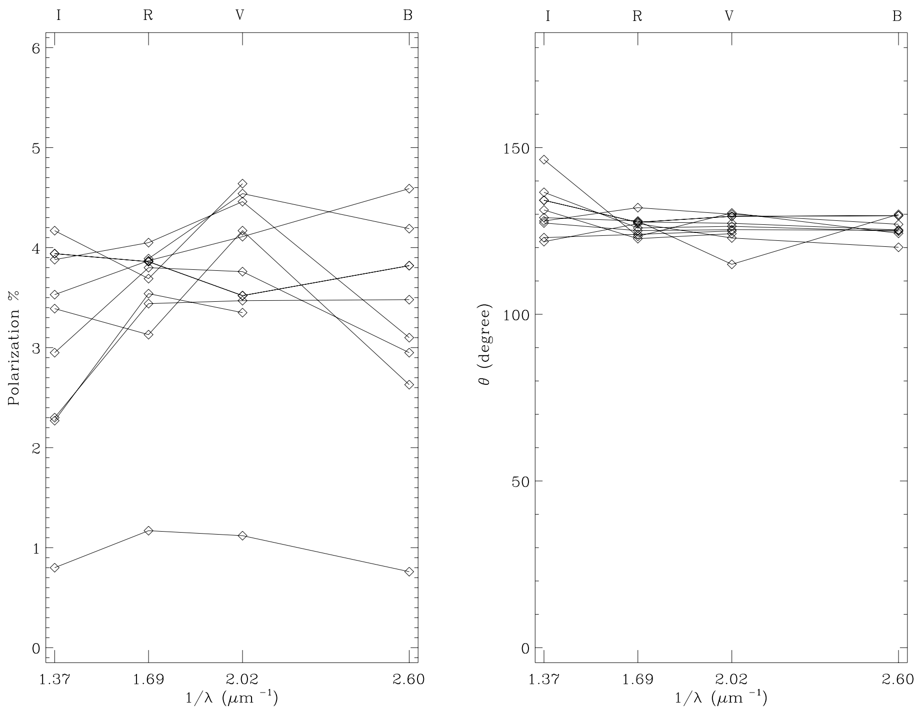

Fig. 2. Wavelength dependence of polarization P and position angle θ for different epochs of observation

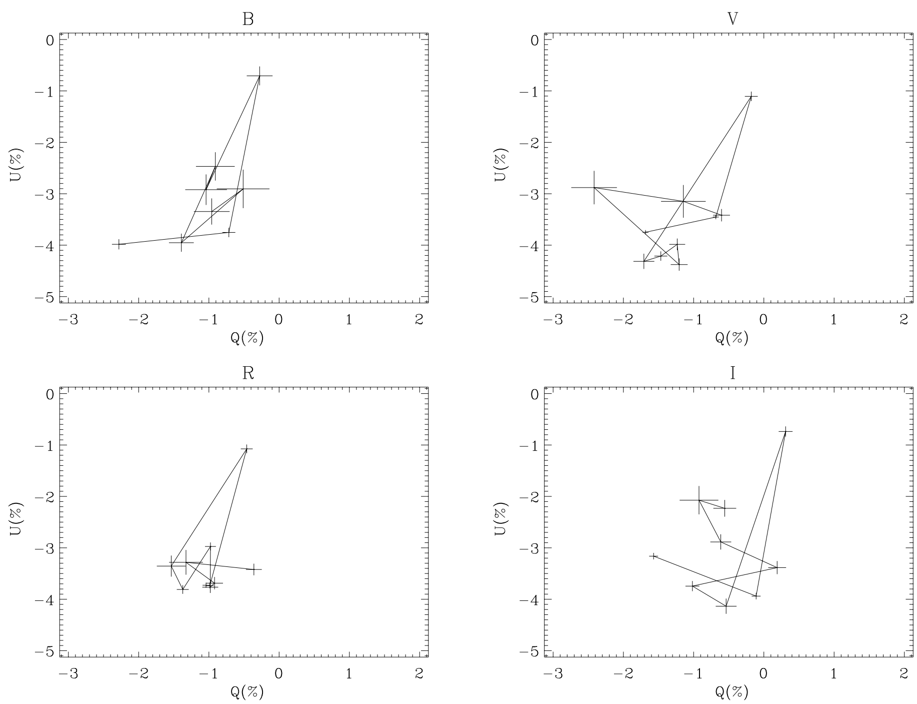

Fig. 3. Polarimetric variations of HR Car plotted in the $Q-U$ plane for B, V, R, I bands

The measured linear polarization is the vector sum of the polarization intrinsic to the star and the interstellar polarization caused by interstellar dust along the line of sight to the star. Variations in the measured polarization must be caused by variations in the intrinsic polarization. However, separation of the two components (intrinsic stellar and interstellar) is not easy. An estimate of the interstellar polarization in the direction of HR Car can be made by considering the polarization map (shown in Fig. 4) for stars within 2^o of the HR Car and having distance modulii, $\Delta m > 11.5$ mag, the distance modulus of HR Car being 13.5 mag. The data for Fig. 4 are taken from Mathewson et al. (1978).

If the polarization for a majority of the stars in this region is dominated by the interstellar medium, then from the data in Mathewson et al. (1978) and the polarization map in Fig. 4 it is seen that the interstellar polarization in this direction is characterized by: θ (in the Equatorial coordinate system) = 115.1 ± 3.7^o (in the Galactic coordinate system used in Fig. 4,

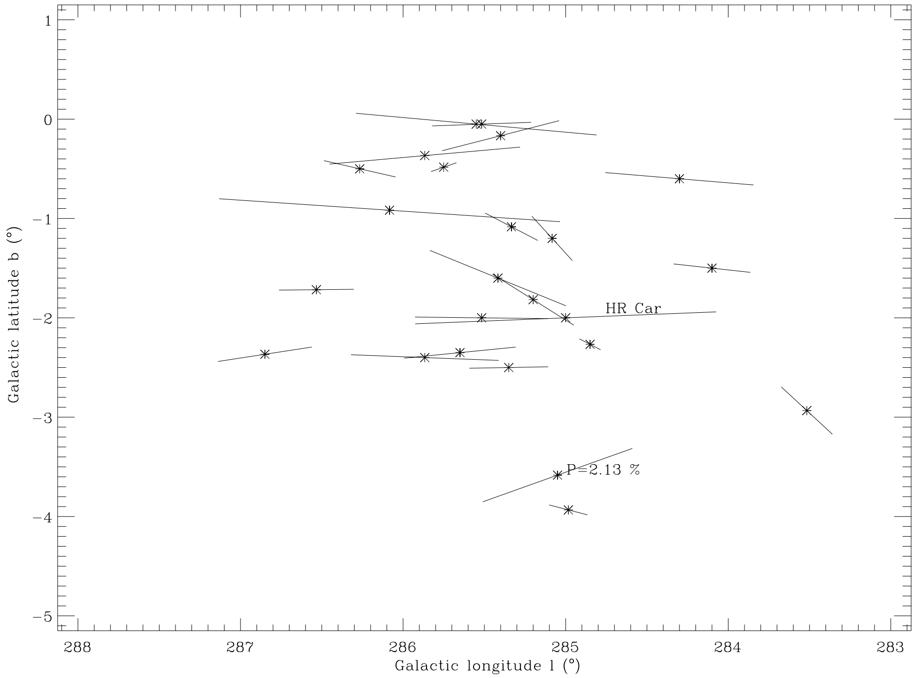

Fig. 4. Polarization map, in the Galactic coordinate system, for stars in the region of HR Car. The length of the vectors is proportional to $P(\%)$.

$\theta_g = 84.2 \pm 3.7^o$) and P/E(B-V) = 3.34 ± 0.35 where E(B-V) is the reddening for the star. This position angle is nearly parallel to the Galactic plane. For HR Car the reddening E(B-V) = 1.06. Using the mean ratio P/E(B-V) =3.34, the expected interstellar polarization for HR Car would be P = 3.54%. The star closest (Δ m = 13.1 and angular separation = 0.37^o) to HR Car for which polarization measurements are available in Mathewson et al. (1978) is BD -59^o 2116. For this star the polarization position angle θ =120.8^o and P/E(B-V) = 5.47. If the interstellar polarization towards HR Car is characterized more closely by that for BD -59 2116 then the likely values for the interstellar component would be P = 5.8% and $\theta = 120.8^o$.

From spectropolarimetric measurements and by assuming that the Hα line is intrinsically unpolarized at the center of the line profile (where any scattered component would be much weaker compared to the direct emission in the core of the line), Clampin et al. (1995) estimate the interstellar component in the polarization of HR Car. In the V band the interstellar polarization is found (Fig. 5 in Clampin et al. 1995) to be P = 3.86%, $\theta = 127.9^o$ with Q=-3.74 $\pm$ 0.02% and U = -0.945 ± 0.02%.

The observed polarization position angle ($\theta = 125.6 \pm 4.5^o$) for HR Car is not significantly different from the position angles for the interstellar polarization estimated either from the field stars ($\theta = 120.8^o$) or from spectropolarimetry of HR Car ($\theta = 127.9^o$). This may result if the interstellar component is significantly larger then the intrinsic component in the observed polarization of HR Car. From the multi-wavelength polarimetric measurements the interstellar and intrinsic polarization components could also be separated by the method given by Poeckert et al. (1979). This method assumes that the intrinsic polarization position angle is independent of time and wavelength and requires observed changes in the position angle either as a function of wavelength or time. As seen from the non-colinear distribution of points in the Q-U plane of Fig. 3, in the case of HR Car the intrinsic position angle is variable. The method is therefore not applicable. We have therefore adopted the estimate of Clampin et al. (1995) for the interstellar component, which is also similar to the ones based on the field stars in the region.

Table 2. Intrinsic polarization parameters in V band for HR Car

JD	Q* (	θ^* (^{o})		
2240603	0.13 ±0.11	0.20 ±0.11	0.24 ±0.16	29 ±19
2240625	-0.20 ±0.11	0.32 ±0.11	0.38 ±0.16	61 ±12
2447919	-0.73 ±0.44	-0.02 ±0.44	0.73 ±0.06	91 ±2
2447970	0.21 ±0.44	0.30 ±0.44	0.36 ±0.06	28 ±5
2448305	0.75 ±0.09	2.64 ±0.09	2.74 ±0.13	37 ±1
2448335	-0.79 ±0.15	-0.56 ±0.15	0.97 ±0.21	108 ±6
2448368	-0.58 ±0.09	-0.45 ±0.09	0.73 ±0.13	109 ±5
2448396	-0.34 ±0.11	–0.23 ±0.11	0.41 ±0.16	107 ±11
2448598	-0.31 ±0.12	-0.62 ±0.12	0.69 ±0.17	122 ±7
2448648	-1.47 ±0.33	0.86 ±0.33	1.70 ±0.46	75 ±8
2448712	-0.20 ±0.32	0.59 ±0.32	0.62 ±0.45	54 ±20
2449014	0.34 ±0.12	0.32 ±0.12	0.47 ±0.17	22 ±10
2449030	0.11 ±0.02	0.37 ±0.02	0.39 ±0.02	37 ±2

When the interstellar component is subtracted from the observed polarization the result is the intrinsic polariation for HR Car. This is done for V band. The Q*, U*, P* and θ^* for the stellar intrinsic polarization have been computed and are given in Table 2. The results from the Serkowski et al. (1975) data (JD 2240603 and JD 2240625) and from the data of Clampin et al. (1995) (JD 2449030) are also given in Tables 2 and 3.

Clampin et al. (1995) estimated the interstellar polarization in V band for HR Car. Using this interstellar polarization and assuming that the interstellar component follows the Serkowski law as given in Whittet et al. (1992) (also see Clampin et al.

Table 3. Intrinsic polarization of HR Car in BVRI bands at various epochs

JD	P_B (%) $\theta_B(^o)$	P_V (%) $\theta_V(^o)$	P_R (%) $\theta_R(^o)$	P_I (%) $\theta_I(^o)$
2240603	0.33	0.24	0.15	
	42	29	48	
2240625	0.55	0.38	0.19	
	61	61	100	
2447919	1.44	0.73	0.26	0.82
	98	91	114	97
2447970	0.30	0.36	0.22	1.15
	162	28	130	151
2448305	2.95	2.74	2.50	2.46
	39	37	40	32
2448335		0.97	0.63	1.17
		108	83	139
2448368	0.69	0.73	0.57	0.82
	51	109	105	124
2448396	1.11	0.41	0.56	1.07
	45	107	49	169
2448598	0.63	0.69	0.25	
	107	122	129	
2448648	0.79	1.70	0.16	0.16
	30	75	130	16
2448712		0.62	0.50	0.91
		54	75	50
2449014	0.25	0.47	0.54	0.76
	51	22	06	38
2449030		0.39		
		37		

1995) we have computed the interstellar polarization in UBVRI bands. We use $P_{max} = 3.86\%$, $\lambda_{max} = 0.55\mu$m and $\theta = 127.9^o$ for the interstellar polarization. By subtracting the interstellar polarization from the observed polarization data (Table 1) we have obtained the intrinsic polarization of HR Car in UBVRI bands and are given lin Table 3.

In Table 3, the percentage of intrinsic polarization P^* and the position angle θ^* in degrees for BVRI bands are given. The errors ϵ_P, ϵ_θ are not listed in Table 3. The errors in P^* in BVRI are same as the errors in the observed polarization (Table 1). The errors in position angles given in Table 3 can be derived using:

$$\epsilon_\theta^* = 28.65\frac{\epsilon_P^*}{P^*}$$

We made one measurement of polarization in U band on JD 2447970 ($U_p = 1.57{\pm}0.91\%$ and $\theta = 108{\pm}17^o$). The intrinsic polarization and position angle in U band on JD 2447970 are found to be 2.32 and 51 respectively. Serkowski et al. (1975) made two measurements in U band and the intrinsic polarization and position angle on these dates were JD 2240603: 0.01 and 116 and JD 2240625: 0.23 and 52 respectively.

4. Discussion and conclusions

From the results given in Tables 1, 2 and 3 it is clear that there are intrinsic variations in HR Car polarization and position angle in UBVRI bands. The wavelength dependence is clearly different from that of the interstellar polarization. The intrinsic percentage polarization spectrum observed by Clampin et al. (1995) on JD 2449030 was nearly flat and was interpreted as being due to electron scattering. Results presented here show that the wavelength dependence of intrinsic polarization is also variable. This raises some doubts about electron scattering as the cause of polarization. The scattering material seems to be bi-polar. Nota et al. (1997) obtained high resolution coronographic images of the nebula around HR Car. On the basis of nebular morphology and kinematics they conclude that the nebula around HR Car is truly bipolar and similar to the Eta Carinae nebula. The small compact inner nebula, a few arcsec in size represents the waist of the bipolar distribution. From an analysis of chemical composition Nota et al. (1997) find that the nebula is over-abundant in nitrogen, indicating that the nebula around HR Car is composed of CNO processed stellar material. The characteristics of HR Car nebula appear to be very similar to that of bipolar Type I planetary nebulae which are also over-abundant in nitrogen.

Recently Voors et al. (1997) obtained mid-infrared imaging of HR Car. The 10-micron broad-band N image reveals a geometry which is not point symmetric with respect to the central star on an arcsecond scale. From the 12.8 micron narrow-band [NeII] images Voors et al. (1997) found clumpy structure which does not follow the N-band distribution. The morphology of the infrared nebula and in particular its asymmetry is not at all in agreement with the large scale structure seen in optical images (Voor et al. 1997). The multi-wavelength images of HR Car indicate several episodes of shell ejection. The variability of the intrinsic polarization and position angle found here also means that the variations in the distribution of the scattering material are not axisymmetric or in a plane. So, even though the nebula is bipolar on a large scale, on a smaller scale, there are deviations from the bipolar geometry. The inner nebula of HR Car may be clumpy and may contain jet like filaments with temporal variations. Imaging polarimetry in several wavelengths may further enable us to understand the HR Car nebula.

On JD 2448305 we find large increase in intrinsic polarization in all the BVRI bands compared to the intrinsic polarization on other dates. This epoch is close to the maxmium in the light curve (Clampin et al. 1995). From our intrinsic polarization results of HR Car we find that the variation in V band ranges from 0.24% to 2.74%. Because of the gaps in our data it is not possible to detect a period if present. In our measurements significant variability is seen on time scales of about 30 days. So changes in the material distribution are probably taking place at 10^{12} cm from the star if the movement of scattering material causes the variability. The scattering may have contribution from both Rayleigh and Mie scattering. The variations (Table 3) may be due to temporal variations in the structure of the circumstellar material. The most commom intrinsic polarization position angle is about 35 ± 15 degrees, which is also the position angle of the inner elongated nebula. The optical depth in the circumstellar environment appears to be much larger than unity, with the entire ultraviolet varying in antiphase with the visual (Shore et al. 1996). Polarization measurements in the UV with WUPPE may enable us to further understand the causes for variations in the intrinsic polarization.

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