

*Letter to the Editor***A two-component infrared nebula around HR Car\*****R.H.M. Voors<sup>1,2</sup>, L.B.F.M. Waters<sup>3,4</sup>, N.R. Trams<sup>5</sup>, and H.U. Käuff<sup>6</sup>**<sup>1</sup> Astronomical Institute, University of Utrecht, Princetonplein 5, 3508 TA Utrecht, The Netherlands<sup>2</sup> SRON Laboratory for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands<sup>3</sup> Astronomical Institute Anton Pannekoek, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands<sup>4</sup> SRON Laboratory for Space Research, PO Box 800, 9700 AV Groningen, The Netherlands<sup>5</sup> ISO Science Operations Center, Astrophysics Division of ESA, PO Box 50727, E-28080 Villafranca, Madrid, Spain<sup>6</sup> European Southern Observatory, D-8046 Garching bei München, Germany

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**Abstract.** We present mid-infrared imaging of the LBV HR Car and its surrounding nebula. The  $10\mu\text{m}$  broad-band N image reveals a geometry which is not point symmetric with respect to the central star on an arcsecond scale. The  $12.8\mu\text{m}$  narrow-band [Ne II] image shows a clumpy structure which does not follow the N-band distribution. In addition, we detect a faint and probably clumpy outer nebula about  $15''$  across.

The morphology of the infrared nebula and in particular its asymmetry is not at all in agreement with the large-scale structures as seen in optical images. Three different episodes of shell ejection can now be distinguished for HR Car: the arc-like structures seen in the optical, about  $35''$  across, the faint IR nebula seen in the N-band, about  $15''$  across, and the small, irregular nebula less than  $8''$  across. The main conclusion we draw from this is that the geometry of mass-ejections in HR Car is highly time-dependent and that multiple shell ejections can occur in LBVs.

The distance of the small IR nebula from the central star can be well explained by a dust shell that is composed of silicates and is in radiative equilibrium with the central star.

**Key words:** HR Car – Circumstellar matter – Infrared: stars – Mass-loss

**1. Introduction**

The class of Luminous Blue Variable (LBV) stars is thought to represent a short-lived and violent post-main-sequence phase in the evolution of very massive ( $> 40M_{\odot}$ ) stars. During this phase they are characterized by a high continuous mass-loss rate ( $10^{-6}$  to  $10^{-4} M_{\odot} \text{ yr}^{-1}$ ), a high luminosity ( $\log L/L_{\odot} \approx 5.5$  to  $6.5$ ) and typical brightness and spectral variations of 1 to 2 magnitudes in  $V$  in about 1 to 10 years (Humphreys & Davidson 1994). HR Car is known to change its spectral type from

B2 I to B9 I (Bateson 1987-1996), which corresponds to a change in  $T_{\text{eff}}$  from roughly 18,000 to 10,000 K.

Almost all known LBVs are surrounded by a nebula, varying in shape from nearly circular (Wray 751) to strongly bipolar ( $\eta$  Car). The origin of these nebulae is still uncertain: are they due to giant eruptions (Hutsemékers 1994) or to the high mass loss rate over a long period of time (e.g. García-Segura *et al.* 1996)? In only two galactic LBVs, P Cyg and  $\eta$  Car, giant eruptions have been observed. From statistical arguments it is estimated that giant eruptions occur with a frequency of about  $10^{-3}$  to  $10^{-4} \text{ yr}^{-1}$  (Lamers 1987).

The nebula of HR Car was discovered (Hutsemékers & van Drom 1991) by narrow band filter imaging. Clampin *et al.* (1995) and Nota *et al.* (1997), report coronagraphic imaging, long-slit spectroscopy and spectropolarimetry of the HR Car nebula. They conclude that the nebula is of filamentary, bipolar and nearly point-symmetric structure and that the large-scale morphology is in agreement with the asymmetries on a smaller scale as detected by spectropolarimetry. From IRAS photometry McGregor *et al.* (1988) estimate a dust temperature of 165 K and a dust mass of  $2.6 \cdot 10^{-4} M_{\odot}$ , assuming a distance of 2.5 kpc. This low temperature suggests that the dust is situated far from the central star, but is considerably warmer than that in e.g. AG Car.

In this *Letter* we present mid-infrared images of HR Car and its nebula, in both the broad N-band and the narrow [Ne II]  $12.8\mu\text{m}$ -band. For the first time this allows us to get a view of the surroundings close to the star, which in the optical region cannot be observed due to the relative brightness of the central star (Clampin *et al.* 1995).

**2. Observations and reduction**

The observations were done on February 2nd 1995 at the 3.6m telescope at La Silla, Chile, with the Thermal Infrared MultiMode Instrument (TIMMI) (Käuff *et al.* 1994). Ground-based imaging in the thermal infrared is normally done by chopping the secondary and/or nodding the telescope. TIMMI uses both techniques in such a way that the nodding is done by exactly the chopper throw in order to maximize the efficiency. The detector used was a  $64 \times 64$  pixel Ga:Si array, with a cut-off wavelength of  $17.8\mu\text{m}$ . HR Car was imaged in the broad-

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\* based on observations obtained at ESO, La Silla, Chile

**Table 1.** Log of the TIMMI observations.

Object	Image	Filter	Scale ("/pix)	Remarks
HR Car	c058071	N-band	0.498	
HR Car	c072085	N-band	0.498	
HR Car	c086099	N-band	0.336	
HR Car	c100143	N-band	0.336	offset pointing
HR Car	c144187	[Ne II]	0.336	
$\alpha$ Cen	c188193	[Ne II]	0.336	flux calib.
$\alpha$ Cen	c194199	N-band	0.336	flux calib.
$\alpha$ CMa	c021028	N-band	0.498	flat field

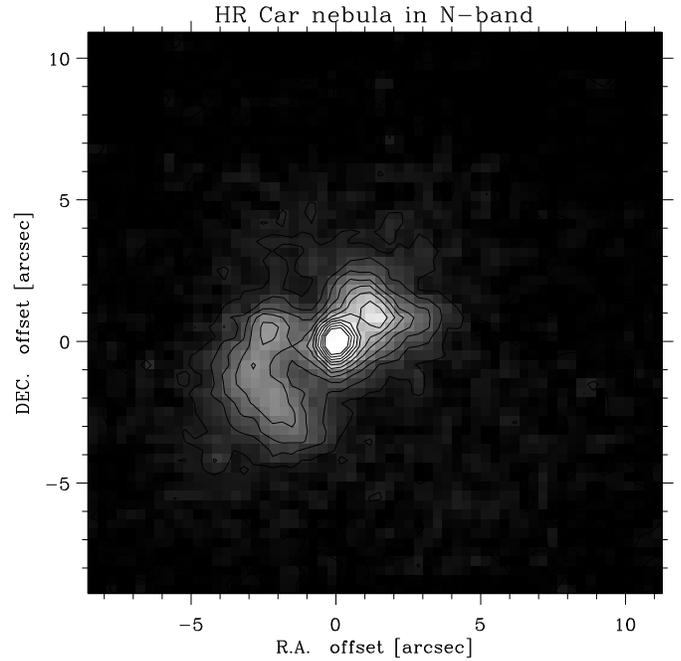
band N filter ( $\lambda_c=10.10\ \mu\text{m}$  and  $\Delta\lambda=5.10\ \mu\text{m}$ ) and in the narrow-band [Ne II]  $12.8\ \mu\text{m}$  filter ( $\lambda_c = 12.78\ \mu\text{m}$  and  $\Delta\lambda = 0.25\ \mu\text{m}$ ). The log of the observations is shown in table 1. The seeing was estimated to be  $1''.0$ , using the standard star  $\alpha$  Cen. For flux calibration we used  $\alpha$  Cen and adopted  $164\ \text{Jy}$  at  $10.1\ \mu\text{m}$  and  $F_\lambda \propto \lambda^{-4}$ .

### 2.1. data reduction

The final N-band image is the result of averaging 29 separate images, taken at two different pointings in order to remove effects that could be due to the position of the image on the array. (E.g. c100143 is the average of 22 separate images, each being the difference between an on-source image and an off-source image.) The [Ne II] image is the result of 22 separate images. Each image is the average of 20 nodded exposures (10 positive minus 10 negative ones), each of which were cleaned of bad pixels and bad pixel rows. The distribution of bad rows was not random but certain rows (30,33,52 and 61) were of a lesser quality in many of the images. These occasional bad rows are mainly due to the fact that for some readouts there is an erratic but small offset to one of the ADCs. In the case of the final [Ne II] image this means that the area 3 arcseconds North of the central star (rows 30 to 33) is less well determined than the Southern area. A single flat-field for both images was created by fitting a second order polynomial to the measured brightness of the standard star  $\alpha$  CMa at several positions on the array. This removes the global structure of the array, but not the pixel-to-pixel variations. Effectively these are removed by subtracting negative images from positive ones. Only the images that were made with the  $f=60$  lens were used to compute the average image. For these 1 pixel corresponds to  $0''.336$ . The images with the  $f=40$  lens have a larger field of view; all the main features seen in the  $f=60$  images were also seen but no emission beyond the field of the  $f=60$  images was detected.

Both the N-band and the [Ne II] images were cleaned of high frequency noise using a low pass filter. Especially for the [Ne II] image this greatly enhances the quality of the image. The spatial frequency of the photon noise of one per pixel is much higher than the spatial frequency of the “real” signal which mainly depends on the PSF, which is of the order of 3 pixels FWHM. Therefore a clear distinction can be made and the photon noise can be filtered effectively from the total signal. In applying the low pass filter we made sure that the FWHM of the beam did not increase.

To test the reality of the features found in the N-band image we treated the c086099 image and the offset image c100143 separately and compared those. This showed that all the features in the images that we present are seen in both images and are therefore not due to detector effects or to an over-interpretation of residual noise.



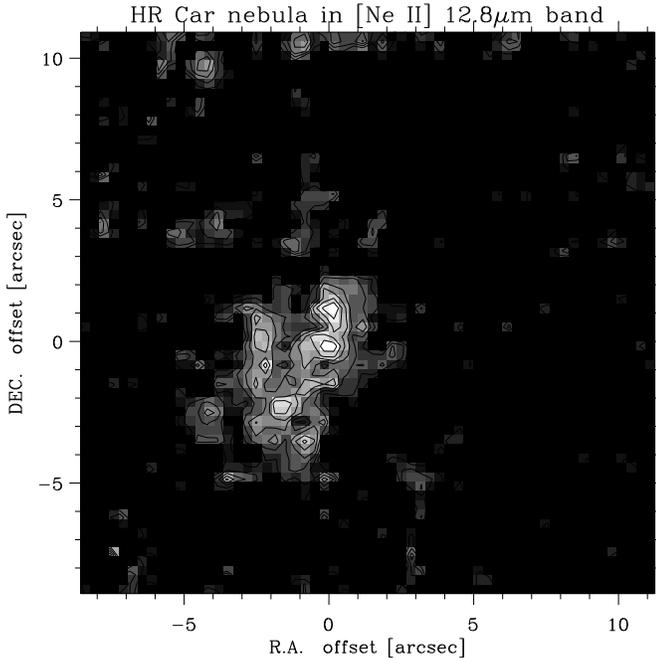
**Fig. 1.** Image of the HR Car nebula in the N-band. North is up and East is to the left. The first contour is at  $10\ \text{mJy}/('')^2$  and contours increase by steps of  $40\ \text{mJy}/('')^2$ .

### 3. The structure of the nebula

The processed N-band and [Ne II]  $12.8\ \mu\text{m}$  images of HR Car and its surrounding nebula are shown in figures 1 and 2, respectively. In the N-band the HR Car nebula has a slightly bipolar structure, as have many LBV nebulae. The distribution, however, is not point-symmetric around the star. The N-band image shows the star as a clear central peak. The integrated flux of the central source is  $1.5\ \text{Jy}$ , which compares well with an estimated stellar flux of  $\approx 1\ \text{Jy}$  from extrapolating the ISO-SWS spectrum (Lamers *et al.* 1996), both numbers having an error of at least 25 percent. A somewhat “patchy” arc is seen E to SE of the star and a brighter blob NW of the star. The total fluxes of the regions NW and SE respectively are almost equal. Assuming the dust emission to be optically thin at  $10\ \mu\text{m}$  and equal dust temperatures in both regions, this implies that more or less the same amount of dust is present at the SE and the NW of the star, but that towards the NW it is more confined. The assumption of optically thin dust emission is very reasonable at  $10\ \mu\text{m}$ , given the optical extinction and IR colors of the object (see Hutsemékers & van Drom 1991b), but the assumption of equal temperatures cannot be tested using our images alone. A fainter extended nebula is also seen,  $15''$  to  $20''$  across, which shows no clear sign of bipolarity. This more extended region is probably the source of the colder dust seen with IRAS and ISO. The total integrated flux of the compact nebula alone is  $6.5\ \text{Jy}$  and the total flux of the  $20'' \times 20''$  region is  $11.7\ \text{Jy}$ , with an uncertainty of about 20 percent.

The average projected distance of the SE-arc is about  $3''$  and the blob NW of the star has a projected distance of about  $1''.5$ . Assuming the distance to HR Car to be  $5.4\ \text{kpc}$  (Hutsemékers & van Drom 1991b)  $1''$  corresponds to a projected distance of  $0.026\ \text{pc}$ . This means that the NW-peak is at a projected distance of only  $0.04\ \text{pc}$ .

The [Ne II]  $12.8\ \mu\text{m}$  image shows a somewhat different picture. Due to the narrow band-width of the filter, the quality of the [Ne II] image is less than the N-band image, yet we are confident that all the



**Fig. 2.** Image of the HR Car nebula in the [Ne II] 12.8 $\mu$ m-band. North is up and East is to the left. The first contour is at 25 mJy/( $''$ )<sup>2</sup> and contours increase by steps of 33 mJy/( $''$ )<sup>2</sup>.

spatially extended features visible in the presented image are real. The central star is still seen as the brightest source, with an estimated flux density of  $1.8 \pm 1$  Jy. This is within the uncertainty of the extrapolated continuum flux of 0.8 Jy from ISO-SWS, but a possible excess could be due to [Ne II] line emission from the present day stellar wind. Contrary to what is seen in the N-band image the nebula as seen in the [Ne II] band shows no clear bipolarity; virtually no emission is seen to the NW of the star but the region SE of the star shows a similar arc-like structure as the N-band image, but is slightly closer to the star; the ionized [Ne II] region appears to be on the inside of the dusty nebula. Its structure is also more “patchy” than the continuum N-band image. This may be caused by the fact that the [Ne II] line flux is proportional to  $\rho^2$ , whereas the dust flux is a linear function of the density. The integrated flux of the  $20'' \times 20''$  region is 11.9 Jy with an uncertainty of about 50 percent.

In principle the signal in the [Ne II]-band could be due to *continuum* dust-emission rather than to [Ne II] 12.8 $\mu$ m *line* emission. The ratio of the observed flux in the nebula of the [Ne II] over the N-band filter is slightly higher than the ratio of the respective filter throughputs, by a factor of 1.3, but due to the large uncertainty in the [Ne II] flux, it cannot be ruled out that a significant portion of the flux measured through the [Ne II] filter is in fact *continuum* flux. Also, high resolution [Ne II] 12.8 $\mu$ m spectroscopy of the HR Car nebula, which will be discussed elsewhere more extensively, gives only an upper limit to the nebular continuum flux at 12.8 $\mu$ m, which is too high to be able to dismiss the possibility that we observe mainly *continuum* radiation through the [Ne II] filter rather than *line* radiation.

It should be noted that the images taken through the [Ne II] filter and the N-band filter do not coincide spatially, which indicates that we are seeing different material through the different filters. It also indicates that optical depth effects play a role; the central star ionizes only part of the nebula.

## 4. Discussion

The angular size of the dust, can be used to derive constraints on the dust properties and the geometry of the outflow. For simplicity we assume that the dust is optically thin at 10 $\mu$ m. The expected angular size of the dust shell around HR Car depends on the way the emissivity of the dust varies with wavelength. From ISO-SWS measurements (Lamers et al. 1996) we see that the spectrum of HR Car shows a pronounced bump near 10 $\mu$ m, which is interpreted as emission from silicates. Silicate dust has peculiar absorbing and emitting properties that can not be described by a power law dependence. In order to calculate the emission from an spherically symmetric silicate dust shell, we calculate the radiative equilibrium temperature structure of the shell and assume the dust particles to radiate according to the astrophysical silicate model of Draine and Lee (1984). We assume that the density varies with density as  $\rho_d = \rho_0 r^{-2}$ . The free parameters of the model are: the inner and outer radius of the dust shell and  $T_*$ , which determine the shape of the spectrum, and  $\rho_0$ , which is used as a scaling factor. From the images it is clear that the dust shell is not spherically symmetric, but the approximation of spherical symmetry is suitable for obtaining a reasonable estimate of the size and the mass of the nebula.

The best fit model to the inner nebula for the ISO-SWS spectrum gives a well-defined inner radius of the shell of  $4.5 \cdot 10^4 R_*$  with a stellar temperature of 18500 K. This model also gives a good fit to IRAS photometry. With a luminosity of  $\log L/L_\odot = 5.63$ , this gives a stellar radius of  $64 R_\odot$ . The dust temperature at the inner radius of the shell is 150 K, which is slightly less than the BB-temperature fit of 165 K of McGregor *et al.* (1988) to IRAS data. In retrospect, the assumption of an optically thin approximation at 10 $\mu$ m was justified, as  $\tau(10\mu m) \approx 3 \cdot 10^{-3}$ . The refractive properties of silicate grains are still not very well known, but if we extrapolate a fairly flat distribution, where  $Q_\nu \propto \nu$ , then the optical depth at the wavelength corresponding to the ionizing potential of Ne (21.564 eV  $\Leftrightarrow$  575 Å) equals 0.6. This shows that it is well possible that a substantial part of the radiation at 575 Å is blocked in certain parts of the nebula, so that Ne remains neutral. This is well reflected in the images, from which it is seen that the [Ne II] flux SE of the star comes from a region slightly inside the arc seen in the N-band. An additional source of UV opacity will be the Lyman continuum, in the region where there is gas, but no dust present.

The outer radius is less well defined, but assuming a density distribution that is not steeper than  $r^{-2}$ , i.e. what is expected for a constant stellar outflow, the total dust mass of the shell is less than  $8 \cdot 10^{-4} M_\odot$ . At a distance of 5.4 kpc,  $4.5 \cdot 10^4 R_*$  is equal to approx.  $2''.5$ , which coincides very well with what we see in the TIMMI images. We conclude that our simple spherically symmetric dust model can well explain the average distance at which we see the nebula in our TIMMI images.

We can set an upper limit to the grain size distribution using millimeter photometry. We have recently performed millimeter photometry of the dust emission from HR Car using the Swedish Sub-millimeter Telescope SEST at La Silla, at a wavelength of 1.1 mm for which we find an upper limit of 24 mJy ( $3\sigma$  rms). Such a low flux rules out the possibility that the grains are grey out to 1.1 mm, i.e. a significant fraction of the grains must be smaller than 1 mm.

The irregular shape of the nebula complicates the explanation of the formation mechanism. In principle there are two possible origins for the peculiar shape; either the surrounding interstellar medium is highly inhomogeneous or the star itself ejects matter in a non-symmetric manner. The first possibility seems rather implausible in view of the fact that HR Car is considered to be a massive post main-sequence star. During its main sequence stage it has blown a large cavity around it by means of its high velocity stellar wind. This cavity is much larger than

the size of the patchy nebula we observe. A filamentary nebula with an approximate radius of  $130''$  was noted by Nota *et al.* (1997). Its dynamics suggests it is physically connected to HR Car and the chemical composition which is approximately that of a regular H II region, suggests that it contains mainly swept-up material rather than chemically processed material, as could be expected in the case of an outburst. This means that the star itself ejects material in a very non-symmetric and non-spherical way, either as a result of a companion star or as a result of its internal instability. The presence of a companion, however, is expected to give rise to a more axisymmetric nebula than is seen in this case. We therefore conclude that the star itself ejects material into the surrounding medium in a non-symmetrical way, induced by its own instability. This should be taken into account in the modeling of the mass-loss of HR Car and of LBVs in general.

Comparing our results with those of optical investigations (Hutsemékers & van Drom 1991b and Clampin *et al.* 1995) we see that the dust and ionized gas distributions near the star ( $< 6''$ ) is “more asymmetric” than the gas distribution further away ( $> 10''$ ). The roughly symmetric shape as noted by Clampin *et al.* (1995) suggests that the symmetry/geometry of the outflow changes with time. Almost all LBV nebulae show a clear symmetry axis and the inner nebula of HR Car is shown to be a rare exception to this rule. It is not immediately clear, however, if this apparent asymmetric shape is intrinsic or due to projection effects, such that light from one part of the nebula is blocked.

A determination of the kinematic age of the inner nebula can be obtained from high resolution [Ne II] spectroscopy of the nebula (Waters and Voors 1997 in prep.). An outflow velocity of  $46 \pm 10 \text{ km s}^{-1}$  and a distance of 0.04 pc give an age of  $850 \pm 185 \text{ yr}$ . Projection effects are not taken into account and will affect the dynamic age of the nebula. The dynamic age of the outer nebula is estimated to be 5200 yr (Nota *et al.* 1997). Therefore, the inner and outer nebula can only be of similar age if projection effects play a dominant role in determining the true age of the inner nebula. Apart from the nebulae of  $\eta$  Car and P Cygni – stars of which the outbursts were observed that may have caused their surrounding nebula – this is the youngest LBV nebula known.

From the limited sample of LBV nebulae there appears to be a tight relation between the age and the mass of the nebula (Nota 1997). The small mass and its young age of the HR Car nebula agree with this relation. The existence of such a relation could indicate that the nebulae are not formed in a single outburst, but in a series of events, during which the mass continuously increases. However, there is a strong observational bias to this relation: a large nebula must contain a lot of mass if it is to be observed. The small nebula that now is observed may well have diluted in a few  $10^3$  years to such an extent that it will not be visible anymore.

## 5. Conclusions

New broad-band N and narrow-band [Ne II]  $12.8 \mu\text{m}$  imaging of the HR Car show that its surrounding nebula has a clumpy non point-symmetric structure on the scale of a few arcseconds, more so in the ionized gas than in the dust, which is seen at a projected distance of less than 0.04 pc from the central star. We also observe a faint, probably clumpy nebula about  $15''$  across, which does not appear to be bipolar and which is therefore thought to represent an earlier period of increased mass-loss.

The size of the compact IR nebula can well be explained by a dust shell which is composed mainly of silicates and is in thermal equilibrium with the central star. The dust and the gas emission appear to originate from different areas, which suggests the shielding of stellar radiation by the circumstellar dust. A simple dust shell model, which

gives a reasonable fit to the ISO-SWS spectrum, shows that based on the dust optical depth of the nebula at  $10 \mu\text{m}$ , this is well possible.

The morphology of the dust and gas close to the star is not in agreement with that of optical images of the star, which suggest a filamentary and highly symmetric nebula. This indicates that the geometry of the mass ejections in HR Car is time-dependent. Together with the two-component nebula we observe, now at least three different episodes of shell ejection can be distinguished for HR Car.

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