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The Radio Nebula Around HR Carinae

S. M. White
Astronomy Department, University of Maryland, College Park, MD 20742

and

R. A. Duncan
Australia Telescope National Facility, PO Box 76, Epping NSW 2121, Australia

ABSTRACT

We present a sensitive radio image of the nebula associated with the Luminous Blue Variable star HR Carinae. This nebula is small and difficult to observe optically due to the presence of the bright star. The radio image shows the filaments in the outer regions of the nebula seen in optical coronagraphic images. The core of the nebula is elongated north–south on the sky. A compact source associated with HR Car is clearly detected at the western edge of the nebula, but the nebula is very asymmetric with respect to the star, lying almost entirely to the east. The inner nebula shows no evidence for the bipolar structure inferred to exist from observations of the outer nebula: the symmetry axes in the inner nebula are 45° away from the bipolar axes. If the compact radio emission at the location of the star is a classical stellar wind source, we estimate a mass loss rate for ionized gas of 1.8×10^{-5} $M_\odot$ yr^{-1}. The mass in the central core of the nebula is about 0.3 $M_\odot$, while the outer nebula may contain as much as 0.5 $M_\odot$. We believe that a colliding–winds explanation of the nebula is unlikely; a symbiotic–like explanation in which ionization of neutral ejecta is provided by a hot companion star may be possible if the companion star is on the far side of the nebula and heavily extincted, but it is not clear whether the properties required of this star are compatible with the fact that it is not detected in a 10 μm image. A B0V companion without much dust may be consistent with the data.

Subject headings: stars: peculiar; stars: atmospheres; circumstellar matter; stars: individual: HR Carinae; radio continuum: stars

1. INTRODUCTION

Luminous Blue Variable (LBV) stars are very massive and luminous stars which display irregular variations in their spectra and intensity. They are believed to be a short–lived phase in the evolution of massive O stars into Wolf–Rayet stars following the end of core hydrogen burning on the main sequence. In this phase the star's outer layers are unstable and spectacular ejections of mass can occur: all the known LBVs are accompanied by nebulae. The amount of mass ejected in this evolutionary phase can be several solar masses or more, and the mass loss can have an important impact on the subsequent evolution of the star. In addition, the mass ejections (with velocities of up to several hundreds of km s^{-1}) represent a major energy input into the interstellar medium.

Relatively few LBVs are known in our galaxy where they can be studied with reasonable spatial resolution: η Carinae, AG Carinae, HR Carinae, He 3-519, WRA 751, HD 168625, P Cygni and possibly G25.5+0.2 (Humphreys & Davidson 1994, Nota et al. 1995, Subrahmanyan et al. 1993). In addition, study of the nebulae at optical wavelengths can be complicated by the presence of the bright star nearby. Radio observations offer an alternative method for studying these ionized nebulae since they emit free–free radio emission. In this paper we present a radio study of HR Carinae which has one of the more interesting nebulae in this class of stars. While not particularly luminous or hot for an LBV (van Genderen et al. 1991) the star nonetheless has a bolometric luminosity estimated at 10^6 $L_\odot$ (Shore, Altner & Waxin 1996). Hutsemékers & Van Drom (1991) showed that it has a multiple–shell expanding atmosphere producing broad wings in emission lines, and were the first to carry out direct narrowband imaging of the star which showed that the nebula is filamentary with a core which is only a few arcseconds across. They also identified a faint visual companion some $3\farcs7$ to the east of the primary star. Clampin et al. (1995) carried out a much more detailed study of the nebula using coronagraphic observations and measured polarization in the Hα line. Weis et al. (1997) used direct imaging and high–dispersion spectroscopy and detected a funnel–shaped nebula $2\farcm5$ to the north–west of the star. They confirmed that the nebula is bipolar and were able to show that the lobes of the nebula are expanding. They also noted similarities with the nebula of η Carinae. Nota et al. (1997) carried out additional spectroscopic and coronagraphic observations, and found a coherent velocity pattern across the nebula consistent with a bipolar flow. They also investigated the excitation state of the nebula, analyzed the chemical abundances in the nebula and determined densities from [S II] line ratios. Hulbert et al. (1999) have presented a preliminary analysis of HST Hα observations of HR Car which show additional detail within the core of the nebula: in particular, the inner nebula appears quite clumpy.

However the structure of the inner nebula within several arcseconds of the star could not easily be studied in these optical observations. Radio observations can complement optical observations in several ways: they are sensitive to the same ionized gas which produces optical recombination lines, but there is no bright star present contaminating the image of the nebula. In addition, radio data suffer no extinction and penetrate dust which can obscure features at optical wavelengths. We present an arcsecond–resolution radio image of HR Carinae and discuss its interpretation. The nebula is not centered on the star at all, but rather several arcseconds to the east. The morphology of the inner core shows no sign of the bipolar axes inferred from the outer nebula.

2. OBSERVATIONS

The radio data were acquired with the Australia Telescope Compact Array (ATCA) over the course of several observations in a range of configurations in 1994 and 1995. The data used here were taken in the 3 and 6 cm wavelength bands (corresponding to frequency bands 5 – 6 GHz and 8 – 9 GHz, respectively) as shown in Table 1; an additional observation at lower frequencies is also listed. Most of the data were taken in 6 km configurations which yield the best spatial resolution of which the ATCA is presently capable: about $1''$ at 9 GHz. All the observing sessions were about 12 hours in length with observations of HR Car spread fairly uniformly in time over this period; the time given in Table 1 is the on-source time for HR Car. In all except one session, a single frequency in the 6 cm band and one in the 3 cm band were observed simultaneously, usually with bandwidths of 128 MHz for each.

As we discuss further below, inspection of the data indicates that the radio spectrum of the nebula is essentially flat at these frequencies and to improve the quality of the image we have combined all the data above 5 GHz together. A confusing source south of HR Car was subtracted from all the 6 cm data before combination with the 3 cm data.

A number of analyses were performed on these data. The image used here consists of a maximum entropy deconvolution of the naturally–weighted dirty map resulting from all data combined. A cell size of $0\farcs3$ is used for the map, and the resulting model brightness distribution solution is convolved with circular gaussian beams of $0\farcs8$ for the high–resolution image and $1\farcs2$ for the lower resolution image. Maximum entropy produces a model brightness distribution required to fit the dirty map to within the noise level of the data, with a spatial resolution which depends on the local signal–to–noise level. The sensitivity in the resulting image is excellent, although the true noise level is difficult to estimate. We also made images from all the 3 cm data and all the 6 cm data separately, using the same procedure followed for the map used here. There is excellent agreement between the 3 and 6 cm maps despite the very different spatial coverages and the differing amounts of data. We regard the excellent agreement between the 3 and 6 cm images as evidence for the fidelity of the image which we analyze here: any artefacts associated with sidelobes would be expected to scale with wavelength and thus should be quite different in the 3 and 6 cm images.

3. THE RADIO NEBULA

Figure 1 shows images of the nebula associated with HR Car at the wavelength of Hα (from Nota et al. 1997) and the radio image (scaled to emphasize the weaker outlying structure). The Hα image shows filaments extending predominantly to the south–east and north–west (Hutsemékers & Van Drom 1991, Clampin et al. 1995, Nota et al. 1997), extending up to several arcminutes from the star (Nota et al. 1997, Weis et al. 1997). The radio image shows the same filaments although with the relative brightness of different features differing from the Hα image. For example, $14''$ south of the star the brightest feature in the Hα nebula is a nearly horizontal bar (note that the nebular feature at the bottom of the Hα image is apparently not related to HR Car). In the radio image this bar is present but is not as bright as an adjacent feature running from the south–eastern edge of the bar back towards the star, which was also seen in HST WFPC2 images and labelled a "jet–like filament" by Hulbert et al. (1999). Both radio and Hα images seem to show 5 main filaments extending away from the bright core of the nebula.

The optical images show essentially three spatial scales in the HR Car nebula: the inner core just a few arcseconds across, which is not easily studied in the optical data; the inner filaments extending out to $15''$ from the star; and the extended outer filaments located $2'$ - $3'$ to the northwest of the star. The latter features are only seen in deep Hα images (Nota et al. 1997, Weis et al. 1997; Nota et al call them an HII region) and have a surface brightness much less than that of the inner filaments, so we believe that they are below the detection level of the radio images. The radio image of the inner filaments is essentially consistent with the Hα images, and hence shows that there is no large mass of ionized gas hidden behind dust in this region.

Figure 2 shows the high–resolution radio image of the core of the HR Car nebula. This is an approximately $5'' \times 8''$ region elongated north–south. The Hipparcos position of HR Carinae is plotted (the cross labelled "A") as is the position of a second star 5 magnitudes fainter than the primary and some $3\overset{''}{.}7$ to the east (cross labelled "B"), first identified by Hutsemékers & Van Drom (1991). The radio core has a peak at its geometric center as well as a pronounced peak at the western edge of the core and weaker peaks about $2''$ both north and south of the center of the nebula. Hulbert et al. (1999) identify 4 "clumps" in the HST WFPC2 F656N image which match the structure in the radio core fairly well: their clumps

B and C are essentially coincident with the central radio peak in the nebula, while their clump D has the same position and orientation as the radio feature just 2″ to the south of the radio peak and their clump A is close to the northern extension of the radio peak. Unlike the HST image, the radio image suggests that clumps B and C together are much more massive than clump A, but clumps B and C may be affected in the HST image by the removal of the stellar HR Car feature 2″ away.

We identify the radio peak at the western edge of the nebula with the star HR Car: the positions are coincident to within the uncertainties in the coalignment of the radio and optical frames in this region of the sky. The stellar radio source cannot easily be separated from the rest of the nebula, so we are unable to determine its radio spectrum with any confidence. The stellar source is more prominent in the 3 cm image than in the 6 cm image, but that may be due to the higher effective spatial resolution of the former: the fluxes at the location of the stellar peak are similar at both 3 and 6 cm. Inspection of the high–resolution model images indicates that the flux in the pixels identified with the star totals 2.5 mJy at both 3 and 6 cm. Gaussian fits to the source which take into account a sloping background yield a total flux of 1.0 mJy for the compact stellar component, located at α = 10h 22m 53.858s, δ = -59° 37′ 28.″3 (0.″13 from the Hipparcos position). We can estimate the stellar mass loss rate based on this flux assuming optically thick free–free emission (Olnon 1975, Panagia & Felli 1975, Wright & Barlow 1975; this assumption is not strictly consistent with the apparently flat spectrum, but due to the difficulties of separating the stellar flux from the nebular flux at 6 cm it is certainly possible that the radio spectrum of the star has the appropriate $\nu^{0.6}$ spectrum, where ν is the frequency; at any rate, the stellar spectrum does not appear to be nonthermal). Adopting a stellar wind velocity of 150 km s^{-1} (Hutsemékers & Van Drom 1991), we find a mass loss rate of ionized gas of 1.8×10^{-5} M$_\odot$ yr^{-1} (using a stellar flux of 1.0 mJy), which is plausible for an LBV and remarkably close to the estimate of 1.7×10^{-5} M$_\odot$ yr^{-1} derived by Lamers et al. (1996) based on ISO spectra. However, we note that the radio emission may not be due to the stellar wind, and even if it is the assumption of a wind which remains fully ionized to infinite distance from the star may be incorrect: if the ionized volume of the wind is bounded due to recombination at a height where the UV emission is too weak to maintain a fully–ionized wind then the estimate above will be less than the true mass loss rate. We therefore regard our measurement as a lower limit to the mass loss rate. The observed radio flux requires an optically–thick stellar source of radius 0.″05 (250 AU at 5 kpc) at 8.6 GHz if the temperature of the gas is 10^4 K, i.e., the ionized region of the wind must be at least this large.

The most remarkable aspect of the radio nebula is that it is clearly not centered on the LBV, but rather 2″ to the east. Essentially all the ionized gas lies to one side of the star. The unbalanced nature of the nebula has not been previously reported based on ground–based optical observations, but is also clearly apparent in the HST WFPC2 images of the region (Hulbert et al. 1999) and is noted by Voors et al. (1997) in their mid–infrared images. The radio data establish that this unbalanced appearance is not due to optical obscuration of one side of the nebula. We discuss this further below.

4. THE NEBULAR MASS

Radio measurements give us a means to estimate the mass of ionized gas in nebulae such as HR Carinae's which provides a check on estimates based on optical recombination line fluxes. For HR Car, the mass estimate based on the total nebular Hα flux is 2.1 $M_\odot$ (Clampin et al. 1995). In this calculation the actual Hα flux used for the calculation was almost 20 times larger than the measured flux due to the extinction correction for $E(B-V) = 1.0$ (Hutsemékers & Van Drom 1991, Shore, Altner & Waxin 1996, Nota et al. 1997), and the density was assumed to be 600 cm^{-3}. Using [S II] line ratios, Nota et al. (1997) find electron densities n_e ranging from 10^4 cm^{-3} in the center of the core to 10^3 cm^{-3} at the edge of the core $5''$ away, with a nebular temperature of 11000 K.

The total radio flux in a region of dimension $26\farcs7 \times 34\farcs8$ centered on the nebular centroid, which includes most of the flux evident in Figure 1, is 19.8 mJy. In the image made from the 3 cm data alone the corresponding flux is 19.8 mJy, and is 19.5 mJy in the 6 cm image; in less sensitive lower–resolution images at lower frequencies we find fluxes of order 19 $\pm$ 0.5 mJy at 2.5 GHz (13 cm) and 16 $\pm$ 1 mJy at 1.4 GHz (20 cm). These measurements of a flat radio spectrum are the basis for the argument that the radio nebula is due to optically–thin bremsstrahlung from ionized gas.

The radio flux in the core region of Figure 2 of dimension $7\farcs5 \times 11\farcs1$ is 14.5 mJy. The radio fluxes can be used to obtain an independent estimate of the mass of nebular material using various models. Normally with an LBV one would assume that the gas arises in the outflow from the star and the density should have an r^{-2} dependence on radius r. However in an optically–thin nebula an r^{-2} density law produces an r^{-3} dependence for the radio brightness distribution (with the emission presumably becoming optically thick at the center of the outflow). Such a brightness distribution is very strongly centrally peaked: the observed one–dimensional profiles of the nebula are not consistent with an r^{-3} dependence away from the center of the nebula, and furthermore the location of the center of the nebula is not coincident with the star which would be the source of the r^{-2} outflow.

We therefore do not adopt an r^{-2} density dependence for the purposes of calculating the nebular mass, but instead adopt a simple model which loosely fits the measured profiles: a filled spherical shell of uniform density, whose brightness distribution on the sky has a variation with radius r of $\sqrt{(R^2 - r^2)}$ where R is the outer radius of the shell. We assume that the mean mass per electron is 1.5 proton masses (i.e., He/H abundance of 0.1) and the gas temperature is 10^4 K. For a filled constant–density optically–thin sphere of radius θ'' at a distance d_{pc} parsecs, the radio flux S is $6 \times 10^{-15}\ n_e^2\, \theta^3\, d_{pc}$ Jy and the nebular mass is $1.8 \times 10^{-17}\ n_e\, \theta^3\, d_{pc}^3$ solar masses. HR Car is believed to be at a distance of 5 kpc (Hutsemékers & Van Drom 1991, van Genderen et al. 1991). We use the measured flux to determine n_e. In this approach, the final mass scales as $S^{0.5}\, \theta^{1.5}\, d_{pc}^{2.5}$.

We represent the approximately $6'' \times 8''$ core of the nebula with a sphere of radius $\theta = 3\farcs5$. The resulting numbers are n_e = 3200 cm^{-3} (consistent with the estimates of Nota et al. 1999) and a core nebular mass of 0.3 M$_\odot$. We treat the outer regions of the nebula separately. Since they consist largely of thin filaments, a filled sphere model is clearly inappropriate, and instead we use a thin shell model where the thickness of the shell is the thickness of the filaments. For a homogeneous thin spherical shell of radius θ'' and thickness $\Delta\theta''$ the radio flux S is $1.8 \times 10^{-14}\ n_e^2\, \theta^2\, \Delta\theta\, d_{pc}$ Jy and the nebular mass is $5.3 \times 10^{-17}\ n_e\, \theta^2\, \Delta\theta\, d_{pc}^3$ solar masses. We approximate the $20'' \times 30''$ region of the outer nebula with $\theta = 12''$ and $\Delta\theta = 1''$: adopting a flux density of 4 mJy for this region we find n_e =550 cm^{-3} and a mass of 0.5 M$_\odot$ in the outer nebula. If we assume a thicker shell then a lower density is implied and a much larger mass is inferred, so there is considerable uncertainty in the mass outside the core of the nebula. Our estimates of the nebular mass are slightly smaller than but generally consistent with those based on Hα data (total mass of 2.1 M$_\odot$ with 0.4 M$_\odot$ in the core: Clampin et al. 1995, Hulbert et al. 1999), with the advantage that the radio data require no correction for extinction.

5. DISCUSSION

5.1. The morphology of the inner nebula

Nota et al. (1997) have argued on the basis of the coronagraphic Hα image (Fig. 1) that the nebula of HR Car consists of two bipolar lobes of diameter $19''$ lying along a polar axis at a position angle of about 135° on the sky. The kinematic data from both Hα slit spectra (Nota et al. 1997) and from echelle data (Weis et al. 1997) strongly support this interpretation: they show a pattern in which the velocity peaks at a position angle consistent with the polar axis inferred from the images, and reversing from a peak value of +90 km s^{-1} (receding) in the north to -120 km s^{-1} (approaching) in the south. The projected velocity also decreases as you move away from the polar axis.

Nota et al. (1997) argued on this basis that the core of the nebula should be the "waist" region of the bipolar flow, possibly containing a disk similar to that seen in η Carinae. However, the radio image shows no signs of the bipolar flow in the inner nebula: the axes of symmetry are near position angles of $0°$ and $90°$ on the sky, whereas the symmetry axes of the bipolar flow should be near $45°$ and $135°$. The radio emission is optically thin and should therefore represent the distribution of emission measure $\int {n_e}^2\, dl$ faithfully; in particular, dust is transparent to radio emission and cannot obscure ionized gas from us. We presently have no explanation linking the the morphology of the inner nebula with the apparently bipolar morphology of the filaments in the outer nebula.

Voors et al. (1997) have published high–resolution N band (10 μm) and [Ne II] 12.8 μm images of HR Car. The N band image should represent optically–thin thermal dust emission, and it does not resemble either the optical images or the radio image of the ionized gas (Fig. 2): the N band image shows a bright compact source presumed to be HR Car, with well–defined features $1''.5$ to the north–west and an arc of emission $2''$ – $3''$ from the star with its upper edge due east of the star and extending down almost to a point due south of the star. The [Ne II] 12.8 μm image has less signal and shows no feature to the north–west of the star, but does show a weak arc to the south–east similar to the arc in the N band image. There is thus no sign of the bipolar axis in the [Ne II] 12.8 μm image, but the NW feature and the star lie on the bipolar axis in the continuum image. The companion star is not detected in either image. Overall the distribution of 10μm continuum emission is reasonably balanced on the two sides of the star, unlike the radio emission which is very unbalanced with respect to HR Car.

5.2. A colliding–winds model?

The symmetry axes of the radio nebula are much more consistent with the line joining HR Car and the star $3''.7$ to the east, raising the possibility that the nebula is due to interaction of the winds of the two stars. This interpretation could help to explain why the nebula is not centered at HR Car: the two winds could slow each other in the region between the two stars, increasing the density and thus rendering the free–free emission visible. (Most colliding–wind radio sources are nonthermal, which is not the case here.) Very little is known about this star due to its proximity to HR Car and the nebula: it is known to be 5 - 6 magnitudes fainter than HR Car, but its spectrum is unknown as is the question of whether it is physically associated with HR Car. Hutsemékers and Van Drom (1991) describe it as 0.4 magnitudes brighter than another nearby star through a red filter. Wide–field images of the region (e.g., Weis et al. 1997) suggest that there are only a few stars this bright in a 6′.7 field around HR Car, so the a priori probability of one of these bright stars lying just 3″.7 from HR Car purely by chance is quite small.

In a colliding–winds model, momentum balance between the two winds determines the location of the interface between them: if anything, the emission peak in the nebula is slightly closer to HR Car, implying that the wind from the secondary star would have to have a momentum at least as large as HR Car's wind. We estimate HR Car's mass loss rate $\dot{M}$ to be 1.8×10^{-5} $M_\odot$ per year at $v_w = 150$ km s^{-1}; while we cannot rule it out, we think it unlikely that a star capable of generating a wind with this momentum would be 6 magnitudes fainter than HR Car. Furthermore, since we do not detect the companion star in the radio image, its wind needs to be low–density compared to HR Car's. The radio flux from a stellar wind is proportional to $(\dot{M}/v_w)^{4/3}$, so the stellar wind of the companion could have the same momentum $\dot{M}\, v_w$ as HR Car's wind yet produce an order of magnitude less radio flux if the wind speed is, e.g., 3 times higher than HR Car's and the mass loss rate is 3 times smaller. These parameters would be consistent with a hot star wind.

An additional argument concerns the mass available from the stellar winds alone. We have estimated that the mass of the inner core of the nebula is 0.3 $M_\odot$. At 150 km s^{-1}, HR Car's wind will travel 2″ to the center of the nebula in 315 yrs, in which time the total mass lost via the steady LBV wind is only 0.006 $M_\odot$. Any contribution from the companion would be much smaller than this based on the arguments above. Thus the observed mass of material in the inner nebula cannot come from the steady wind of either star based on their current properties. If the nebula was ejected in a single massive LBV outburst rather than by a steady wind, then it is not plausible that the morphology of the nebula is determined by interaction with a relatively much weaker wind from the secondary star. Consequently we feel that a colliding winds model cannot explain the observed morphology.

5.3. A symbiotic model?

The other difficulty with assuming that the observed radio nebula represents the material ejected by the LBV in an outburst is the asymmetry of the nebula with respect to the star: with a velocity of 50 km s^{-1} (Hutsemékers & Van Drom 1991) an ejected mass of order 1 $M_\odot$ which is all thrown out to one side of the star would give a substantial velocity recoil even for a star as massive as HR Car presumably is. It seems unlikely that such an unbalanced mass ejection would take place: none of the nebulae around other LBV stars are as unbalanced with respect to the primary star as is HR Car's. The alternative is that the actual ejection was more balanced (in terms of the net momentum lost by the star), but that the material presently illuminated is unbalanced for other reasons. One possibility known in other contexts is the symbiotic phenomenon: the gas which we observe as a radio nebula is ejected as neutral gas by one star and then ionized remotely by a second star. Classical symbiotic systems consist of a late–type mass–losing giant and a white dwarf. A clear example of this type of behaviour is shown by Antares (M1.5 Iab + B2.5V): the radio image (Hjellming & Newell 1983) shows a compact thermal source at the location of the cool giant and an extended source towards the B star, representing the cavity in the slow dense wind of the cool star which is ionized by the B star. The diffuse radio source has a very sharp edge on the side facing the cool star because the wind density increases rapidly in that direction. If this scenario were to apply to HR Car, the secondary star would have to be a very hot star in order to provide more ionizing photons than HR Car itself (which, as Nota et al. 1997 have noted, is rather cool for an LBV and therefore not a strong source of ionizing photons: they remark that it could only ionize a region $0\farcs2$ in radius). If this were the case, it seems likely that that the only way the companion star could appear to be so much fainter than HR Car is if it is heavily extincted, presumably lying on the far side of the nebula with respect to our line of sight. If this were to be the geometry of the system, it would explain why the the nebula does not have a sharp edge on the side apparently facing the LBV star: we are looking at that side face–on since the plane of the sky is roughly orthogonal to the line joining the two stars. Figure 3 presents a simplified picture of the proposed geometry for this model.

We have used an argument similar to this to explain the observed modulation of the radio flux from η Carinae (Duncan et al. 1995, Duncan, White & Lim 1997): the outflow of the LBV is largely neutral, but the hot companion in the system can ionize gas in the outflow when it is near aphelion of the highly elliptical orbit, i.e., when it is not buried in the dense inner regions of the LBV wind and therefore its ionizing photons can reach more distant lower–density circumstellar gas in the system (White 1999). This does result in an observed distribution which is unbalanced with respect to the LBV in the sense that we only observe blue–shifted emission, because the geometry of the system is such that only blue–shifted gas is ionized by the companion. However, the inner core of the radio emission from η Car also shows the bipolar axes inferred from the geometry of the Homunculus nebula, and the nebula as a whole is reasonably balanced with respect to the star, so even in this interpretation there would remain some important differences between the two nebulae.

There may be a difficulty in applying a symbiotic model to the HR Car nebula. At a projected separation of $3\farcs7$ on the sky and a distance of 5 kpc, the companion is at least 0.1 pc from HR Car. This is a much larger separation than is typical of symbiotic systems (e.g., .003 pc in the case of Antares) but the relevant question is whether there is sufficient density in the gas surrounding the companion star, and we have already argued that this density must be much larger than one infers from the current wind parameters. Using a nebular mass of 0.3 $M_\odot$ and a density of 3200 cm^{-3}, we find that 3×10^{47} ionizing photons s^{-1} are required to keep the nebula ionized. The number of ionizing photons which the star must emit then depends on the solid angle subtended by the nebula as seen from the companion star, which is difficult to estimate. We have argued that the star needs to be on the far side of the nebula, so the nebula should not intercept all the ionizing photons (Figure 3). If the star is at a distance of 0.1 pc from the nebula which has a dimension of order 0.2 pc, the solid angle subtended is of order 3 sr requiring that the star produce over 10^{48} ionizing photons s^{-1} (equivalent to a B0V star: Schaerer & de Koter 1997), but if the distance from the companion star to the nebula is much larger than it appears due to projection effects then the required rate could easily be 10^{49} s^{-1} (equivalent to an O7V star) or larger. The fact that the companion star is not detected in the IR images of Voors et al. (1997), which suffer much less extinction than optical wavelengths and have excellent dynamic range (of order 50), places constraints on the nature of the star since we would expect hot luminous stars to be detected. We estimate from their Figure 1 that the 10 μm flux of the companion star is at least a factor of 150 smaller than that of HR Car, i.e., at most 10 mJy. This upper limit is well above the 10 μm flux expected from a B0V star photosphere at 5 kpc (of order 1 mJy) and O8I(f) stars would have fluxes of order 10 mJy at 5 kpc (Persi, Ferrari-Toniolo & Grasdalen 1983), so it is possible that a B0V star would not be detected in the 10 μm image as long as there was not much dust in its outflow, but we would expect a more luminous star to be detected.

In view of the possible problems with the companion star being responsible for ionizing the inner nebula, we also consider whether it might have been ionized by HR Car itself. HR Car, along with all LBVs, is by classification variable and the effective temperatures of LBV stars can vary considerably (Nota et al. 1997 note that HR Car's stellar temperature changed from 15000 K to 20000 K in a few months), so it is conceivable that HR Car has been hot enough to ionize the nebular mass in the past even though it cannot do so at present. However, for the densities both measured and inferred in the nebula the recombination time $(\alpha n_e)^{-1}$ is very short: 30 years for a density of 3200 cm^{-3} assuming a recombination coefficient $\alpha = 3 \times 10^{-13}$ cm^3 s^{-1}. There does not seem to be any evidence that HR Car has been hot enough to ionize the inner nebula on such a short timescale, which is also much smaller than the dynamical timescales for the nebula (of order thousands of years: Hulbert et al. 1999).

6. CONCLUSIONS

We have presented a sensitive radio image of the nebula associated with the LBV star HR Carinae. Unlike any other known LBV nebula, HR Car's nebula is very unbalanced with respect to the star: the radio emission from the nebula nearly all lies to the east of the star, which itself appears as a compact source. We estimate a core nebular mass of 0.3 $M_\odot$ and additional mass in the outer nebula of up to 0.5 $M_\odot$. Based on the stellar radio flux and a wind speed of 150 km s^{-1}, we estimate a steady mass loss rate of 1.8×10^{-5} $M_\odot$ yr^{-1} for the LBV.

The inner nebula shows no evidence for the bipolar outflow inferred to exist from the structure and kinematics of the outer nebula: the symmetry axes of the inner nebula are at 45° to the bipolar axes, and better match the line joining HR Car to a visual companion $3''.7$ to the east. The dimensions and inferred mass of the nebula are too large for it to be fed by stellar mass loss at the current rate, so it must result from an episode with a much higher mass loss rate. We argue that a colliding–winds scenario is unlikely to explain the observed nebula: the radio emission is thermal rather than nonthermal as in most colliding–wind sources, and the faintness of the visual companion makes it unlikely to have a wind whose momentum would be strong enough to match that of HR Car at the elevated mass loss rate required. We cannot rule out a symbiotic interpretation in which the radio nebula is part of a neutral ejection shell which is ionized on one side by a hot companion star: this requires that the companion star actually be located on the far side of the nebula and implies that the observed companion should be a heavily–extincted hot luminous star. This interpretation has the advantage of explaining why the distribution of gas appears unbalanced with respect to the star. If instead the observed unbalanced nebula was ejected by the star in a single eruptive episode, then the star should have received a hefty recoil in the process. However, the properties required of the companion star in order for it to ionize the observed nebula may be difficult to reconcile with the fact that the star is not detected in the 10 μm image of Voors et al. (1997): a B0V companion without much dust may be consistent with the data.

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Table 1. ATCA Observations of HR Carinae.

Date	Frequencies (MHz)	Observing time (hours)	Array length (km)
1994 Aug 23	5444, 8585	2.1	6.0A
1994 Sep 05	5444, 8585	1.1	6.0A
1995 Jan 02	5855, 9200	11.0	6.0A
1995 Apr 11	8256, 9024	11.7	6.0C
1995 May 28	5855, 8256	10.0	1.5B
1995 Nov 08	5444, 8585	1.5	6.0A
1995 Dec 09	5444, 8585	1.4	6.0C
1998 Mar 01	1420, 2496	4.8	6.0B

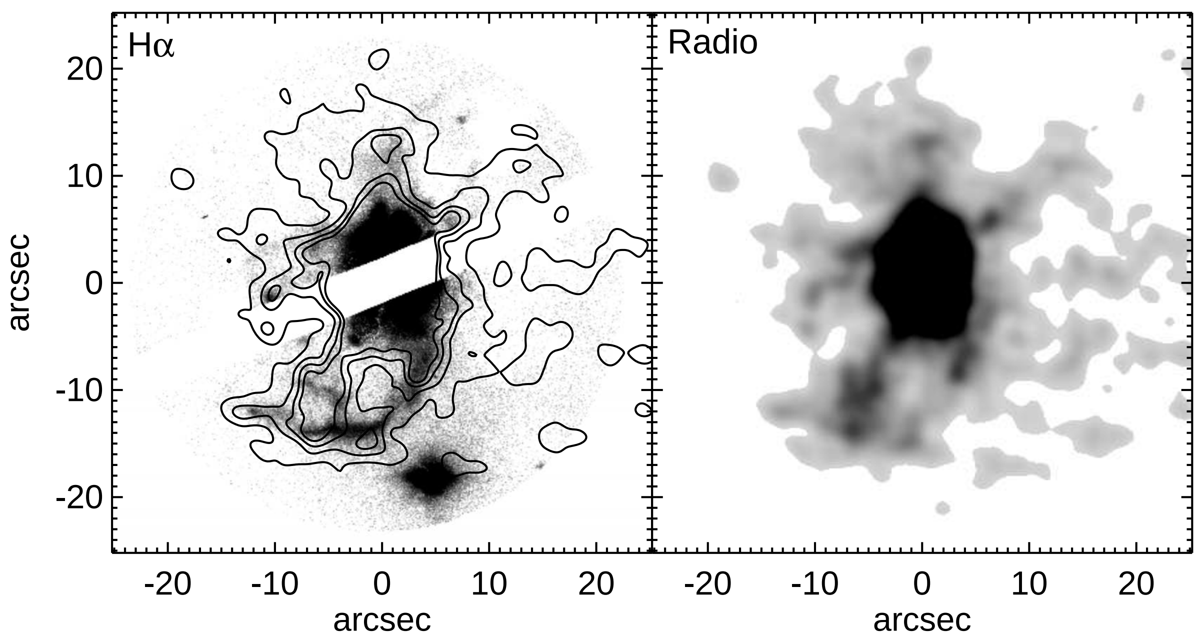

Fig. 1.— The left panel shows an overlay of contours of the ATCA radio image of the HR Carinae nebula on the coronagraphic image (greyscale) in Hα acquired by Nota et al. (1997). The contours and the greyscale display are chosen to emphasize weak features in the outer regions of the nebula. The radio image has been convolved to a beam size of $1.2''$. The diagonal blank stripe across the Hα image is the coronagraphic occulting bar. The contours are at 6, 10, 14, and 18 μJy per beam. The right panel shows a greyscale representation of the radio image saturating at 30 μJy per beam.

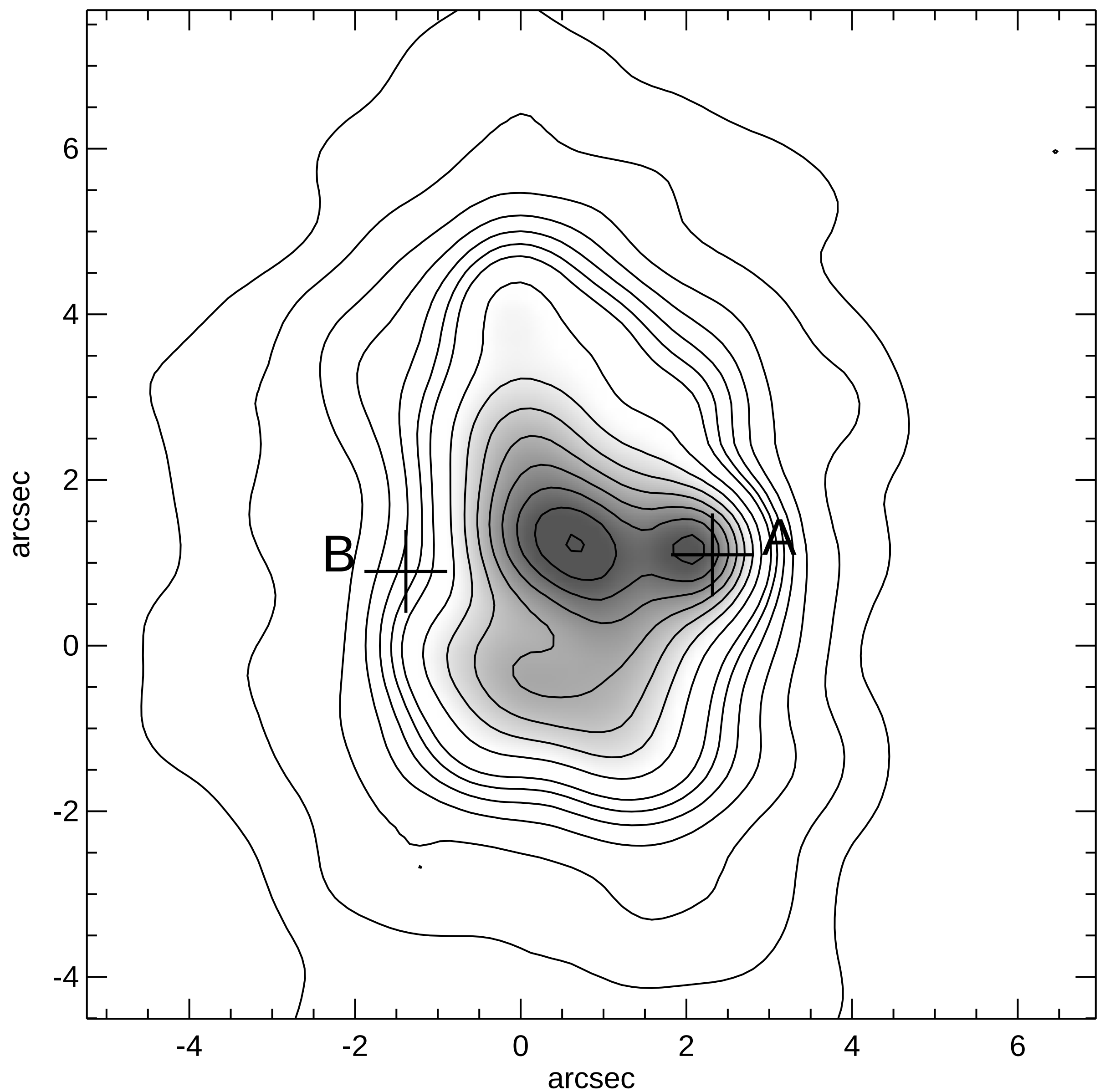

Fig. 2.— The core of the nebula associated with HR Carinae. The contours show the radio emission at a resolution of 0.″8 using contours at 15, 30, 60, 90, 120, 150, 180, 240, 300, 360, 420, 480, 540, 600 and 660 μJy per beam. The greyscale display emphasizes the brightest features in the nebula. Crosses mark the positions of HR Carinae (labelled "A") and its visual companion 3.″7 to the east (labelled "B").

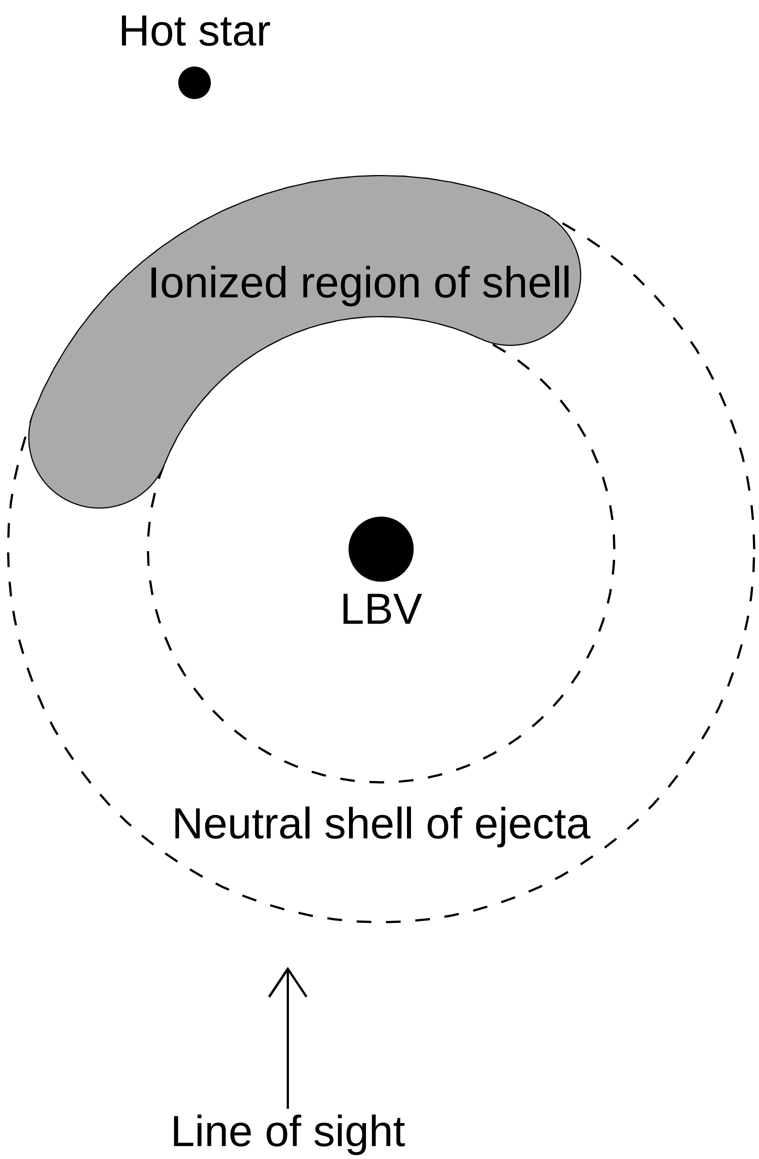

Fig. 3.— A rough model for the geometry of a symbiotic interpretation of the nebula of HR Carinae. In this figure the system is viewed from “above” (along the declination axis) with the line of sight to the Earth as shown and the right ascension axis across the page horizontally. In this model the ionized nebula consists of gas from an earlier ejection episode from HR Car which lies in a shell around the Luminous Blue Variable. Most of the gas in this shell is neutral and hence undetected, but the region of the shell closest to the hot companion is ionized and produces the observed radio emission. Since the observed nebula is elongated north–south, the ejecta shell cannot be spherically symmetric in this model but must be ellipsoidal, e.g., due to higher velocities along the poles of the outflow.