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ISOCAM imaging of AG Car and HR Car *

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Abstract. We present infrared images obtained with the ISOCAM instrument on board the Infrared Space Observatory of two Luminous Blue Variables (AG Car and HR Car). The images were obtained at eight wavelengths between 8.5 and 16 μm using the Circular Variable Filters (CVFs), with a pixel size of 6 by 6 arcsec and a total field of view of 192 by 192 arcsec. The nebula around AG Car is clearly resolved. The nebula is particularly strong in the [Ne II] emission line and at the longer wavelengths in the continuum. Using these images independent spectral energy distributions are obtained of the star and the nebula. The spectral energy distribution indicates that most of the infrared radiation in AG Car originates in the extended nebula, and may be due to thermal radiation of dust in the nebula. In fact most of the IR radiation of this object longward of 10 μm originates in the nebula. The star HR Car is not clearly resolved, although the spectra calculated by adding the pixels show some marked differences between the spectrum of the central pixel and the area around the central pixel, indicating the presence of extended emission also in this object.

Key words: Stars: imaging – Stars: circumstellar matter – Stars: early type; Infrared: stars

1. Introduction

Luminous Blue Variables (LBVs) are among the most luminous stars in the universe. They are located close to the upper luminosity limit in the H-R diagram (the Humphreys-Davidson limit, Humphreys & Davidson, (1979)). The LBVs are characterized by:

1. Variability (photometric and spectroscopic) on a variety of scales:
   Eruptions or outbursts ΔM>3 mag. Large and sudden variations have been observed in three of the LBVs (P Cygni, η Car and V12 in NGC 2403). During these outbursts large amounts of mass are expelled from the star.
   Moderate variations ΔM=1-2 mag. These variations are common in the LBVs and are observed on timescales of decades. They are connected to variations in the mass loss of the stars.
   Smaller variations ΔM=0.5 mag. These variations occur on timescales of months to years.
   Microvariations ΔM<0.1 mag. These variations are very similar to the variations seen in normal supergiants
2. Spectra showing evidence of very large mass loss rates (as high as 10^{-4} to $10^{-5} M_{\odot}/yr$).
3. Temperature variations between maximum and minimum brightness (typically the temperatures vary between 8000 and 20000 K).
4. High intrinsic luminosity: M_B <-9.
5. Evidence for some IR excess due to dust or free-free emission.

A good review of the LBVs can be found in Humphreys (1989)

In this paper we present ISO results on two LBVs: AG Car and HR Car. AG Car (HD94910, Sp.T. B0 I to A1 I) is a well known LBV. It has been extensively studied in the ultraviolet, optical and near infrared. It has an optical nebula Thackeray (1950). This nebula has been imaged in the optical at high resolution by Paresce and Nota (1989), and more recently by Nota et al. (1995). They find evidence for a bipolar structure in the nebula, with strong emission especially in the NE and SW, and an elogation in the NW and SE directions. The nebula has a size of about 40 by 30 arcsec. Far infrared radiation has been observed in the nebular ring (McGregor et al., 1988a and 1988b). The star HR Car is less well studied then AG Car. Recently, however, Hutsemekers & Van Drom (1991) found

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an arc-shaped nebula about 13 to 17 arcsec from the star in the SE direction in an Hα image. Recent coronographic imaging by Clampin et al (1995), shows a filametary structure in a NW-SE bipolar nebula.

Nota et al. (1995) suggest that the morphology of both nebula can be explained by interaction of the stellar wind with a pre-existing density contrast between the polar and equatorial directions. A review of the ring nebulae around LBVs can be found in Smith, (1994).

2. The Observations

Observations were carried out with ISOCAM in staring mode with the 6" pixel field of view, the LW-l beam, an integration time of 2 seconds and a gain of 2. A description of the ISOCAM instrument can be found in Cesarski et al. (1996). The other observing paremeters are given in Table 1.

Table 1. Observing parameters for the CAM images of AG Car and HR Car. The wavelengths are the actual observed wavelength taken from the data products. The number of stabilizations and exposures are the numbers entered into PGA.

λ	$\Delta\lambda$	N_{stab}	N_{exp}	comment
8.689	0.196	15	20	continuum
8.993	0.201	15	20	[Ar III]
11.480	0.277	13	20	cont. and PAH
12.410	0.286	13	20	Humphreys α
12.820	0.290	13	20	[Ne II]
13.530	0.297	14	20	continuum
15.580	0.314	16	20	[Ne III]
15.960	0.317	18	20	continuum

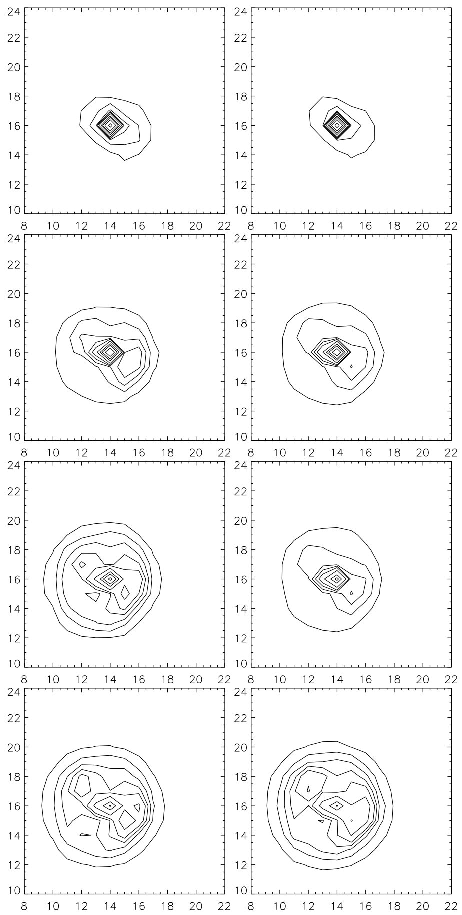

Fig. 1. The contour plots of the 8 images of AG Car. From top left to bottom right the images are taken at the following wavelengths: 8.689 μm; 8.993 μm; 11.480 μm; 12.410 μm; 12.820 μm; 13.530 μm; 15.580 μm; 15.960 μm. North is at the top, east at the left. The contour levels vary between 0 and 3 Jy. The x and y axes are in pixels.

The images were processed on 1 July 1996 through Version 4.1.2 of the standard pipeline processing, using CAM calibration data version 2.20, and the CAM Auto Analysis results (CMAP files) are used in the rest of this paper.

Figure 1 shows a mosaic of contour maps of the eight CAM images of AG Car. The nebula of this star is clearly seen, and is especially strong at the longest wavelengths (the bottom two pictures) and in the [Ne II] line. The nebula is not spherically symetric, but shows a bright "bar" running from SW to NE. This is very similar to the optical image shown by Paresce & Nota (1989) and by Nota et al. (1995), abd also to the K-band image shown by McGregor et al. (1988a).

Figure 2 shows a mosaic of contour plots of the eight CAM images of HR Car. In this case the nebula is not evident in the images. There is some emission present outside the central pixels, but this is at a very low level, and at this time it is not clear whether this is the nebula or radiation diffracted from the central pixels. Also there appears to be no clear brightening of the source in the [Ne II] line.

3. Star versus Nebula

The eight images at different wavelengths can be used to determine the spectral energy distribution between 8 and 16 micron of the star and the nebula independently.

In Figure 3 we have added the flux in a 10 by 10 pixel area around AG Carinae, but subtracting the central pixel (thus in effect subtracting the central star). This is then the spectrum of the nebula as seen through a 60 by 60 arcsec aperture, but with the central 6 by 6 arcsec blocked off. Diffraction measurements show that at 8.7 μm 11 % of the flux of a point source will be diffracted to adjacent pixels. At 16 μm this is 57 %. The squares indicate the spectrum of the central pixel (the star). It is clear that most of the IR flux originates in the nebula. The star

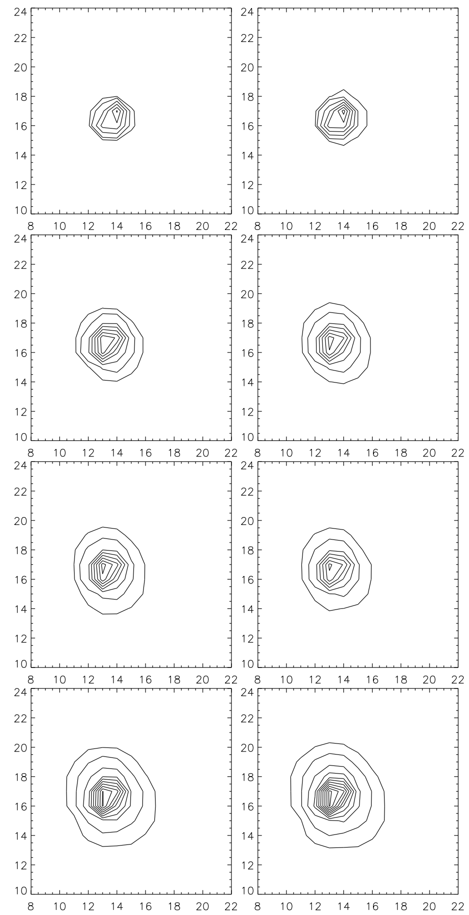

Fig. 2. The contour plots of the 8 images of HR Car. See Fig. 1 for the wavelengths and contour levels. North is at the top and east to the left. The x and y axes are in pixels.

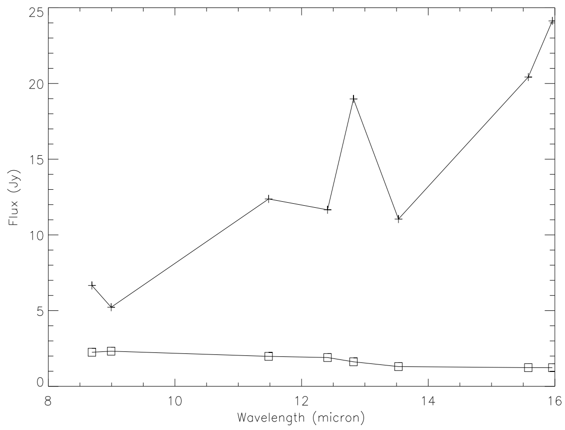

Fig. 3. The spectra of AG Car. This shows the total spectrum of a 10 by 10 pixel area centered on the star, but with the central pixel excluded (+) and the spectrum of the central pixel (□).

only contributes 56 % at 8 micron to less than 20 % at 16 micron (corrected for diffraction), in agreement with the far infrared observations of McGregor et al. (1988a)

It is clear from the spectra that the [Ne II] emission is especially strong in the nebula. There is also some indication for Humphreys α emission from the star. Indeed the SWS spectrum, as presented by Lamers et al. (1996) shows a clear Hu-α emission line. Interestingly enough the points in the nebular spectrum at 8.6 and 11.5 μm seem to lie somewhat above the continuum. This could indicate the presence of PAHs in the nebula of AG Car. The nebular continuum is clearly rising towards the longer wavelengths whereas the stellar continuum is falling (but less steep than a Raleigh-Jeans law).

For HR Car the source is not clearly resolved, therefore it is not a priori clear that the spectra of the area around the star and the star itself (central pixel) will be different. However in Figure 4 we plot the spectra of the star (i.e. of pixel 15,17; the squares) and the added spectrum of a 6 by 6 pixel area centered on the star (plusses) but with the central pixel excluded. Clearly there are some marked differences. First of all the [Ne II] emission is much more clearly seen in the added spectrum. More importantly however, the flux in the added spectrum increases towards longer wavelengths, whereas the stellar spectrum is more or less flat (it starts to increase at about 13 micron). This clearly indicates that there is nebular emission outside the central pixel. We thus conclude that also HR Car is extended at these wavelengths, the nebula however is too weak with respect to the star to show up with any confidence in the images produced with the current processing.

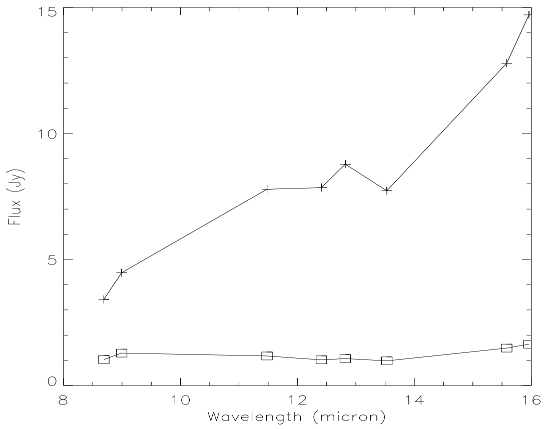

Fig. 4. The spectrum of HR Car. This plot shows the total spectrum of a 6 by 6 pixel area centered on the star, but with the central pixel excluded (+) and the spectrum of the central pixel (□).

4. The [Ne II] Line in AG Car

To better understand the physics of the AG Car nebula, we calculated images for the line to continuum ratio of the [Ne II] line and the line flux of the [Ne II] line (i.e. the line minus continuum image; Figure 5). The continuum flux was estimated using a linear interpolation between the 12.410 and the 13.530 micron images. The resulting images show some striking differences. The most important difference is that the line flux (line minus continuum) is strongest in the SW part of the nebula and also has a smaller peak in the NE part. The line to continuum ratio (i.e the relative strength of the line w.r.t. the continuum) on the other hand peaks in the SE and NW parts of the nebula and is significantly weaker in the SW and NE parts. The explanation for this probably lies in the dust continuum. The dust continuum in the SW and NE parts is significantly stronger (see the spectra in Figure 3). Therefore the [Ne II] lines will appear weaker relative to this dust continuum, although in an absolute sense they are stronger.

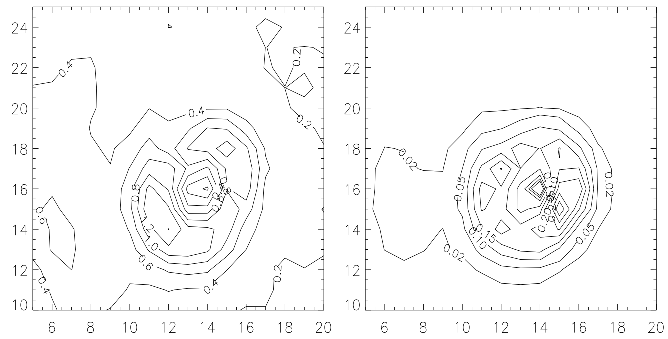

Fig. 5. The contour plot of the [Ne II] line to continuum ratio (left panel) and the [Ne II] line minus continuum (right panel) for AG Car. These contour plots only shows the central part of the image.

5. Discussion and Conclusions

Our ISOCAM images of AG Car and HR Car show that the first source is clearly extended. Although HR Car does not appear extended in the images themselves, when the total spectrum is calculated of an area around the central star, it clearly differs from the stellar spectrum, suggesting that also in this case some flux is seen from an extended source. The spectra of both objects show clear differences between the star and the nebula, with the [Ne II] line and the spectral index as the most significant difference. The [Ne II] line in AG Car is strongest in the SW and NE regions of the nebula where also the dust continuum is strongest. This is in agreement with the observations of McGregor et al. (1988a) who found that the far infrared radiation from the nebula coincides with the ionized region observed in H α. Similar to the far infrared observations no emission at shorter wavelengths is seen outside the ionized region. The line to continuum ratio peaks in the SE and NW regions where the dust continuum is weaker. From the spectra of the star and the nebula for AG Car it is clear that most of the IR radiation originates in the nebula. One possible source of this radiation is thermal emission of dust in the nebula. This would mean that there is warm dust present in the nebula at distances upto 1 pc from the star. This is also in agreement with the results presented by Lamers et al. (1996). This dust would then also be the material responsible for the scattering of the stellar continuum radiation at optical wavelengths.

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