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Publication date
1996

Published in
Astronomy & Astrophysics

Link to publication

Citation for published version (APA):
Lamers, H. J. G. L. M., Morris, P. W., van Gent, J. I., de Graauw, T., Waters, L. B. F. M., Kudritzki, R. P., Najarro, F., Salama, A., & Heras, A. M. (1996). The ISO-SWS spectra of luminous blue variables. *Astronomy & Astrophysics*, *315*, L225-L228.

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Astron. Astrophys. 315, L225–L228 (1996)

ASTRONOMY AND ASTROPHYSICS

The ISO-SWS spectra of Luminous Blue Variables*

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Received 23 July 1996 / Accepted 19 August 1996

Abstract. We present the infrared spectra between 2.4 and 45 μm of two Luminous Blue Variables (AG Car, HR Car) observed with the *Short Wavelength Spectrometer* of ISO. The spectra consist of two parts: (1) the tail of the photospheric energy distribution with the free-free excess from the lower layers of the stellar wind, (2) emission from circumstellar dust. The free-free emission can be explained by models with the following parameters: $T_{\rm eff}$ = 13000 K, R_*=250 $R_\odot$, and $\dot{M}$ = 9×10^{-5} $M_\odot$ yr^{-1} for AG Car and $T_{\rm eff}$ = 10000 K, R_*=220 $R_\odot$, and $\dot{M}$ = 1.7×10^{-5} $M_\odot$ yr^{-1} for HR Car. The mass loss rate has an uncertainty of a factor 1.5 within the context of our models. We also derive the properties of the dust by modelling the energy distribution with optically thin dust models. The difference in the flux measured through two different apertures gives information on the projected distribution of the dust. The distribution of the dust around AG Car corresponds with that of the gaseous nebula and has a dust mass of 0.03 $M_\odot$. The dust around HR Car extends to a much larger distance than the gaseous nebula and cannot be modelled with a single spherically symmetric shell.

Key words: infrared radiation – stars: circumstellar matter – stars: variable – stars: mass loss – stars: supergiant – stars: individual: AG Car – stars: individual: HR Car

1. Introduction

Luminous Blue Variables (LBVs) are the most unstable single stars, apart from Supernovae. They are photometrically variable on all time scales from weeks to decades. During "typical LBV variations" the radius of the star increases for a few years by about a factor 4 to 8 from about 30 to 250 $R_\odot$. The mass loss rate of LBVs is typically 2 to 4 times 10^{-5} $M_\odot$ yr^{-1} and the wind velocity is about 150 to 250 km s^{-1}. Several LBVs have shown historic giant eruptions, e.g. P Cyg and η Car. During these eruptions the LBVs eject about a $M_\odot$ of gas. From statistics of a small number of LBVs and from the observed circumstellar (CS) shells around LBVs it is estimated that most if not all LBVs have giant eruptions at intervals on the order of 10^3 years. Most LBVs are surrounded by a nebula containing gas and dust, which is mainly the result of the large eruptions, but might also in part be due to the high mass loss rate of LBVs. For recent reviews see Humphreys and Davidson (1994) and Lamers (1996).

In an attempt to study the past history of the LBVs and their present mass loss we observed two LBVs with the $ISO-SWS$ instrument. We derive the present mass loss rate from the near IR free-free emission and the dust distribution from the far IR emission.

2. The program stars and the observations

The program stars selected for this study are listed in Table 1. The stellar data are from Clampin et al. (1995), Humphreys et al. (1989), Humpreys and Davidson (1994), Hutsemékers and van Drom (1991), Lamers (1988) and van Genderen et al. (1991). The masses are derived from evolutionary tracks by Schaller et al. (1992). HR Car and AG Car are highly variable in visual magnitude, effective temperature and radius but the luminosity is approximately constant. The mass has an uncertainty of about 10 $M_\odot$ because of the uncertain evolutionary phase of LBVs.

The stars were observed with the *ISO Short Wavelength Spectrometer* over the full SWS grating range (2.38 – 45.2 μm) using the ISO Astronomical Observing Template S01 (Kessler et al. 1996; de Graauw et al., 1996). The spectra of AG Car and HR Car were scanned on JD 50262.335 at the fastest of the four S01 scanning rates (17.5 minutes). This gives a nominal (point source) spectral resolution in the range of $\lambda/\Delta\lambda \simeq 250 - 600$.

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of $ISAS$ and $NASA$

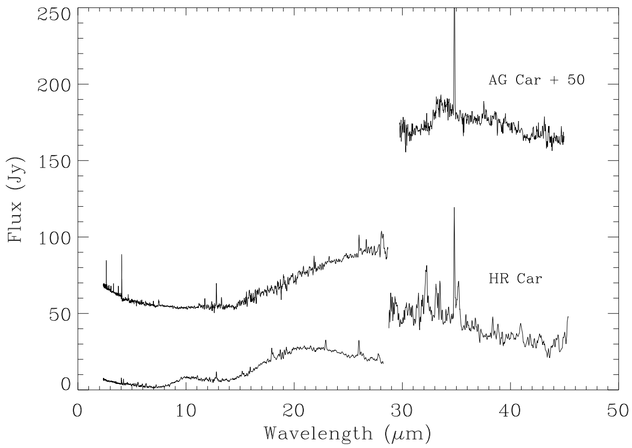

Fig. 1. The energy distribution of AG Car and HR Car observed with the *ISO-SWS* in the observing mode of *AOT1*. The spectrum of AG Car is shifted upwards by 50 Jy. The jumps in the energy distributions at 28 μm are real and explained below.

Table 1. The program stars

Star	$\log(L_*)$	M_*	d	E(B-V)
	$L_\odot$	$M_\odot$	kpc	magn
AG Car	6.22	53	6	0.63
HR Car	5.63	30	5.4	1.0

Each spectrum was processed at the ISO Science Operations Center at VILSPA using software of the SWS Interactive Analysis (IA) package. General descriptions of the software and the calibrations may be found in de Graauw et al. (1996), Schaeidt et al. (1996) and Valentijn et al. (1996). Combining the output of each of the 12 detectors in each of the four grating bands was done iteratively, treating each combination of detector block, aperture and order separately. The up and down grating scans were inspected for memory and dark current effects. Further details on the data reduction will be given in a future publication. The flux in Band 1 (2.4 – 4.2 μm) has an accuracy of about 10 percent. The flux in the other bands has an accuracy of about 20 percent.

3. The energy distributions

The energy distributions of AG Car and HR Car are shown in Figure 1.

AG Car. The CS nebula of AG Car was studied in the optical by Paresce and Nota (1989), Nota et al. (1992) and by de Freitas Pacheco et al. (1992) and in the IR by McGregor et al. (1988). The optical nebula is elliptical with a diameter of 30 × 39 arcsec (Thackeray 1950). The dust has a bipolar structure along the NE-SW direction extending from a few to ≈15 arcsec.

The *SWS*-energy distribution of AG Car shows that the flux decreases from 2.4 to about 12 or 15 μm and increases again to longer wavelengths. The first part is due to the photospheric radiation and the free-free emission and the second part is due to CS dust. There is a jump in the energy distribution near 29 μm at the transition between spectral scans with Band 3 and 4. This is due to the fact that the aperture of Band 3 is 14 × 27 arcsec, whereas that of Band 4 is 20 × 33 arcsec. The jump shows that the radiation at $\lambda \simeq 30\mu$m comes from a region that is larger than the aperture of Band 3 (see §5). The bump in the energy distribution at 33 to 35 μm is real. It is also seen in the *SWS* observations of Planetary Nebulae and indicates the presence of an unidentified dust feature (Waters et al. 1996).

HR Car. The nebula of HR Car was studied in the optical by Clampin et al. (1995) and Hutsemékers and van Drom (1991) and in the near IR by Voors et al. (1996). They found a small clumpy inner nebula of about 8 arcsec across and filaments out to 18 arcsec from the star.

The *SWS*-energy distribution shows the typical slope of free-free emission at $\lambda < 7\mu$m. The bump near 10 μm shows the presence of the 9.7 μm silicate emission feature, which agrees with the expected C-deficient and N-rich environment of post main sequence stars. The jump in the flux between Band 3 and 4 at 29 μm and the peak of the emission around 32 μm suggest that the dust is extended beyond the size of the aperture of Band 3. The structure in the energy distribution at $\lambda > 30$ μm is possibly real and due to several dust features.

4. Modelling the free-free emission

4.1. AG Car

The star shows large photometric variations in the visual of about 2 magn due to large irregular changes in R_* and $T_{\rm eff}$. The visual photometry of AG Car is not known at the time of the *SWS* observations. Therefore we have to estimate V and the corresponding values of $T_{\rm eff}$ and R_* on the basis of the *SWS* data. We adopted the Galactic extinction curve of Rieke and Lebofsky (1985).

The observed continuum flux of AG Car between 2.4 and 12 μm, corrected for interstellar extinction, is shown in Fig 2. The energy distribution is almost a powerlaw, $F_\nu \sim \nu^\alpha$ with α = 1.28. We extrapolate this powerlaw to a wavelength of 5500 Å and derive a reddened V = 5.5 at the time of the SWS observations. This is only a rough first estimate, because the real slope of the energy distribution is not expected to be constant between 2.4 and 0.55 μm. Adopting the luminosity of Table 1 and the relation between Bolometric Correction and $T_{\rm eff}$ from Kurucz (1991) we find for a first estimate that $T_{\rm eff} \simeq$ 10 000 K and $R_* \simeq 280$ $R_\odot$ at the time of observations. We then iterated the modelling.

The free-free emission of AG Car was modelled with the program *EMISSEI* (Van Gent and Lamers, 1996), which calculates the spectrum of an atmosphere and wind with a given temperature structure, density structure and composition. We adopted a He/H ratio of 0.4 which is about the value derived for several LBVs. The density structure is related to the velocity law and the mass loss rate via the mass continuity equation

$$\dot{M} = 4\pi r^2 \rho(r) v(r) = 4\pi r^2 \rho(r) v_\infty \{1 - r_s/r\}^\beta \quad (1)$$

where v_∞ is the terminal velocity of the wind, β describes the steepness of the velocity law and r_s is the radius where the sound velocity (typically about 20 km s^{-1}) is reached with $r_s \simeq R_*$. The free parameters for fitting the energy distribution are $(\dot{M}/v_\infty)$ and β. We adopted a very simple temperature structure

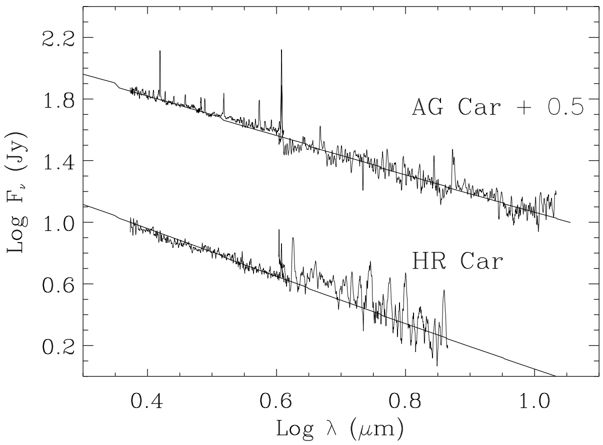

Fig. 2. The observed near IR energy distributions of AG Car and HR Car compared with predicted free-free energy distributions. The spectrum of AG Car has an offset of 0.5 dex.

Table 2. The stellar data derived from free-free emission

Star	$T_{\rm eff}$	R_*	V	v_∞	β	$\dot M$
	kK	$R_\odot$	(mag)	km s^{-1}		$M_\odot$ yr^{-1}
AG Car	13	250	6.00	150	1.0	10×10^{-5}
	13	250	6.00	150	2.0	8×10^{-5}
HR Car	10	220	7.82	150	1.0	2×10^{-5}
	10	220	7.82	150	2.0	1.5×10^{-5}

of $T(r) = T_{\rm eff}(r/R_*)^{-m}$ with $m = 0.5$, which roughly fits the temperature structure in detailed wind models (Morris and Lamers, 1996). The free-free emission is formed close to the star, so the model is not very sensitive to the details of the temperature structure. The fitted spectrum also gives the ratio of the flux at 5500 Å and at 2.4 μm. With this ratio, the V magnitude was recalculated and a new value of $T_{\rm eff}$ and R_* were derived. The method is then repeated until it converges. The resulting model produces a spectrum that fits the SWS energy distribution for a star with the luminosity as given in Table 1.

We adopted two values of β, in the range of values found for the lower layers of the winds of LBVs (Smith et al. 1994, Lamers, Najarro et al. 1996). and a terminal velocity of 150 km s^{-1}, which is a typical value for LBVs close to visual maximum (Lamers, 1989). The observed and fitted energy distributions are shown in Figure 2 and the resulting stellar data are given in Table 2. The stellar temperature and radius turn out to be rather insensitive to the choice of β, only the mass loss rate changes. The final estimate of the temperature is 13000 K which corresponds to V=6.00. We note that the match is not perfect, and that the uncertainty in the calibration of the SWS flux of 10 % limits the accuracy of the final model to about a factor 1.5 in the mass loss rate within the context of our model. We conclude that the mass loss rate of AG Car at the time of the *SWS* observations was 9×10^{-5} $M_\odot$ yr^{-1} within a factor 1.5.

4.2. HR Car

The method used for HR Car is the same as for AG Car. In this case the dereddened SWS spectral energy distribution is almost a power law with a slope of 1.53, which results in a first estimate of the reddened visual magnitude of $V \simeq 7.5$. This is very close to the value at maximum visual brightness (Spoon et al. 1994). Adopting the luminosity of Table 1 and using the same procedure as for AG Car we find as a first estimate of the stellar data: $T_{\rm eff} \simeq 8000$ to 10000 K and $R_* \simeq 340$ to 220 $R_\odot$. The model calculations with the spectral fits are derived in the same iterative way as described above. The resulting spectral fit is shown in Figure 2 and the data are listed in Table 2. The uncertainty in the flux calibration introduces an uncertainty in the mean spectral slope between 2.4 and 12 μm of $1.47 < \alpha < 1.78$. Since the star is close to visual maximum, we adopted v_∞=150 km s^{-1} and β=1.0 or 2.0. The resulting mass loss rates are 2.0 and 1.5 $\times 10^{-5}$ $M_\odot$ yr^{-1}and the visual magnitude is V = 7.82.

5. Modelling the dust emission

We have modelled the IR energy distribution of AG Car and HR Car with an optically thin dust model, following Sopka et al. (1985). We assume a spherically symmetric model with a density distribution of the dust that varies with distance as $\rho_d = \rho_0(r/R_*)^{-2}$. The dust is assumed to be in radiative equilibrium with the stellar radiation. The wavelength dependence of the opacity is approximated by a powerlaw dependence as $Q_\nu \sim \nu^p$, where $p \simeq 1$ to 2 (Draine and Lee 1984; Mathis 1996). The free parameters of the models are: the inner and outer radius of the dust, ρ_0 and the value of p. The assumption of radiative equilibrium gives the temperature distribution in the CS dust shell: $T(r) = T_0(r/R_*)^{-2/4+p}$, where T_0 is a normalisation temperature usually of the order of 0.6 T_* (Sopka 1985). The inner radius determines the highest dust temperature, which is directly reflected in the short wavelength rise of the dust emission. The outer radius determines the coolest dust and its distance from the star.

In fitting the data we took into account the size of the aperture of the *SWS* spectrograph for the different bands. The aperture was oriented nearly along the NE-SW direction during the *SWS* observations of AG Car. However, there may have been a small offset of the star from the center of the slit by as much as 4 arcsec. For simplicity we adopted a circular aperture centered at the star, with an area equal to that of the real aperture. Although this approximation is a crude one, it is suitable for discriminating models for which the projected dust distribution does not agree with the observations. The result is shown in Fig. 3.

AG Car. The jump in the flux between Band 3 and 4 is almost a factor 3, whereas the ratio of the apertures is a factor 1.75. This means that most of the "cold dust" is outside the aperture of Band 3 of 14 × 27 arcsec. The best fit is reached for $p \simeq 1$, an inner radius of the dust of 4.3×10^5 R_*= 1.44×10^{18} cm which corresponds to an angular distance of 16 arcec. The outer dust radius is best constrained by using both the *ISO-SWS* observations and photometry at longer wavelengths, IRAS (60 μm) and KAO (50 and 100 μm) measurements (McGregor et al. 1988). This gives an outer radius of the dust at 5.0×10^5 R_*= 1.67×10^{18} cm.

The inner radius of 16 arcsec corresponds roughly with the inner radius of the optical nebula which indicates that the dust

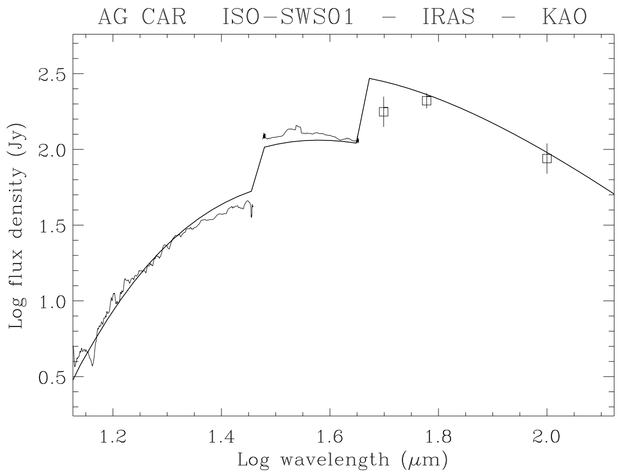

Fig. 3. The far-IR energy distribution of AG Car, based on SWS, $IRAS$ and KAO data, are fitted with an optically thin dust model. The jumps are due to the difference in apertures.

and the gaseous nebula coincide. Assuming a circumstellar grain size of 0.1 μm, a mass density of grain material of 3 g cm^{-3} and a grain emissivity of 7.5 $\times 10^{-4}$ at 125 μm (Hillebrand 1983), we find the total dust mass is 0.03 $M_{\odot}$. This is higher than the dust mass of 0.015 $M_{\odot}$ derived by Smith et al. (1994) who assumed an isothermal dust cloud. With the canonical gas to dust mass ratio of 10^2 this amounts to a total mass of ≈ 3 $M_{\odot}$ for the entire nebula. This is close to the value of 4.2 $M_{\odot}$ found by Nota et al. (1992)

HR Car. The jump in the spectrum of HR Car at 28 μm is surprising. Ground-based (Voors et al. 1996) and ISOCAM (Trams et al. 1996) images between 10 an 15 μm only show the presence of a small inner nebula of a diameter of less than 10 arcsec. If this were the only dust component present around HR Car there would be no jump in flux between Bands 3 and 4. Clearly there is also a colder and therefore more extended dust component, which is not yet seen at wavelengths shorter than $\approx$ 15 μm. Optical images show the presence of a thin filamentary nebula surrounding HR Car, that extends out to $\approx$ 18 arcsec (Hutsemékers & van Drom 1991).

It is not possible to obtain a reasonable fit to the observed *SWS* spectrum of HR Car using an optically thin, spherically symmetric single shell dust model. The warm dust of HR Car is closer to the star than in the case of AG Car. If the temperature distribution of the dust is the same for the two stars, the cold dust that emits near 30 μm would be within the size of the aperture of Band 3 and would produce no jump in the SWS spectrum. So multiple dustshells or a shell with a non-standard temperature distribution are needed to explain the presence of the jump.

6. Summary and Discussion

We have observed the free-free emission and the dust emission of the the LBVs AG Car and HR Car. In the analysis of the free-free emission we have assumed that the nebula does not significantly contribute to the radiation in the range of about 2.4 to 6 μm. The IR data suggest that both stars are close to maximum radius and low $T_{\rm eff}$ during the *SWS* observations. We modelled the free-free emission and derived the mass loss rate at the time of the IR observations.

The lightcurves of AG Car and HR Car have been published by Spoon et al. (1994). The derived value of V = 6.00 for AG Car during the *ISO* observations (July 1996) is brighter than V = 6.53 measured in March 1996 (L.J. Smith, private comm.). So either AG Car has brightened in early 1996 or *SWS*-flux between 2 and 10 μm was severely affected by emission from the nebula. This will be investigated in a forthcoming paper. The derived magnitude V = 7.82 of HR Car agrees with recent visual estimates (L.J. Smith, private comm).

We have modelled the dust with a simple optically thin dust model, taking into account the different sizes of the entrance apertures of Band 3 and Band 4. For AG Car we find a reasonable fit of the observed dust emission. For HR Car however the fits do not match the observations at all. Obviously a single shell model with a standard temperature distribution is too simple to explain the observations of this star. This will be studied in more detail in a forthcoming paper. In forthcoming papers we will study the many permitted and forbidden emission lines in the spectrum of the LBVs and the dust features.

Acknowledgements. We thank the referee, Linda J. Smith, for usefull comments and suggestions.

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