Herschel observations of nebulae ejected by massive evolved stars

C. Vamvatira-Nakou[1], D. Hutsemékers[1,2], P. Royer[3], Y. Nazé[1,2], N. L. J. Cox[3], K. Exter[3], M. A. T. Groenewegen[4], P. Magain[1], C. Waelkens[3]

1 Institut d'Astrophysique et de Géophysique, Université de Liège, Belgium 2 FRS-FNRS, Belgium
3 Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Belgium 4 Royal Observatory of Belgium

Abstract

We have obtained far-infrared Herschel PACS imaging and spectroscopic observations of nebulae associated to massive evolved stars. The study of these nebulae is crucial to understand the evolution of these stars as it can reveal the mass-loss history.

The infrared images along with available data at other wavelengths give a complete view of their morphology. The dust modeling provides the dust parameters, such as the temperature, the mass and the composition of dust. The spectroscopic analysis provides the gas C,N,O abundances and mass. Based on these observations, the evolutionary status of the star at the time of the nebula ejection can be constrained.

We present here selected results of an ongoing exhaustive study of nebulae around low- and high-luminosity LBVs (AG Car, HR Car, WRAY 15-751, G79.29+0.46, HD168625), WN stars (NGC6888, M1-67, He3-519) and Of stars (NGC6164/5).

1. Introduction

In current evolutionary scenarios (Maeder & Meynet 2010), an early-type O star evolves into a Wolf-Rayet star by losing a significant fraction of its initial mass. Progressively, the outer layers of the star are removed, revealing a "bare core" that becomes a WR star. One way to lose mass is through stellar winds. However, in the past few years the mass-loss rates of O stars have been revised downward by up to one order of magnitude (Fullerton et al. 2006) and more often by a factor of a few (Bouret et al. 2005; Puls et al. 2008), highlighting the key role played by episodes of extreme mass-loss in an intermediate evolutionary phase (LBV or red supergiant phase). In this study we use observations of the circumstellar environment of a representative sample of evolved massive stars (Table 1) to constrain the evolution of the central stars and the epoch at which these nebulae were ejected. We obtained PACS imaging (targets in Table 1) and spectroscopic observations (for the brightest targets only). Part of these observations was done in the framework of *Mass-loss of Evolved StarS (MESS)* Herschel Guaranteed Time Key Program (Groenewegen et. al. 2011).

Table 1. List of targets

name of star (nebula)	type of star
AG Car	LBV
HR Car	LBV
WRAY 15-751	LBV
G79.29+0.46	LBV
Hen 3-519	LBV candidate/WR
HD 168625	LBV candidate
M1-67	WR
WR136 (NGC 6888)	WR
HD 148937 (NGC 6164/5)	Of?p

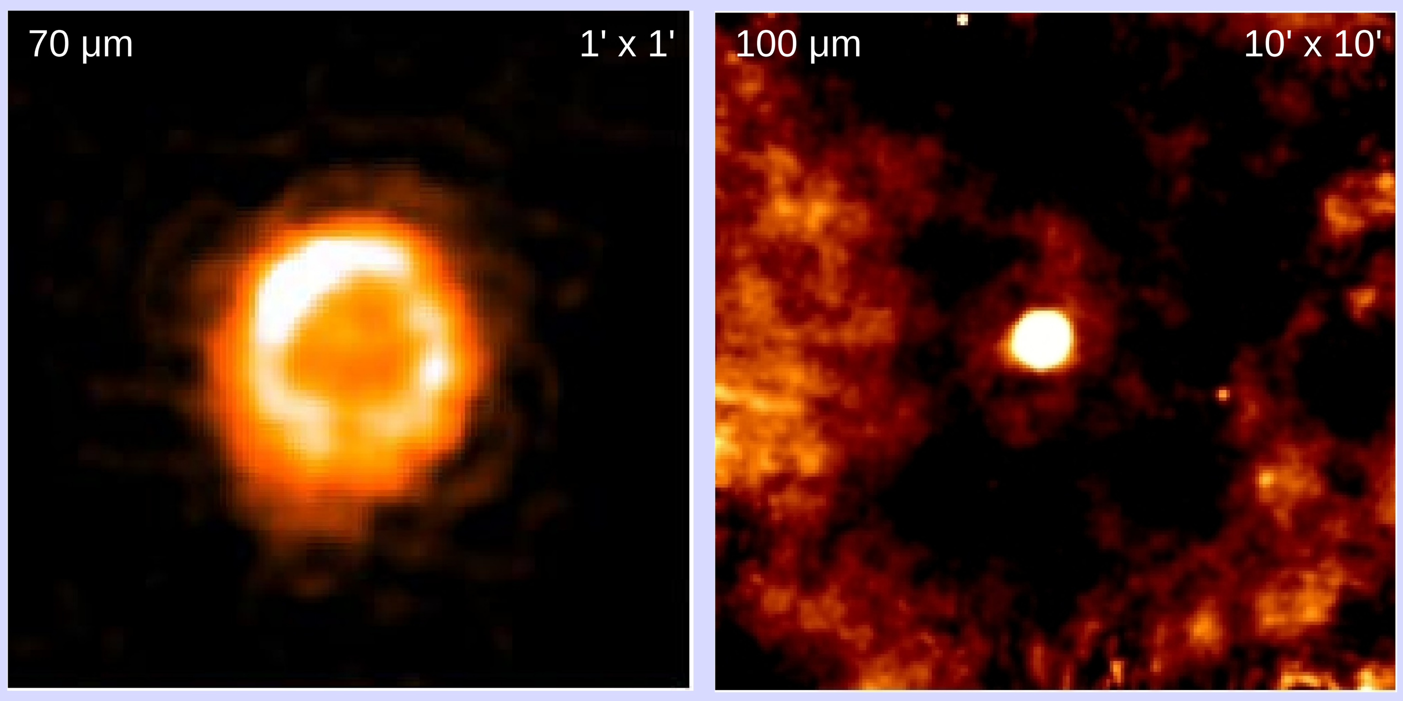

Fig. 1 The nebula around WRAY 15-751. Left: The PACS deconvolved image at 70 μm. Right: the PACS 100 μm image. North is up and East is to the left.

3. The nebula around the high-luminosity LBV AG Car

The PACS images (Fig. 4) show that the dusty nebula is an axisymetric shell that extends up to ~35'' in radius, with a width of ~13'', corresponding to 1.02 pc and 0.38 pc respectively at a distance of 6 kpc. This nebula is twice the size of the one around WRAY 15-751 and it also extends outside the Hα nebula. The far-infrared spectrum of the nebula (Fig. 5) reveals forbidden emission lines coming from ionized and neutral gas. The ongoing analysis includes a 2-D model of the dust shell to derive dust properties. The comparison with WRAY 15-751 can further constrain massive star evolution.

4. The nebula around the LBV G79.29+0.46

The PACS 70 μm image of the environment around the LBV G79.29+0.46 (Fig. 6) shows the main bright dusty nebula with a diameter of ~4' and the second fainter and almost perfectly circular nebula with a diameter of ~7' (previously detected by Spitzer at 24 μm; Jiménez-Esteban et al. 2010). The multi-wavelength study of its morphology and the analysis of the main nebular emission spectrum will give information on the possible multiple ejection episodes.

Acknowledgements

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2. The nebulae around the low-luminosity LBV WRAY 15-751

The PACS images (Fig. 1) reveal a main, dusty nebular shell expanding up to ~18'' in radius, with a width of ~12'', corresponding to 0.5 pc and 0.35 pc respectively at a distance of 6 kpc. This dust nebula extends outside the Hα nebula. Furthermore, these images revealed, for the first time, a second much larger, very faint ellipsoidal nebula with a mean radius of 2 pc. Both nebulae lie in an empty cavity, very likely the remnant of the O-star wind bubble formed when the star was on the main sequence. Each nebula contains ~0.05 $M_\odot$ of dust. Modeling of the inner nebula indicates a Fe-rich dust. From the far-infrared spectrum of the main nebula (Fig. 2) that shows forbidden emission lines coming from ionized and neutral gas we conclude that it consists of a shell of ionized gas surrounded by a thin photodissociation region. The total mass ejected by WRAY 15-751 amounts to 4 ± 2 $M_\odot$. The derived abundance ratios N/O = 1.0 ± 0.4 and C/O = 0.4 ± 0.2 indicate a mild N/O enrichment. The measured abundances, masses and kinematic ages of the nebulae point to an ejection during the red super-giant (RSG) evolutionary phase of an ~40 $M_\odot$ star with little rotation (Fig. 3). The multiple shells around the star suggest that the mass-loss was not a continuous ejection but rather a series of episodes of extreme mass-loss. Our measurements support the O–BSG–RSG–YSG–LBV evolutionary path and the idea that high-luminosity and low luminosity LBVs follow different evolutionary paths. The complete study can be found in Vamvatira-Nakou et al. 2013.

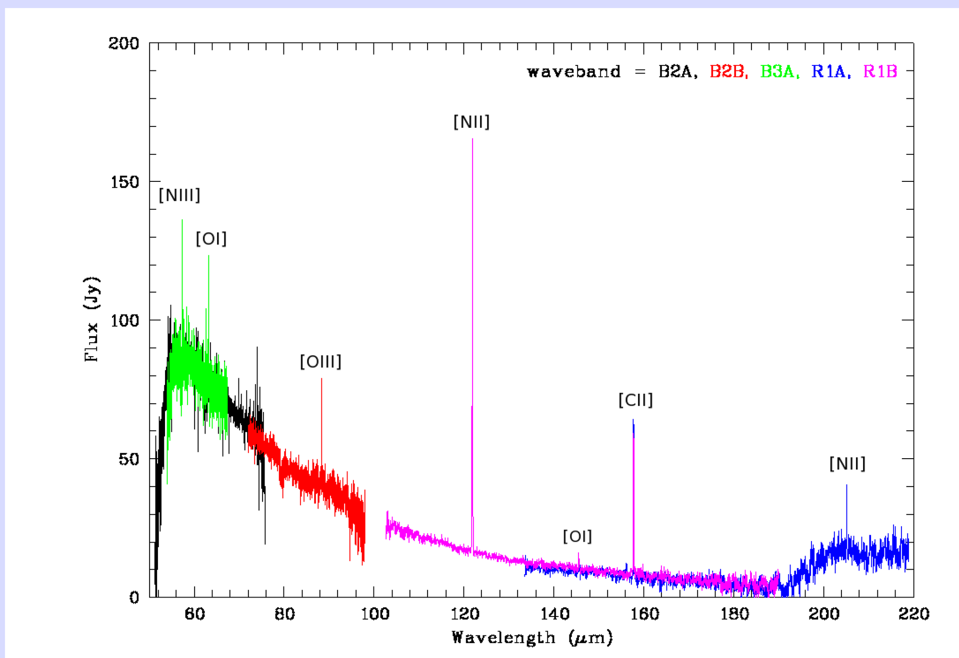

Fig. 2 The spectrum of the nebula around WRAY 15-751. The emission lines are indicated on the dust continuum.

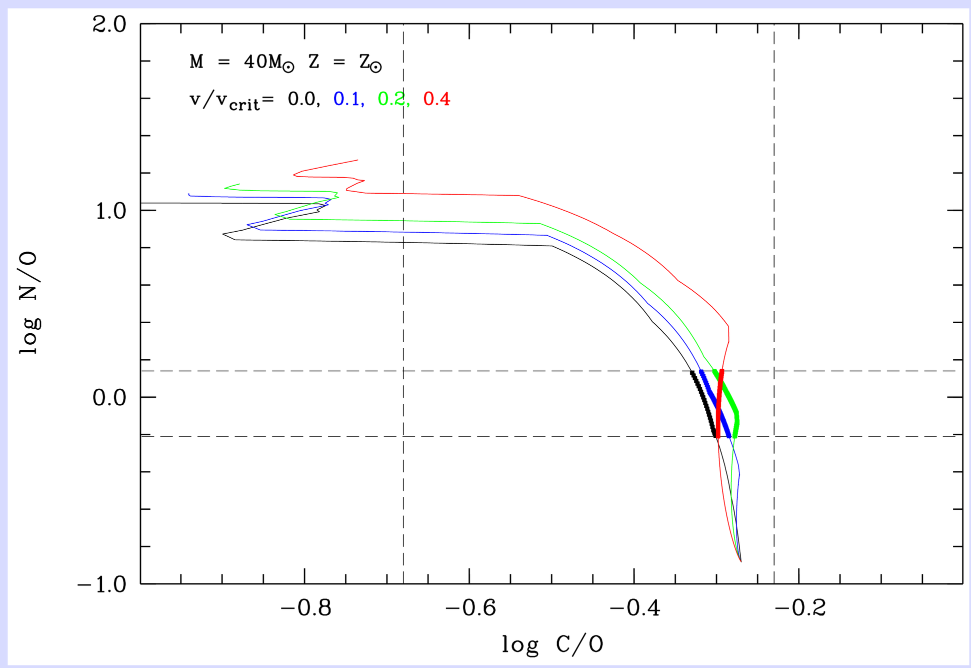

Fig. 3 Evolution of the N/O versus the C/O surface abundance ratios for a 40 $M_\odot$ using the models of Ekström et al. (2012).

5. The NGC 6888 nebula around the WR136

The false 3-color PACS image of the NGC 6888 nebula (12'x18') that surrounds the WR136 star is shown in Fig. 7. It seems to lie in a slightly larger cavity. This nebula also produces diffuse X-ray emission due to the shocks between the WR wind and the circumstellar material. The detailed analysis of the PACS data of this nebula and its environment will help to link the LBV and the WR evolutionary phases.

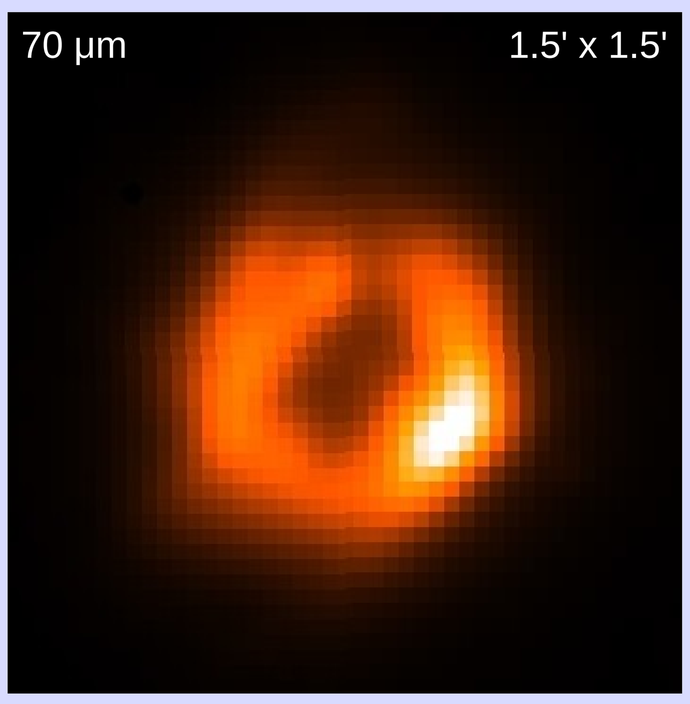

Fig. 4 The PACS 70 μm image of the nebula around AG Car. North is up and East is to the left.

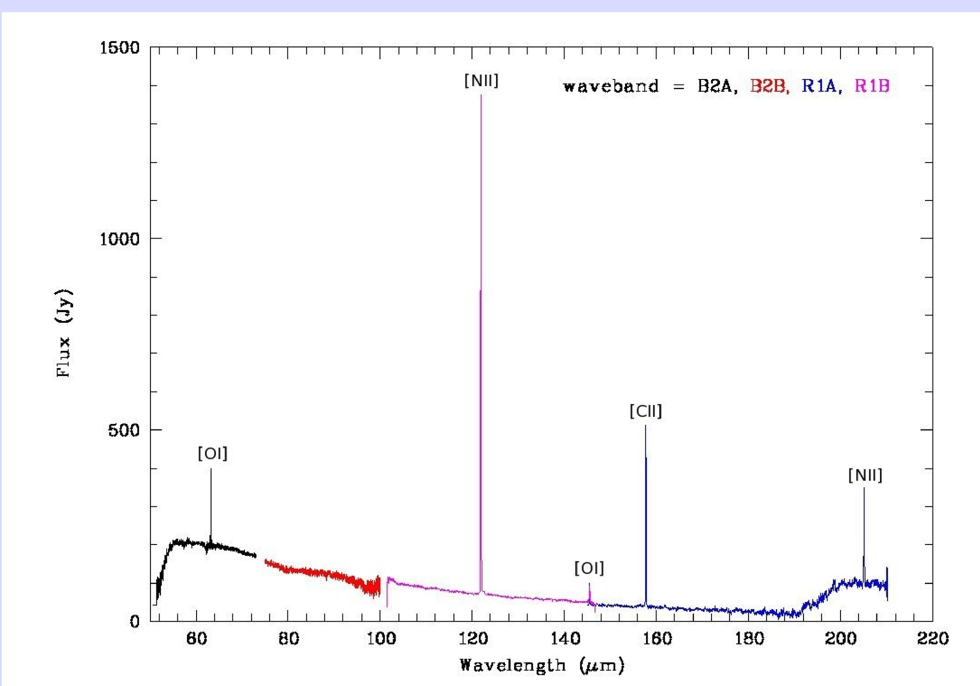

Fig. 5 The spectrum of the nebula around AG Car. The emission lines are indicated on the dust continuum.

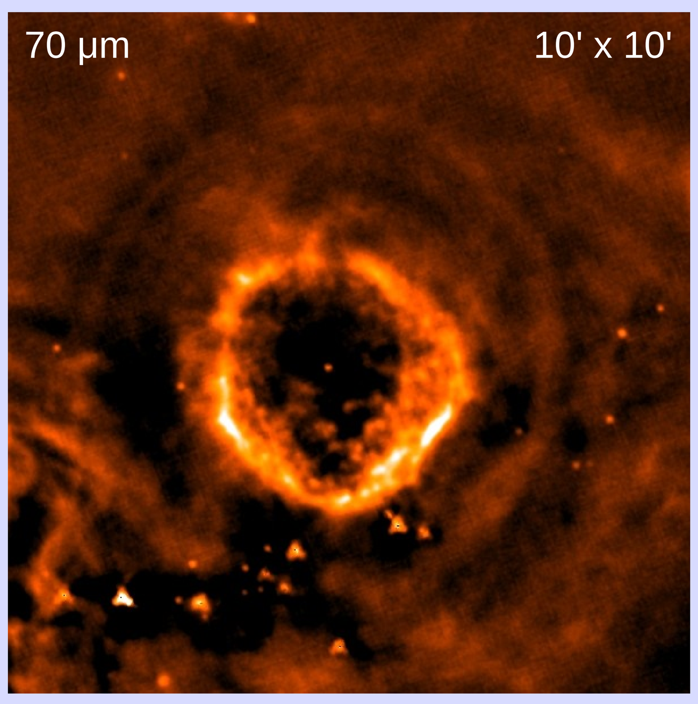

Fig. 6 The nebulae around the LBV G79.29+0.46. North is up and East is to the left.

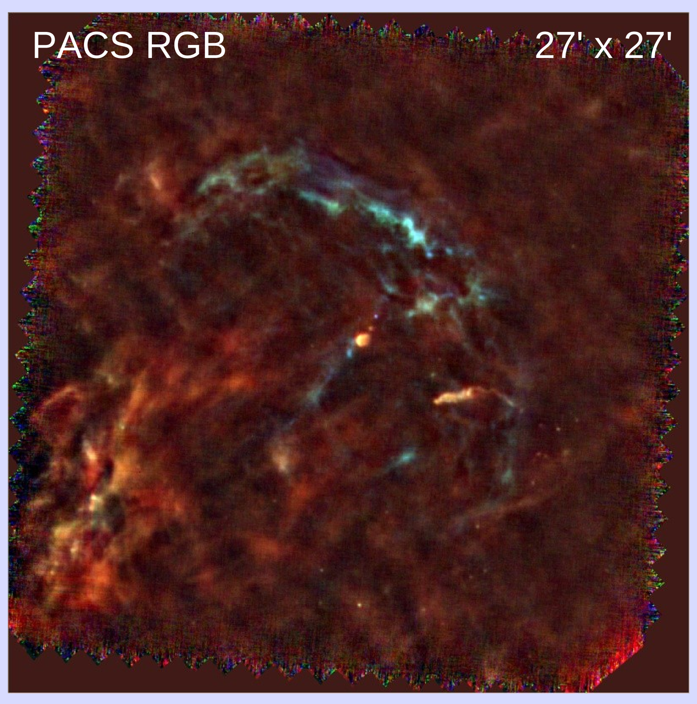

Fig. 7 An RGB image of the NGC 6888 nebula (R: 160 μm, G: 100 μm, B: 70 μm). North is up and East is to the left.

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