A massive parsec-scale dust ring nebula around the yellow hypergiant Hen 3-1379

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ABSTRACT

On the basis of far-infrared images obtained by the Herschel Space Observatory, we report the discovery of a large and massive dust shell around the yellow hypergiant Hen 3-1379. The nebula appears as a detached ring of 1 pc diameter which contains 0.17 M⊙ of dust. We estimate the total gas mass to be 7 M⊙ ejected some 1.6 × 10⁴ years ago. The ring nebula is very similar to nebulae found around luminous blue variables (LBVs) except it is not photoionized. We argued that Hen 3-1379 is in a pre-LBV stage, providing direct evidence that massive LBV ring nebulae can be ejected during the red supergiant phase.

Key words. circumstellar matter – Stars: massive – Stars: mass-loss – Stars: individual: Hen 3-1379

1. Introduction

According to current evolutionary models of massive stars (e.g., Maeder and Meynet 2010), O-type stars evolve into Wolf-Rayet stars by losing a significant fraction of their initial mass. Luminous blue variable stars (LBVs) represent a short (a few 10⁴ yr) unstable phase in the upper part of the Hertzsprung-Russell (HR) diagram. Their luminosities are typically 5.3 < log L/L⊙ < 6.3 and their spectral types between O9 and A (Humphreys and Davidson 1994). LBVs are often surrounded by massive dusty nebulae (Hutsemékers 1994, Nota et al. 1995), which reveal episodes of extreme mass-loss. LBVs likely represent an intermediate stage between main-sequence O-type and Wolf-Rayet stars, for stars with initial mass higher than ~30 M⊙.

It is not clear at which evolutionary stage the massive (≥1 M⊙) nebulae observed around LBVs are ejected, and what is the physical mechanism responsible for their ejection. Based on a dust composition found to be very similar to that of red supergiants (RSGs), Waters et al. (1997) and Voors et al. (2000) argued that LBV nebulae were ejected when the stars were RSGs, although no RSG has been observed with log L/L⊙ ≥ 5.8. By comparing the N/O abundances in the ejected nebulae to the predicted surface composition of massive stars during various phases of their evolution, Lamers et al. (2001) concluded that LBV nebulae are ejected during the blue supergiant phase and that the stars have not gone through a RSG phase. But Lamers et al. (2001) only considered a sample of very luminous LBVs, all with log L/L⊙ > 5.8. On the other hand, the determination of C, N, O abundances in the nebula around the less luminous LBV Wray15-751, based on far-infrared spectroscopy with the Herschel space observatory, led to the conclusion that the nebula was ejected during a RSG phase (Vamvatira-Nakou et al., in prep.).

Here we report the discovery of a massive parsec-scale dust nebula around the yellow hypergiant Hen 3-1379 which has not yet reached the LBV stage, providing direct evidence for the ejection of LBV-type nebulae during the RSG phase.

Hen 3-1379 (~ IRAS 17163-3907) is an emission-line star discovered by Henize (1976). It has been studied in detail by Le Bertre et al. (1989, 1993). In particular, Hen 3-1379 was found irregularly variable, both photometrically and spectroscopically, with strong infrared emission due to dust, mostly silicate. These authors noticed the strong spectral similarity with the LBV HR CAR, but classified Hen 3-1379 as a post-AGB star due to its low luminosity.

From a detailed study of foreground interstellar absorption, Lagadec et al. (2011) revised the distance to Hen 3-1379. They found the star located at ~4 kpc, then with a luminosity log L/L⊙ ≈ 5.7, comparable to that of the LBV Wray15-751, and a late B or early A spectral type, characteristic of yellow hypergiants (YHGs, e.g., Oudmaijer et al. 2009). Mid-infrared imaging (~10 μm) revealed the presence of two concentric dust shells around the star, with radii 0′′.6 and 1′′.5, indicative of mass-loss enhancement. By modeling the mid- to far-infrared emission, they also predict the existence of a larger and colder dust shell.

2. A large dust nebula around Hen 3-1379

Figures 1 and 2 illustrate the circumstellar environment of Hen 3-1379. A ring nebula is clearly observed in the far-infrared images, with a diameter of approximately 50″.

The observations were carried out with the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) onboard the Herschel Space Observatory (Pilbratt et al. 2010), in the framework of the Herschel Infrared Galactic Plane survey (HI-GAL, Molinari et al. 2010). Hi-GAL is a key programme of Herschel, mapping the inner part of the Galactic plane at 70 and 160 μm with PACS and 250, 350 and 500 μm with the Spectral and Photometric Imaging Receiver (SPIRE, Griffin et al. 2010). The data are acquired in the PACS/SPIRE parallel mode by mov-
two orthogonal scans are secured. This redundancy regularizes results in image elongation along the scan direction. In Hi-GAL the PSF which is roughly symmetric with FWHM of 10″ at 70 and 160 μm respectively (Traficante et al. 2011). The observations, made immediately public for legacy, were retrieved from the Herschel archive, pre-processed up to level 1 using the Herschel Interactive Processing Environment (HIPE version 9; Ott 2010), and subsequently reduced and combined using Scanamorphos (version 18; Roussel 2012). Only PACS data were considered, Hen 3-1379 being out of the SPIRE fields.

The dust nebula around Hen 3-1379 appears as a circular, clumpy ring, extending from about 18″ to 40″ around the star with a maximum at roughly 25″. At the distance of 4 kpc, this corresponds to a radius of 0.5 pc, typical of LBV nebulae and identical to the radius of the ring nebula around Wray15-751. The morphology, round and clumpy, is similar to the morphology of the inner “Fried Egg” nebula unveiled by Lagadec et al. (2011) using the Very Large Telescope Imager and Spectrometer for mid-Infrared (VISIR). On the PACS images, the “Fried Egg” nebula is unresolved and appears as the bright central spot observed at both 70 and 160 μm. The ring nebula is located in a cavity, best seen at 160 μm, 2′−3′ (~3 pc) in diameter, which delineate a bubble in the ambient interstellar medium, likely blown out by the O star wind in a previous evolutionary phase, although a remnant of an even older phase of mass-loss enhancement cannot be excluded.

Attempts to detect an ionized gas nebula around Hen 3-1379 through Hα imaging failed, either from the ground (Le Bertre et al. 1989) or using the Hubble Space Telescope (Siodmiak et al. 2008). In Fig. 1 we show images from the AAO/UKST SuperCOSMOS Hα survey obtained in a narrow-band Hα+[NII] and a broad-band Short Red filter, with bandwidths 6555-6625 Å and 5900-6900 Å respectively (Parker et al. 2005). This survey provides a 5-Rayleigh (i.e., 3 × 10^{-17} erg cm^{-2} s^{-1} arcsec^{-2}) sensitivity with arcsecond spatial resolution. A faint arc is detected approximately 22″ NW of the star, at a position corresponding to the brightest part of the far-infrared ring. This arc is equally seen in both filters and thus likely due to dust scattering and not to Hα emission. This confirms the absence of ionized gas emission around Hen 3-1379, in particular from the far-infrared dust ring. For comparison, the ionized gas nebula around Wray15-751 (Hutsemékers and Van Drom 1991) is well detected on the images of the SuperCOSMOS Hα survey.

3. Spectral energy distribution and nebular mass

From the PACS images we measure the flux densities $F_\nu = 386 \pm 3$ Jy at 70 μm and $55 \pm 3$ Jy at 160 μm for the whole nebula, using a 80″ aperture and after subtraction of the background emission estimated in the surrounding cavity. The contribution of the unresolved central source is 50 ±2 Jy at 70 μm and 4.8 ±0.5 Jy at 160 μm using a 12″ aperture. In this case, we consider both the surrounding cavity and the ring itself to estimate the background emission, the difference being accounted for in the error budget. To account for the small aperture, the flux measured at 70 μm has been increased by 10% and the flux measured at 160 μm by 25% (Ibar et al. 2010); we conservatively assume that the correction at 70 μm is of the order of correction at 100 μm).

To build the spectral energy distribution (SED), we use the ground-based near- and mid-infrared photometric measurements of Le Bertre et al. (1989) and Lagadec et al. (2011b). These data only refer to the star and the inner “Fried Egg” nebula. Other measurements were retrieved from the NASA/IPAC Infrared Science Archive. Only good quality data are used. We consider the IRAS flux densities at 12, 25, and 60 μm, the AKARI FIS
measurements at 65 and 90 μm, and the MSX6 data at 4.29, 4.35, 8.3, 12, 15, and 21 μm. The beam size of the IRAS and AKARI observations is too large to resolve the different dust shells so that these measurements refer to the whole nebula.

All these data are plotted in Figs. 3 and 4. They agree within the uncertainties and variability limits. No color-correction has been applied, because it is small (most often <10%) and difficult to evaluate given the complex SED and the presence of strong silicate emission reported by Le Bertre et al. (1989) on the basis of IRAS Low Resolution Spectra.

The total emission can be fitted as the sum of two modified black-body curves \( F_\nu \propto \nu^\beta B_\nu(T_d) \). Since silicates are clearly detected in the nebula around Hen 3-1379 (Le Bertre et al. 1989), we adopt \( \beta = 2 \). The contributions of the inner “Fried Egg” nebula with a dust temperature \( T_d = 182 \) K and the larger ring nebula with \( T_d = 63 \) K are clearly separated.

To further model the dust emission we use the two-dimensional radiative transfer code 2-Dust (Ueta and Meixner 2003). 2-Dust is a versatile code which can be supplied with various grain size distributions and optical properties as well as complex density distributions. For 2-Dust, the inner radius of the dust shell is an observable that can be measured from images so that the dust temperature at that radius can be readily computed.

We assume that the nebula around Hen 3-1379 is spherically symmetric, which is a good approximation of the overall geometry, and formed of two separate shells, the first one being the “Fried Egg” nebula imaged by Lagadec et al. (2011), with \( r_{in} = 0'.45 \) and \( r_{out} = 2'.25 \), and the second one the large ring seen on the PACS images, with \( r_{in} = 21'.5 \) and \( r_{out} = 40'.5 \). In the latter case, the exact value of \( r_{in} \) was determined by comparing the PACS images to synthetic ones produced by 2-Dust and convolved with the PSF. In each shell we assume that the dust density runs as \( r^{-2} \). The addition of a third shell to better account for the structure of the “Fried Egg” nebula appeared as an unnecessary complication, only increasing the parameter space. For the stellar parameters, we use the luminosity \( \log L/L_\odot = 5.7 \), the effective temperature \( T_{eff} = 8500 \) K, and the distance \( d = 4 \) kpc (Lagadec et al. 2011). Since the dust in Hen 3-1379 is dominated by silicates, we adopt a composition similar to the one used for modeling Wray15-751 and other LBVs (Voors et al. 2000; Vamvatira-Nakou et al., in prep.), i.e., pyroxenes with a 50/50 Fe to Mg abundance (bulk density 3.2 g cm\(^{-3}\)). The optical constants are taken from Dorschner et al. (1995) and extrapolated to a constant refraction index in the far-ultraviolet. We assume a MRN size distribution for the dust grains (Mathis et al. 1977): \( n(a) \propto a^{-3.5} \) with \( a_{min} < a < a_{max} \), \( a \) denoting the grain radius. We did not attempt to fit the 5 μm emission which is likely due to translucent heated dust grains and/or hot dust very close to the star. Adjustment to the data is mostly done by tuning the optical depth, which controls the strength of the emission, \( a_{max} \) which controls the 20 μm/100 μm flux ratio in the hotter shell, and the density ratio between the two shells. The two shells were considered simultaneously to produce the total energy distribution as well as separately to measure their individual contributions. A good fit is obtained (Fig. 4) except for the 18 μm/10 μm silicate emission band ratio which is too high in the model, without incidence on our results. Acceptable values of \( a_{max} \) are found in the 1–3 μm range, indicating the presence of large dust grains around Hen 3-1379 as in LBV nebulae (Voors et al. 2000).

Although there is some degeneracy in the parameter space, the derived dust temperatures and masses are reasonably robust. From the 2-Dust modeling, the temperature of the “Fried Egg” nebula is between 280 and 130 K, in agreement with Lagadec et al. (2011). For the outer ring, the temperature is between 64 and 52 K. The dust mass is \( M_d = 2.1 \times 10^{-3} M_\odot \) for the “Fried Egg” nebula and \( M_d = 0.17 M_\odot \) for the large ring. Considering other acceptable models, we estimate the uncertainty of the mass to be around 20–30%. \( M_d \) can also be derived empirically using \( M_d = F_d d^2 B_{\nu}^{-1} K_{\nu}^{-1} \) where \( K_{\nu} \) is the mass absorption coefficient roughly independent of the grain radius (Hildebrand 1983). For the silicates of Dorschner et al. (1995), \( K_{\nu} \approx 49 \) cm\(^2\)g\(^{-1}\) at 70 μm. With \( T_d = 182 \) K, we find \( M_d = 1.4 \times 10^{-3} M_\odot \) for the “Fried Egg” nebula, and \( M_d = 0.12 M_\odot \) for the larger ring nebula with \( T_d = 63 \) K, in agreement with the 2-Dust results.
Table 1. Comparison of Wray15-751 and Hen 3-1379

|                | Wray15-751 | Hen 3-1379 |
|----------------|------------|------------|
| \( \log L/\dot{L}_\odot \) | 5.7 ± 0.2  | 5.7 ± 0.1  |
| \( T_{\text{eff}} \) (10^4 K) | 30 ± 9     | 8.5 ± 1.0  |
| \( d \) (kpc) | 6.0 ± 1.0  | 4.0 ± 0.5  |
| \( r \) (inner shell) (pc) | 0.5        | 0.04       |
| \( r \) (outer shell) (pc) | 2.0        | 0.5        |
| \( v_{\text{exp}} \) (km s\(^{-1}\)) | 26         | ~30        |
| \( t_{\text{iso}} \) (inner shell) (10^4 yr) | 1.9        | 0.13       |
| \( t_{\text{iso}} \) (outer shell) (10^4 yr) | 7.5        | 1.6        |
| \( M_d \) (inner shell) (10^{-2} \( M_\odot \)) | 4.5 ± 0.5  | 0.21 ± 0.06 |
| \( M_d \) (outer shell) (10^{-2} \( M_\odot \)) | 5.0 ± 2.0  | 17 ± 5     |

Source: Sterken et al. [2008] Vamvatira-Nakou et al., in prep.; Lagadec et al. [2011] this work. The expansion velocity of the Hen 3-1379 nebula is assumed similar to the one measured for the shell around yellow hypergiant IRC+10420, i.e., \( v_{\text{exp}} \approx 25-37 \) km s\(^{-1}\) (Castro-Carrizo et al. [2007]).

5. Conclusions

We have found a large dust ring nebula around the yellow hypergiant Hen 3-1379. With 1 pc in diameter and a total gas mass estimated to 7 \( M_\odot \), this nebula is comparable to the nebulae observed around LBVs. In particular, Hen 3-1379 appears very similar to the low-luminosity (IoL; \( L/\dot{L}_\odot \leq 5.8 \)) LBV Wray15-751. The fact that the nebula is not seen in \( H\alpha \) indicates that Hen 3-1379 has not yet moved to a hotter phase, and is still in a pre-LBV stage. Hen 3-1379 might be just ready to cross the yellow void and become a hot LBV, a scenario also suggested for IRC+10420 (Humphreys et al. [2002]). Our observations strongly support the evolutionary path: RSG → YHG → IoL-LBV, providing direct evidence that massive LBV nebulae can be ejected during the RSG phase.

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Appendix A

According to the kinematical age of the nebulae, Hen 3-1379 looks younger than Wray15-751, with the inner shell possibly still in formation. Hen 3-1379 is most likely in a pre-LBV evolutionary stage. The kinematical age of the ring nebula around Hen 3-1379, \( 1.6 \times 10^4 \) yr, indicates that the star has already spent a significant fraction of its time as a post-red supergiant star (cf. the models for a 40 \( M_\odot \) star by Ekström et al. [2012]). This also suggests that the ring nebula should have been ejected close to the beginning of the RSG phase, possibly due to the dynamical instability mechanism proposed by Stothers and Chin (1995). If we adopt a gas to dust ratio of 40 as measured for the Wray15-751 nebula (Vamvatira-Nakou et al., in prep.), Hen 3-1379 has lost \( \sim 7 M_\odot \) of gas and dust since the beginning of the RSG phase. Interestingly enough, Wray15-751 has ejected two shells of comparable mass, while for Hen 3-1379, most of the mass is concentrated in the outer ring.
Appendix A: Detection limit of the nebula in Hα

We can roughly estimate the time needed in the hot phase to produce a detectable Hα nebula. Given its sensitivity (Sect. 2), the SuperCOSMOS survey can detect $F(\text{H}\alpha) > 6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ from a (homogeneous) ionized nebula 25″ in radius. Within a time $t$, a star emitting $Q_0$ ionizing photon s$^{-1}$ ionizes $Q_0 t$ hydrogen atoms. The ionized gas will recombine and emits $F(\text{H}\alpha) = (1/4\pi) n_e n_p h \nu \alpha_{\text{eff}}^{\text{H}\alpha} V d^{-2}$ where $n_e$ and $n_p$ are the electron and proton densities, $\alpha_{\text{eff}}^{\text{H}\alpha}$ the effective recombination coefficient, $\nu$ the frequency of Hα, $h$ the Planck constant, $V$ the emitting volume and $d$ the distance to the nebula. Making $n_e n_p = (Q_0 t/V)^2$ we can estimate the time that the star must emit $Q_0$ ionizing photon s$^{-1}$ to make its surrounding nebula glowing in Hα above the detection limit of the SuperCOSMOS survey. With $Q_0 = 10^{47}$ photon s$^{-1}$ as found for Wray15-751 (Vamvatira-Nakou et al., in prep.), we find $t \sim 20$ years.