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The "Papillon" nebula: a compact H II blob in the LMC resolved by *HST*⋆

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Abstract. We present high spatial resolution *HST* imaging of the LMC compact H II region N159-5. This high excitation blob is revealed to be a "*papillon*" or butterfly-shaped ionized nebula with the "wings" separated by $\sim 2''.3$ (0.6 pc). Two subarcsecond features resembling a "smoke ring" and a "globule" are detected in the wings, the origin of which is briefly discussed. N159-5 may represent a new type of H II region in the Magellanic Clouds overlooked so far because of insufficient spatial resolution. Our images also show a strikingly turbulent medium around the *Papillon* in the giant H II region N 159, which manifests itself by a large number of subarcsecond filaments, arcs, ridges, and fronts carved in the ionized gas by the stellar winds from massive stars in the N 159 complex.

Key words: galaxies: Magellanic Clouds – ISM: kinematics and dynamics – ISM: individual objects: N 159-5 – ISM: H II regions – ISM: dust, extinction – stars: early-type

1. Introduction

The formation process of massive stars is still a largely unsolved problem. Although it is believed that stars generally originate from the collapse and subsequent accretion of clumps within molecular clouds (Palla & Stahler 1993), this model cannot explain the formation of stars beyond $\sim 10\ M_\odot$ (Bonnell et al. 1998). The strong radiation pressure of massive stars can halt the infall of matter limiting the mass of the star (Yorke & Krügel 1977, Wolfire & Cassinelli 1987, Beech & Mitalas 1994), while a large fraction of the infalling material may as well be deflected into bipolar outflows by processes which we do not yet know in detail (Churchwell 1997).

Moreover, since the evolutionary time scales of massive stars are comparatively short, these stars are believed to enter the main sequence while still embedded in their parent molecular clouds (Yorke & Krügel 1977, Shu et al. 1987, Palla & Stahler 1990, Beech & Mitalas 1994, Bernasconi & Maeder 1996). This means that massive stars may already experience significant mass loss and subsequent evolution while still accreting mass from the parental cloud.

In order to understand the formation of massive stars it is therefore necessary to study them at the earliest phases where they can be reached through the enshrouding material at different wavelengths. While high-resolution radio continuum observations allow the investigation of ultracompact H II regions (Churchwell 1990) formed around newborn massive stars, high angular resolution observations in ultraviolet, visible, and infrared wavelengths (Walborn & Fitzpatrick 1990, Walborn et al. 1995, Schaerer & de Koter 1997, Hanson et al. 1996) are necessary to access accurate physical parameters of these stars and then evaluate their states of evolution.

Our search for the youngest massive stars in the Magellanic Clouds started almost two decades ago on the basis of ground-based observations. This led to the discovery of a distinct and very rare class of H II regions, that we called high-excitation compact H II "blobs" (HEBs). The blob in N 159, which is the subject of this paper, was the prototype of this category of nebulae (Heydari-Malayeri & Testor 1982). So far only four other HEBs have been found in the LMC: N 160A1, N 160A2, N 83B-1, and N 11A (Heydari-Malayeri & Testor 1983, 1985, 1986, Heydari-Malayeri et al. 1990) and two more in the SMC: N 88A and N 81 (Testor & Pakull 1985, Heydari-Malayeri et al. 1988). To further improve our understanding of those compact H II regions and overcome the difficulties related to their small size, we used the superior resolving power of *HST* to image N 81 and N 88A, in the SMC, as well as N 159-5 in the LMC. The analysis and discussion for the first two objects was presented by Heydari-Malayeri et al. (1999a, 1999b, hereafter Papers I and II respectively).

In the present paper we study our third *HST* target, the LMC blob N 159-5. This object lies in the H II complex N 159 (Henize

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1956), situated some 30′ (∼ 500 pc) south of 30 Dor. N 159 is associated with one of the most important concentrations of molecular gas in the LMC (Johansson et al. 1998 and references therein) and contains several signposts of ongoing star formation (cocoon stars, IR sources, masers). N 159-5 is the name given by Heydari-Malayeri & Testor (1982) to a compact H II region of size ∼ 6″ (1.5 pc) with high excitation ([O III]/Hβ = 8) and suffering a considerable extinction of A_V = 5 mag as derived from Hβ and radio continuum (Heydari-Malayeri & Testor 1985). They also showed that the chemical composition of the object is compatible with that of typical LMC H II regions. Israel & Koornneef (1988) detected near-IR molecular hydrogen emission towards the object, partly shocked and partly radiatively excited. They also confirmed the high extinction of the object from a comparison of Br γ and Hβ and estimated that N 159-5 contributes ∼ 25% to the total flux of the IRAS source LMC 1518 (Israel & Koornneef 1991). More recently, Comerón & Claes (1998) used ISOCAM to obtain an image of N 159-5 at 15 μm. Similarly, Hunt & Whiteoak (1994) used the Australia Telescope Compact Array (ATCA) to obtain the highest angular resolution radio continuum observations in existence of N 159-5 (beam 8″.3 × 7″.4). However, none of these observations were able to resolve N 159-5.

2. Observations

The observations of N 159-5 described in this paper were obtained with the Wide Field Planetary Camera (WFPC2) on board the *HST* on September 5, 1998 as part of the project GO 6535. We used several wide- and narrow-band filters (F300W, F467M, F410M, F547M, F469N, F487N, F502N, F656N, F814W) to image the stellar population as well as the ionized gas. The observational techniques, exposure times, and reduction procedures are similar to those explained in detail in Paper I.

3. Results

3.1. Morphology

In Fig. 1 we present the WFPC2 image of the eastern part of the giant H II region N 159. This image reveals a very turbulent medium in which ionized subarcsecond structures are interwoven with fine absorption features. A large number of filaments, arcs, ridges, and fronts are clearly visible. In the south-western part of Fig. 1, we note a relatively large, high excitation ridge bordering a remarkable cavity ∼ 25″ (∼ 6 pc) in size. Another conspicuous cavity lies in the northern part of the image. These are most probably created by strong winds of massive stars. Moreover, a salient, dark gulf running westward into N 159 cuts the glowing gas in that direction and as it advances takes a filamentary appearance. A comparison with the CO map of Johansson et al. (1998) indicates that this absorption is due to the molecular cloud N 159-E.

The H II blob N 159-5 stands out as a prominent high excitation compact nebula in the center of the WFPC2 field (Fig. 1), at the edge of two distinct absorption lanes of size ∼ 3″× 13″ (∼ 0.8 × 3.3 pc).

The most important result of our WFPC2 observations is shown in the inset of Fig. 1, namely the N159-5 blob resolved for the first time. In fact N 159-5 consists of two distinct ionized components separated by a low brightness zone the eastern border of which has a sharp front. The overall shape of N 159-5 is reminiscent of a butterfly or *papillon* in French.[1] The centers of the two wings are ∼ 2″.3 (0.6 pc) apart. The brightest part of the right wing appears as a "smoke ring" or a doughnut with a projected radius of ∼ 0″.6 (0.14 pc). The left wing is characterized by a very bright "globule" of radius ∼ 0″.4 (0.1 pc) to which are linked several bright stripes all parallel and directed towards the central sharp front.

An obvious questions is: where is (are) the ionizing star(s) of N159-5? No conspicuous stars can be detected within the Papillon itself, although its overall high excitation and morphology require the source of ionization to be very close to the center of this structure. A faint star of y = 17.9 mag can be seen between the two wings (Fig. 1, inset) and may well be the major source of ionization, heavily obscured by foreground dust. At least three more stars weaker than $y \sim 20$ mag are detected (not visible in Fig. 1), two of them lying in the brightest parts of the smoke ring and one towards the other wing, east of the front. No star is detected towards the globule.

3.2. Nebular reddening

The *HST* observations allow us to study the spatial variation of the extinction in the direction of the Papillon nebula. The Hα/Hβ ratio is high in both wings (Fig. 2a), varying between 5 and 10, corresponding to a visual extinction A_V between 1.5 and 3.5 mag, if the LMC interstellar reddening law is used (Prévot et al. 1984). The extinction towards the zone separating the two wings also shows comparable ratios. The Hα/Hβ map was used to de-redden the Hβ flux on a pixel to pixel basis.

3.3. Ionized gas emission

The [O III] λ 5007/Hβ map also displays the butterfly-like structure (Fig. 2b) with line ratios varying between 3.5 and 8. The band separating the wings has overall smaller values. A comparison of the [O III] and Hα images shows that the Papillon has the same size and morphology in both filters. This suggests a hard radiation field in which the high excitation O^{++} ions occupy the same zone as the ionized hydrogen. A simple calculation (Paper II) shows that almost all oxygen atoms are doubly ionized.

We measure a total Hβ flux F(Hβ) = 2.68×10^{-13} erg cm^{-2} s^{-1} above 3σ level for both wings (accurate to ∼ 3%). Correcting for the extinction (Sect. 3.2) gives $F_0 = 5.35 \times 10^{-12}$ erg cm^{-2} s^{-1}. The flux is not equally distributed between the two

[1] The term "butterfly" is already used to designate several planetary nebulae in our Galaxy: M 76, M2-9, NGC 6302, NGC 2440, and PN G010.8+18.0. It has also recently been used to describe the K-L nebula (see Sect. 4).

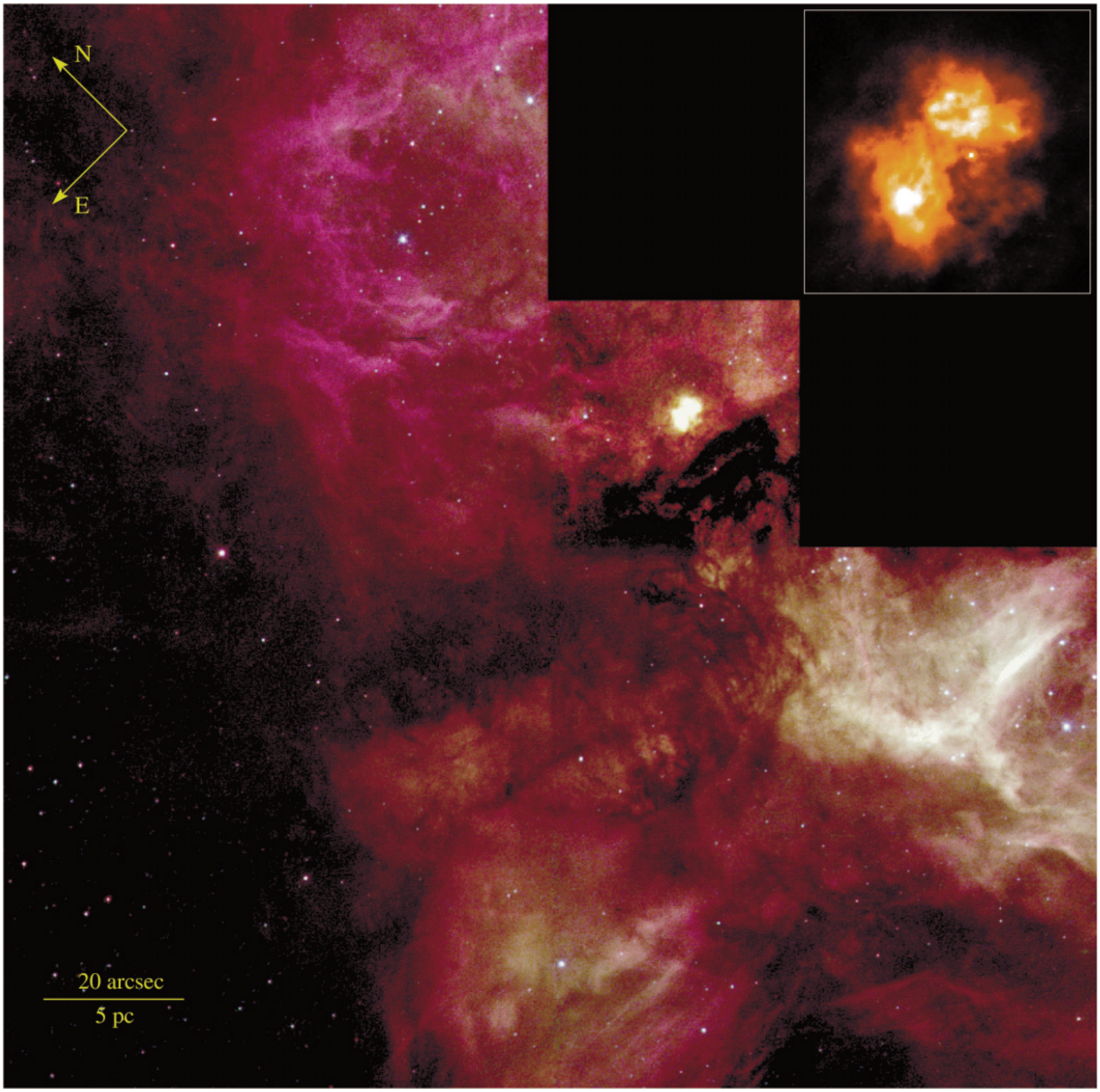

Fig. 1. A “true color” composite image of the LMC H II region N 159 as seen by WFPC2, based on images taken with filters Hα (red), [O III] (green), and Hβ (blue). The N 159-5 “blob” is the high excitation compact object lying in the center of the smaller PC frame. Note how the hardness of the radiation field varies from north to south across the image. The yellowish colors represent higher excitation gas as traced by the [O III] emission line and are mainly found in the giant ridge in the southern part of N 159 and in the blob. In the northern part the emission is principally due to relatively lower energy Hα photons. **inset**:A false color image of N 159-5 in Hα showing the internal morphology of the butterfly-shaped H II region. Field size $\sim 5'' \times 5''$ (1.3 × 1.3 pc).

wings since $\sim$60% is generated by the eastern wing (globule), whereas the western wing (smoke ring) contributes by $\sim$40%.

A Lyman continuum flux of $N_L = 4.17 \times 10^{48}$ photons s^{-1} can be derived for the whole N 159-5 taking $T_e = 10\,500$ K (Heydari-Malayeri & Testor 1985), assuming a distance of 55 kpc, and considering that the H II region is ionization-bounded. A single O8V star can account for this ionizing flux (Vacca et al. 1996, Schaerer & de Koter 1997). However, this should be viewed as a lower limit, since the region is probably not ionization-bounded.

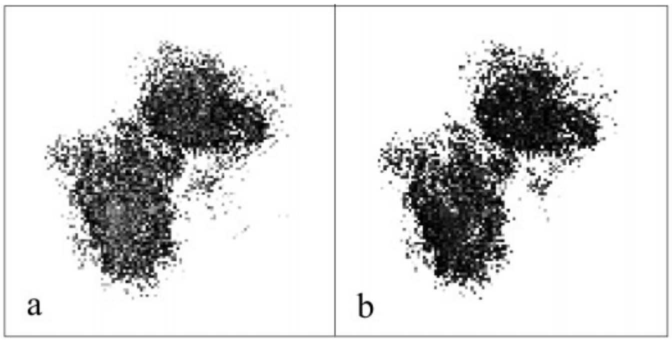

Fig. 2a and b. Spatial variation of the extinction and ionization across N 159-5. **a** The Hα/Hβ ratio varies between 5 and 10 corresponding to a visual extinction between 1.5 and 3.5 mag. **b** The [O III] λ 5007/Hβ varies between 3.5 and 8. The field size and orientation of both frames are identical to the inset of Fig. 1.

4. Discussion and concluding remarks

The three Magellanic Cloud blobs studied so far with *HST* (N 81, N 88A, and N 159-5) represent very young massive stars leaving their natal molecular clouds. While N 81 is a rather isolated starburst, N 88A and N 159-5 are formed in richer regions of gas where a preceding generation of massive stars has taken place. Being very young, these two regions are also similar in that they are heavily affected by dust. In spite of these similarities, N 159-5 has a bewildering morphology which is seen neither in the other blobs, nor, generally speaking, in any of the known Magellanic Cloud H II regions. The global morphology of the Papillon and more especially the presence of peculiar fine structure features in the wings make this object a unique H II region in the LMC. It is also the first bipolar nebula indicating young massive star formation in an outer galaxy. In this respect the Papillon may even represent a new type of very young H II region in the Magellanic Clouds overlooked so far because of insufficient spatial resolution.

Even though high resolution spectroscopy would be necessary for a conclusive picture of the Papillon's nature, the parallel ray-like features of the globule as well as the smoke ring strongly suggest a dynamical origin. Several observational facts also advocate a common process for the formation of these two compact features: their proximity ($\sim 2''.3$), their location in a distinct, more diffuse nebular structure, and the uniqueness of the phenomenon in the large field of the N 159 complex. In order to explain the observed morphology of N 159-5, two different models can be envisaged.

1) We are looking at a bipolar region produced by strong stellar wind of hot star(s) hidden behind the central absorption zone. It has been shown that in hot, rotating stars the mass loss rate is much larger at the poles than at the equator (Maeder 1999). This model can account for the high excitation of the two wings, as well as the global bipolar morphology. Although we cannot yet firmly advocate a bipolar phenomenon, we underline the morphological similarity between the Papillon and the high resolution image of Kleinmann-Low nebula in Orion recently obtained with the Subaru 8.3 m telescope at 2.12 μm (Subaru team 1999). This image shows a butterfly-shaped exploding area produced by the wind of a young cluster of stars, among which IRc2, a particularly active star estimated to have a mass over 30 $M_{\odot}$. However, this model does not explain the smoke ring neither the parallel stripes.

One may also compare N 159-5 with the well-studied Galactic H II region Sh 106 which has a prominent bipolar shape, marvellously shown in an *HST* Hα image (Bally et al. 1998 and references therein). Its exciting star is hidden in the absorption region between the two lobes where extinction amounts to 20 mag in the visual. The southern lobe is much brighter than the northern one because it is blueshifted, while the other is expanding away from the observer. Also, both lobes get gradually fainter in their external parts. However, we do not see such global trends in N 159-5 and, more importantly, no smoke ring or globule features are present in Sh 106.

2) Alternatively, N 159-5 may represent two close but distinct nebulae each with its own massive star providing a high excitation for the ionized gas. In this possibility, the globule may be a bow shock created by an O star with a powerful stellar wind moving at speeds of $\sim 10\,\mathrm{km\,s^{-1}}$ through the molecular cloud (models of Van Buren & Mac Low 1992 and references therein). The presence of the parallel rays and the sharp front make this explanation attractive. Since no stars are detected towards the globule, we may speculate that the star is hidden behind the bow shock/globule that is heading towards the observer. As for the smoke ring, it may be due to the interaction of a stellar wind from a central star with the surrounding medium creating a bubble structure. If this is the case, the mass loss should be important, comparable to that observed in Luminous Blue Variables. However, LBVs are evolved massive stars and it is not clear how this phenomenon can occur in such a young region.

Another explanation for the smoke ring can be provided by the mentioned bow shock models. They predict the formation of a stellar wind bubble when the star's motion is subsonic. The smoke ring can therefore be due to such a slower moving star. If this picture is correct, we are witnessing a very turbulent star forming site where massive stars formed in group are leaving their birthplace.

One should stress the noteworthy absence of prominent stars towards the Papillon. As in the case of the SMC N 88A (Paper II), this is certainly due to the very young age and the high dust content of this star formation region. N 159-5 is just hatching from its natal molecular cloud, and its exciting stars should therefore be buried inside dust/gas concentrations. In order for a star of type O8 with M_V = –4.66 mag (Vacca et al. 1996) to remain undetected in our Strömgren y image, we need extinctions larger than A_V = 6 mag, which is quite possible given the above estimates. However, N 159-5 will gradually evolve into a more extended, less dense region exhibiting its exciting stars, like the SMC N 81 (Paper I).

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