The most recent eruption of $\eta$ Carina: Discovery of chemically peculiar and asymmetric ejecta

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ABSTRACT

We investigated continuum and molecular line emission of four species (CO, HCN, H$^{13}$CN, and HCO$^+$) at 0.8 mm in the inner arcsec around $\eta$ Car, using ALMA observations at a resolution better than 0.2 arcsec. We report the discovery of two key features: (1) an extended continuum structure asymmetrically located with respect to the star and clearly independent from the point source. This structure, associated with the Weigelt blobs, is only traced in HCO$^+$ and not detected in the other lines; and (2) an absorption component toward the continuum point source, only traced by HCN and H$^{13}$CN in their vibrational-ground and vibrationally-excited states. This absorbing gas is attributed to a hot bullet of N-enriched material expelled at a projected velocity of 40 km s$^{-1}$. In the extended structure we measure unusual abundances due to the lack of nitrogen-bearing molecules. We explore possible explanations for this situation, that clearly differentiates this region from the ejecta of the Great Eruption, rich in CNO-processed matter. In addition, we find that morphology and kinematics of this structure are consistent with a one-sided mass ejection. Its dynamical age is lower than 90 years, which places the structure in relation to the 1941 $\eta$ Car brightening.

Key words: stars: individual: $\eta$ Carina – stars: massive – stars: mass-loss – stars: evolution – ISM: molecules – ISM: abundances

1 INTRODUCTION

Luminous blue variables (LBVs) are evolved massive stars characterized by remarkable spectrophotometric variability and heavy mass loss in the form of dense and steady winds and occasional eruptions. LBVs shed out large amounts of dust and CNO-enriched material into their surroundings. The shocks and strong FUV fields produced by LBVs represent a continuous energy input to the stellar neighbourhood, eventually altering its structure and composition.

$\eta$ Car is the archetypal member of the LBV family, and one of the most luminous sources in the Galaxy ($5 \times 10^6 L_\odot$). This massive star is part of a very eccentric binary LBV + O/WR system with a total mass of 250 M$\odot$ (Damineli et al. 1997). It is located at 2350±50 pc in the Carina arm (Smith 2006), with a LSR velocity of -19.7 km s$^{-1}$ (Smith 2004). Its peculiarity, brightness and closeness represent a unique chance to witness the last breaths of a high mass star. Consequently, $\eta$ Car and its surroundings have been exhaustively observed during the last decades, becoming one of the best studied objects in the Galaxy (e.g. Davidson et al. 1995, Smith et al. 2003b, Smith 2008).

$\eta$ Car underwent a devastating outburst in the 1840s, an event nicknamed the Great Eruption that led to the formation of the bipolar Homunculus Nebula (Davidson 1989). This event was followed by at least two other outbursts, spaced by remarkably similar times of about 50 years. In the 1890s, a weaker eruption gave birth to a smaller structure commonly referred to as the Little Homunculus (Ishibashi et al. 2003). Later in 1941, $\eta$ Car experimented a sudden luminosity increase. Radio recombination line observations with ALMA provided indirect evidence for a new structure associated with this event, baptised as the Baby Homunculus (Abraham et al. 2014). The region was modelled as an expanding shell of ionized gas, smaller than 1 arcsec and possibly linked to the Weigelt blobs (slowly moving, close-in ejecta of about 100 au, located at less than 0.3 arcsec of the star, Weigelt & Ebersberger 1986). However, the ejection epoch of these blobs is not clear, with arguments supporting both the 1890s (Smith 2004) and the 1940s events (Dorland et al. 2004).

Molecular line observations could play a key role in revealing the true nature of this structure. Pioneering research by Rizzo et al. (2001, 2003b, 2008) demonstrated the potential of molecular gas associated with evolved massive stars as a tool to understand their mass-loss processes. Molec-
ular hydrogen around $\eta$ Car was first detected by Smith (2002), distributed over the surface of the Homunculus. Later, Smith et al. (2006) reported a tentative detection of NH$_3$ towards the inner region of the nebula. Loinard et al. (2012) carried out the first molecular survey with APEX, reporting the detection of eight species—including CO and four N-bearing molecules such as CN, HCN, and HNC—. Recently, ALMA observations with a resolution of about 1 arcsec (Smith et al. 2018) revealed an expanding torus of CO in the waist of the Homunculus. A similar structure has been already discovered around the LBV object MN101, possibly in a more advanced stage (Bordiu et al. 2019).

In this letter we present ALMA observations of CO, HCO$^+$, HCN and H$^{13}$CN towards $\eta$ Car with an unprecedented resolution better than 0.2 arcsec. We analyse the spatial distribution of the emission in the innermost region of the Homunculus, providing hints on its chemistry and linking the observed features to the violent history of $\eta$ Car.

2 DATA AND RESULTS

We make use of ALMA band 7 archival observations from project 2016.1.00585.S (P.I: G. Pech-Castillo). The source was observed on 2016 October 24 under excellent weather conditions –0.57 mm of precipitable water vapour—, with an integration time of 668 s. A total of 41 12-m antennas were used, providing a maximum baseline of 1.8 km. Quasars J1107-4449, J1047-6217 and J0538-4405 were used for flux, phase and bandpass calibration respectively. The correlator was set to observe four simultaneous spectral windows of 1 GHz each, targeting the rotational lines of CO $J = 3 \rightarrow 2$ (345.795989 GHz), H$^{13}$CN $J = 4 \rightarrow 3$ (345.399769 GHz), HCN $J = 4 \rightarrow 3$ (354.505475 GHz) and HCO$^+\ J = 4 \rightarrow 3$ (356.734223 GHz). Visibilities were reduced following the standard ALMA pipeline with casa v.4.7.0 r38335. The resulting QA2 products included four spectral cubes and a continuum map, with a characteristic beam of 0.17×0.13 arcsec (P.A. -60$^\circ$). The phase centre is shifted by (-0.141,0.15) with respect to the continuum peak, presumably the star.

We adopt the following conventions: (1) intensities are given in a brightness temperature scale ($T_b$). The conversion from flux density to $T_b$ is made through the expression

$$T_b = 1.22 \times 10^6 \frac{S_\nu}{\nu ^2 \theta_{maj} \theta_{min}}$$

with $T_b$ in K, $S_\nu$ in Jy beam$^{-1}$, $\nu$ the frequency in GHz and $\theta_{maj}$ and $\theta_{min}$ the major and minor beam sizes in arcsec; (2) positions are offsets relative to the J2000 coordinates of the source; and (3) velocities are expressed in the local standard of rest frame (LSR).

Fig. 1 presents the peak-intensity maps of CO, HCN, H$^{13}$CN and HCO$^+$ in a region of 8×8 arcsec around the star. In CO, HCN and H$^{13}$CN we distinguish a clumpy C-shaped structure that surrounds the binary at an average radius of ~2 arcsec —about 4700 au—. This structure corresponds to the disrupted torus described by Smith et al. (2018) from CO $J = 2 \rightarrow 1$ observations, who dated it back to the Great Eruption. The clumpiness of the gas translates into multiple velocity components in the range (~100, +100) km s$^{-1}$.

Contrary to CO, HCN and H$^{13}$CN—which display a remarkably similar spatial distribution—, HCO$^+$ tells a very different story. The torus is still visible as faint spots, but the most intense emission, with a peak intensity of 77.5 ± 6.8 K, arises from a slightly elongated region very close to the star, roughly 0.6 × 0.4 arcsec. Hereafter we refer to this structure as ‘the Peanut’ due to its particular shape (see inset).

Continuum emission is only detected in the inner ~0.6 arcsec, as shown in Fig. 2. It depicts a point-like source—presumably related to $\eta$ Car—and an extended component matching the Peanut. We attempted to isolate the point source emission by fitting it to a single 2D Gaussian. Surprisingly, the point source has an extension slightly larger than the beam, with a deconvolved size of 0.11×0.11 arcsec (i.e. 260 au). This unresolved region is fairly smaller than the estimates by Abraham et al. (2014) for the RRL emitting region. The contours in Fig. 2 show the extended component isolated from the point source. The peak intensity of the point source is 6.41 ± 0.02 Jy beam$^{-1}$, while the integrated fluxes of the point-like and extended sources are 13.1 ± 0.5 and 17.4 ± 1.1 Jy, respectively. This flux is notably below those quoted by Abraham et al. (2014) and Loinard et al. (2016), but the high variability of the continuum flux across the orbit should be considered; the observations presented here have been gathered close to the periastron, when the flux decreases significantly (White et al. 2005).

The right panels of Fig. 2 also show the discovery of CO, HCN and H$^{13}$CN absorbing the continuum. The CO absorption is projected onto the whole continuum-emitting region, with a central velocity of ~9 km s$^{-1}$ and a width of ~0.6 km s$^{-1}$. The absorptions of HCN and H$^{13}$CN are notoriously different: they are only seen in the point source, centred at ~60 km s$^{-1}$, with widths of ~12 km s$^{-1}$. Strikingly, we also detected the $\nu_2 = 1$ lines of HCN and H$^{13}$CN, as shown in the figure. The two lines are found exclusively in absorption against the point source, without emission or absorption elsewhere. HCN and H$^{13}$CN $\nu_2 = 1$ excited states correspond to a double degenerate bending mode with an energy of 729.7 cm$^{-1}$ (~1050 K), a very unusual value for thermal emission in most astrophysical environments. It is therefore not surprising to find these lines exclusively towards the star.

3 ANALYSIS

3.1 The Peanut

The Peanut is only detected in HCO$^+$ and continuum, without any hints of the other observed molecules. It is located ~0.1–0.2 arcsec away the star towards the NW—approximately the direction in which the torus is disrupted. At the best of our knowledge, this is the first detection of such extended component beyond infrared.

The Peanut is closer to $\eta$ Car and smaller than the torus; therefore, it is presumably much younger. In addition, the
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3.2 Line absorptions

In Sect. 2 we described the line absorptions of CO, HCN and H$^{13}$CN. Considering the V$_{LSR}$ of η Car of −19.7 km s$^{-1}$, CO seems an interstellar cloud located somewhere in the foreground of η Car. Its velocity (−9 km s$^{-1}$) lies halfway between the corresponding velocities of a local cloud (0 km s$^{-1}$) and the Carina arm (−20/−25 km s$^{-1}$); its linewidth (0.6 km s$^{-1}$) is typically found in cold clouds. Contrarily, HCN and H$^{13}$CN absorptions are very likely associated with the hot star. Velocity (−60 km s$^{-1}$) and linewidths (10 − 12 km s$^{-1}$) are similar to those measured in emission in the torus and the Peanut.

The four HCN lines (HCN and H$^{13}$CN, ν = 0 and ν$_2$ = 1) appear in absorption exclusively toward the star but not the Peanut. While this fact may be explained merely by excitation arguments in the case of the ν$_2$ = 1 lines, the lack of absorption of ν = 0 lines in the Peanut implies that the absorbing volume is strictly located towards the star.

All these observational findings are consistent with a bullet-like cloud being expelled from η Car at a projected velocity of 40 km s$^{-1}$. It is finally noteworthy the lack of emission or absorption of the other molecules toward the star, which indicates that this hot bullet is very N-enriched.

3.3 Relative abundances

We estimated the column densities of the observed species in different positions, as depicted in Fig. 3: the torus –positions A and B–, the clump at (0.′′4,−0.′′65) –position C–, the Peanut and the absorbing bullet. For the emission lines we assumed that the gas is in local thermodynamic equilibrium (LTE), the emission is optically thin and that radiative excitation dominates over collisions due to the strong radiation field. If gas and dust are thermally coupled, gas temperature may be approximated by the dust temperature. We took the equation by Smith et al. (2003a):

\[
T_{\text{dust}}(K) \approx 13100 \times D(\text{au})^{-1/2}
\]

where $T_{\text{dust}}$ is the blackbody equilibrium temperature of a dust grain at a distance $D$ of the source. The derived temperatures range from 170 to 350 K in the torus, and about 500 K in the Peanut.

Figure 1. Peak-intensity maps of CO $J = 3 \rightarrow 2$, HCN $J = 4 \rightarrow 3$, H$^{13}$CN $J = 4 \rightarrow 3$ and HCO$^+$ $J = 4 \rightarrow 3$ in colour scale. Spectral lines are indicated in the top right corner. Contours are 30, 50 and 70 K. A close-in view of the central HCO$^+$ emission (the Peanut) is shown in the inset, with the position of η Car indicated by the red marker. Beam width is shown in the bottom left corner of each panel.

Figure 2. Continuum emission and line absorptions at 345.8 GHz. The continuum image (left, colour scale) is composed by a point-like source and an extended source coincident with the Peanut. Contours are 1.4, 1.6, 1.8, 2.0, and 2.2 Jy beam$^{-1}$, and correspond to the resultant image after a point source subtraction. Half power beam width is indicated by the white ellipse at the lower right corner. Spectra depicted in the right panels are the emission or absorption of the other molecules toward the star but not the Peanut. Velocity (HCN and H$^{13}$CN, ν = 0 and ν$_2$ = 1) appears in absorption exclusively toward the star but not the Peanut. While this fact may be explained merely by excitation arguments in the case of the ν$_2$ = 1 lines, the lack of absorption of ν = 0 lines in the Peanut implies that the absorbing volume is strictly located towards the star.

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Peanut’s peaks roughly match the positions of the Weigelt blobs (Dorland et al. 2004), which puts the two structures in relation: the Weigelt knots are likely the densest parts of a halo of hot dust and gas.

A minimum of 1050 K is required to excite this mode, and this value is only reached in the hot star.

References

Ando et al. 2016;

Dorland et al. 2004;

Smith et al. 2003a;
Lisztt & Gerin 2018). The continuum and excitation temperatures result to be 3390 and 500 K, respectively. The four lines are optically thin, with opacities from 0.01 to 0.025. Table 1 summarizes the resulting column densities.

Some molecular abundances vary drastically among the different positions. The torus presents [HCO$^+$/[CO] ratios of $\sim 10^{-4}$, comparable to those measured around massive evolved stars, like the Wolf-Rayet nebula NGC2359 (Rizzo et al. 2003a). Similar ratios are also found the Orion Bar photodissociation region (Young Owl et al. 2000) and some molecular clouds, such as TMC-1 (Pratap et al. 1997).

On the contrary, we found significantly altered [HCN]/[CO] relative abundances, with values of a few $\sim 10^{-3}$. These are almost 100 times larger than the ratios measured in TMC-1 and NGC2359 and just slightly above those of the Orion Bar PDR, but still much lower than in ambients where the grain chemistry dominates (Shalabiea & Greenberg 1996). The highest ratios are measured towards the clump and the absorbing bullet, which suggests that these two features may be similar in nature. While these relative abundances may be a hint of N-enriched matter from the CNO cycle, we can not report N-enrichment in absolute terms as we lack information about H$_2$ in these specific regions. Never the less, the [HCN]/[$^{13}$CN] ratio is a good proxy to confirm that all this gas is CNO-processed ejecta (and thus N-rich, since $^{13}$C and N are two intermediate products of the CNO cycle). In every region we measure [HCN]/[$^{13}$CN] relative abundances close to unity. This value is exceptional, and holds for the vibrationally-excited lines as well. It indicates an extremely low [$^{12}$C]/[$^{13}$C] isotopic ratio, even for a massive star (typically in the range 3 – 10, e.g. Lambert et al. 1984, Bordiu et al. 2019).

The situation in the Peanut is completely different, as Fig. 1 suggested. Since CO, HCN and $^{13}$CN are not detected towards this region, we use the 3$\sigma$ level to estimate upper limits. In addition, N(HCO$^+$) reaches $\sim 10^{16}$ cm$^{-2}$, two orders of magnitude above the torus. As a consequence, both the [HCO$^+$]/[CO] and [HCO$^+$]/[HCN] ratios increase by a factor of up to 125. The lack of nitrogen-bearing molecules in the Peanut as a chemical argument to confirm the Peanut as an independent structure, not related to the Great Eruption. But most importantly, it raises two interesting possibilities, worth to be explored: either we are observing a transient stage, still far from chemical equilibrium, or we are witnessing the very end of the CNO cycle.

### 3.4 The most recent eruption of $\eta$ Car?

The morphology of the Peanut is compatible with an asymmetric mass ejection. The occurrence of such ‘one-sided’ events in $\eta$ Car was first proposed by Kiminki et al. (2016), and later used by Smith et al. (2018) to explain the gap in the CO torus. If the Peanut was expelled in such a manner as well, when did it occur?

The left panel in Fig. 4 shows the first-order moment map of HCO$^+$. We notice a clear gradient from the SE to the NW, which is consistent with the asymmetric eruption hypothesis. A crude approach to the dynamic age of the structure is given by $t_{\text{dyn}} = \frac{\Delta s}{v_{\text{sys}}}$, being $\Delta s$ the spatial ex-
tent of the emission and Δν its velocity extension. Approximating the gradient by the total velocity dispersion with an uncertainty of 10 km s$^{-1}$, we obtain a dynamical age of $t_{\text{dyn}} \leq 18$ years, hence dating the structure between 1928 and 1948. This result links the formation of the Peanut with the luminosity increase of 1941. Consequently, the Peanut may represent the first resolved image of the Baby Homunculus in sub-mm wavelengths. Besides, the striking correlation of the Weigelt blobs with the HCO$^+$ peaks somehow confirms that these clumps were ejected in the first half of the 20th century (Dorland et al. 2004).

4 CONCLUDING REMARKS

We present ALMA observations (continuum, CO, HCN, H$^{13}$CN and HCO$^+$) of the inner 8 arcsec of the Homunculus around η Car. The unprecedented resolution allowed us to discover some key ingredients related to the recent mass-loss history of the source.

We found that the disrupted torus described by Smith et al. (2018) is made of CNO-processed matter, as revealed by the HCN relative abundances and the extremely low [HCN]/[H$^{13}$CN] ratios. In addition, we discovered a hot bullet of N-enriched matter towards the star, absorbing the continuum, and possibly another one in position C. These bullets resemble the warm spots of ammonia found spread within the LBV nebula G79.29+0.46 (Rizzo et al. 2014).

Furthermore, we report the discovery of an inner extended structure closer to the star, the Peanut. The Peanut is only visible in continuum and HCO$^+$, and perhaps poor in CO material. From a kinematic point of view, the Peanut is compatible with a one-sided eruption in the first half of the 20th century, possibly being the first direct image of the Baby Homunculus, at least at sub-mm wavelengths.

All these findings uncover a really complex scenario that requires new physical and chemical models to be fully understood. We propose two possible explanations for the observed chemical differences. The first is that the we are observing a transient stage, in which the molecular soup expelled in the latest eruption has had no time to reach equilibrium. In this situation, HCO$^+$ may be one of the first polyatomic molecules to form. The second possibility, supported by the abundances measured in the Wolf-Rayet nebula NGC2359, is that η Car shed out the last layers of CNO-processed material during the Great Eruption. Therefore, the CNO cycle has come to an end, and nitrogen-rich material is likely less abundant in the most recent ejecta.

Further monitoring of the chemical evolution of the Peanut, together with a revision of stellar evolution models, would be key to test both hypotheses. Moreover, observing other molecules and transitions at the highest resolution possible will allow to constrain the physical conditions of the gas and complete the chemical puzzle of η Car.

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