MOLECULES IN η CARINAE

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ABSTRACT

We report the detection toward η Carinae of six new molecules, CO, CN, HCO+, HCN, HNC, and N2H+, and of two of their less abundant isotopic counterparts, 13CO and H13CN. The line profiles are moderately broad (~100 km s\(^{-1}\)), indicating that the emission originates in the dense, possibly clumpy, central arcsecond of the Homunculus Nebula. Contrary to previous claims, CO and HCO+ do not appear to be underabundant in η Carinae. On the other hand, molecules containing nitrogen or the 13C isotope of carbon are overabundant by about one order of magnitude. This demonstrates that, together with the dust responsible for the dimming of η Carinae following the Great Eruption, the molecules detected here must have formed in situ out of CNO-processed stellar material.

Key words: astrochemistry – circumstellar matter – ISM: molecules – stars: chemically peculiar – stars: mass-loss – stars: winds, outflows

1. INTRODUCTION

η Carinae is well known to have experienced a major outburst in the 1840s, during which it became the second-brightest star in the entire sky (e.g., Humphreys & Davidson 1999). Known as the Great Eruption, this outburst was associated with an episode of extreme mass loss (about 10\(^{-5}\) M\(_\odot\) of material was expelled in about 20 years) that resulted in the creation of the bipolar-shaped Homunculus Nebula whose current size is about 16′ × 10′, or 0.18 × 0.11 pc assuming a distance of 2.3 kpc (Walborn 1995; Allen & Hillier 1993). Over the following decades, the visual brightness of η Carinae faded by many magnitudes, but early infrared observations by Neugebauer & Westphal (1968) revealed that the bolometric luminosity in the second half of the 20th century remained comparable to that during the Great Eruption. The dimming at optical wavelengths resulted from obscuration by dust particles, presumably formed in situ out of the ejected material.

A scant handful of molecular species have been detected toward η Carinae. Molecular hydrogen, traced by its 2.12 \(\mu\)m line, appears to be distributed over the outer surface of the Homunculus Nebula and is strongest toward the polar caps where the intercepted column is largest (Smith 2002, 2006). Two other simple diatomic molecules (CH and OH) were identified in Hubble Space Telescope STIS spectra through their UV absorption lines (Verner et al. 2005). Both also originate in the thin outer layer of the Homunculus. Finally, radio emission from ammonia (NH\(_3\)) was detected by Smith et al. (2006) using the Australia Telescope Compact Array. The ammonia emission is confined to a region roughly 1 arcsec across, and shares the kinematics of the H\(_2\) 2.12 \(\mu\)m line in the same region.

Interestingly, carbon monoxide (CO) has never been detected toward η Carinae in spite of sensitive searches at millimeter, infrared, and UV wavelengths (Cox & Bronfman 1995; Smith 2002; Verner et al. 2005). As discussed by Smith et al. (2006), this lack of CO detection could reflect the C/O depletion and N enrichment of the material ejected during the Great Eruption. Indeed, the ionized gas surrounding the Homunculus Nebula is known to be composed of such nitrogen-rich CNO-processed material (Davidson et al. 1982, 1986; Dufour et al. 1997; Hillier et al. 2001; Smith & Morse 2004). In addition, the abundance of the nitrogen-bearing ammonia molecule in the Homunculus itself is estimated to be about 2 × 10\(^{-7}\), roughly one order of magnitude higher than in cold interstellar clouds (Smith et al. 2006). It should be emphasized, however, that the existing, unsuccessful searches for CO in η Carinae are insufficient to place meaningful limits on the [CO]/[NH\(_3\)] abundance ratio in the Homunculus (Smith et al. 2006). Thus, the low abundance of carbon monoxide in η Carinae is still not firmly established.

The formation and survival of molecules in the harsh environment of η Carinae, within 1″ (0.01 pc) of a 100 M\(_\odot\) star, remain poorly understood. Other classes of massive stars (such as red supergiants and Wolf–Rayet stars) are known to be surrounded by significant quantities of molecular gas, although at greater distances, which might indicate that it represents swept-up ambient interstellar material (Pulliam et al. 2011; Cappa et al. 2001; Rizzo et al. 2001, 2003). It is unclear whether or not there is a relation between the mechanisms at work in these objects and those occurring in the Homunculus. To tackle these issues, it is important to characterize the molecular content of the Homunculus, and to determine the physical properties and spatial distribution of the molecular gas. In this Letter, we present new submillimeter spectroscopic observations of η Carinae designed to search for several new molecular species, including carbon monoxide.

2. OBSERVATIONS

The observations were performed in 2011 October 12–17 and December 15–20 with the Atacama Pathfinder EXperiment telescope (APEX; Güsten et al. 2006) located at an altitude of 5100 m on Llano Chajnantor, Chile. The molecular transitions targeted are listed in Table 1. Two different receivers were used: a modified version of the First Light Apex Submillimeter Heterodyne receiver (FLASH; Heyminck et al. 2006) for transitions in the 345 and 460 GHz bands, and the Carbon Heterodyne Array of the MPIfR (CHAMP+; Güsten et al. 2008) for transitions in the 690 GHz band. While FLASH is a single-beam receiver, CHAMP+ provides spectra simultaneously at seven positions. Those positions correspond to the central (directly on-source) pixel and to six lateral points distributed in a hexagonal pattern around the central pixel and separated from it by about...
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Table 1
Observing Log and Results

| Transition     | ν (MHz) | Rx          | θ_{mb}^a | η_{mb}^b | W^c |
|----------------|---------|-------------|----------|----------|------|
| CO(3–2)        | 345795.9890 | FLASH       | 17.5     | 0.73     | 24.0 ± 3.6 |
| CO(4–3)        | 460418.8125 | FLASH       | 13.3     | 0.60     | 31.8 ± 4.8 |
| CO(6–5)        | 691473.0763 | CHAMP+      | 4.0      | 0.48     | 73.5 ± 11.0 |
| ^13CO(3–2)     | 330887.9653 | FLASH       | 17.5     | 0.73     | 7.4 ± 1.1 |
| ^13CO(6–5)     | 661067.2766 | CHAMP+      | 9.0      | 0.48     | 20.9 ± 3.1 |
| CN(3–2)d       | 356734.2230 | FLASH       | 17.5     | 0.73     | 10.1 ± 0.1 |
| HCO+(4–3)      | 354505.4773 | FLASH       | 17.5     | 0.73     | 3.7 ± 0.6 |
| CN(3–2)d       | 357634.2230 | FLASH       | 17.5     | 0.73     | 10.1 ± 1.5 |
| HCN(4–3)       | 354505.4773 | FLASH       | 17.5     | 0.73     | 10.7 ± 1.6 |
| HCN(4–3)       | 354539.7694 | FLASH       | 17.5     | 0.73     | 8.3 ± 1.2 |
| N2H+(4–3)      | 362630.3030 | FLASH       | 17.5     | 0.73     | 7.0 ± 0.4 |
| N2H+(4–3)      | 372672.4645 | FLASH       | 17.5     | 0.73     | 24.5 ± 3.7 |

Notes.

^a θ_{mb} is the beam size at each frequency.
^b η_{mb} is the main beam efficiency, used to convert the measured antenna temperatures to main beam temperatures.
^c The values reported in this column were obtained by integrating over the entire velocity range where emission is detected. W = ∫ T_{mb}dv.
^d CN(3–2) was not specifically targeted, but happened to be detected near the edge of one of the observed bands. As a consequence, only about half of the hyperfine components were included in the band (see Figure 1), and this observation will have to be repeated in the future.

3. RESULTS AND ANALYSIS

All of the targeted lines were detected toward the source (Figure 1), but no emission was seen in the lateral pixels of the CHAMP+ observations. This demonstrates that the molecular emission is confined to the Homunculus itself. In addition, the line profiles are quite broad (up to about 300 km s^{-1} full width at zero point, with “cores” of roughly 100 km s^{-1} FWHM; Figure 1) and reminiscent of the NH₃ spectra presented by Smith et al. (2006). In comparison, the Homunculus has expansion velocities of roughly 600 km s^{-1}, while the Weigelt knots near the star have outward velocities less than 50 km s^{-1} (e.g., Hofmann & Weigelt 1988; Weigelt et al. 1995; Davidson et al. 1997). The similarity between the NH₃ spectra (Smith et al. 2006) and those reported here likely indicates that the emission originates in the central few arcseconds of the Homunculus. The emission is centered at V_{lsr} ~ +20 km s^{-1}, a value somewhat more positive than the systemic velocity of η Carinae (−20 km s^{-1}; Davidson et al. 1997; Smith 2004). This is, again, similar to the situation with ammonia (Smith et al. 2006). The observed profiles are clearly not Gaussian. Instead, they exhibit significant sub-structure, suggesting that the emission might come from a clumpy material. Indeed, all of our spectra are consistent with four velocity components at V_{lsr} = −76.2, −8.9, +30.5, and +63.5 km s^{-1}. Particularly noteworthy is the narrow component at V_{lsr} = −76.2 km s^{-1} seen in most of our spectra, and most likely associated with the strong H₂ 1–0(1) emission detected by Smith (2004; see also Smith et al. 2006) at the same radial velocity.

The combination of observed CO and ^13CO spectra can be used to constrain the physical conditions of the emitting material. First, we note that the relative peak intensities of the CO 3→2, 4→3, and 6→5 lines (0.15, 0.25, and 0.5 K; see the red marks in Figure 1) are almost exactly in the inverse proportion of the corresponding beam areas (1 : 1.7 : 3.8). This shows that the CO lines are optically thick and come from a region smaller than all of the beams (even that at 690 GHz). For such optically thick lines, there is a degeneracy between temperature and filling factor. This degeneracy can be removed using the ^13CO line intensities, and we find that all the CO and ^13CO lines can be reproduced for an excitation temperature of order 70 K and a source size of order 1″. A higher excitation temperature (of, say, 200 K) could reproduce the CO lines provided the source size were 0.5″, but would predict a ^13CO(6–5)/^13CO(3–2) line ratio of about 8.5, inconsistent with the observed value of 5. Given the similarities between all the spectra observed here (Figure 1), it is reasonable to assume that all the molecular emission comes from the same material, so we conclude that all the lines reported here originate in a source about 1″ in size where the gas is at a temperature of order 70 K.

To estimate the molecular column densities, we used the myXCLASS program4 (see Comito et al. 2005, and references therein), and modeled the emission as a superposition of the four distinct velocity components identified earlier. We used line widths for each component consistent with the observed widths of the optically thin lines (Δν = 13.2, 35.8, 21.6, and 36.4 km s^{-1}, respectively, for the four velocity components) and found reasonable fits to all the lines for excitation temperatures of 40, 50, 40, and 90 K, respectively, for the four components. Our approach to column density determinations entails a number of approximations. First, the calculations are made under the assumption of local thermodynamic equilibrium (LTE). To check that this did not strongly affect our results, we used the publicly available non-LTE radiative transfer code RADEX (van der Tak et al. 2007) to verify that the excitation conditions were consistent with LTE. Second, our calculations do not consider the opacity due to possible spatial overlap between different velocity components. To decide to which extent this problem might affect our conclusions, high angular resolution observations will be necessary. The column densities resulting from our analysis are given for each species in Table 2, and the corresponding model spectra are shown in Figure 1. We note that the CO column density itself is somewhat uncertain due to its substantial opacity.

The abundance of each species was calculated relative to CO and to molecular hydrogen, assuming a column density N(H₂) =

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5 Note that our spectra are measured in the LSR rest frame, whereas those in Smith (2002, 2004) and Smith et al. (2006) are reported in the Heliocentric system. For η Carinae, η_{lsr} ≈ η_{mb} + 12 km s^{-1}.

4 http://www.astro.uni-koeln.de/projects/schilke/XCLASS
Figure 1. Observed spectra toward $\eta$ Carinae. The magenta curves show the theoretical spectra expected in the conditions described in the text. The horizontal red lines in the three spectra of the left column indicate the typical intensity of the CO lines mentioned in Section 3. The CN line was on the edge of the band and the corresponding profile misses some hyperfine components.

Table 2

| Species     | N (cm$^{-2}$) | N/H (H$_2$) | N/H (CO) |
|-------------|--------------|-------------|----------|
| CO          | $6.5 \times 10^{18}$ | $2.2 \times 10^{-4}$ | $1$      |
| $^{13}$CO   | $1.4 \times 10^{18}$ | $4.7 \times 10^{-5}$ | $2.2 \times 10^{-1}$ |
| CN          | $9.0 \times 10^{15}$ | $3.0 \times 10^{-7}$ | $1.4 \times 10^{-3}$ |
| HCO$^+$     | $1.7 \times 10^{15}$ | $5.7 \times 10^{-8}$ | $2.6 \times 10^{-4}$ |
| HCN         | $5.5 \times 10^{15}$ | $1.8 \times 10^{-7}$ | $8.5 \times 10^{-4}$ |
| H$_2$CN     | $3.1 \times 10^{15}$ | $1.0 \times 10^{-7}$ | $4.8 \times 10^{-4}$ |
| HNC         | $2.1 \times 10^{15}$ | $7.0 \times 10^{-8}$ | $3.2 \times 10^{-4}$ |
| N$_2$H$^+$  | $6.1 \times 10^{15}$ | $2.0 \times 10^{-7}$ | $9.4 \times 10^{-4}$ |

Note. $^a$ Abundance of each species relative to H$_2$, assuming $N$(H$_2$) = $3 \times 10^{22}$ cm$^{-2}$ (Smith et al. 2006).

3 $\times 10^{22}$ cm$^{-2}$ as estimated to be appropriate for this part of the Homunculus by Smith et al. (2006). We note, however, that a somewhat larger column density of H$_2$ might also be plausible. Based on submillimeter and far-infrared observations, Gomez et al. (2010) recently determined the mass of dust surrounding $\eta$ Carinae to be about 0.4 $M_\odot$. For a standard gas-to-dust ratio of 100, this would yield an average H$_2$ column density of about $2 \times 10^{23}$ cm$^{-2}$. If the dust distribution were clumpy, however, the column density appropriate for the individual clumps might be several times larger, and the abundances quoted in Table 2 could be proportionately lower.

4. DISCUSSION

Within its uncertainty, the abundance of CO derived here for $\eta$ Carinae is similar to its canonical interstellar value of $10^{-4}$. It is also similar to the typical CO abundances found in O-rich circumstellar envelopes (Ziurys et al. 2009). Thus, CO does not appear to be underabundant in the Homunculus Nebula, contrary to previous claims based on unsuccessful CO searches. The abundance of HCO$^+$ is similar to its value in dense massive cores ($\sim 2 \times 10^{-8}$; Vasyunina et al. 2011) and in the dense envelopes surrounding low-mass stars ($\sim 1.2 \times 10^{-8}$; Hogerheijde et al. 1997). It is also in the midrange of observed abundances in evolved stars with oxygen-rich circumstellar envelopes (0.5–13 $\times 10^{-8}$; Pulliam et al. 2011), but significantly larger than the abundance in carbon-rich stars, such as IRC +10216 (where it is $4 \times 10^{-9}$; Pulliam et al. 2011). We conclude that both CO and HCO$^+$ have roughly standard abundances in the Homunculus.

The nitrogen-bearing molecules, on the other hand, are found to be highly overabundant in $\eta$ Carinae. While the average abundance of HCN and HNC in low- and high-mass dense cores is $2 \times 10^{-9}$ (Vasyunina et al. 2011), their abundances in $\eta$ Carinae are $(0.7–2) \times 10^{-7}$ (Table 2). Similarly, the abundance of N$_2$H$^+$ is about two orders of magnitude higher in the Homunculus than in dense cores (where it is, on average, $2 \times 10^{-9}$; Vasyunina et al. 2011). The situation is much the same for ammonia (Smith et al. 2006) showing that nitrogen-bearing molecules are consistently one order of magnitude more abundant in the Homunculus than in the dense interstellar medium. Although chemical effects might affect the abundance of specific individual molecules, this combination of results suggests that the abundance of nitrogen itself must be enhanced by one order of magnitude in the Homunculus. The comparison between the abundances of N-bearing species in $\eta$ Carinae and those in O-rich circumstellar envelopes is somewhat confusing. While HCN is about one order of magnitude less abundant in $\eta$ Carinae than in O-rich envelopes, the abundance of HNC is similar in both kinds of objects. As a consequence, the [HCN]/[HNC] ratio in $\eta$ Carinae is of the order of a few,
similar to its value, of order unity, in quiescent interstellar
cores (Padovani et al. 2011), but very different from its value
two orders of magnitude more abundant in $\eta$ Carinae than in O-rich envelopes (Ziurys et al. 2009).

The high abundance of nitrogen in the ionized gas surrounding the Homunculus (Smith & Morse 2004) and in the Homunculus itself (as documented above) are also expected consequences of the CNO cycle. Thus, the molecular observations presented here strongly support the idea that the material expelled during the Great Eruption is CNO-processed stellar matter.

We mentioned in the Introduction that dust grains must have formed out of the material ejected by $\eta$ Carinae during the Great Eruption. The present results demonstrate that large quantities of molecular material have also formed out of this material. It will be interesting to analyze the chemistry that led to the formation of these molecules from the theoretical standpoint, because the elemental composition of the gas (particularly the N and $^{13}$C enrichment) and the physical conditions (especially the strong UV field) are very different from those in the interstellar gas. Additionally, the chemistry at play occurred in just a few decades. From the observational point of view, it will be important to further characterize the molecular content of $\eta$ Carinae. Searching for additional nitrogen-bearing molecules such as HC$_3$N would be particularly interesting. To further characterize the isotopic composition of the gas, it would also be important to search for molecules containing the $^{15}$N, $^{17}$O, and $^{18}$O isotopes because CNO nucleosynthesis models make specific predictions for the relative abundance of these elements. Finally, it would be very interesting to characterize the spatial distribution of the molecular material in the Homunculus. Our observations suggest a source size of order 1$''$, but it is clear from the composite nature of the line profiles that observations at sub-arcsecond resolution would enable a detailed study of the spatial distribution of the molecular material and of its kinematics. ALMA (the Atacama Large Millimeter/submillimeter Array) will, of course, be the instrument of choice for such observations.

5. CONCLUSIONS AND PERSPECTIVES

In this Letter, we have reported the detection of six new molecules, including carbon monoxide, and two of their less abundant isotopic forms toward $\eta$ Carinae. This replicates the number of molecules known in this object. While the abundances of CO and HCO$^+$ are found to be standard, molecules containing nitrogen or the $^{13}$C isotopic form of carbon are about order of magnitude. This indicates that the material expelled by $\eta$ Carinae during the Great Eruption is CNO-processed stellar matter.

Additional single-dish and interferometric observations will be very important to further characterize the chemical composition of the gas on the Homunculus, and to establish its spatial distribution. Observations of additional nitrogen-bearing molecules and of species containing specific isotopes of carbon, oxygen, and nitrogen will be particularly interesting. 

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