NEUTRAL ATOMIC CARBON IN THE GLOBULES OF THE HELIX

K. YOUNG
Smithsonian Astrophysical Observatory, 60 Garden Street, MS 78, Cambridge, MA 02138

P. COX
Institut d’Astrophysique Spatiale, Université de Paris XI, F91405 Orsay, France, and
Institut d’Astrophysique de Paris, 92 bis Boulevard Arago, F-75014 Paris, France

P. J. HUGGINS
Department of Physics, New York University, 4 Washington Place, New York, NY 10003

T. FORVEILLE
Observatoire de Grenoble, B.P. 53X, F-38041 Grenoble Cedex, France

AND

R. BACHILLER
Observatorio Astronómico Nacional, Instituto Geográfico Nacional, Apdo. 1143, E-28800 Alcalá de Henares, Spain

Received 1997 February 4; accepted 1997 March 18

ABSTRACT

We report detection of the 609 mμm3P1 → 3P0 line of neutral atomic carbon in globules of the Helix Nebula. The measurements were made toward the position of peak CO emission. At the same position, we obtained high-quality CO(2–1) and 13CO(2–1) spectra and a 135° × 135° map in CO(2–1). The velocity distribution of C i shows six narrow (1–2 km s−1) components, which are associated with individual globules traced in CO. The C i column densities are (0.5–1.2) × 1016 cm−2. C i is found to be a factor of ~6 more abundant than CO. The large abundance of C i in the Helix can be understood as a result of the gradual photoionization of the molecular envelope by the central star’s radiation field.

Subject headings: planetary nebulae: individual: (NGC 7293) — radio lines: stars — stars: AGB and post-AGB — stars: mass loss

1. INTRODUCTION

The Helix (NGC 7293, PK 36−57.1) is the nearest planetary nebula (PN) with a massive molecular envelope (Huggins et al. 1996). At a distance of ~160 pc (see, e.g., Cahn, Kaler, & Stanghellini 1992), it affords the best opportunity to explore in detail the relation between neutral and ionized gas in an evolved nebula. Molecular gas in the Helix forms a large broken ring surrounding the ionized cavity (Healy & Huggins 1990; Cox et al. 1997), and its mass is at least 0.03 M J, or ≥25% of the total nebular mass (Huggins & Healy 1986). High-resolution observations show that the molecular gas is fragmented into numerous substructures (Forveille & Huggins 1991), some of which survive within the ionized cavity and are seen as the well-known cometary globules (Huggins et al. 1992). Hubble Space Telescope studies of these remarkable structures have been reported by O’Dell & Handron (1996).

The molecular gas in PNs is exposed to strong UV radiation from the central star, which is expected to establish photodissociation regions (PDRs) with an important component of atomic gas at the interface with the ionized gas. A characteristic of such regions is emission in the ground-state 3P1 → 3P0 fine-structure line of neutral atomic carbon at 609 mμm. This line has been detected in the young PN NGC 7027 (Young et al. 1997), where C i is found to be a minor constituent. It has also been detected in the Ring Nebula (Bachiller et al. 1994), where the abundance of C i exceeds that of CO, although the detailed structure of the gas is not resolved.

In this Letter, we report the detection of the 609 mμm C i line in the Helix. The observations, made toward the position of peak CO emission, reveal multiple, narrow (1–2 km s−1) C i components that we unambiguously associate with the globules through mapping the components in CO. The observations show that C i is a major constituent of the neutral gas in the globules.

2. OBSERVATIONS AND RESULTS

The observations were made using the 10.4 m telescope of the Caltech Submillimeter Observatory (CSO). The region observed lies on the western limb of the ionized nebula and corresponds to the position of peak CO emission (see Fig. 1). The observations include deep integrations at the field center in C i, CO(2–1), and 13CO(2–1) and mapping of the region in CO(2–1) to determine the local structure of the gas.

The C i observations at 609 mμm (492 GHz) were obtained in 1996 July in excellent weather conditions. The single-sideband system temperature (Tsys) of the receiver was typically ~1900 K, and the spectrometer’s resolution was 1 km s−1. The beam size at 492 GHz was 15′′ (FWHM). We checked pointing by mapping CO(4–3) in the nearby star EP Aqr and found its error to be ≤4′′. A chopping secondary mirror was used to observe two reference positions ±500″ from the source in azimuth. Observations were taken only when the source was near transit, to ensure that the reference positions were locations previously found to be free of CO emission.
We also obtained CO(2–1) and $^{13}$CO(2–1) spectra at the position observed in C I and mapped a region of $135\,\times\,135^\circ$ around this position in CO(2–1) with $15^\circ$ spacing. For these observations, $T_{\text{mb}} = \sim 250$ K and the spectrometer’s resolution was $\sim 0.1$ km s$^{-1}$. All intensities in this Letter are in units of main-beam temperature.

The C I, CO, and $^{13}$CO spectra are shown in Figure 2. The three spectra are characterized by multiple velocity components, most clearly seen in the CO spectrum. There are at least five separate components at velocities between $-28$ and $-9$ km s$^{-1}$ and additional, weaker components around $-30$ km s$^{-1}$ and, possibly, $-6$ km s$^{-1}$. The strongest components can be identified in all three spectra.

To characterize the spectra, we made multiple-Gaussian fits to the data. For the CO spectrum, we fitted the five main components with the velocities ($v_o$), intensities ($T$), and line widths ($\Delta v$) as free parameters. These values for $v_o$ and $\Delta v$ were then used for the fits to the $^{13}$CO and C I spectra. The results are given in Table 1, which lists the velocity, line width, and the velocity-integrated line intensities ($I$) for each of the components (labeled A–E for reference).

The CO mapping data are shown in Figure 3 as a series of channel maps, with a velocity spacing of 1 km s$^{-1}$. The CO emission is seen to extend along a southeast-northwest direction and shows a complex structure. The emission shows peaks at different positions in different channel maps, indicating that the distribution of matter is characterized by small globules or clumps, which have a typical velocity dispersion $\lesssim 2$ km s$^{-1}$ and are unresolved or partially resolved by the $30^\circ$ beam. Most of the components identified in the spectra in Figure 2 can be associated with discrete structures in the channel maps. Thus the bulk of the CO and the C I emission is localized within the neutral globules.

3. DISCUSSION

3.1. C I and CO Column Densities

We first discuss interpretation of the observed lines in terms of column densities, using the simplifying assumptions of low optical depth and LTE. The recent study of molecular gas in PNs, including the Helix, by Bachiller et al. (1997) indicates a relatively low opacity for the CO lines and provides an estimate for the excitation temperature of $T_{\text{ex}} = 25$ K, based upon the ratio of the 2–1 and 1–0 lines of $^{13}$CO. The low intensity of the C I line and the similarity of the levels to the low-lying CO lines suggests that these results are also appropriate for C I. For $T_{\text{ex}} = 25$ K, the C I and CO column densities (in cm$^{-2}$) are related to the integrated intensities of the observed lines (in K km s$^{-1}$) by the expressions $N$(C I) = 1.3 ×
10^{20} (C I) and N(CO) = 5.3 \times 10^{14} (CO). These relations are not very sensitive to $T_e$ and they vary by less than a factor of 2 over the range 10–80 K.

Estimated column densities are given in Table 1 together with the C I/CO column density ratio and the $I(12\text{CO})/I(13\text{CO})$ ratio. These results show that the characteristics of the globules are remarkably uniform: the $^{12}\text{C}/^{13}\text{C}$ value is $\approx 15$, and the column density in C I is systematically higher than that of CO by a factor of $\approx 6$.

3.2. Properties of the Globules

The large abundance of C I that we find in the Helix demonstrates that atomic carbon is an important component of the envelope's neutral gas. This is likely caused in part by the radiation field of the central star, which will develop PDRs in the neutral gas. The material observed lies along the ionization front in the dark/extinguished area of the optical nebula (see Fig. 1), and the morphology of the gas (Fig. 3)

---

**Table 1**

| Globule  | $v_0$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $I$(CO) (K km s$^{-1}$) | $I$(12CO) (K km s$^{-1}$) | $I$(C I) (K km s$^{-1}$) | $I_{12}/I_{13}$ | $N$(CO) (10$^{15}$ cm$^{-2}$) | $N$(C I) (10$^{15}$ cm$^{-2}$) | $N$(C I)/$N$(CO) |
|---------|---------------------|--------------------------|-------------------------|--------------------------|-------------------------|----------------|----------------------|----------------------|---------------|
| A........ | -21.9               | 1.7                      | 3.4                     | 0.26                     | 0.93                    | 13             | 1.80                 | 12.2                 | 6.8            |
| B........ | -20.1               | 1.2                      | 1.7                     | 0.10                     | 0.45                    | 16             | 0.89                 | 5.9                  | 6.7            |
| C........ | -17.3               | 2.4                      | 2.4                     | 0.17                     | 0.63                    | 14             | 1.27                 | 8.3                  | 6.5            |
| D........ | -13.7               | 2.1                      | 2.5                     | 0.13                     | 0.40                    | 20             | 1.32                 | 5.3                  | 4.0            |
| E........ | -11.1               | 1.4                      | 1.6                     | 0.16                     | 0.44                    | 11             | 0.87                 | 5.8                  | 6.7            |

---

**Fig. 3.**—Maps of the CO(2–1) line intensity integrated in velocity intervals of 1 km s$^{-1}$. The central LSR velocity of each interval is given in each panel. The contours are 0.3, 0.6, 0.9, …, 3 K km s$^{-1}$. The bottom right panel displays the velocity-integrated emission (from $-26$ to $-9$ km s$^{-1}$)—contours are 1 to 12 by 3 K km s$^{-1}$. The beam (30”) shown in the upper left panel corresponds to the position observed in Fig. 2.
indicates a very broken structure that is probably permeated by the stellar radiation.

The C/O ratio in the Helix has not been measured, but there is considerable evidence that it is carbon rich. Howe, Hartquist, & Williams (1994) have constructed chemical models of the globules and found that the abundance of C I is predicted to be roughly the same as that of CO for a large range in optical depths if C/O > 1. This is consistent with our observations. For the case with C/O < 1, however, the abundance of C I is predicted to be much less than CO, which is not observed, indicating that the Helix is a C-rich nebula. Additional evidence comes from the similarity of the molecular abundances in the Helix with other C-rich nebulae measured by Bachiller et al. (1997) and the presence of PAH emission (Cox et al. 1997).

The globules' sizes determined from the channel maps are typically $30'' \times 30''$, or $7 \times 2$ in units of $10^6$ cm (at 160 pc). Their masses can be estimated from the observed lines by adopting an abundance ratio for CO or C. Estimates of the mass of molecular gas in the globules can be made by assuming that all the oxygen is in CO, i.e., CO/H = O/H, which is measured to be $3 \times 10^{-4}$ in the ionized gas (Kaler, Shaw, & Kwitter 1990). Using the same assumptions about the opacity and temperature as before, the beam-averaged column densities of hydrogen (in H I and H$_2$) are $3 \times 10^{19}$ cm$^{-2}$ for clumps A, B, C, and E, and the masses are typically $(1-3) \times 10^{-3} M_\odot$ for each clump. We note that component D corresponds to material at the edge of a CO layer, which could explain its lower N(C I)/N(CO) ratio.

The average value of the C I/CO ratio of $\approx 6$ that we find means that the above mass estimates based upon the molecular observations are lower limits to the total mass of neutral gas. Adopting a nominal C/O ratio of 1.2 (as in the Ring Nebula; see Bachiller et al. 1994 and references therein), the corresponding mass of neutral gas of each clump will be about $10^{-4} M_\odot$. Taking the total number of clumps over the entire surface of the nebula, estimated to be 3000 by O'Dell & Handron (1996), and assuming that they are similar to the clumps described in this Letter, we derive a total mass of neutral gas of 0.4 $M_\odot$ in the Helix. This is an order of magnitude greater than the estimate published by Huggins & Healy (1989). This number could be an overestimate, because clumps inside the ionized cavity are known to have smaller masses of typically $5 \times 10^{-6} M_\odot$ (Huggins et al. 1992). On the other hand, taking into account the contribution of the C I 158 $\mu$m fine-structure line, which is likely to be present in the neutral gas, will increase the above mass estimate. Work in progress will explore the C I content in the Helix Nebula. In any case, it is clear that the mass of the neutral gas in the Helix represents a significant fraction, perhaps up to 50%, of the total nebular mass. Comparable results were found for the Ring Nebula by Bachiller et al. (1994), which is in a similar evolutionary status to the Helix.

3.3. Evolution

The large abundance of C I in the Helix is very different from that found at earlier stages of evolution. C I has not been detected in any envelopes of asymptotic giant branch (AGB) stars except IRC +10216, which has only a small amount of C I in the outer envelope (Keene et al. 1993). The young PN NGC 7027 has a larger C I content (about half that of CO in the inner envelope) associated with the PDR surrounding the compact ionized nebula (Young et al. 1997). This is consistent with the ionizing front's gradually etching out the molecular envelope ejected during the AGB phase. Further evolution is seen in the Helix and Ring Nebulae (Bachiller et al. 1994), where vast amounts of C I are detected.

Evidence that such an evolution has taken place inside the Helix is also suggested by the difference in mass between the globules seen in the ionized cavity and those of the outer molecular envelope. The masses of molecular gas derived for the globules in the envelope are about a factor 2–6 times greater than the mass estimates for the cometary globules, which lie inside the ionized cavity of the Helix (Huggins et al. 1992). This difference can be understood in the general picture wherein the ionization front overtakes clumps already present in the molecular envelope and photoionizes their surface layers. As they are gradually etched away, the dense molecular core will become smaller, and the remains, if any, will probably resemble the clumps detected in the ionized region. We note that this evolutionary picture is fully consistent with the results of the recent CO survey by Huggins et al. (1996).

4. Conclusion

These observations place important constraints on the properties of the neutral gas in the Helix Nebula. The mapping observations show that the structure of the gas on the periphery of the ionized nebula is highly fragmented, leading naturally to the formation of cometary globules in the ionized cavity. Our observations show that C I is the major form of atomic carbon in the neutral gas of the Helix and probably dominates the cooling of the gas. The C I results also indicate that the Helix is a carbon-rich nebula. The total mass of neutral gas in the Helix is derived to be of order 0.4 $M_\odot$, an order of magnitude larger than previous estimates. The present findings are in agreement with current ideas on the evolution from the AGB phase to fully evolved PN, during which the neutral envelope ejected in the AGB phase is gradually photodissociated and photoionized by the radiation field of the hot central star.

We thank R. Martin of the RGO for providing the R-band image. This work was supported in part by NSF grant AST-9314408 (to P. J. H.). The CSO is supported by NSF grant AST-9313929.

REFERENCES

Bachiller, R., Forveille, T., Huggins, P. J., & Cox, P. 1997, A&A, in press
Bachiller, R., Huggins, P. J., Cox, P., & Forveille, T. 1994, A&A, 281, 193
Cahn, J. H., Kalber, J. B., & Stanghellini, L. 1992, A&AS, 94, 399
Cox, P., et al. 1997, in preparation
Forveille, T., & Huggins, P. J. 1991, A&A, 248, 599
Healy, A. P., & Huggins, P. J. 1990, AJ, 100, 511
Howe, D. A., Hartquist, T. W., & Williams, D. A. 1994, MNRAS, 271, 811
Huggins, P. J., Bachiller, R., Cox, P., & Forveille, T. 1992, ApJ, 401, L43
———. 1996, A&A, 315, 284
Huggins, P. J., & Healy, A. P. 1986, ApJ, 305, L29
———. 1989, ApJ, 346, 201
Kaler, J. B., Shaw, R. A., & Kwitter, K. B. 1990, ApJ, 359, 392
Keene, J., Young, K., Phillips, T. J., Blüttgenbach, T. H., & Carlstrom, J. E. 1993, ApJ, 415, L131
O'Dell, R. R., & Handron, K. D. 1996, AJ, 111, 1630
Young, K., Keene, J., Phillips, T. G., Betz, A. L., & Boldt, R. T. 1997, in preparation

L104  YOUNG ET AL.