HIGH-RESOLUTION CO AND H$_2$ MOLECULAR LINE IMAGING OF A COMETARY GLOBULE
IN THE HELIX NEBULA

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ABSTRACT

We report high-resolution imaging of a prominent cometary globule in the Helix Nebula in the CO $J = 1–0$ (2.6 mm) and H$_2$ $v = 1–0$ S(1) (12.1 mm) lines. The observations confirm that globules consist of dense condensations of molecular gas embedded in the ionized nebula. The head of the globule is seen as a peak in the CO emission with an extremely narrow line width (0.5 km s$^{-1}$) and is outlined by a limb-brightened surface of H$_2$ emission facing the central star and lying within the photoionized halo. The emission from both molecular species extends into the tail region. The presence of this extended molecular emission provides new constraints on the structure of the tails and on the origin and evolution of the globules.

Subject headings: planetary nebulae: general — planetary nebulae: individual (NGC 7293) — stars: AGB and post-AGB

1. INTRODUCTION

The cometary globules in the Helix Nebula (NGC 7293) are among the most remarkable structures seen in planetary nebulae (PNe). They occur in large numbers in the lower ionization regions of the nebula and appear in high-resolution optical images as small (∼1"), convex, photoionized surfaces facing the central star, with comet-like tails extending in the opposite direction (e.g., Meaburn et al. 1992; O’Dell & Handron 1996). These structures are seen in other PNe (e.g., O’Dell et al. 2002) and are probably quite common, but they are best seen in the Helix Nebula because it is the nearest example, at a distance of $D \sim 200$ pc (parallax = 4.70 ± 0.75 mas; Harris et al. 1997).

A key step in understanding the nature of the Helix globules has been their detection in CO by Huggins et al. (1992). With a resolution of ∼12", the CO observations did not resolve their structure but demonstrated that globules contain a major mass component of molecular gas, consistent with observations of dust, seen in absorption against the nebula emission by Meaburn et al. (1992). The molecular gas places important constraints on the origin and evolution of the globules and provides a direct connection with the massive shell of neutral gas that surrounds the ionized nebula (Forveille & Huggins 1991; Young et al. 1999; Rodríguez, Goss, & Williams 2002). This connection is underscored by wide-field imaging of the nebula in the infrared lines of H$_2$ by Kastner et al. (1996), Cox et al. (1998), and Speck et al. (2002), at resolutions from 8" to 2", that show a highly fragmented envelope.

In order to determine the detailed relation between the molecular gas and the structure of the globules revealed by optical images, we have made new observations of the Helix Nebula in both CO and H$_2$ with significantly better resolution than previous observations. In this Letter, we report results on the molecular gas in a single cometary globule that resolve its head-tail structure.

2. OBSERVATIONS

The globule observed is a prominent feature lying within the ionized nebula to the north of the central star at offsets ($-10^\circ$, $+135^\circ$). It is designated C1 by Huggins et al. (1992), and its location is shown in Figure 3a of Meaburn et al. (1998), where it is labeled “1.” Optical images of the globule from Walsh & Meaburn (1993) in He$^+$/[N ii] λ6584 and in [O iii] λ5007, where it is seen in absorption against the nebular emission, are shown in the top right panels of Figure 1.

The CO observations were made in the 2.6 mm (115 GHz) $J = 1–0$ line using the IRAM interferometer at Plateau de Bure, France, in 1999 May. The array consisted of 15 m antennas, equipped with SIS heterodyne receivers. The observations were made with the D configuration of the array, with maximum baselines of ∼147 m. The primary beam size of the interferometer is 44" at 2.6 mm, and the effective velocity resolution for the analysis is 0.2 km s$^{-1}$. The $u$-$v$ data were Fourier-transformed and CLEANed, using the Clark algorithm, and the restored Gaussian clean beam is $7''9 \times 3''8$ at a position angle of 14°. The results are shown in Figures 1 and 2.

Images of the H$_2$ $v = 1–0$ S(1) emission in the northern quadrant of the Helix Nebula were obtained with the SOFI infrared camera on the ESO New Technology Telescope in 2001 June. The instrument has a 1024$^2$ HAWAII array and was used with an image scale of 0''24 pixel$^{-1}$. The seeing was 1''2. The observations were made with an H$_2$ filter of width 0.028 $\mu$m, centered at 2.124 $\mu$m, well separated from the He I $2^1P_2–2^1S_2$ 2.058 $\mu$m and H I $2.166 \mu$m lines, the latter having a transmission of a few percent in the filter passband. Fifteen 1 minute exposures were made, using sky offset positions at 5° north, 5° east, and 7° northeast. The individual images were sky-cleaned, flat-fielded, and combined with shift-and-add registration using the brightest stellar images.

Many globules are detected in the full H$_2$ image, and the region around globule C1 is shown in the top center left panel in Figure 1. An approximate calibration has been made by...
Fig. 1.—Observations of the Helix globule C1. Top row, from left to right: CO (1–0) integrated intensity, H$_2$, H$_a$/[N ii] $\lambda$6584, and dust absorption seen against the nebula emission in [O iii] $\lambda$5007. Bottom row: CO (1–0) channel maps. The channels are 0.2 km s$^{-1}$ wide and are centered at the velocities given in the upper right of each panel. The contour intervals are 0.4 K km s$^{-1}$ for the CO integrated intensity map and 0.9 K for the channel maps. The ellipse in the top left panel shows the beam size for the CO observations. For each panel, the offsets are relative to a field center of $h$ ms R.A. $p$22 29 37.78 decl. $p$20 $p$48 $p$02 $p$00 (J2000.0), which is used for all images in this Letter.

comparing the smoothed, full image with the data of Speck et al. (2002). The intensity of the emission at the head of the globule is $\sim 10^4$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Astrometry of the H$_2$ and optical images was carried out using stars in the USNO catalog, and the registration between the images is $\sim 0.1$ rms. The accuracy of the absolute positions for comparison with the CO interferometry is $\sim 0.3$–0.5.

3. PROPERTIES OF THE GLOBULE
3.1. Overview

The observations presented in Figure 1 provide complementary views of the Helix globule. The CO (1–0) line, with an upper level of $E_a = 5.5$ K above the ground state, shows the overall distribution and kinematics of the cool molecular gas; the high-lying ($E_a \sim 7000$ K) H$_2$ $v = 1$–0 S(1) line traces excited molecular gas; the image in [O iii] shows the distribution of dust, seen in absorption against the nebular emission; and the image in H$_a$+[N ii] shows the photoionized surfaces facing the central star.

The observations immediately confirm the molecular nature of the globule and reveal some important details of its structure.

3.2. CO Structure and Kinematics

The CO (1–0) velocity-integrated intensity map (Fig. 1) is seen to be extended with respect to the telescope beam, and the deconvolved source size, assuming a Gaussian distribution, is $\sim 2'' \times 10''$ (1'' corresponds to $3 \times 10^{15}$ cm at 200 pc). The emission is marginally resolved in right ascension but is resolved in declination and extends roughly along the head-tail axis of the globule. The peak intensity is 2.6 K km s$^{-1}$, and the total flux is 166 K km s$^{-1}$ arcsec$^2$.

The CO velocity strip (Fig. 2) shows that to the south, toward the head of the globule, the line width is extremely narrow, $\Delta V = 0.5$ km s$^{-1}$ (FWHM), and it broadens out to $\sim 0.8$ km s$^{-1}$ farther north into the tail region. The CO radial velocity is precisely determined to be $V_{tot} = -27.9$ km s$^{-1}$ (the correction to $V_{hel}$ is $-2.9$ km s$^{-1}$), consistent with $-28.7 \pm 2$ km s$^{-1}$ measured in [N ii] $\lambda$6584 by Meaburn et al. (1998). The systemic velocity of the whole envelope of the Helix Nebula is $\sim 23$ km s$^{-1}$ (Young et al. 1999), so the globule is blueshifted by $\sim 5$ km s$^{-1}$. For a radial expansion velocity of the globule system of $\sim 20$ km s$^{-1}$ (Young et al. 1999), the globule lies on the near side of the nebula, on a radius vector from the star inclined to the line of sight by $\sim 75^\circ$. The head-tail axis, assumed radial, is also seen at this angle.

The CO channel maps (Fig. 1) show the structure in the molecular gas. There are two peaks, offset 3'' north and 8'' north from the field center. The first is just north of the maximum absorption in the [O iii] image (centered at 175 north), and we identify this molecular emission with the head of the globule whose photoionized surface toward the central star is seen in
the Hα+[N ii] image. Substantial CO emission, however, extends away from the head into the tail region, and the second CO peak lies close to a second, weak maximum in the dust absorption image (at 8° north). This extended CO emission, together with the line broadening into the tail, accounts for the offset of the peak in the CO integrated intensity map from the head of the globule.

These observations demonstrate that the molecular gas in the cometary globule is not a compact spheroidal bullet but has a substantial component extending into the tail region.

3.3. H2 Distribution and Excitation

The distribution of the H2 emission in the globule is strikingly different from that of CO (see Fig. 1). The strongest H2 emission occurs at the face of the globule toward the central star. There is little emission directly behind the globule, but observable emission extends to large distances (≈24′′) along the tail. Remarkably, the H2 distribution most closely follows that of the ionized gas seen in Hα+[N ii].

The high spatial resolution of our observations and the well-defined geometry of the globule provide a unique perspective on the question of the excitation of the H2 (Cox et al. 1998), which affects its observed distribution. The bright H2 emission clearly arises in a thin surface layer in the molecular gas. Figure 3 shows a close-up of the globule head, comparing the H2 and Hα+[N ii] emission with [O iii]. The H2 emission forms a limb-brightened cap on the globule facing the central star and lies just inside (0′′.5−1′′) the halo of photoionized gas seen in Hα+[N ii]. In the tail region too (Fig. 1), the H2 is enhanced near two Hα+[N ii] peaks, at 8′′ north and 12′′ north on the east side, which are directly illuminated by the star. More detailed observations are needed to determine whether these are separate, small globules along the line of sight or substructures of the main tail.

The observed distribution of the H2 emission is in complete accord with the expectations of H2 excitation in a thin photo-dissociation region (PDR) at the surface of the molecular gas. The observed intensity of the line is probably consistent with this interpretation (Natta & Hollenbach 1998; Speck et al. 2002), although detailed PDR models of the globules have not yet been developed. The possibility that the observed distribution is caused by shocks is unlikely, in view of the small crossing time (≤400 yr) for shocks (v ≳ 5 km s−1) able to excite the v = 1−0 S(1) H2 line (e.g., Burton, Hollenbach, & Tielens 1992); shocks in the bulk of the molecular gas are ruled out by the absence of any disturbance in the CO emission with velocities larger than −0.5 km s−1.

3.4. Physical Properties of the Molecular Gas

Using the CO (2−1) observations of the globule by Huggins et al. (1992), we find the (2−1)/(1−0) flux ratio to be 2−3 [assuming significant (1−0) flux is not resolved out on the shortest baselines], which suggests that the lines are at least partly optically thin, with an excitation temperature T~18−40 K in the thin limit. For a representative value of 25 K and a CO abundance of 3 × 10−4 the CO (1−0) flux gives a mass of molecular gas in the globule of M~1 × 10−3 M⊙. The corresponding average density in a volume with projected dimensions of 2′ × 10′, which includes the head and the tail seen in CO, is n~2 × 104 cm−3.

These values are consistent with a mass of ~2 × 10−3 M⊙ and n~4 × 103 cm−3 determined for the head of the globule by Meaburn et al. (1992) from the dust absorption seen in [O iii], corrected to a distance of 200 pc. The typical mass of photoionized gas at the surface of a globule, ~10−3 M⊙ (e.g., O’Dell & Handron 1996), is negligible in comparison.

4. ORIGINS AND EVOLUTION

The structure and kinematics of the molecular gas in the head and in the tail of the globule provide basic constraints on their origin and evolution.

One scenario for the origin of globules is that they form in the atmosphere of the progenitor star and are carried out in the expanding circumstellar envelope (Dyson et al. 1989). In this case, the windswep appearance of the globules suggests a model in which material from the head is swept into the tail by a radially directed wind, and Dyson, Hartquist, & Biro (1993) have shown...
that the wind needs to be subsonic to form a narrow tail. Our observations constrain this model in showing no evidence for a windswept flow pattern at the present time. There is no difference in velocity between the CO emission in the head and the tail of the globule, and from the CO strip map (Fig. 2) the differential motion is \( \approx 0.2 \text{ km s}^{-1} \) along the line of sight, or \( \approx 0.8 \text{ km s}^{-1} \) in a radial direction, corrected for the inclination. This would produce a tail of length \( \approx 4'' \) in 5000 yr, which is likely the maximum time available for such a process. The tails could have been fully formed at an earlier epoch, or it might be that ablation occurs only from the ionized edges of the head of the globule, but this would not account for the presence of molecular gas seen in \( \text{H}_2 \) along the whole length of the tail.

A different view of the gasdynamics around the globule at the present time is provided by the photoevaporation model, which has been discussed in the context of the Helix globules by López-Martín et al. (2001). In this model, photoionization of the neutral globule, whose molecular core is unambiguously discriminated by López-Martín et al. (2001). In this model, photoionization of the neutral globule, whose molecular core is unambiguously confirmed by our observations, produces an ionized outflow from the surface. Given that the density of the ionized gas at the head of the globule is \( \approx 10^3 \text{ cm}^{-3} \), and that of the ambient gas is much lower, \( \approx 50 \text{ cm}^{-3} \) (e.g., O’Dell & Handron 1996), any subsonic flow of the ambient gas around the globule is unlikely to have important dynamical effects in shaping the gas in the tail.

An alternative mechanism for growing a tail on a preexisting globule is by shadowing (Canto et al. 1998), which can form a tail behind the globule as the result of underpressure of the gas in the shadowed region. For the simplest case of a neutral globule in ionized gas, this model produces only modest density increases in the tail and is unlikely to lead to the substantial molecular tails revealed by the present observations. Striking effects of shadowing of the ionizing radiation are, however, seen in optical images of the Helix (e.g., Henry, Kwitter, & Dufour 1999), where long, radial plumes appear as extensions to globules and their tails. Similar shadowing of the stellar radiation at wavelengths longer than the Lyman limit must also occur, and the consequent reduction of the CO and \( \text{H}_2 \) photodissociation rates in the shadowed regions must play a key role in preserving the molecular gas in the extended tails.

If globules originate close to the star as proposed by Dyson et al. (1989), the most crucial phase in their evolution occurs when they are overrun by the ionization front of the nebula. At this stage, the shadowing of preexisting molecules or hydrodynamic flows, or both, could lead to globules with molecular tails. An alternative scenario is one in which the globules and their tails originate simultaneously in instabilities at the ionization front (e.g., Capriotti 1973). In this model, shadowing and possibly hydrodynamic flows would also likely play a role, and the fingers of gas that result from the instability could contribute directly to the formation of the tails. The later development of these two models will likely be similar and can plausibly lead to the globules with substantial molecular tails that we now observe. Further studies should allow us to discriminate between them.

As for the fate of the globules, Meaburn et al. (1998) estimated an ablation rate for globule C1 of \( 3 \times 10^{-8} M_\odot \text{ yr}^{-1} \) based on densities inferred from the [O iii] image and an assumed ablation flow velocity of 10 km s\(^{-1}\). This implies an improbably short lifetime of \( \approx 500 \text{ yr} \), which led Meaburn et al. to consider ad hoc, restricted flow models around the globule. The absence of an observable ablation flow in the globule reported here for CO \( (\approx 0.8 \text{ km s}^{-1}) \) completely resolves this problem by increasing the original estimate of the ablation timescale by at least an order of magnitude. In fact, the current mass-loss rate of the globule is likely dominated by photoevaporation (López-Martín et al. 2001), and the corresponding timescale is \( \approx 10^5 \text{ yr} \). Thus, the globules are long-lived and may even escape the nebula.

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