THE SHAPING EFFECT OF COLLIMATED FAST OUTFLOWS IN THE EGG NEBULA

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ABSTRACT

We present high angular resolution observations of the HC$_3$N $J = 5-4$ line from the Egg nebula, which is the archetype of proto-planetary nebulae (PPNs). We find that the HC$_3$N emission in the approaching and receding portion of the envelope traces a clumpy hollow shell, similar to that seen in normal carbon-rich envelopes. Near the systemic velocity, the hollow shell is fragmented into several large blobs or arcs with missing portions correspond spatially to locations of previously reported high-velocity outflows in the Egg nebula. This provides direct evidence for the disruption of the slowly expanding envelope ejected during the AGB phase by the collimated fast outflows initiated during the transition to the PPN phase. From modeling the HC$_3$N distribution, we could reproduce quantitatively the spatial kinematics of the HC$_3$N $J = 5-4$ emission using a HC$_3$N shell with two pairs of cavities cleared by the collimated high-velocity outflows along the polar direction and in the equatorial plane. We infer a relatively high abundance of HC$_3$N/H$_2$ $\sim 3 \times 10^{-6}$ for an estimated mass-loss rate of $3 \times 10^{-5}$ $M_\odot$ yr$^{-1}$ in the HC$_3$N shell. The high abundance of HC$_3$N and the presence of some weaker $J = 5-4$ emission in the vicinity of the central post-AGB star suggest an unusually efficient formation of this molecule in the Egg nebula.

Key words: circumstellar matter – ISM: molecules – planetary nebulae: general – stars: AGB and post-AGB – stars: individual (CRL 2688) – stars: mass loss

Online-only material: color figures

1. INTRODUCTION

The rapid evolution of low- and intermediate-mass stars (1 to 10 $M_\odot$) after the end of the asymptotic giant branch (AGB) phase is accompanied by a radical change in the morphology of the circumstellar envelopes around them. The circumstellar envelope created by the slow and dusty stellar wind during the AGB phase is known to be roughly spherically symmetric as the radiation pressure on dust grains is expected to be isotropic. On the other hand, a variety of morphologies ranging from spherical to multipolar shapes have been observed in post-AGB envelopes and planetary nebulae. It is also during this phase that collimated high-velocity outflows are seen, such as in the Egg nebula (Cox et al. 2000) and in CRL 618 (Sánchez-Contreras et al. 2004). The shaping of the complex envelope morphology and the mechanism that generates the high-velocity outflows of post-AGB stars are very poorly understood. Lee & Sahai (2003) suggest that envelopes with bipolar morphologies are shaped by the interactions with a fast-collimated outflow or jet launched in the polar directions. Their hydrodynamic simulations are able to reproduce both the envelope morphology and other properties such as intensity of emission lines excited in the shocked gas at the interface between the jet and the slow wind.

The Egg nebula (CRL 2688) is widely considered as the prototype of proto-planetary nebulae (PPNs), a class of stars in the rapid transition phase between the AGB and planetary nebulae. During the PPN phase, the central post-AGB star contracts and gradually becomes hotter, but is not yet hot enough to ionize its surrounding envelope. Using high-resolution spectroscopic observations of the scattered stellar light, Klochkova et al. (2000) determine a spectral-type F5IIa for the central star with an effective temperature of $T_{\text{eff}} = 6500$ K. The abundance analysis reveals the enrichment of C and N together with strong enhancement of slow neutron captures (s-process) elements, as expected for the carbon-rich post-AGB star at the center of the Egg nebula.

Recently, using multiepoch optical images from the Hubble Space Telescope, Ueta et al. (2006) successfully measured the spatial expansion of the nebula and thereby determined the distance to CRL 2688 of 420 pc. We shall henceforth use this distance for the Egg nebula.

High spatial resolution optical images of CRL 2688 reveal a pair of bipolar lobes seen as search-light beams emanating from the central (obscured) star and oriented perpendicular to a dark lane (Sahai et al. 1998a). This conspicuous dark lane has commonly been interpreted as an equatorial disk of cold dust. High angular resolution images of the molecular hydrogen emission at 2.2 $\mu$m reveal shocked gas, tracing the strong interaction between the fast outflows and the slow wind (Sahai et al. 1998b). Surprisingly, hot molecular hydrogen emission is seen in both bipolar lobes and in the equatorial plane far beyond the dark lane, indicating the presence of multiple fast-collimated outflows.

Indeed, high spatial resolution mapping of the CO $J = 2-1$ emission by Cox et al. (2000) reveals the presence of several pairs of collimated fast molecular outflows along both the bipolar axis and the equatorial plane. These molecular outflows can be traced back to a common origin, presumably the location of the central post-AGB star in the Egg nebula. Cox et al. (2000) suggest that the observed CO emission does not constitute the actual fast-collimated outflows, but rather molecular gas swept up by even faster-collimated outflows that comprise mainly atomic or ionized gas. By contrast to its appearance in the optical, no equatorial disk in the Egg nebula is seen in the CO $J = 2-1$ emission by Cox et al. (2000). High spatial resolution observation of HCN $J = 1-0$ by Bieging & Nguyen-Q-Rieu (1996) traces molecular gas at higher densities along both the bipolar lobes and the equatorial plane, consistent with the suggestion that the molecular gas is swept up gas by the fast...
interferometric observation of HC3N emission in the outer part of the envelope and its emission lines could be used to infer the structure of the envelope at high angular resolution.

Emission lines from cyanopolyne molecules such as HC3N are very prominent in the centimeter and millimeter wavelength regions toward the Egg nebula. Cyanopolyne molecules, as large as HC9N, have been detected (Truong-Bach et al. 1993). The line profiles of the cyanopolyne molecules do not exhibit high-velocity wings, suggesting that their emission originate from the slowly expanding shell ejected during the AGB phase. Current chemical models (Millar et al. 2000; Cherchneff et al. 1993) for carbon-rich envelopes suggest that HC3N molecules are formed by photochemistry in the outer part of the expanding envelope. Thus the spatial distribution of HC3N is predicted to exhibit a hollow shell structure. In the case of the carbon-rich envelope of IRC+10216, the spatial distribution of cyanopolyne molecules has been imaged at high angular resolution (Bieging & Tafalla 1993; Lucas & Guélin 1999; Dinh-V-Trung & Lim 2008) and shown to have the hollow shell structure as expected from chemical models. The relatively high abundance and high electric dipole moment of HC3N make its rotational lines relatively strong in the circumstellar envelope. The HC3N lines might be useful to probe not just the chemistry but also the structure of the envelope at high angular resolution. In the Egg nebula, we also expect this molecule to form in the expanding envelope. Thus the spatial distribution of HC3N is predicted to exhibit a hollow shell structure. In the case of the carbon-rich envelope of IRC+10216, the spatial distribution of cyanopolyne molecules has been imaged at high angular resolution (Bieging & Tafalla 1993; Lucas & Guélin 1999; Dinh-V-Trung & Lim 2008) and shown to have the hollow shell structure as expected from chemical models. The relatively high abundance and high electric dipole moment of HC3N make its rotational lines relatively strong in the circumstellar envelope. The HC3N lines might be useful to probe not just the chemistry but also the structure of the envelope at high angular resolution. In the Egg nebula, we also expect this molecule to form in the expanding envelope. Thus the spatial distribution of HC3N is predicted to exhibit a hollow shell structure.

In this paper, we present high-resolution observations of the HC3N J = 5–4 emission line, which traces the outer molecular envelope of the Egg nebula. The envelope is found to be disturbed by the passage of the fast-collimated outflows along the polar direction and in the equatorial plane. We also present a simple model of the envelope to better understand its spatial kinematics.

2. OBSERVATION

We observed the Egg nebula on 2002 November 24 and 2003 March 3 using the very large array (VLA2) in its C and D configuration. We pointed the telescope at \( \alpha_{2000} = 21^h02^m18^s, \delta_{2000} = 36^d41′38″ \), which is very close to the peak of the continuum emission observed previously by Cox et al. (2000) and Jura et al. (2001). The rest frequency of the HC3N J = 5–4 line as compiled in the Lovas/NIST database (Lovas 2004) is 45.490316 GHz. To observe this line we configured the VLA correlator in the 1A mode with 64 channels spanning a bandwidth of 12.5 MHz, thus providing a velocity resolution of 1.3 km s\(^{-1}\) per channel over a useful velocity range of \( \sim 80 \) km s\(^{-1}\). The total on-source integration time is about 1 hr in C configuration and about 4 hr in D configuration. We monitored the nearby quasar 21095+35330 every 5 minutes to correct for the antennas gain variations caused primarily by atmospheric fluctuations. The stronger quasar 2253+161 was used to correct for the shape of the band pass and its variation with time. The absolute flux scale of our observations was determined from observations of standard quasars 0137+331 and 0410+769.

We edited and calibrated the raw visibilities using the AIPS data reduction package. The calibrated visibilities from different configurations were merged using the task DBCON, and then Fourier transformed to form the DIRTY images. We employed the robust weighting together with tapering of the visibilities to obtain a satisfactory compromise between angular resolution and sensitivity to the extended emission. The DIRTY images were deconvolved using the clean algorithm IMAGR implemented in AIPS, providing a synthesized beam of 1′.3 × 1′.08 at a position angle (P.A.) of 2°.35. The rms noise level in our channel maps of HC3N J = 5–4 is 2.3 mJy beam\(^{-1}\) in each velocity channel of 3.9 km s\(^{-1}\). The conversion factor between the brightness temperature of the HC3N J = 5–4 emission and its flux density is \( \sim 2.37 \) mJy K\(^{-1}\). Table 1 provides a summary of our observations.

### 3. RESULTS

Figure 1 shows our channel maps of the HC3N J = 5–4 emission. In Figure 2, we show the HC3N J = 5–4 line profile derived by integrating the channel maps over a region where the emission is detected above the 2σ level. The HC3N J = 5–4 line has previously been observed by Fakasaku et al. (1994) with the Nobeyama 45 m telescope, which has a primary beam at FWHM of about 40″. Using the main-beam efficiency provided in their paper, we estimate a conversion factor between the main-beam temperature and a flux density of 4 Jy K\(^{-1}\), thus giving a peak flux density of about 2 Jy for the HC3N J = 5–4 line in their observation. We measured in our observations (see Figure 2) a peak flux density for this line of \( \sim 1.6 \) Jy. The shapes of the line profiles in both observations are also very similar, exhibiting a near parabolic shape with a trough around the systemic velocity of \(-35 \) km s\(^{-1}\). We conclude that our VLA observation has recovered about 80% of the emission in the HC3N J = 5–4 line detected in the above-mentioned single-dish observation.

In the channel maps, the HC3N J = 5–4 emission shows the typical characteristics of an expanding shell, i.e. the emission appears largest near the systemic velocity, and contracts toward the center at progressively higher blueshifted and redshifted velocities. The emission spans velocities between \(-53.9 \) and \(-19.1 \) km s\(^{-1}\), from which we estimate an expansion velocity of \( \sim 17 \) km s\(^{-1}\), that is similar to that obtained by Truong-Bach et al. (1993). At redshifted velocities between \(-26.9 \) and \(-19.1 \) km s\(^{-1}\) and the blueshifted velocities between \(-53.9 \) and \(-46.2 \) km s\(^{-1}\), the HC3N J = 5–4 emission traces a clumpy and hollow shell-like structure with radii of \( \sim 4″–5″ \). Such a hollow shell structure is expected from the prediction

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2 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc.
of the HC$_3$N formation in the envelopes of carbon-rich stars (Cherchneff et al. 1993; Millar et al. 2000). We note that similar structures have been seen most prominently in the prototypical carbon-rich star IRC+10216 (Bieging & Tafalla 1993; Dinh-V-Trung & Lim 2008). The large angular size of the hollow shell and more importantly the lack of high-velocity emission wings of the HC$_3$N $J = 5–4$ line suggests that this line traces the remnant envelope created by the slow dusty wind from the central star of the Egg nebula during the AGB phase. Using the distance to the Egg nebula of 420 pc as estimated by Ueta et al. (2006), the linear size of the shell is about $3 \times 10^{16}$ cm. We note that the radius of the HC$_3$N shell in the archetype carbon-rich envelope of IRC+10216, which is located at an estimated distance of 120 pc, is between $15''$ and $20''$. If IRC+10216 was located at the same distance as the Egg nebula, the HC$_3$N shell would have radii of $4''$–$6''$. Assuming that the interstellar radiation field is the same for both objects, the similarity in size of the HC$_3$N shell in both the Egg nebula and IRC+10216 suggests that the mass-loss rate in both objects is comparable. The mass-loss rate of IRC+10216 is estimated to be in the range of $1–3 \times 10^{-5} M_\odot$ yr$^{-1}$ from the modeling results of Crosas & Menten (1997), Dinh-V-Trung & Nguyen-Q-Rieu (2000), and Schoier et al. (2002). The comparably high mass-loss rate of the central star in the Egg nebula at the time it produced the observed envelope suggests that this period might correspond to the superwind phase at the end stage of the evolution on AGB.

Near the systemic velocity, most prominently at and between velocity channels $-30.7$ and $-38.4$ km s$^{-1}$, the hollow shell structure is clearly disrupted and fragmented into several large clumps of intense HC$_3$N $J = 5–4$ emission. At the systemic velocity, the shell is delineated by four large clumps roughly mirror-symmetric with respect to the lines passing through the nebula center at P.A.s of $\sim 20^\circ$ and $110^\circ$. The space between these clumps forms two pairs of cavities. Figure 3 shows the integrated intensity map of the HC$_3$N $J = 5–4$ emission. This integrated intensity map clearly shows the presence of the cavity pair in the equatorial plane and also the pair along the polar direction. These cavities are separated by four intense peaks of the HC$_3$N emission. These evacuated cavities are oriented along the axes of the fast-collimated outflows as traced by the molecular hydrogen emission (Sahai et al. 1998b) and the CO $J = 2–1$ emission (Cox et al. 2000) as sketched in Figure 3. As can be seen in the figure, the spatial correspondence between the cavities and the fast outflows is reasonably good. These fast outflows are confined within the cavities. That is especially evident for the outflows in the polar direction, which are closely
aligned within the narrow cavities oriented at a P.A. of about $20^\circ$. We note that Cox et al. (2000) estimate the average P.A. of the polar outflows to be about $17^\circ$, very similar to that of the cavities seen in our HC$_3$N $J = 5$–$4$ observations. Cox et al. (2000) also suggest that all the outflows can be traced back to a common origin. In Figure 3, we also show the location of different outflows and their intersection together with the position of the 1.3 mm continuum peak observed by Cox et al. (2000). A close inspection of Figure 3 seems to suggest that the 1.3 mm continuum peak and the outflow intersection are located close to but not exactly at the center of the HC$_3$N shell. Because the HC$_3$N shell is only very roughly symmetric, at the current stage it is still difficult to quantify with certainty the above-mentioned offset. Further observations with higher angular resolution and quality would be needed to address this issue.

Interestingly, the HC$_3$N $J = 5$–$4$ emission is also found close to the center of the Egg nebula in several velocity channels between $-30.7$ and $-42.3$ km s$^{-1}$, forming a faint bridge between the northern and southern portions of the shell. The existence of HC$_3$N in the inner envelope is difficult to understand within the framework of current chemical models (Cherchneff et al. 1993; Millar et al. 2000). Previous observations by Audino et al. (1994) show that HC$_3$N emissions from higher-$J$ transitions in the 2 mm and 1 mm bands, which are excited mainly under warmer and denser conditions, peak at the center of the carbon-rich envelope IRC+10216, implying the much enhanced abundance of HC$_3$N toward the center of the envelope. For the lower-$J$ transition, $J = 5$–$4$ seen toward the center of the envelope, the abundance of HC$_3$N needs to be even higher because of the lower optical depth in comparison to higher-$J$ transitions. This suggests that the formation of HC$_3$N is quite efficient in the inner dense region of the Egg nebula. The photochemistry that leads to the formation of molecular species such as HC$_3$N is not expected to be active in the inner region because of the strong attenuation of interstellar UV radiation field due to high dust and gas density. The contribution of the central post-AGB star to the UV radiation field is difficult to assess due to the lack of information on the distribution of the material in the vicinity of the star. However, the relatively low effective temperature of the central star suggests that the contribution might not be significant. Therefore, other mechanisms for the formation of HC$_3$N should be explored in the chemical models for the Egg nebula.

4. A SIMPLE MODEL OF THE HC$_3$N SHELL

From the discussion in the preceding section we suggest that the HC$_3$N emission traces the remnant AGB envelope around the Egg nebula. The AGB envelope is disrupted by the interaction with the fast-collimated outflows. These outflows open channels or cavities along the polar and equatorial directions. Thus the HC$_3$N $J = 5$–$4$ emission is very useful in providing complementary information to previous observations on the structure of the Egg nebula. To gain more insight into the structure of the nebula and to estimate the abundance of HC$_3$N, we construct a simple model of the HC$_3$N shell. In Figure 4, we show a sketch of the overall structure of the HC$_3$N shell. The hollow shell is filled with the remnant AGB wind, which is assumed to be spherically symmetric. Collimated fast outflows emanate from the central post-AGB star along both polar and equatorial directions. These outflows interact with the slow AGB wind, entraining molecular gas along their path. As a result, the remnant AGB envelope is disrupted and two pairs of cavities are excavated by the fast-collimated outflow. For simplicity, we assume that the abundance of HC$_3$N is constant over the whole hollow shell. We do not take into account the presence of the HC$_3$N $J = 5$–$4$ emission near the center of the nebula because a correct derivation of the abundance and spatial distribution would require more constraints from multiline observations. We also assume that the HC$_3$N $J = 5$–$4$ line forms under the LTE condition with a temperature of 30 K. The adopted gas temperature is comparable to the brightness temperature seen in the channel maps of the HC$_3$N $J = 5$–$4$ emission in the Egg nebula (see Figure 1), especially in the velocity

![Figure 3. Integrated intensity map of the HC$_3$N $J = 5$–$4$ emission from the Egg nebula. The contour levels start from 0.1 Jy km s$^{-1}$ in step of 0.1 Jy km s$^{-1}$. The synthesized beam of $1^\prime \times 1^\prime 08$ is shown in the lower left corner. The high-velocity outflows identified by Cox et al. (2000) are marked with crosses and solid lines. The larger cross denotes the position of the 1.3 mm continuum source observed by Cox et al. (2000).](Image)

![Figure 4. Sketch of the HC$_3$N shell in the Egg nebula. The spherical shell has holes or cavities along the polar directions and in the equatorial plane due to the disruptive effect of the high-velocity jets.](Image)
channels around the systemic velocity, and also consistent with the prediction of the gas temperature at a radial distance of a few $10^{16}$ cm in the envelope of the carbon star IRC+10216 (Crosas & Menten 1997). Although the LTE assumption might be quite crude in the circumstellar envelope environment, it is commonly used to estimate the relative abundance of molecules. For our purpose of studying the spatial kinematics and estimate of the abundance, that assumption should be adequate. When multiline observations are available, a more elaborate model can be constructed. We project a spherical hollow shell into a three-dimensional regular grid. The intensity of the HC$_3$N $J = 5–4$ line is calculated by solving directly the radiative transfer equation along each line of sight. We then use the emerging intensity to form the model channel maps. The channel maps are then convolved with the synthesized beam of our VLA observations. The emission is shown in both gray scale and in contours. The contour levels are the same as in Figure 1.

In Figure 5, we show the channel maps of the HC$_3$N $J = 5–4$ emission calculated with our model. The main features found in the observed channel maps, namely the cavities and the changing morphology of the emission between velocity channels, are qualitatively reproduced in our model. The predicted total intensity profile of the HC$_3$N $J = 5–4$ line is shown in Figure 6. For a HC$_3$N abundance of $3 \times 10^{-6}$, the predicted line profile is similar to that seen in the single dish observation cavities in both the polar direction and in the equatorial plane is $40^\circ$. The P.A. of the nebular axis on the plane of the sky is set to $20^\circ$, which is close to the value estimated by Cox et al. (2000). The complex distribution of HC$_3$N does not allow a more accurate estimate of the P.A. Besides, there are several outflows contributing to the cavities in the polar direction, making the definition of the P.A. somewhat ill-defined. The parameters of our simple model are collected in Table 2.

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### Table 2

| Model Parameters       | Values |
|------------------------|--------|
| Distance               | 420 pc |
| Mass-loss rate         | $3 \times 10^{-5} M_\odot$ yr$^{-1}$ |
| Expansion velocity     | $17$ km s$^{-1}$ |
| $[\text{HC}_3\text{N}]/[\text{H}_2]$ | $3 \times 10^{-6}$ |
| Inner radius of the HC$_3$N shell | $10^{16}$ cm |
| Outer radius of the HC$_3$N shell | $4 \times 10^{16}$ cm |
| Turbulence velocity    | $1$ km s$^{-1}$ |
| Opening angle of bipolar lobes | $40^\circ$ |
| Opening angle of equatorial cavities | $40^\circ$ |
| Inclination angle      | $15^\circ$ |
| P.A. of bipolar lobes  | $20^\circ$ |
of Fakasaku et al. (1994) and also in our observations. The observed strength (about 2 Jy at the peak intensity) and the parabolic shape with a depression around the systemic velocity, which is caused by the presence of the two pairs of cavities, of this line are also reproduced with our model. We note that the derived HC$_3$N abundance in the Egg nebula is higher than that determined by Audinos et al. (1994) in the carbon star IRC+10216. In addition, because of the LTE assumption in our model, the HC$_3$N abundance is directly related to the assumed mass-loss rate, i.e. a higher mass-loss rate can be compensated by a corresponding lower HC$_3$N abundance to produce similar intensity in the HC$_3$N $J = 5$–$4$ line.

5. SUMMARY

We have imaged at high angular resolution the distribution of HC$_3$N $J = 5$–$4$ emission line in the Egg nebula. We find that in the approaching and preceding portion of the envelope, the HC$_3$N emission traces a clumpy hollow shell structure, similar to that seen in normal carbon-rich envelopes. Near the systemic velocity, however, the hollow shell is fragmented into several large blobs or arcs. The missing portions of the hollow shell correspond spatially to locations of the high-velocity outflows observed previously in the Egg nebula. We interpret the observed spatial-kinematics of the HC$_3$N $J = 5$–$4$ emission as the direct evidence for the disruption of the slowly expanding envelope ejected during the AGB phase by the interaction with collimated high-velocity outflows initiated during the transition. From modeling the HC$_3$N distribution we could reproduce qualitatively the spatial kinematics of the HC$_3$N $J = 5$–$4$ emission using a HC$_3$N shell with two pairs of cavities with an opening angle of $\sim 40^\circ$ excavated by the collimated high-velocity outflows along the polar direction and in the equatorial plane. We infer a relatively high abundance of HC$_3$N/H$_2$ $\sim 3 \times 10^{-6}$ for an estimated mass-loss rate of $3 \times 10^{-5}$ $M_\odot$ yr$^{-1}$. The relatively high abundance of HC$_3$N and the presence of some weaker $J = 5$–$4$ emission in the vicinity of the central post-AGB star suggest an efficient formation of this molecule in the Egg nebula.

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