Multiple Outflows in AFGL 2688

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Abstract. We present high resolution (1′′1 × 0′′9) imaging of the proto-planetary nebula AFGL 2688 in the CO (J=2–1) line using the IRAM interferometer. The observations reveal with unprecedented detail the structure and the kinematics of the gas ejected by the star over the past few hundred years and exemplify the mechanism by which point symmetries are imprinted on the structure of planetary nebulae at early stages of their formation.

1. Introduction

The physical mechanisms which govern the evolution of proto-planetary nebulae (PPNe) are poorly documented because relatively few objects are known to be in this rapid transition between the AGB and planetary nebula phase (Kwok 1993). The role played by high-velocity winds which interact with the slowly expanding AGB envelope has been recognized as essential in the shaping of the planetary nebulae. However, the details of the interaction and the precise evolution from the symmetric AGB envelope to the asymmetries which characterize planetary nebulae are not well understood.

AFGL 2688 (the ‘Egg nebula’) is one of the prime examples of a PPN which has evolved from the AGB phase about a hundred years ago (Jura & Kroto 1990). The nearly circular slowly expanding AGB envelope (with a diameter of about 20′′) is shocked by a warm, optically thin, fast wind (e.g., Young et al. 1992). Studies at high spatial resolution (e.g., Bieging & Nguyen-Quang-Rieu 1996) have shown that the bulk of the molecular gas is concentrated in the central 4′′ (or 6 × 10^{16} cm for an adopted distance of 1 kpc), coincident with the dark lane seen in optical images, with weaker extensions along the north-south axis. Observations at near-infrared wavelengths have revealed that high-velocity H₂ gas is present both in the north-south and east-west direction suggesting a quadrupolar outflow (e.g., Cox et al. 1997).
This paper presents high angular resolution observations ($1''07 \times 0''85$) made in the CO J=2–1 line using the IRAM interferometer which provide a detailed picture of the morphology and the kinematics of the gas recently ejected by the central star in AFGL 2688.

2. Multiple Molecular Outflows

The results of the observations are summarized in Fig. 1. In the velocity integrated CO map, the distribution of the CO emission consists of a central core $\sim 4''$ in diameter, with extensions in both the north-south and east-west directions. At negative (approaching) velocities, the CO is detected in the northern and eastern extensions of the nebula. Along the north extension, velocities increase away from the centre; the tip of the eastern arm is seen over a range of velocities from $-60$ to $-72 \text{ km s}^{-1}$; and the highest velocity gas is found near the centre of the nebula up to $\sim -80 \text{ km s}^{-1}$. At positive (receding) velocities, the CO gas is extended to the south and west, with a similar velocity structure to the blue-shifted gas, reversed about the systemic velocity. The channel maps provide definite evidence of two distinct high-velocity outflow directions in AFGL 2688, one along a north-south axis at a P.A. of $17^\circ$, and the other in a roughly orthogonal direction east-west. Detailed examination of the CO data reveals that the two main outflows are resolved into a series of more collimated, bipolar outflows which are symmetric in direction and velocity about the center (Cox et al. 1999) and which are identified in Fig. 1: four collimated outflows in the east-west direction, and three in the north-south direction. It is striking that, for most of these outflows, the tips correspond precisely with the H$_2$ peaks seen in the HST image (Fig. 1). The only exceptions are in the central regions and to the west side of the equatorial plane, where the high-velocity red-shifted CO gas (located behind the dense central gas) has no clear H$_2$ counterpart in the HST image, most likely as a result of extinction in the near-infrared.

Along all the outflow axes (A to G), the CO velocity increases with distance from the centre. This implies that the observed CO gas is entrained by high-velocity jets which could be atomic or ionized. The velocity of the CO gas in the outflows is also higher by a factor of $\sim 2.5$ than the velocity of the H$_2$ which is close to the expansion velocity of the AGB envelope (Kastner et al. 1999). The high-velocity jets entrain the CO gas and shock the molecular hydrogen of the AGB envelope.

Assuming the model-dependent value of $i \sim 16^\circ$ for the inclination of the north-south axis to the plane of the sky with the northern lobe towards the observer (Yusef-Zadeh et al. 1984), the deprojected flow velocity of F1 (at $6''$ from the centre) is $22 \text{ km s}^{-1}$, corresponding to a kinematic age of $\sim 1200$ years. In comparison, the projected velocities of the jets D and E are $\sim 30 \text{ km s}^{-1}$, implying ages of $\sim 250$ and 125 years, if the same inclination is assumed. Finally, we note that the position of the central exciting star of AFGL 2688 recently derived from polarisation measurements (J. Kastner, private communication) lies within the positional errors at the intersection of the outflows.
Figure 1. The Plateau de Bure interferometer data compared to the \( \text{H}_2 \) 1–0 S(1) line emission and nearby 2.15 \( \mu \)m continuum from Sahai et al. (1998), in background. Upper right: velocity integrated CO(2–1) with beam size shown in white; upper left: outflow axes; lower panels: blue-shifted (−80 to −60 \( \text{km s}^{-1} \)) and red-shifted CO (−22 to −2 \( \text{km s}^{-1} \)).

3. The Core Region

In addition to the collimated outflows, the Plateau de Bure observations reveal in the central 2\arcsec a shell-like structure expanding with a velocity of \( \sim 10 \text{ km s}^{-1} \) (Cox et al. 1999). This CO structure is not aligned with any of the outflow axes and lies at a P.A. of \( \sim 54^\circ \), which is comparable to that of the 1.3 mm dust continuum emission. The size of this structure (1\arcsec or \( 1.5 \times 10^{16} \) cm) implies that it was ejected \( \sim 500 \) years ago and that it could trace the last episode of mass-loss on the AGB; the expansion velocity of this structure is much slower than that of the envelope (\( \sim 20 \text{ km s}^{-1} \); see, e.g., Young et al. 1992). Neither the distribution of the dense gas at the center nor its kinematics indicate the presence of an equatorial disk in AFGL 2688. The present data thus do not support the interpretation of a rotating equatorial disk to explain the east-west kinematics in AFGL 2688 (cf. Bieging & Nguyen-Quang-Rieu 1996, Kastner et al. 1999).
Instead, the CO kinematics reveal the presence of a central expanding shell-like structure (not seen in H$_2$) and high-velocity gas with a morphology similar to the shocked H$_2$ gas tracing multiple, collimated outflows.

4. Origin and Effects of the Outflows

The observations discussed here reveal the detailed structure and kinematics of the molecular outflows in AFGL 2688. A series of young (a few 100 years), high velocity, collimated jets originate from the central star, and are directed along the north-south optical axis and in the east-west direction. The detailed correlation of the CO outflows with H$_2$ emission seen in AFGL 2688 provides direct evidence for their interaction with the nearly spherical envelope ejected on the AGB. The presence of multiple, collimated outflows in two, roughly orthogonal directions cannot be explained by the standard two-winds model (e.g., Balick 1987). Proto-planetary nebulae with morphologies similar to AFGL 2688 have recently been found (e.g., Kwok et al. 1998) and multipolar jets appear to be a common phenomenon in young planetary nebulae (Forveille et al. 1998, Sahai & Trauger 1998). Whatever detailed processes are involved, the high-velocity winds must be intimately linked to the abrupt transition in the evolution of the star after the AGB phase. One important consequence of the jets is their shaping effect on the molecular envelope ejected on the AGB. They generate complex point symmetries in the envelope which later emerge in the ionized gas during the PN phase.

References

Balick B. 1987, AJ 94, 671  
Bieging J.H., Nguyen-Quang-Rieu 1996, AJ 112, 706  
Cox P., Maillard J.-P., Huggins P.J. et al. 1997, AA 321, 907  
Cox P., et al. 1999, AA (submitted)  
Forveille T., Huggins P.J., Bachiller R., Cox P. 1998 ApJ 495, L111  
Jura M., Kroto H. 1990 ApJ 351, 222  
Kastner J.H., Henn L.A., Weintraub D.A., Gatley I. 1999, in AGB Stars, IAU Symp. 191, T. Le Bertre, A. Lebre, C. Waelkens (eds), ASP conf. series, p. 431  
Kwok S. 1993, ARAA 31, 63  
Kwok S., Su Y.L.S., Hrivnak B.J. 1998, ApJ 501, L117  
Sahai R., Hines, D.C., Kastner, J.H. et al. 1998, ApJ 492, L163  
Sahai R., Trauger, J.T. 1998, AJ 116, 1357  
Young K., Serabyn G., Phillips T.G., Knapp G.R., Güsten R., Schultz A. 1992, ApJ 385, 265  
Yusef-Zadeh F., Morris M., White R.L. 1984, ApJ 278, 186