Astron. Astrophys. 353, L5–L8 (2000)

ASTRONOMY
AND
ASTROPHYSICS

LETTER

Letter to the Editor

Molecular bullets in the planetary nebula BD+30°3639

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Received 13 October 1999 / Accepted 2 December 1999

Abstract. We report high resolution ($1\farcs0 \times 0\farcs5$) CO line imaging of the compact planetary nebula BD+30°3639 that reveals a remarkable pair of high-velocity, molecular knots, or "bullets". These bullets are $\sim 1''$ in size, and are symmetrical about the central star in position ($\pm 3''$ at P.A. $\sim 22°$) and in velocity (± 50 km s^{-1}). The mass of each bullet is $\gtrsim 7 \times 10^{-4}\ M_\odot$ and their kinematic age is ~ 500 yr. The high velocity and symmetry of these structures indicate underlying bipolar jets from the central star that interact with the surrounding neutral gas. The unexpected presence of the bullets in BD+30°3639 strengthens the idea that jets are common and play a crucial role in the shaping of planetary nebulae.

Key words: ISM: planetary nebulae: general – ISM: planetary nebulae: individual: BD+30°3639 – ISM: jets and outflows – stars: Wolf-Rayet – stars: winds, outflows

1. Introduction

Neutral envelopes are widely detected around planetary nebulae (PNe) and provide important links with the precursor AGB and proto-PN phases (Huggins et al. 1996). The neutral gas plays a critical role in the morphology of the ionized nebulae, so the evolution of the envelopes is an important factor in PN shaping. One mechanism that shapes the neutral gas is interaction with collimated outflows or jets. Recent optical studies have shown that these are common, especially in young PNe (e.g., López 1997, Sahai & Trauger 1998), and observations of molecular gas in a number of cases directly reveal their shaping effects on the envelopes (e.g., Forveille et al. 1998; Cox et al. 1999a).

BD+30°3639 (PN 064+05.0) is one of the most intensively studied PNe. It has been observed from x-ray to radio wavelengths, including optical imaging with the *HST* (Harrington et al. 1997). The low temperature of the central star ($T \sim 40\,000$ K) and the short expansion time of the nebula (900 yr, Kawamura & Masson 1996) confirm its recent emergence from the proto-PN phase. The ionized nebula shows a classic ring morphology, and it is one of the rare cases where x-rays have actually been detected and may signal the presence of a wind-shocked bubble inside the nebula, as expected in the interacting-winds model (Arnaud et al. 1996).

Surrounding BD+30°3639 is a massive envelope of neutral gas which has been observed in several species, including H I (Taylor et al. 1990), H_2 (Cox et al. 1999b, Shupe et al. 1998, and references therein), and CO (Bachiller et al. 1991, 1992). The dominant mass of the envelope is in H I, but it is not currently possible to map this in any detail. Images of the envelope in H_2 reveal a disturbed, expanding, molecular torus, and a most unusual feature is seen in CO. The CO spectrum shows gas only at high expansion velocities of ~ 50 km s^{-1}, roughly twice that of the bulk of the ionized nebula and the H I envelope. In order to investigate this we have observed the CO at high angular resolution, and we report the results in this letter. We find that the CO emitting gas forms a highly-collimated, bipolar structure which cannot be explained by the interacting-winds model, and demonstrates the importance of outflows or jets in shaping the nebula.

2. Observations and continuum images

The observations were carried out in January and March 1998 with the IRAM 5-antenna interferometer at Plateau de Bure, France. Two configurations of the array were used with baselines up to 280 m. The antennae were equipped with SIS receivers operating simultaneously at the frequencies of the CO J=2–1 and J=1–0 lines (230.538 GHz and 115.271 GHz, respectively). The J=1–0 data reveal structure similar to that seen in the 2–1 line, but with a lower S/N ratio and lower angular resolution; it is also affected by nearby H38α emission (Bachiller et al. 1992), so our discussion focuses on the the 2–1 observations. Typical SSB system temperatures were 300 K at this wavelength. Correlator channels free of line emission were combined to measure the continuum with effective bandwidths of 320 MHz at 2.6 mm, and 640 MHz at 1.3 mm. The receiver

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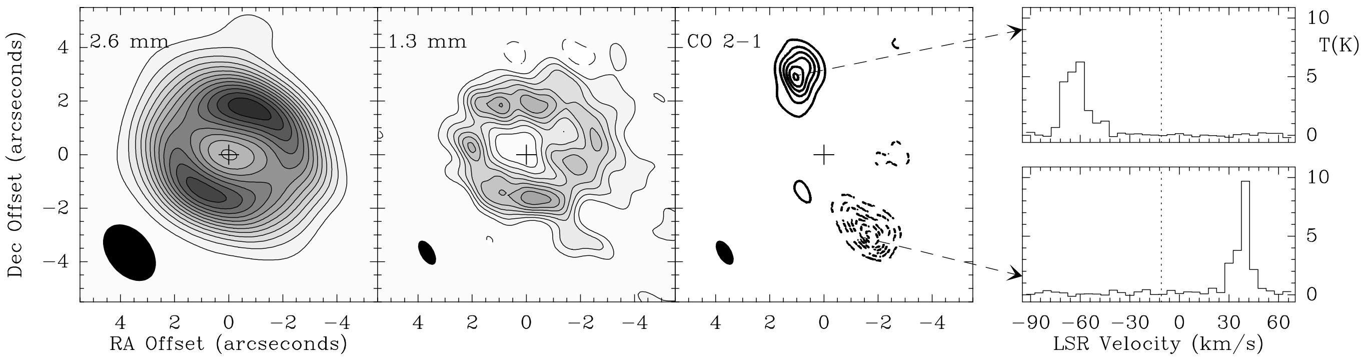

Fig. 1. Maps of BD +30°3639 in the 2.6 and 1.3 mm continuum and the CO 2–1 line. For each map the first contour and the contour intervals are: 5 mJy beam^{-1} (2.6 mm), 2.5 mJy beam^{-1} (1.3 mm), and 20 K km s^{-1} (CO 2–1). The cross marks the position of the central star, 19:34:45.23, +30:30:59.07 (J2000.0), and the ellipses indicate the clean beams. In the CO map, solid and dashed contours denote blue and red shifted emission, respectively; the spectra of the peaks are shown to the right, smoothed to 5 km s^{-1}.

bandwidths were calibrated using 3C273, and the phase and amplitude using J1923+210 and J2013+370. The final images were produced using natural weighting, and the clean beam at the CO 2–1 frequency is $1\farcs0 \times 0\farcs5$ (at P.A. 30°).

The left hand panels of Fig. 1 present the continuum observations of BD+30°3639. These maps show an elliptical, $6'' \times 5''$ nebula with enhanced emission to the NW and the SE rims, similar to cm-wave maps obtained at the VLA (e.g., Kawamura & Masson 1996). The total flux at 2.6 mm is 0.41 Jy. The 1.3 mm interferometric data contain only $\sim 20\%$ of the total flux of 0.40 Jy measured by Hoare et al. (1992) with a $19''$ beam. This total flux has been used to provide zero-spacing information for the map shown in Fig. 1. The continuum fluxes are consistent with free-free radiation. Incomplete uv sampling and limited S/N for the larger uv spacings at 1.3 mm, as well as the inhomogeneous distribution of the gas (Harrington et al. 1997), likely account for the clumpy structure observed in the 1.3 mm map.

3. CO high-velocity bullets

Our CO observations of BD+30°3639 are shown in the right hand panels of Fig. 1. The CO distribution is striking, with two discrete condensations on opposite sides of the central star. Note that the CO map contains essentially all ($\gtrsim 90\%$) the flux seen in our single dish observations (Bachiller et al. 1991), so there is no significant emission from an extended component that is filtered out by the interferometer.

The spectra of the two condensations are also striking. The emission to the NE is centered at $V_{LSR} \sim -60$ km s^{-1}, whereas that to the SW is at $\sim$ +40 km s^{-1}. These velocities are roughly symmetric with respect to the systemic velocity of the ionized nebula (-13 km s^{-1}, Schneider et al. 1993), and imply expansion velocities of $\sim$ 50 km s^{-1}, about twice that of the bulk of the ionized gas and the H I envelope. In agreement with the single-dish spectra of Bachiller et al. (1991), no emission is detected in the velocity range from about -40 km s^{-1} to +20 km s^{-1}.

On account of the discreteness and high expansion velocity of the CO condensations, we will refer to them as "bullets". Their double symmetry, in both position and velocity, shows that they are aligned in a narrowly collimated, bipolar distribution with respect to the central star. The bipolar axis lies at a P.A. of 22°. This does not lie along the major axis of the nebula seen in the radio continuum at 2.6 mm (Fig. 1) or at cm wavelengths (where the P.A. is $\sim 60°$–$80°$), so the bullet axis does not appear to be a principal axis of the nebula.

The detailed structure of the bullets is shown in the velocity channel maps of Fig. 2. The left panels show the blue shifted (approaching) emission, and the right panels show the red shifted (receding) emission; there is no CO in the channels within ± 33 km s^{-1} of the systemic velocity, so these are not shown. Both CO bullets are seen to exhibit substructure. A certain degree of symmetry is also seen in the individual velocity channels, since the lower velocity gas (both blue and red shifted) lies closer to the star than that at higher velocity.

The angular distance of the bullets from the central star is $\sim 3''$ which gives a projected distance of 0.025 pc at the adopted distance of 1.5 kpc (Kawamura & Masson 1996). Using the average expansion velocity, this corresponds to an expansion timescale for the bullets of $\sim$ 500 yr, assuming an inclination angle of 45°. In fact the inclination angle cannot be derived from the present observations, so there is some uncertainty in the kinematic parameters.

The ratio of the intensities of the 2–1 to the 1–0 CO lines is $\sim$ 2, which implies that the emission is optically thin. We therefore estimate the mass of the bullets using the optically thin formula from Huggins et al. (1996). The mass of each bullet is found to be $\gtrsim 7 \times 10^{-4}\ M_\odot$, where the lower limit corresponds to full association of CO with an abundance of 3×10^{-4}. This could be a small fraction ($\sim$ 4%) of the mass of the ionized nebula (0.02 $M_\odot$), but if the CO abundance is lower than assumed (which is likely given the unusual conditions) the mass is correspondingly higher. The mass and size of the bullets imply a gas density in H_2 of $\gtrsim 10^4$ cm^{-3}.

4. Origin of the bullets

Our detection of molecular bullets in BD+30°3639 is of special interest because they have not previously been seen in any other

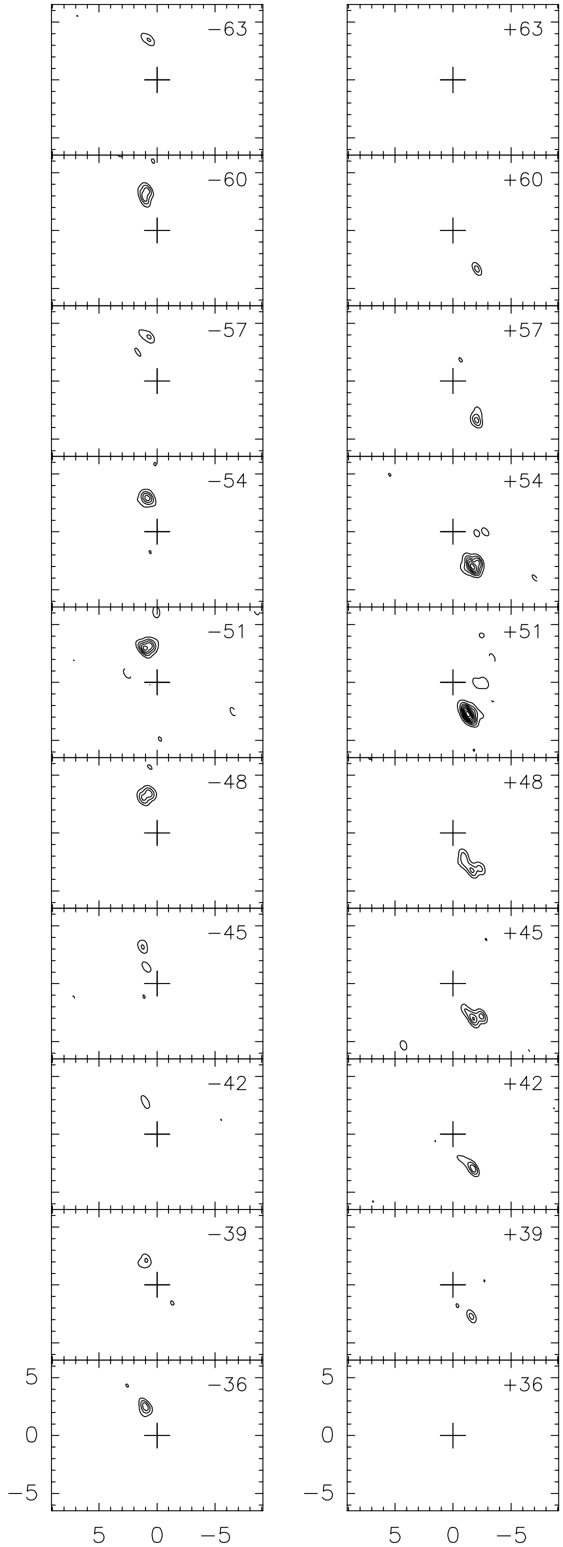

Fig. 2. Channel maps of the CO 2–1 emission in BD+30°3639. The channels are 3 km s^{-1} wide, with the central velocity of each one, in km s^{-1} with respect to the systemic velocity, indicated in each panel. They are arranged with the blue and red shifted channels in the left and right columns, respectively. No CO emission detected between ±33 km s^{-1}, so the corresponding channels are not shown. First contour and step are 5.25 K km s^{-1}. The cross and coordinates are as in Fig. 1.

PNe. Their high velocity and high degree of collimation with respect to the center of the nebula strongly suggest that they originate in underlying bipolar jets emanating from the central star. The location of the bullets just outside the ionized nebula (see Fig. 1) implies that they have formed by interaction of the jets with the surrounding neutral envelope. The emission would then likely come from gas that has been swept up in bow shocks.

The relation of the CO bullets to the surrounding envelope seen in H_2 emission is shown in Fig. 3. The different distributions are striking. The kinematics of CO and H_2 are also quite different (Shupe et al. 1998), but this is not surprising given their very different distributions. A detailed discussion will be given elsewhere (Cox et al. 1999b). The absence of CO emission in the extended envelope can be explained by photo-dissociation, and this is supported by the importance of atomic gas in the envelope (Taylor et al. 1990; Huggins et al. 1996). The presence of CO in the bullets means that either the gas was compressed non-dissociatively at an early stage and the CO has survived, or the CO has reformed in the bullets in post-shock gas. Both possibilities are plausible in view of the relatively low shock velocities ($\sim$ 30 km s^{-1}) involved (e.g., Hartquist & Caselli 1998). The absence of strong H_2 emission in the bullets, which might be expected from shocks or the UV radiation that excites the extended H_2 envelope (Shupe et al. 1998), is an interesting issue that requires further study.

The bullets and jets are not prominent in other observations of BD+30°3639, but certain features in optical HST images (Harrington et al. 1997; Sahai & Trauger 1998) do correspond. Gaps are seen in the ionized rims along the CO bipolar axis, suggesting that jets have punctured the main nebula. Other emission line features in the HST images may also be related. In addition, the absorption map made by Harrington et al. (1997, their Fig. 6) reveals a dust clump of $A_{\rm V} \sim 3$ mag that corresponds within $\sim 1''$ to the NE (blue shifted) bullet. The clump is larger than the bullet, but may represent some of the material excavated by the jets. Note that a possible counterpart to the SW (red shifted) bullet would not be seen in absorption because it would lie on the far side of the nebula. The kinematics of the nebula recently reported by Bryce & Mellema (1999) may also be related. The main kinematic axis in the ionized gas is found to lie roughly NE(blue)–SW(red), in the same sense as the bullet axis, and a high velocity ($\sim$ 90 km s^{-1}) ionized feature points to localized gas flows outside the main nebula.

The most conspicuous effects of the bullets and their underlying jets are seen in the surrounding neutral envelope. In Fig. 3, the bullets correspond to distinct breaks and disturbed structure in the H_2; in fact the centers of the breaks are slightly offset in position angle from the bullets, which may indicate that the jets have changed direction with time. In any event, the idea that the jets have punctured the nebula is strongly reinforced.

5. Implications for PN shaping

The bipolar outflows that we observe in BD+30°3639 clearly play a role in shaping the nebula, and they challenge the idea that the primary shaping mechanism is that of the interacting-winds

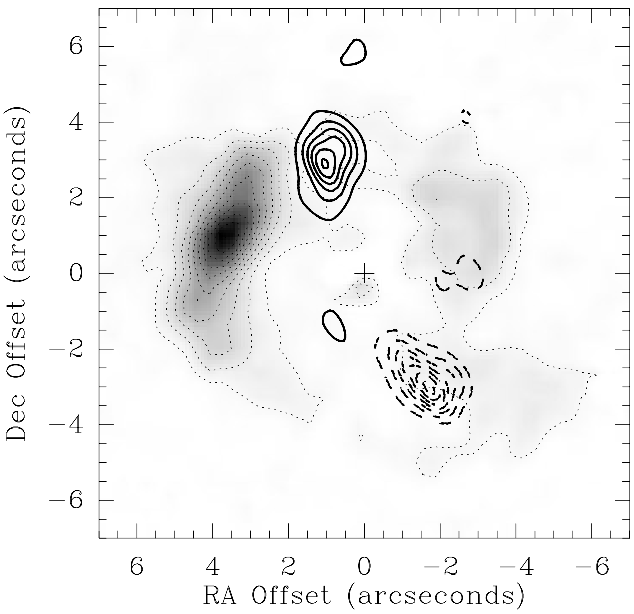

Fig. 3. Comparison of the CO 2–1 line emission (Fig. 1) with the H_2 1–0 S(1) emission (grey scale) from Cox et al. (1999b).

model. This is significant because BD+30°3639 is one of the more plausible cases for this model. The ionized nebula shows a ring morphology that has been modeled by Masson (1989) as a thin, ellipsoidal shell. The central star emits a powerful, fast ($\sim$700 km s^{-1}) wind (Leuenhagen et al. 1996), and it is one of the rare PNe where x-rays have been detected from a hot (3×10^6 K), diffuse plasma (Arnaud et al. 1996). Although the x-rays are not spatially resolved, they are believed to be emitted by a hot bubble that fills the inner cavity and drives the nebula dynamics.

Our observations of high velocity molecular gas cannot be explained by the simple interacting-winds model, in which a hot bubble drives the ionized shell into a slower moving, neutral envelope. More importantly, our observations show that collimated outflows or jets emanate from the central regions. The bullets are sufficiently close to the central star that their formation by focusing an isotropic wind on the scale of the ionized nebula can likely be ruled out. It is true that the mass we detect in the bullets may be relatively small, but the kinetic energy is larger because of the high velocity, and when one examines Fig. 3, it appears that a substantial part of the molecular envelope has been disturbed by bipolar interactions, either by multiple or wobbling jets. It is also possible, and even likely, that the molecular gas along the polar directions has already been cleared by related outflows.

This shaping scenario is essentially the same as seen in some other cases where the interactions are caused by much more prominent collimated outflows or jets that are easily identified from their optical or molecular emission, e.g., CRL 2688 (Cox et al. 1999a) and KjPn 8 (Forveille et al. 1998). The observations reported here open up the interesting possibility that low level jet-envelope interactions, which are hard to detect, are common, and play a wide role in PN dynamics.

Acknowledgements. We thank the IRAM Plateau de Bure staff for help with the observations. RB acknowledges support from DGES grant PB96-104, and PJH from NSF grant AST-9617941.

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