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LETTER

Letter to the Editor

Jets and high-velocity bullets in the Orion A outflows. Is the IRc2 outflow powered by a variable jet?

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Abstract. We present high sensitivity maps of the High Velocity (HV) CO emission toward the molecular outflows around IRc2 and Orion–S in the Orion A molecular cloud. The maps reveal the presence of HV bullets in both outflows with velocities between 40-80 $\mathrm{km\,s^{-1}}$ from the ambient gas velocity. The blue and redshifted CO HV bullets associated with the IRc2 outflow are distributed in thin ($12'' - 20''$, 0.02–0.04 pc) elliptical ring-like structures with a size of $\sim 10'' \times 50''$ (0.02×0.1 pc). The CO emission at the most extreme blue and redshifted velocities (EHV) peaks $20''$ north of source I, just inside the rings of the HV bullets.

The low velocity H_2O masers and the H_2^* bullets around IRc2 are located at the inner edges of the ring of CO HV bullets and surrounding the EHV CO emission. Furthermore, the high velocity H_2O masers are very well correlated with the EHV CO emission. This morphology is consistent with a model of a jet driven molecular outflow oriented close to the line of sight.

In the Orion–S outflow, the morphology of the CO HV bullets shows a bipolar structure in the southeast↔northwest direction, and the H_2O masers are found only at low velocities in the region between the exciting source and the CO HV bullets.

The morphology of the CO HV bullets, the radial velocities and the spatial distribution of the H_2O masers in both outflows, as well as the H_2^* features around IRc2, are consistent with a model in which these outflows are driven by a jet variable in direction. In this scenario, the large traverse velocity measured for the H_2O masers in the IRc2 outflow, $\sim 18\,\mathrm{km\,s^{-1}}$, supports the evolutionary connection between the jet and the shell-like outflows.

Key words: ISM: clouds – ISM: individual objects: Orion A – ISM: jets and outflows – stars: formation – stars: mass-loss

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1. Introduction

Molecular outflows associated with young stellar objects are mostly made of ambient material entrained by a primary wind from the central source. While young molecular outflows are highly collimated with HV jets (see e.g. Bachiller, 1996), more evolved outflows are poorly collimated with shell-like structures (see e.g. Snell et al., 1980; Fuente et al., 1998). Different kinds of models (wind-driven bubbles and steady state jets) have been developed to explain the two types of outflows (see e.g. Cabrit, 1995) but none of them can account for all the observational properties. A jet variable in velocity and/or direction, would explain the momentum distribution (Chernin & Masson, 1995), the multiple acceleration sites (see e.g. Bachiller, 1996), and the evidences of a wiggling molecular outflow (Davis et al., 1997). Furthermore, models of the interaction of a jet variable in time and direction predict that the jet breaks, given rise to independent HV bullets located in a shell-like structure with a non-negligible transverse velocity component (see e.g. Raga & Biro, 1993). Thus, observations of molecular outflows oriented along the line of sight and powered by a variable jet should show a ring-like structure of HV jet-bullets, and would allow to test these kind of models.

In this letter, we present high sensitivity CO observations of the molecular outflows in the Orion A molecular cloud (IRc2, see e.g. Wilson et al.,1986; and Orion-S, Schmid−Burgk et al., 1990). The morphology of the HV CO emission around the IRc2 outflow reveals the presence of a bipolar structure $20''$ from I source surrounded by a HV, ring-like structure of CO bullets that cannot be explained by the weakly collimated bipolar outflow model proposed by Chernin & Wright (1996), and suggest a jet driven molecular outflow oriented along the line of sight (Johnston et al., 1992). The combination of our results with those of the H_2O masers, strongly supports the idea that these molecular outflows are driven by jets which change in direction with time.

2. Observations

The observations of the $J = 2 \rightarrow 1$ lines of CO where carried out with the IRAM 30-m telescope at Pico Veleta (Spain). The observation were made with a SIS receiver tuned to single side band (SSB) with an image rejection of ~ 8 dB. The SSB noise temperatures of the receivers at the rest frequency was 300 K. The half power beam width of the telescope was $12''$. For spectrometers, we used a filter banks of 512×1 MHz that provided a velocity resolution of 1.3 km s^{-1}. The observation procedure was position switching with the reference taken at a fixed position located $15'$ away in right ascension. The mapping was carried out by combining 5 on-source spectra with one reference spectrum. The typical integration times were 20 sec for the on-positions and 45 sec for the reference spectra. Pointing was checked frequently on nearby continuum sources and Jupiter, and the pointing errors were $\leq 4''$. The calibration of the data was made by observing the sky, a hot and a cold load. The line intensity scale has been converted to units of main beam brightness temperatures by using a main beam efficiency of 0.45. The RMS noise of the map was 0.6 K.

3. HV bullets in the IRc2 and Orion-S outflows

3.1. Spectral features

The left panel of Fig. 1 (panel a) shows a sample of spectra taken toward the IRc2 outflow. The profiles show the typical broad line wings (± 100 km s^{-1}) associated with this molecular outflow. Superposed on these, because of the better sensitivity than previous published data, we have detected well defined spectral HV features restricted to certain radial velocity ranges (see the vertical arrows in the spectra of Fig. 1a). Most of the HV features in the IRc2 outflow appear at radial velocities between 30 and 90 km s^{-1}. Similar HV features are also clearly identified in the spectra of Orion-S outflow (left panel of Fig. 2; Schmid-Burgk, private communication). The HV spectral features detected in both molecular outflows are reminiscent of the HV bullets found in the molecular outflows driven by low mass stars (see Bachiller, 1996). Furthermore, the CO profiles towards the IRc2 outflow are similar to the recently discovered H_2^* bullets (Stolovy et al., 1998). The CO HV features reported here represents the first detection of HV bullets in molecular outflow powered by a massive star.

3.2. Morphology

The upper right panels (b and c) of Fig. 1, and the right panel of Fig. 2 show, respectively, the spatial distribution of the integrated intensity of the blue and redshifted CO HV bullets in the IRc2 and Orion-S outflows. The spatial distribution of the HV bullets have been obtained by subtracting the smooth broad velocity component by fitting a Gaussian profile. It is remarkable that the blue and redshifted CO HV bullets around IRc2 (Fig. 1b, and c) are distributed in an elliptical ring-like structure with a size of $\sim 10'' \times 50''$ (0.02×0.1 pc at the distance of 0.5 Kpc) with IRc2 located in the southeast edge of the HV bullets rings. The ring morphology of the CO HV bullets in the IRc2 outflow shows only minor changes with the radial velocity, indicating a nearly uniform distribution over the whole velocity range. Although the typical thickness of the rings is $12'' - 20''$ (0.02–0.04 pc), some positions are unresolved (thicknesses $\leq 6''$; 0.01 pc). This suggests that the blue and redshifted CO HV bullets are generated in a thin layer of HV gas distributed in a ring-like structure. It is interesting to note that the HV bullet rings are broken in the northwest edge just at the bottom of the H_2^* fingers (Allen & Burton, 1993). This indicates that the H_2^* fingers might have been produced when the hot gas within the shocked region breaks into the more diffuse medium and rapidly expands (McCaughrean & Mac Low, 1997).

In panels d and e of Fig. 1 we also show the spatial distribution of the CO emission for the most EHV components ($\geq\mid 90 \mid$ km s^{-1}). The bulk of the blueshifted and redshifted EHV gas is located $20''$ north of source I. None of the current jet and wind models can account of all the observational properties of the IRc2 outflow. The morphology of the CO emission at moderate velocities favors a biconical outflow structure that has a wide (130°) opening angle (Chernin & Wright, 1996) powered by source I (Menten & Reid, 1995). The morphology of the SiO maser spots near source I is consistent with a wide angle biconical outflow, but this simple model cannot account for the H_2O maser emission (Greenhill et al., 1998; Doeleman et al., 1999). The morphology of the HV CO bullet ring-like structures roughly trace the edges of the proposed biconical structures. However, the bipolar distribution of the EHV gas emission $20''$ north of source I, surrounded by the CO HV bullet rings is inconsistent with a wide angle biconical outflow model. In the next section, we analyze the alternative model of a jet driven molecular outflow directed along the line of sight (Johnston et al., 1992).

Fig. 2b shows the spatial distribution of the HV bullets for the Orion–S outflow. The HV bullets are small condensations (size $\sim 30''$; 0.07 pc) and show the typical bipolar distribution with the blue and redshifted features spatially separated from the powering source. The HV bullets basically outlines the full extent of this outflow. The outflow containing the CO bullets reported in this letter is perpendicular to the low velocity redshifted outflow found by Schmid-Burgk et al. (1990), and consistent with the spatial distribution of the SiO outflow found by Ziurys et al. (1990). The possible driving source, as defined by the center of symmetry from the kinematics of the HV gas, must lie at a position $\sim 18''$ north from FIR 4 where no prominent continuum source has been detected so far (Mundy et al., 1986; Wilson et al., 1986). In this outflow, the blue HV bullet shows different spatial distribution and velocity than the redshifted one. While the red CO bullet has a moderate radial velocities of ~ 60 km s^{-1} and is close to the exciting source, the blue CO bullet has very high velocity (~ 100 km s^{-1}) and is located further away from the exciting source. The different distribution might be due to the fact that the blue bullet is less massive than the red one, and it has been already accelerated up to the terminal velocity. In fact, the Orion–S outflow is rather young with a dynamical age of only 10^3 years.

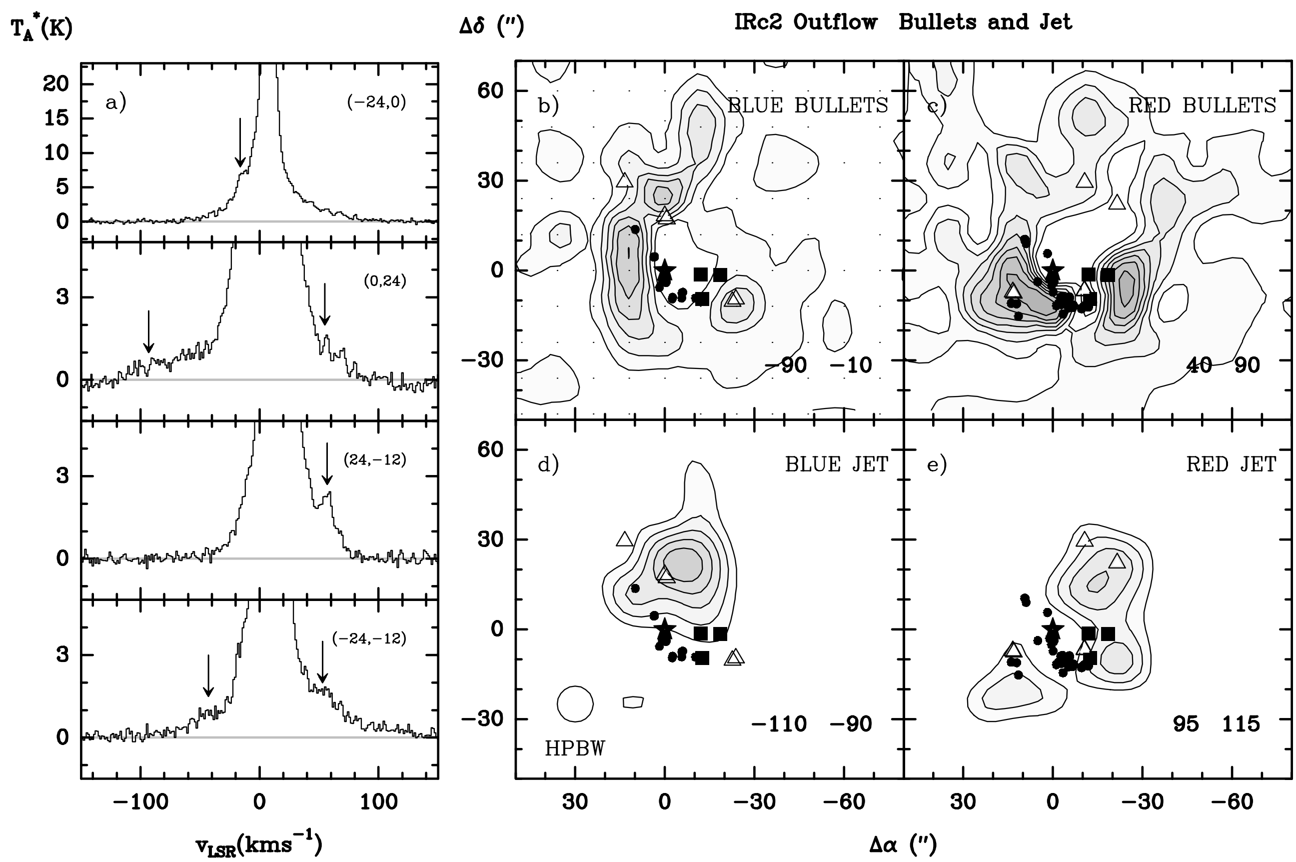

Fig. 1a–e. Left panels: **a** sample CO $J = 2 \rightarrow 1$ line profiles taken towards selected positions in the vicinity of the molecular outflow surrounding IRc2. The offsets shown in the upper right corner of each box are relative to IRc2. The vertical arrows show the location of HV "bullets" similar to those observed in some bipolar outflows driven by low mass stars. Central panels: **b** and **c** integrated intensity of the CO $J = 2 \rightarrow 1$ line emission between -90 and -10 km s^{-1}, and between 40 and 90 km s^{-1} for the blue and red HV bullets respectively. The maps have been obtained by subtracting a Gaussian profile to the broad line wings. The first contours level is 2 K km s^{-1}, and the interval between levels is 7 K km s^{-1}. **d** and **e** integrated intensity maps of the CO $J = 2 \rightarrow 1$ line over the most extreme velocities ("molecular jet"), from -110 to -90 km s^{-1} for the blue jet, and from 95 to 115 km s^{-1} for the red jet. For these two panels, the first contour level is 2 K km s^{-1} and the interval between levels is 1 K km s^{-1}. The circle in the lower left panel represents the size of the beam. For all the panels, the filled star represents the position of IRc2, and triangles and dots represent, respectively, the positions of the high and low velocity H_2O maser taken from Gaume et al. (1998), and the filled squares the positions of some H_2^* features (Stolovy et al., 1998).

4. Discussion

4.1. Jet driven molecular outflow in Orion A

With the present data we conclude that the CO HV bullet rings around IRc2 represent thin layers of HV condensations which have been shocked and accelerated by a fast jet oriented along the line of sight. The orientation of the flow along the line of sight is also suggested by the kinematics of the SiO masers around source I (Doeleman et al., 1999). In addition to the morphological arguments, the location of different shock tracers in this region like the H_2O masers, their kinematics, and the H_2^* features can be accounted by this model. Fig. 1b, c, d and e, show the location of the low (filled circles), the high velocity (open triangles) H_2O masers, and the H_2^* bullets (filled squares) adapted from Stolovy et al. (1998). The shock tracers, the low velocity H_2O masers and the H_2^* bullets, are located in the inner border of the CO HV bullets ring and, therefore, are surrounding the EHV jet. The H_2^* bullets and the H_2O masers are displaced from the CO HV bullets by $\sim 10''$ (2×10^{-2} pc). On the other hand, the high velocity H_2O masers are well correlated with the EHV jet indicating that they, indeed, arise from the interaction of the jet with gas which was already accelerated close to the terminal velocity of the outflow.

The observed morphologies of the CO bullet ring, the shock tracers, and the EHV gas can be explained by a fast jet moving along the line of sight and interacting with the surrounding molecular gas. In this scenario, the fast jet with material moving at velocities ≥ 100 km s^{-1} will interact with the surrounding ambient gas generating strong shocks that will compress, heat the gas, and even photodissociate molecules in its surroundings and in the head of the jet. As one moves away from the working surfaces of the jet, the material will cool down. First, H_2 molecules will be formed producing the strong H_2^* features in the densest hot clumps, and also the H_2O maser emission. As the accelerated post-shock material moves further away from the interface region it will cool further forming CO molecules

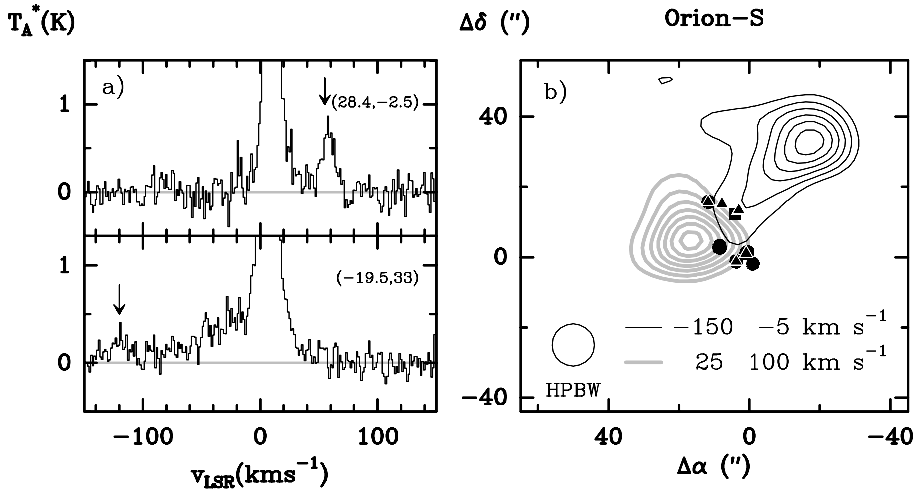

Fig. 2a and b. Left panels: **a** sample of CO $J = 2 \rightarrow 1$ spectra taken towards selected positions of the molecular outflow Orion–S. The offsets shown in the upper right corner of each box are relative to the position of FIR 4. The vertical arrows show the location of HV "bullets". Right panel: **b** integrated intensity maps of the CO $J = 2 \rightarrow 1$ line in the Orion–S outflow. The offsets are relative to the position of FIR 4. The intervals of velocity integration are: from -150 to $-5\,\mathrm{km\,s^{-1}}$ for the blue wing, and from 25 to $100\,\mathrm{km\,s^{-1}}$ for the red wing. For both wings the first contour level is $9\,\mathrm{K\,km\,s^{-1}}$ and the interval between levels is $2.5\,\mathrm{K\,km\,s^{-1}}$. The circle in the lower left panel represents the size of the beam. The filled triangles and dots represent, respectively, the positions of the blue and red H_2O maser taken from Gaume et al. (1998). The filled square shows the position of the possible exciting source.

(see Hollenbach & McKee, 1989) and given rise to the CO HV bullets.

The stratification of the different shock tracers indicates that the shocked gas is not only accelerated along the line of sight, but also perpendicularly to the jet axis. This is consistent with the measured proper motion of the low velocity H_2O masers which indicates that these are expanding at a velocity of $18\,\mathrm{km\,s^{-1}}$ (Genzel et al., 1981). This allows us to measure for the first time the transverse velocity in a jet driven molecular outflow which is $\sim 20\%$ of the jet velocity. For a transverse velocity of $18\,\mathrm{km\,s^{-1}}$, the separation between the CO bullet ring and the H_2^* indicates that the CO bullets ring has gone through the shock $\sim 10^3$ years ago, which is at least one order of magnitude larger than the typical time required to cool down the material and to produce CO molecules efficiently (Hollenbach & McKee, 1989). This indicates that the H_2^* and the H_2O emissions trace very recent shocks produced less than 100 years ago, and the CO HV bullets must have been produced by shocks more than 10^3 years ago.

In contrast to the IRc2 outflow, the Orion–S outflow seems to be oriented nearly perpendicular to the line of sight. The combination of these two outflows powered by massive stars with strong H_2O maser emission, but oriented with very different angles to the line of sight allows a three dimensional study of the interaction of the HV jets with the ambient cloud.

We now study the history of the young Orion–S outflow using the picture of the time dependent shock tracers obtained from the IRc2 outflow. In the case of the Orion–S outflow, all the H_2O masers are associated with the HV gas seen in CO (lower panel of Fig. 2b). The redshifted H_2O masers are on the western part of the red bullet facing the exciting source where a jet, nearly perpendicular to the line of sight, impinges. The interaction of the jet with the CO HV bullets is not only supported by the morphology, but also by the H_2O masers which have radial velocities similar to that of the red CO bullet. This indicates that the most recent shocks are indeed produced in the HV bullet. The blueshifted bullet seems to be in a different stage of evolution. As previously mentioned, the blue bullet is further from the exciting source than the red one, and the blueshifted masers are only found close to the exciting source at radial velocities close to the ambient velocities. This indicates that the most recent interaction of the jet is not occurring with the HV bullet material, but in ambient material which has not been yet affected by the jet, suggesting that the jet might have slightly changed the direction at which it is ejected. Therefore this can be understood in a model in which the molecular outflows are powered by a jet whose direction is changing with time (see e.g. Raga & Biro, 1993).

4.2. The Origin of shell-like molecular outflows

The large amount of the molecular gas mass observed in outflows suggests that these are mostly made by ambient material entrained by a "primary jet" (Bachiller, 1996). Entrainment can be divided in two categories: prompt entrainment at the jet heads (bowshock), and steady-state entrainment along the side of the jet due to Kelvin-Helmholtz (KH) instabilities. Most of the studies of the lines profiles seem to indicate that the prompt entrainment at the jet heads is the main mechanism for molecular entrainment (Chernin et al., 1994). However, to explain the data, Chernin et al. (1994) proposed a jet/bowshock model in which the jet is variable in velocity and/or direction. In the proposed scenario of a jet along the line of sight powering the IRc2 outflow, changes in the direction of the jet would explain the ring-like structure of the CO bullets (Raga & Biro, 1993), the spatial distribution of all the H_2O masers, as well as the large number of the H_2O masers at relatively low radial velocities. One important aspect of our interpretation is that the entrained material is moving perpendicular to the jet with velocities of up to 20% of the jet velocity. This indicates that in a time scale of 10^5 years, the IRc2 molecular outflow will form a cavity around the driving source with typical size of ~ 3 pc. This is similar to those found in molecular outflows powered by intermediate mass stars (NGC 7023; Fuente et al., 1998) and by low mass stars (L 1551-IRS5; Snell et al., 1980).

In summary, the morphology and the radial velocities of the CO HV bullets, the H_2O masers and the H_2^* bullets in the Orion A outflows can be explained by the interaction of jet-driven molecular outflows powered by variable jets in direction with the ambient gas.

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