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LARGE-SCALE INTERACTION OF THE OUTFLOW AND QUIESCENT GAS IN ORION

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ABSTRACT

We report on the detection of widespread high-velocity molecular gas in the Orion A molecular cloud. The high-velocity emission occurs over a range of ± 40 km s^{-1}. This high-velocity gas is more extended (up to 150″ from IRc2) than the very compact (40″) and well-studied molecular outflow around IRc2. The terminal velocities of the CO wings decrease from 100 km s^{-1} (corresponding to the very fast molecular flow) to the typical terminal velocities of the extended high-velocity gas when the distance to IRc2 changes from 40″ to 60″. The origin of the large-scale high-velocity gas is discussed: it is very likely the link between the very compact and energetic molecular outflow around IRc2 and the ionized high-velocity gas and the HH objects. Our data suggest that the influence of the molecular outflow in Orion on the surrounding molecular clouds is more important than previously thought. The mass, momentum, and energy of the extended high-velocity gas are crudely estimated to be $\approx 1\ M_{\odot}$, $\approx 20\ M_{\odot}$ km s^{-1}, and $\approx 2 \times 10^{45}$ ergs, respectively (i.e., a factor of ≈ 10 smaller than those of the fast molecular outflow).

High angular resolution mapping (22″) of the $J = 12$–11 line of HC_3N in Orion is also presented. The data show four long ($\lesssim 180''$) and thin ($\approx 15''$) filaments (like "fingers") located north of IRc2 and west of the molecular ridge where the extended high-velocity CO has been detected. From the HC_3N column densities of the filaments, we estimate H_2 densities of 5–50 $\times 10^4$ cm^{-3} and masses of $\approx 10\ M_{\odot}$. The location and the proper motions of the HH objects suggest the stellar wind is interacting with these fingers.

Subject headings: interstellar: molecules — nebulae: Orion Nebula — stars: winds

I. INTRODUCTION

In the last decade, the discovery of high-velocity molecular outflows has revealed that young stars undergo strong mass loss in their evolution to the main sequence. The first detection of this phenomenon was made toward the core of the molecular cloud in Orion A (Zuckerman, Kuiper, and Rodríguez Kuiper 1976; Kwan and Scoville 1976). Because of its energetics (terminal velocities up to ± 100 km s^{-1}) and its proximity, this molecular outflow has been studied in detail with a variety of angular resolutions and in several CO transitions (Erickson *et al.* 1982; Hasegawa 1986; Masson *et al.* 1984; Olofsson *et al.* 1982; Wilson, Serabyn, and Henkel 1986). Our current ideas about the molecular outflow in Orion are that the high-velocity gas is very fast (± 100 km s^{-1}), bipolar and very concentrated around IRc2 (size 40″). This molecular outflow is strongly interacting with the surrounding molecular cloud giving rise to broad ($\Delta V \approx 60$ km s^{-1}) H_2 emission (e.g., Beckwith *et al.* 1978) over a region more extended than the CO outflow. In this region, the HCO^+ emission also shows a moderately broad pedestal with a line width of $\approx \pm 20$ km s^{-1} to zero intensity (Olofsson *et al.* 1982; Vogel *et al.* 1984). Very high velocity H_2O masers are also found over this region (Genzel and Downes 1977).

On the other hand, Herbig-Haro objects, which are the result of the interaction of the high-velocity wind and the ambient molecular cloud, have been discovered much further away from the BN/KL region (up to projected distances of 100″) than the high-velocity molecular outflow (see, e.g., Axon and Taylor 1984). These HH objects present very large blueshifted velocities (up to -400 km s^{-1}), and proper motion measurements of some of them (Jones and Walker 1985) indicate that they are moving away from a point within the BN/KL region. Furthermore, the blueshifted ionized gas is not only restricted to these HH objects, but it is also found in discrete clumps over an approximately triangular zone, whose apex is situated near the IR cluster (Taylor *et al.* 1986). All these observational facts indicate the existence of a more extended high-velocity ionized outflow in the Orion region and suggest that the interaction of the molecular outflow with the ambient molecular cloud might occur over a larger region than that depicted by the H_2 and HCO^+ broad emissions. In this *Letter* we report on high angular resolution observations of the Orion A molecular cloud in the $J = 2$–1 line of CO and the $J = 12$–11 line of HC_3N. The CO data reveal the presence of a very extended component of high-velocity neutral gas in the region of HH objects which is probably related to the ionized outflow.

II. OBSERVATIONS AND RESULTS

The observations were carried out with the IRAM 30 m telescope at Pico Veleta (Spain). The $J = 12$–11 line of HC_3N and the $J = 2$–1 line of CO were observed with the 3 and the 1.3 mm SIS receivers, respectively. The receivers were tuned to single sideband (SSB) mode with an image rejection of ≈ 8 dB. The SSB noise temperatures of the receivers at 3 and 1.3 mm were, respectively, 250 and 300 K. The spectrometers used for these observations were two filter banks: the 256 $\times$ 100 KHz for the $J = 12$–11 line of HC_3N and the 512 $\times$ 1 MHz for the $J = 2$–1 line of CO. The half-power beamwidths of the telescope were 22″ ($J = 12$–11 line of HC_3N) and 12″ ($J = 2$–1 line of CO). We took the spectra in position-switching mode with a fixed reference position 300″ away in right ascension. The calibration of the data was made with the standard chopper wheel method.

We made a fully sampled map of a region of 200″ $\times$ 300″ around IRc2 in the $J = 12$–11 line of HC_3N. Figure 1 shows

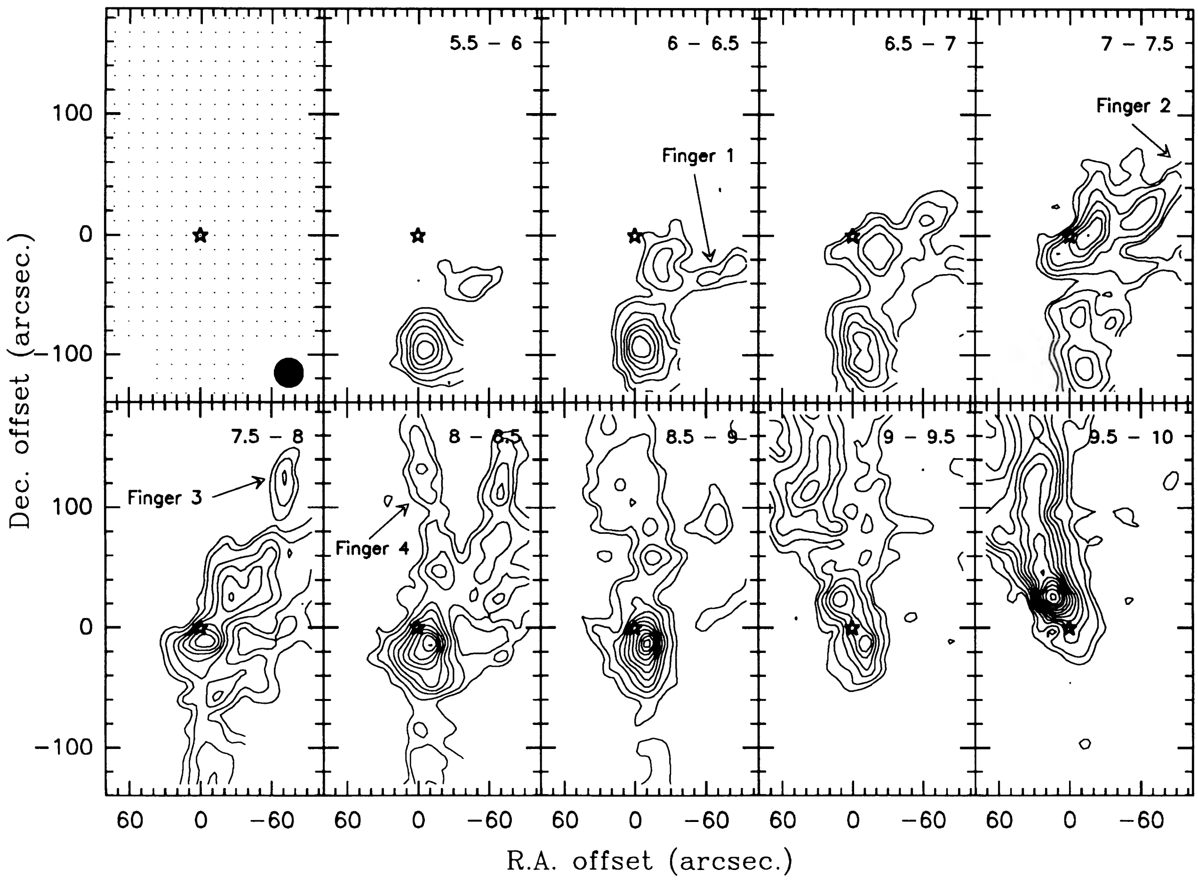

FIG. 1.—Integrated intensity maps of the J = 12–11 transition of HC_3N for different radial velocities intervals in Orion A. The beam size and the positions where the spectra were measured are shown in the upper left-hand panel by a filled circle (*lower left corner*) and by dots respectively. The right ascension and declination offset are measured respect to IRc2 ($\alpha = 5^h32^m47^s.0$, $\delta = -5°24'20''.6$), and its location is given by a star. The velocity intervals used to obtain the integrated intensities are given in the upper right-hand corner. The contour levels for all panels are 0.6, 0.9, and from 1.4 with an interval of 0.4 K km s^{-1}. The locations of the thin and long filaments appearing at radial velocities between 6 and 9 km s^{-1} are indicated as "fingers."

the integrated intensity of the J = 12–11 line of HC_3N for different velocity ranges. In order to emphasize the distribution of the ambient molecular gas (line widths ≈3–5 km s^{-1}) around IRc2, these maps have been obtained after removing the very broad pedestal of the hot core component (see Rodríguez-Franco *et al.* 1990). The HC_3N emission at low radial velocities, <6 km s^{-1}, is mainly concentrated toward source 6 of Batrla *et al.* (1983). For radial velocities around 9.5 km s^{-1} (*lower right panel*), the emission arises in the well-known quiescent molecular ridge north of IRc2 (e.g., Batrla *et al.* 1983). The more remarkable features of the HC_3N emission are found at intermediate radial velocities between 6 and 9 km s^{-1}. We find very thin (nearly unresolved) and long filaments stretching from IRc2 to the north and west. In the following we will refer to them as "fingers." In Figure 1 we have distinguished four fingers numbered from 1 to 4 as a function of increasing radial velocity. The deconvolved size of the longest fingers is ≈180″ × 15″. Finger 3 is clearly visible in the NH_3 map of Batrla *et al.* (1983). As shown in Figure 1, the line widths of the fingers are typical of the quiescent clouds in Orion, ≈1–2.5 km s^{-1}, and their radial velocities are systematically closer to that of the ridge as the projected distance between the ridge and the fingers decreases.

In the left panel of Figure 2 we show a sketch of the molecular ridge and fingers as delineated by the HC_3N emission in Figure 1. The crosses indicate the positions where the J = 2–1 emission have been measured, and the capital letters indicate the positions of the CO spectra shown in the right panel of this figure. The CO profiles show a broad pedestal (±40 km s^{-1}) toward many positions far away from the well-known very high velocity (VHV) molecular outflow around IRc2 (see spectra B, C, E, F, G, I, and J in Fig. 2). The high-velocity gas (hereafter HV to differentiate this component from the VHV outflow) is much more extended in all directions than the previously known molecular outflow. From our limited set of data, we estimate a size for the HV neutral gas of ≈130″ × 250″. The HV neutral gas is not only found toward the northern region of BN/KL as the ionized gas, but also in the southern region. In contrast to the ionized gas, which is mainly blueshifted, the CO profiles show both blueshifted and redshifted emission. There are, however, indications that the spatial distribution of the HV gas is not symmetric with respect to the ridge of molecular emission (thick lines in Fig. 2) showing stronger HV wings to the west of the ridge than to the east (see spectra A, B, C, and D in Fig. 2). Furthermore, there is a very sharp change of the terminal velocities of the high-velocity wings with position. The VHV gas (±100 km s^{-1}) is found within 50″ of IRc2, but the terminal velocities decrease

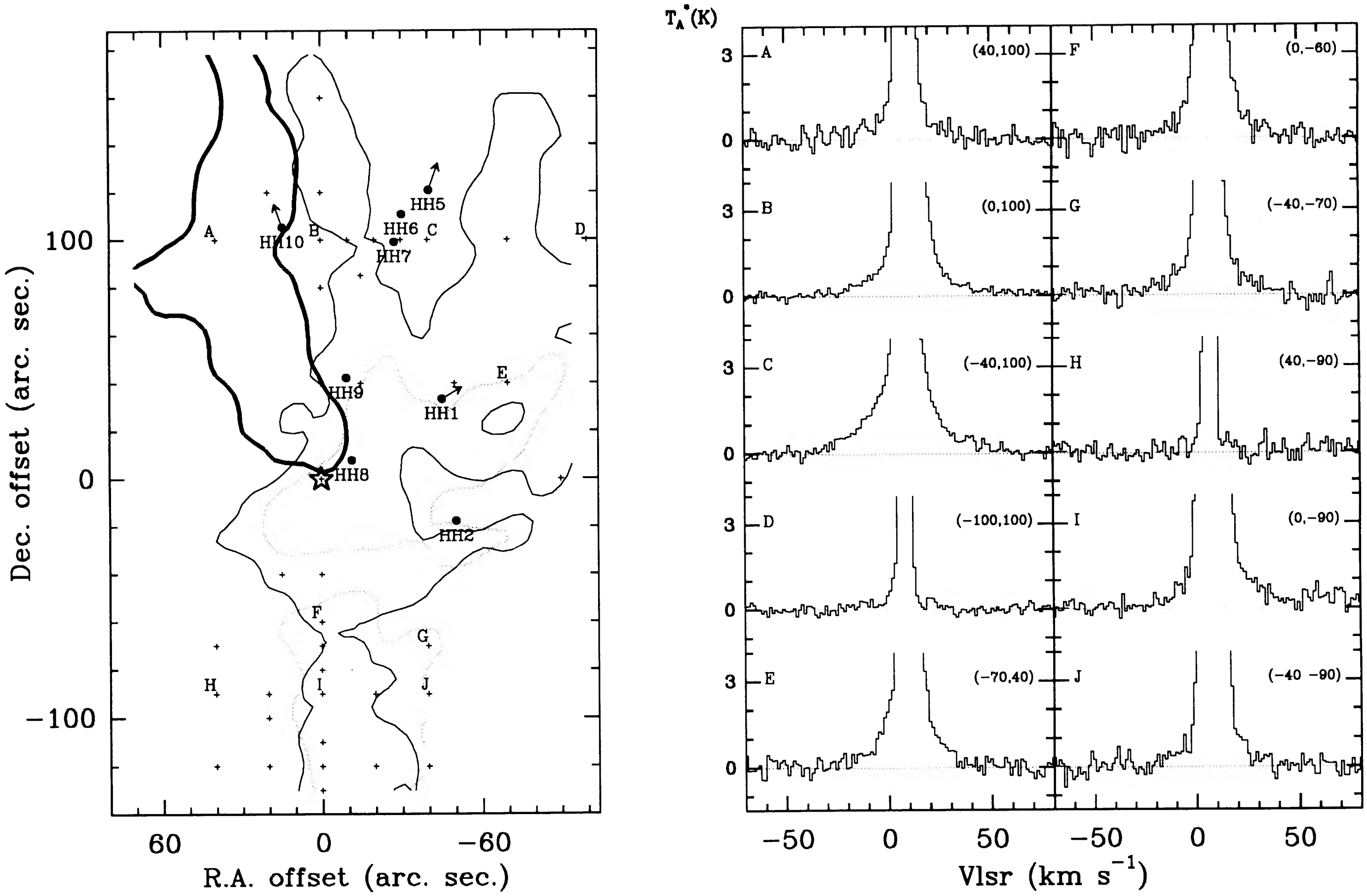

FIG. 2.—The left panel shows a sketch of the most outstanding features (the molecular fingers and the molecular ridge) as observed in the J = 12–11 line of HC_3N. The molecular ridge is represented by a solid thick contour corresponding at a level of 2 K km s^{-1} of the HC_3N integrated intensity between 9.5 and 10 km s^{-1}. The molecular fingers are delineated by thin and dotted contours taken at levels of 0.7 (HC_3N integrated intensity between 8 and 8.5 km s^{-1}) and 1 K km s^{-1} (HC_3N integrated intensity between 7 and 7.5 km s^{-1}), respectively (see Fig. 1). The position of IRc2 is shown by a star. The HH objects are shown as filled circles and the direction of their proper motions is indicated by arrows (Axon and Taylor 1984; Jones and Walker 1985). The HH objects are located close to the edges of the molecular structures and they seem to move in the direction of the fingers. The crosses show the positions where the J = 2–1 CO spectra have been measured. The capital letters close to some crosses indicate the position of the CO spectra displayed on the right panel.

The right panel shows a sample of spectra in the J = 2–1 line of CO taken in the Orion A molecular cloud toward positions far away from IRc2. The positions are indicated by their offsets, in arcseconds, with respect to IRc2 (*upper right corner* on every spectra) and by a capital letter (*upper left corner*) which refer to the left panel.

to those of the HV wings (50–60 km s^{-1}) when the distance to IRc2 changes from 40″ to 60″ (i.e., approximately in the region where H_2 vibrationally excited emission is observed).

III. DISCUSSION

The origin of the extended HV gas found far away from IRc2 is unknown. One could think that multiple embedded sources powering molecular outflows are responsible for the extended HV gas in Orion. In fact, 1ʹ.5 south of IRc2, Ziurys, Wilson, and Mauersberger (1990) have reported the detection of a bipolar outflow in SiO, and they suggested that an obscured star is driving it. This source might also power the extended HV gas observed in CO around this position (see spectra F, G, H, I, and J in Fig. 2). As found from other molecular outflows, the strongest HV line widths in CO are associated with a high-density condensation (see the HC_3N map in Fig. 1).

The explanation of the HV gas north of IRc2 in terms of multiple outflows is, however, unlikely. The strongest HV wings in CO to the north (spectra B and C in Fig. 2) are not found in the high-density gas of the molecular ridge (i.e., the strongest HC_3N emission), but just in the regions without HC_3N emission between the ridge and fingers 3 and 4. On the other hand, over the northern region of the HV molecular gas, Taylor *et al.* (1986) have found blueshifted ionized gas with velocities up to −500 km s^{-1} with a morphology suggesting IRc2 to be the source of the stellar wind. The proper motions of the HH objects in this region (see Fig. 2) also indicate they are activated by the stellar wind of a source located in the BN/KL region (Jones and Walker 1985; Taylor *et al.* 1986). The detection of HV molecular gas in this region provides, for the first time, the link between the very compact and energetic molecular outflow driven by IRc2 and the HH objects and the extended high-velocity ionized gas.

In contrast to the CO profiles which show symmetric HV wings, the ionized flow and the HH objects are only blueshifted. This is probably due to selection effects and the location, along the line of sight, of the molecular cloud and the H II region in Orion. As pointed out by Taylor *et al.* (1986), the ionized blueshifted gas probably arises from gas impacted by the stellar wind and ionized by the stellar ultraviolet flux from the Trapezium stars. The redshifted gas will move away from the H II region and will never become ionized. It has been proposed (Wilson, Serabyn, and Henkel 1986; Taylor *et al.* 1986) that the outflow is bipolar, and it is observed almost along the line of sight with the blueshifted cone located north of IRc2. In this picture, the symmetric HV wings observed in CO could be explained as arising in gas deflected from the VHV molecular outflow after collision with the quiescent gas. In fact, the VHV wings in CO change to HV wings in the region where shock-excited H_2 emission is detected. The line profiles of H_2 and HCO^+ show symmetric high-velocity wings similar to those of CO. Thus it is very plausible that the fast bipolar molecular outflow moving along the line of sight is deflected and decelerated when it collides with the ambient molecular cloud giving rise to the region of shocked gas (H_2 and HCO^+), the HH objects, and the extended HV molecular gas. Similar morphology has been found in the molecular outflows of L1448 and NGC 2024 (Bachiller *et al.* 1990; Richer, Hills, and Padman 1989) which show a very collimated jet for the highest velocity gas and more extended molecular outflows for the lower velocity outflowing gas.

The mass, momentum, and energy of the extended HV gas north of IRc2 are estimated from the CO profiles to be ≈ 1 $M_\odot$, ≈ 20 $M_\odot$ km s^{-1}, and $\approx 2 \times 10^{45}$ ergs, respectively. Considering the sparse data, the uncertainties are probably of a factor of 3. These values have been derived by assuming optically thin emission, a CO excitation temperature of 80 K, a CO/H_2 ratio of 10^{-4}, and a size of $\approx 130'' \times 140''$. The mass, momentum, and energy of the extended outflow are smaller than those of the molecular jet by factors of 4–8, 5–10, and 10–20, respectively (see, e.g., Snell *et al.* 1984 for the parameters of the VHV gas). These values are consistent with the idea that the VHV outflow is powering the more extended HV in Orion.

Our data can be used to derive some physical conditions of the newly detected molecular fingers. By assuming the HC_3N emission to be optically thin and an excitation temperature of 30 K, we derive HC_3N column densities in the fingers of $\approx 2 \times 10^{13}$ cm^{-2}. Using the fractional abundance for HC_3N of $\approx 4 \times 10^{-10}$, derived by combining the $C^{18}O$ and HC_3N column densities of the condensations in the ridge (Wilson *et al.* 1986), we obtain H_2 column densities for the fingers of 5×10^{22} cm^{-2}. This corresponds to H_2 volume densities which vary from 5×10^4 to 5×10^5 cm^{-3} for sizes of the fingers along the line of sight between 180'' and 15''. The derived mass of the longest fingers is ≈ 10 $M_\odot$.

The existence of interaction between the stellar wind and the fingers is suggested from the location and the proper motions of the HH objects (see Fig. 2). Most of the HH objects are located at the edges of the molecular fingers (HH 1, HH 2, HH 7, HH 9, and HH 10), and their proper motions indicate they are moving in the direction of the fingers. This is expected if the HH objects arise from shocked gas at the surface of the high-density filaments and they move along the edge of the filament (Schwartz 1978; Rudolph and Welch 1988). From the data presented here, we cannot discern whether the molecular fingers were formed prior to the mass outflow started or they are a consequence of the interactions between the stellar wind and the quiescent molecular cloud. Rudolph and Welch (1988) have suggested that clumps along the wind axis might form as a consequence of compression of the stationary ambient gas by the stellar wind. The blueshifted radial velocities of the fingers as compared with the ridge might be an indication that they have been pushed by the stellar wind. Contrary to HH 7–11, the fingers in Orion are perpendicular to the wind axis, and it is very unlikely that such a long and massive filaments form and survive within the stellar wind without other additional forces like the magnetic fields. The interaction of the H II and the molecular cloud might be also responsible for the formation of the fingers. Further high angular resolution observations of the fingers are required to understand their origin.

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