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Research Note

Millimeter observations of the HH 222 region[⋆]

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Abstract. The HH 222 streamers in Orion and their associated non-thermal radio jet form a unique object, whose nature remains enigmatic. We have carried out a set of detailed millimeter observations around the non-thermal radio source in several transitions of the CO, ^{13}CO C^{18}O and CS molecules. We find that the radio source is not associated with any molecular outflow nor located within a dense molecular core, and is therefore very unlikely to be a newborn star. The observations are in principle consistent with the radio source being a more evolved T Tauri star undergoing an energetic event, but it could also be an evolved object (an X-ray binary or a microquasar) accidentally passing through the large Orion cloud complex.

Key words. ISM: jets and outflows – ISM: Herbig-Haro objects – ISM: molecules – stars: formation – stars: pre-main sequence – radio lines: ISM

1. Introduction

HH 222 is a major emission line structure located in the L1641 cloud in Orion in the vicinity of, but unrelated to, the HH-34 outflow (Fig. 1). Although it is included in the Herbig-Haro catalogue of Reipurth (1999), it is by no means a typical HH object: it consists of a set of fingers spreading outwards from what appears to be a common point of origin, with one major streamer stretching for about 5 arcmin in a vast arc towards the south-west. Its emission line nature was first established by Cohen & Schwartz (1983). The T Tauri star V571 Ori is located only 15 arcsec from the center of the streamers, leading Reipurth & Sandell (1985) to suggest that the structure might represent the glancing impact of a T Tauri wind with the surface of a dense cloud. Their limited millimeter observations appeared to suggest that there might indeed be a dense cloud to the south-east, behind the origin of the streamers. However, the idea of an external T Tauri wind interacting with the outside of a molecular cloud did not gain support when Yusef-Zadeh et al. (1990) used the VLA to study the region and found a linearly polarized radio continuum source, with a large non-thermal radio lobe precisely at the center of the streamers. The lobe is nearly exactly aligned with the principal axis of the streamer system. Two faint near-infrared sources were found at the location of the VLA source. These data strongly suggested a connection between the unusual non-thermal radio continuum source and the unusual optical streamer system. The production of relativistic electrons in the vicinity of pre-main sequence stars is not easily explained, but an acceleration mechanism related to shocks may be involved (Crusius-Wätzel 1990; Henriksen et al. 1991).

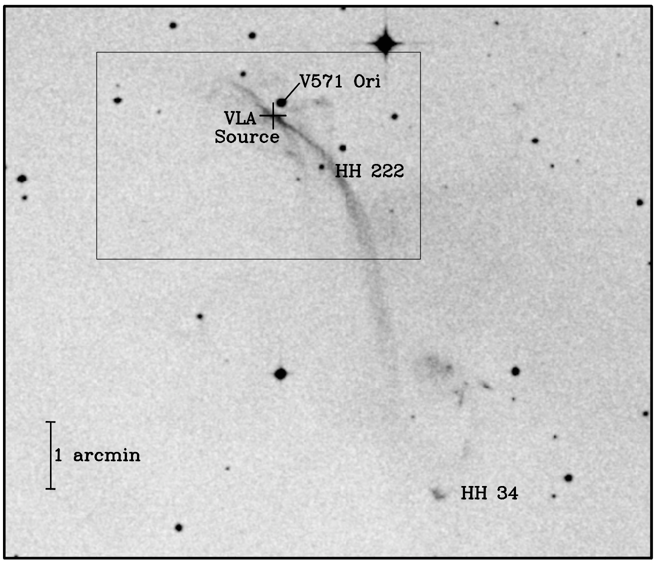

Fig. 1. Red Digitized Sky Survey (DSS) image showing the HH 222 and HH 34 objects. The location of the non-thermal jet seen at the VLA is indicated by the cross, and the T Tauri star V571 Tau is labelled. The region where molecular maps were obtained is shown as a rectangle.

In this paper we present extensive molecular observations of the region surrounding the radio continuum source, with the aim of trying to clarify the nature of this remarkable region.

[⋆] Based on observations collected at IRAM, Spain.

Table 1. Summary of all millimetric observations with the appropriate observing parameters.

Transition	Frequency (GHz)	*HPBW* ($''$)	η_{mb}	$\Delta\nu$ (kHz)	Δv (km s^{-1})	Average rms (km s^{-1})
CO($1 \rightarrow 0$)	115.27	21.3	0.76	39.06	0.10	0.35
CO($2 \rightarrow 1$)	230.54	10.7	0.51	78.12	0.10	0.50
^{13}CO($1 \rightarrow 0$)	110.20	22.3	0.80	39.06	0.11	0.24
^{13}CO($2 \rightarrow 1$)	220.40	11.2	0.53	78.12	0.11	0.60
C^{18}O($1 \rightarrow 0$)	109.78	22.4	0.80	39.06	0.11	0.14
C^{18}O($2 \rightarrow 1$)	219.56	11.2	0.53	78.12	0.11	0.22
CS($2 \rightarrow 1$)	97.98	25.1	0.80	39.06	0.12	0.10
CS($3 \rightarrow 2$)	146.97	16.7	0.65	39.06	0.08	0.17
CS($5 \rightarrow 4$)	244.93	10.0	0.50	78.12	0.10	0.27

2. Observations

We have made large maps of the region around HH 222 in several transitions of the CO, ^{13}CO C^{18}O and CS molecules. These maps were obtained in March 2001 with the IRAM 30-m telescope, located at an altitude of 2920 meters near the summit of Pico Veleta in southern Spain. An area covering $380'' \times 220''$ ($\Delta\alpha \times \Delta\delta$) around HH 222 was observed in the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions of C^{18}O. A smaller area covering $220'' \times 200''$ was observed in the $J = 2 \rightarrow 1$, $J = 3 \rightarrow 2$ and $J = 5 \rightarrow 4$ transitions of CS. Finally a $120'' \times 120''$ field centered on HH 222 was observed in the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions of CO and ^{13}CO. The coordinates ($\Delta\alpha$, $\Delta\delta$) of all the maps shown here are offsets relative to the VLA source position of the HH 222 region, at $\alpha(2000) = 05^{\mathrm{h}}35^{\mathrm{m}}41\overset{\mathrm{s}}{.}9$ and $\delta(2000) = -06°23'03''$. All the observations were obtained on a regular grid with a spacing of $20''$ in both directions, except for the CS $J = 2 \rightarrow 1$ map where the sampling was $40''$.

During each observing session four receivers were used simultaneously. The image sideband rejections of all receivers were always higher than 10 dB. The four receivers were connected to units of the autocorrelator set to provide spectral resolutions of 40 and 80 kHz below and above 150 GHz, respectively. At all frequencies, the velocity resolutions are of the order of 0.1 km s^{-1} (Table 1). The pointing and focus drifts were monitored using planets or strong extragalactic continuum sources. The pointing corrections were found to be always below $3''$.

All data were obtained in the position switching mode, with the OFF position located at $\Delta\alpha = -360''$, $\Delta\delta = 0''$ from the center of HH 222. Because of the extent of the Orion southern molecular cloud, this OFF position is not emission free. Therefore, after each pointing session (every 2 h), we observed the OFF position during 10 min in the frequency switching mode with a throw of 7.9 MHz. The resulting spectrum was subtracted from all spectra observed after that pointing session. All intensities are expressed in units of *main beam brightness temperature*. The corresponding main beam efficiencies at each frequency are listed in Table 1.

3. Results

3.1. ^{12}CO observations

The ^{12}CO lines show little variation throughout the map, except for a smooth gradient in both the brightness temperature and the linewidth across the cloud, from West to East. The main beam temperature of the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ lines increase from 17 K to 19.5 K and 26 K to 31 K, respectively, while the full width at half maximum of the line profiles (which are identical for both transitions) increases from 2.6 to 3.1 km s^{-1}. The shape of the ^{12}CO spectra (Fig. 2) indicates the presence of at least two components along the line of sight. These are also visible, and are better separated from one another, in the ^{13}CO and C^{18}O spectra; they will be discussed in more detail in Sect. 3.2. The main spectral component, associated with L1641, is nearly Gaussian, and its profile varies very little across the map. In particular, there is no evidence for extended high-velocity wings which would be indicative of the presence of a molecular outflow driven by the VLA source.

The value of the main beam temperature of the $J = 2 \rightarrow 1$ line indicates that the kinetic temperature is equal to or greater than about 35 K. To estimate more properly the kinetic temperature, we ran an LVG model with several sets of parameters. This LVG model assumes spherical geometry and uses the CO collision rates of Flower & Launay (1985) with an H_2 ortho-to-para ratio of 0.25. The LVG approximation is better than the LTE because it determines the excitation temperatures directly from the different transitions, instead of assuming thermalized levels. In our case, there are three unknowns (the kinetic temperature, the CO column density, and the H_2 volume density) but only two observations. Fortunately, the H_2 volume density can be obtained using the CS observations (to be described below). Indeed, the LVG model shows that the ratio between the $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ CS intensities at the center of the map (about 1/2) implies an H_2 volume density of $\simeq 2 \times 10^4$ cm^{-3} independently of the temperature. Assuming such a volume density, the LVG model applied to the CO data gives $T_k = 40$ K with an average CO column density of 1.2×10^{17} cm^{-2}. These values for the kinetic

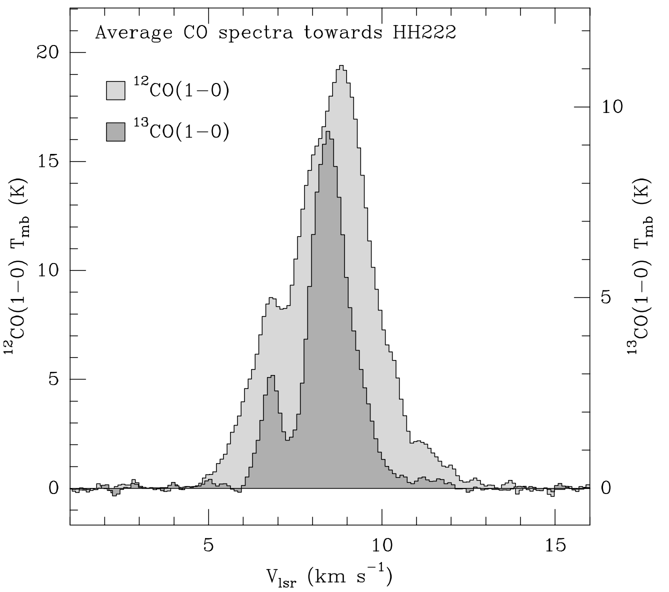

Fig. 2. Average of all the positions observed towards HH 222 in the ^{12}CO and ^{13}CO $J = 1 \rightarrow 0$ line. These positions correspond to a 60″ × 60″ region centered on the VLA source, observed on a regular grid with 20″ spacing. The main component is associated with the gas in the L1641 cloud, whereas the fainter component is likely an unrelated feature located along the line of sight.

temperature and CO column density are typical of the Orion molecular cloud (see for example Castets et al. 1990). However, because CO is optically thick, the value of 40 K is representative of the kinetic temperature of the outer layers while the kinetic temperature in the interior of the molecular cloud is likely somewhat lower (we define the interior as the material located at $A_v > 5$). Since ^{13}CO and C^{18}O are confined to the cool cloud interior, it is reasonable to assume a uniform temperature, lower than the temperature of the ^{12}CO emitting region. Following Batrla et al. (1983) and Cesaroni & Wilson (1994) who used NH$_3$ emission to derive the H$_2$ density and kinetic temperature in dense regions of Orion, we adopt a mean value of 25 K for the kinetic temperature.

3.2. ^{13}CO observations

Most of the ^{13}CO spectra exhibit two velocity components, especially in the northern part of the map. In the spectrum averaged over all positions (Fig. 2), the two velocity components are clearly separated. The main one is at $\upsilon_{\rm lsr}$ = 8.5 km s^{-1} and the other one at $\upsilon_{\rm lsr}$ = 6.6 km s^{-1}. The stronger component corresponds to the L1641 cloud itself, which was also seen around HH-34 by Reipurth et al. (1986). The other component is likely an unrelated cloud located along the line of sight. The average peak brightnesses across the cloud are 9 and 11 K, in the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions, respectively. The maxima are 10 and 15 K in the south-east corner (offset: 40″, −40″), while in the south-west corner (offset: −60″, −40″), the intensity decreases to 6 and 7 K. The maximum corresponds to the tip of a "tongue" of dense gas which connects the HH 222 VLA source to a large condensation to the south-east (Fig. 3). This feature will be discussed in more detail in the next section, with the results of the C^{18}O observations. The ^{13}CO column density at this position, estimated from our LVG code, is about $N(^{13}\mathrm{CO}) = 2.6 \times 10^{16}$ cm^{-2}. However, this value is quite uncertain since both ^{13}CO transitions at that position are found to be somewhat optically thick (τ = 0.6 and 2.2 for the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions, respectively). This situation is similar to that already encountered by Castets et al. (1990), who showed that in Orion the ^{13}CO molecule is not appropriate for estimating properly the column density and the density. Only the C^{18}O molecule can give reliable results for the column density, and higher CS transitions for the density.

3.3. C^{18}O observations

The C^{18}O $J = 2 \rightarrow 1$ map is shown in Fig. 3a, where the location of the HH 222 VLA source is indicated, and superposed on the red DSS[1] image of HH 222 in Fig. 3b. It is noticeable that the HH 222 VLA source is located at the tip of a tongue of dense gas connecting to a dense condensation to the south-east of the map, but is *not* directly associated with any peak in the C^{18}O map. The CS maps (not shown here) are very similar to the C^{18}O one shown in Fig. 3, and do not show any peak at the position of the VLA source either. Indeed, the only position where CS $J = 5 \rightarrow 4$ was detected was at offset 160″, −70″, where C^{18}O is also strongest. One must therefore conclude that the HH 222 VLA source is not directly associated with any prominent dense core.

The only dense core in the map is located at offset 160″, −70″. There, the C^{18}O spectra exhibit two velocity components, the main one at $\upsilon_{\rm lsr}$ = 8.9 km s^{-1} with a linewidth of 0.7 km s^{-1} and the other one at $\upsilon_{\rm lsr}$ = 7.8 km s^{-1} with a linewidth of 0.9 km s^{-1}. Conversely the line at the position of the HH 222 VLA source itself has only one component at $\upsilon_{\rm lsr}$ = 8.15 km s^{-1} with a linewidth of 1.2 km s^{-1}. Finally, the finger connecting the dense core to the HH 222 VLA source exhibits spectra similar to those observed towards the VLA source. Using our LVG code, we estimated the C^{18}O column density from the observations, and converted the result into an H$_2$ column density, using the ratio $N(\mathrm{H_2})/N(\mathrm{C^{18}O}) = 7 \times 10^6$ (Langer & Penzias 1990). In the dense core we obtain a total H$_2$ column density of 3.0×10^{22} cm^{-2} while in the finger we obtain 1.2×10^{22} cm^{-2}, and at the VLA position $N(\mathrm{H_2}) = 8.2 \times 10^{21}$ cm^{-2}. From the morphology and kinematics of the region, it is impossible to tell whether or not there is an actual physical connection between the dense core to the south-east and the VLA HH 222 object, nor whether the location of HH 222 VLA near the tip of the tongue of material has any bearing on its mysterious properties

As Fig. 3b shows, there is no noticeable change in the intensity of the C^{18}O molecular emission along the northern part of the optical streamer. To the south-west, the main streamer

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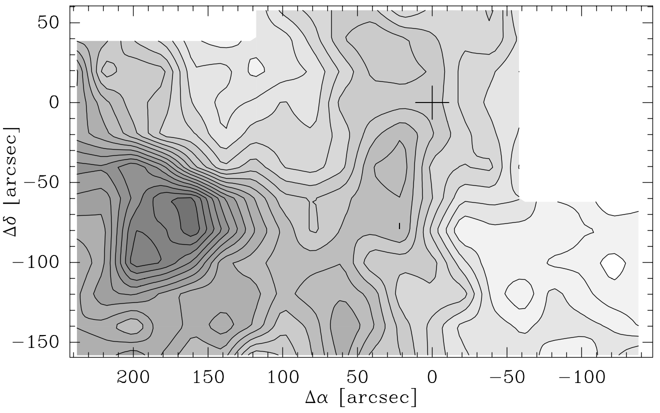
[1] The Digitized Sky Survey was produced at the Space Telescope Science Institute under US Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

(a) $C^{18}O(2-1)$ map



(b) $C^{18}O(2-1)$ map superposed on the DSS red image

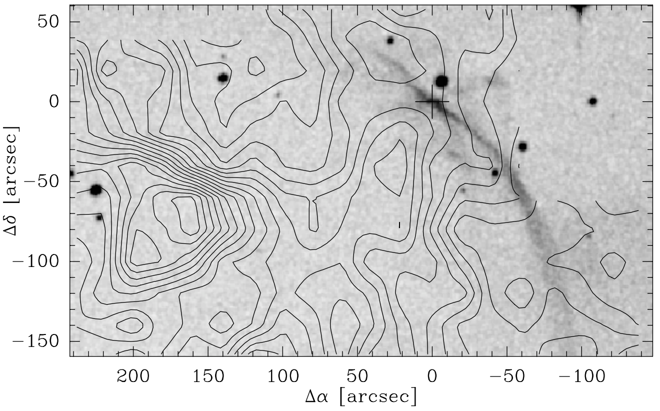


Fig. 3. a) The $C^{18}O$ $J = 2 \rightarrow 1$ integrated map around the HH 222 VLA source (shown as a cross). **b)** Superposition of the $C^{18}O$ (2–1) integrated on the DSS image of Fig. 1. Note the tongue of material connecting HH 222 VLA to the condensation of gas at the south-east of the map, and the absence of any condensation at the position of HH 222 VLA.

enters a region of lower $C^{18}O$ intensity indicative of lower H_2 column density. However, all spectra along the streamer are similar to the ones outside the streamer. Hence, we must conclude that there is no interaction between this optical streamer and the molecular gas.

3.4. CS observations

The CS $J = 3 \rightarrow 2$ emission map (not shown here) is essentially similar to the $C^{18}O$ $J = 2 \rightarrow 1$ map of Fig. 3, confirming the lack of a dense cloud core associated with HH 222 VLA. The CS $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ transitions have fairly uniform brightness temperatures (1 and 0.5 K for the $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ transitions, respectively) across the mapped area, and indicate (as mentioned in a previous section) that the density is about $\simeq 2 \times 10^4$ cm^{-3}. We almost did not detect any CS $J = 5 \rightarrow 4$ molecular emission, with the exception for a few positions in the dense core to the south-east of HH 222 VLA (around 160″, −70″), so the region must be essentially devoid of very dense gas.

4. Discussion: What is the nature of HH 222 VLA?

The nature of the HH 222 complex and its driving VLA source is currently unclear. In the following, we attempt to limit the possibilities in light of the new millimeter observations presented here. We consider four possibilities.

4.1. A very young source located in Orion

The Herbig-Haro-like emission spectrum of HH 222 and its location towards the L1641 cloud, which is rich in newborn stars and HH objects, suggest that the driving source HH 222 VLA could be an extremely young source still embedded in its placental material. For comparison, the best-known non-thermal radio source in a star forming region, the triple source in Serpens (Curiel et al. 1993; Raga et al. 2000), is located in a dense cloud region and the source has very strong sub-millimeter emission from cool circumstellar material. In contrast to this, the HH 222 VLA source has not been detected at 1300 μm, Reipurth et al. (1993) found a 3σ upper limit of 36 mJy, suggesting that very little cold circumstellar material is currently present, although a modern sub-millimeter map of the source region would be valuable to confirm this pointed observation. Our new millimeter data show that, in addition, the source is not directly located towards a dense cloud core, although cloud cores exist in the general neighborhood. The absence of these two prime signatures of extreme youth suggests that HH 222 VLA is unlikely to be a newborn star.

4.2. A less young source located in Orion

HH emission and outflow activity is known to be associated not only with the very youngest stars, but in some cases also with visible T Tauri stars, which are in more evolved, albeit still youthful, states. Such stars have in many cases shed most of their circumstellar material (e.g. André & Montmerle 1994), and they are often no longer seen to be associated with dense cores of placental material. Such objects are known to be able to drive high-energy processes (e.g. Feigelson & Montmerle 1999) which might lead to the non-thermal spectrum of the source and the associated HH-like activity. However, the rather low gas column density we have measured corresponds to a maximum extinction of $A_V \sim 8$ mag, or $A_K \sim 0.8$ mag, suggesting that if the faint infrared source detected by Yusef-Zadeh et al. (1990) is indeed a T Tauri like star, then it must have a very low luminosity, probably not exceeding 10^{-2} $L_\odot$, indicating an object of rather low mass. The currently available observations are not inconsistent with such an interpretation.

4.3. An extragalactic background source

Non-thermal radio emission is commonly detected from extragalactic background sources, and when studying star forming regions such sources show up regularly (e.g. Anglada et al. 1998). So it is certainly a possibility that the non-thermal radio jet and associated compact core is just a background source. However, the radio source is located exactly at the center of the giant HH 222 streamers, and the chance that an extragalactic source should happen to lie so precisely along the line-of-sight to this unique object is very small. According to Condon (1984) the number of sources per square arcminutes having a 6 cm flux density larger than a certain limit S is given by:

$$\frac{N}{\mathrm{arcmin}^{-2}} = 0.011 \left(\frac{S}{\mathrm{mJy}} \right)^{-0.75} .$$

Since the VLA source is located within about 5″ from the center of the streamers, and has a 6 cm flux density of about 6.5 mJy (Yusef-Zadeh et al. 1990), the probability of a chance alignment is about 7.5×10^{-5}. Even considering that a few hundred HH sources have been observed at the VLA so far, this leaves the probability of finding an extragalactic radio source within 5″ of the center of the HH flow at about 1%. In the specific case of HH 222, the possibility of a fortunate line-of-sight association is made even less likely by the good alignment between the optical streamers and the non-thermal lobes.

4.4. An old source drifting through Orion

Evolved binary systems such as microquasars or X-ray binaries may pass through highly energetic phases in which they produce non-thermal radio jets and other signposts of powerful outflow activity (e.g. Rodríguez et al. 1992; Mirabel & Rodríguez 1994). When such objects move through the Galactic plane they may encounter molecular clouds, which may even feed their outflow activity (e.g. Mirabel et al. 1992). It is possible that the HH 222 VLA source is such an evolved source, which is currently passing through the Orion clouds, and producing both the non-thermal radio source and the unusual HH 222 object. However, such sources are usually strong X-ray emitters, and no X-ray source is seen at the position of HH 222 VLA in the ROSAT all-sky survey. Although this does not exclude the possibility that HH 222 VLA is an evolved source passing through the Orion clouds, it certainly does not favour this scenario.

5. Conclusions

We have carried out an extensive millimeter study of the region around the enigmatic object HH 222 associated with a non-thermal radio jet in Orion, and have obtained the following results:

1. The HH 222 VLA source is *not* directly associated with any dense cloud core, although cloud cores are detected in the general neighborhood. It does not seem to be associated with any molecular outflow either. This, together with the previously noted absence of 1300 μm emission, suggests that the source is not a newborn, still deeply embedded class 0 or class I source.
2. The observations are consistent with HH 222 VLA being either a more evolved young star (class II or III) presently undergoing an energetic event, or being a post-main sequence object (e.g. an X-ray binary or a microquasar) which has drifted into the Orion clouds. However, in the former case, it is surprising that there is only a faint near-infrared source at the VLA source position, and in the latter case it is equally surprising that there is not a strong ROSAT X-ray source coincident with the VLA source. We conclude that the HH 222 VLA source remains as enigmatic as ever.

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