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THE INITIAL CONDITIONS OF STAR FORMATION IN INTERMEDIATE- TO HIGH-MASS PROTOCLUSTERS

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Abstract. To better understand how the initial conditions of the highly complex star formation process depend on environmental conditions, it is crucial to study at high-angular resolution the morphology, the kinematics, and eventually the interactions of pre–stellar core candidates associated with intermediate-/high-mass star formation. In this work, we study the cold condensations in the intermediate-/high-mass proto-cluster IRAS 05345+3157, focusing on the interaction with the other objects in the cluster. We have performed millimeter high-angular resolution observations, both in the continuum and several molecular lines, with the PdBI and the SMA. The main results of this work are the following: the observations reveal the presence of 3 warm cores identified in the millimeter continuum, called C1-a, C1-b and C2, and of two very cold and dense cores, called N and S, identified by observations of N_2D^+, a molecular species eminently suitable to trace pre–stellar gas. None of the millimeter cores are associated with cores N and S. C1-b is likely a massive young stellar object driving a powerful ouflow. The study of the gas kinematics across the source indicates a tight interaction between the deuterated condensations and the sources embedded in the millimeter cores. For the nature of N and S, we propose two scenarios: they can be either low-mass pre–stellar condensations in which turbulent motions are dominant, or 'seeds' of future high-mass star(s).

1 Introduction

The physical and chemical properties of pre-stellar cores, i.e. cores on the verge of the gravitational collapse, were extensively investigated in the last decade in nearby low-mass star forming regions. Studies demonstrate that *isolated low-mass pre–stellar cores* have dense ($n \sim 10^5 - 10^6$ cm^{-3}) and cold ($T \sim 10$ K) nuclei, in which C-bearing molecular species such as CO and CS are strongly depleted, while N-bearing species such as N_2H^+ and NH_3 maintain large abundances in the gas phase (see Bergin & Tafalla 2007 for a review). The combination of low temperatures and CO depletion originates high values of *Deuterium fractionation* ($D_{\rm frac}$), defined as the column density ratio between one species containing deuterium and its counterpart containing hydrogen. The production of deuterated species starts from the exothermic proton-deuteron exchange reactions of the simplest molecular ions (e.g. $H_3^+ + HD \rightarrow H_2D^+ + H_2 + 270$ K, Millar et al. 1989): at temperatures lower than $\sim 20-30$ K, the inverse reactions are inhibited, so that the abundance of the deuterated ions (and hence of their daughter species) increases. In addition, these deuterated molecules are mainly destroyed by CO, but in environments where CO is depleted they can survive and give rise to strong lines. Actually the $D_{\rm frac}$ in pre–stellar cores, measured through non-depleted molecules, e.g. NH_2D/NH_3 and N_2D^+/N_2H^+, is orders of magnitude larger than the [D/H] interstellar abundance (Tiné et al. 2000; Crapsi et al. 2005). Can the properties of isolated pre-stellar cores be extended to clustered cores surrounding high mass (proto)stars? In crowded environments, turbulence, relative motions, and interactions with nearby forming (high-mass) protostars can affect the less evolved condensations (Ward-Thompson et al. 2007). To understand if, and how, crowded pre–stellar cores close to intermediate-/high-mass star formation are different from isolated ones, high-angular resolutions studies of the cold and dense gas that surrounds massive (proto-)stellar objects are necessary.

The object of the present work is an intermediate- to high-mass proto-cluster located nearby the luminous IRAS point source 05345+3157 ($\sim 60''$ to the N-E). The region is located at a distance of 1.8 kpc (Zhang et

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al. 2005), and its surface density (~ 1.3 gr cm^{-2}) and mass-to-luminosity ratio ($\sim 8L_\odot/M_\odot$) indicate that it is potentially a site of massive star formation (see Fig. 1 of Chakrabarti & McKee 2005). Hereafter, we will call our target I05345. From IRAM-30m data, Fontani et al. (2006) have measured an average CO depletion factor of ~ 3 and an average deuterium fractionation from the column density ratio $N(\mathrm{N_2D^+})/N(\mathrm{N_2H^+})$ of ~ 0.01, three orders of magnitude higher than the cosmic [D/H] abundance. These findings would indicate the possible presence of pre–stellar cores analogous to those detected in several low-mass star forming regions. However, the angular resolution was insufficient to determine whether we are dealing with a single high-mass core or instead with several low-mass ones. Therefore, we have recently mapped I05345 at high-angular resolution in the $\mathrm{N_2H^+}$ (1–0) line with the IRAM Plateau de Bure Interferometer (PdBI), and in the $\mathrm{N_2H^+}$ and $\mathrm{N_2D^+}$ (3–2) lines with the Submillimeter Array (SMA), in order to derive a detailed map of the deuterium fractionation in the source. Simultaneously, we have obtained observations in the continuum at ~ 96, ~ 225 and ~ 284 GHz with the two interferometers, as well as in several lines of other molecules. We present here the main results of these observations.

2 $\mathrm{N_2D^+}$ and $\mathrm{N_2H^+}$ emission and deuterium fractionation

In left panel of Fig. 1 we summarise the main observational results of the observations of $\mathrm{N_2H^+}$, $\mathrm{N_2D^+}$ and of the 96 GHz continuum: (i) the 96 GHz continuum observed with PdBI (grey-scale in left panel of Fig. 1) reveals the presence of 4 cores; two of these are inside the interferometer primary beam (C1 and C2 in left panel of Fig. 1), while the other two are outside and at the edge of it (C3 and C4, respectively, in left panel of Fig. 1). When observed at a resolution of $\sim 1''$ at 286 GHz, core C1 is resolved in two sources, C1-a and C1-b (see the grey-scale in right panel of Fig. 1). Core C1-b is a hot core and thus likely harbors an early-B ZAMS star; (ii) the distribution of the intensity of the $\mathrm{N_2H^+}$ (1–0) line (green contours in left panel of Fig. 1) is extended and with a complex structure; (iii) the distribution of the $\mathrm{N_2D^+}$ (3–2) line integrated emission (red contours in left panel of Fig. 1) is concentrated in two condensations, called N and S. The integrated emission of the $\mathrm{N_2H^+}$ (3–2) line (not shown in Fig. 1) is compact, and detected towards the strongest continuum peak only. We have derived the masses of N and S, which are ~ 9 and ~ 2.5 $\mathrm{M_\odot}$, respectively. Also, from the $\mathrm{N_2D^+}$ /$\mathrm{N_2H^+}$ column density ratio we have obtained a D_{frac} of ~ 0.1 in both condensations, which are the typical values derived in low-mass pre–stellar cores. For more details, see Fontani et al. (2008).

3 Interaction between the deuterated condensations and a powerful CO outflow

In this section we concentrate on the interaction between the deuterated condensations N and S and a powerful outflow, revealed by CO observations obtained at the SMA simultaneously to the $\mathrm{N_2D^+}$ maps. In right panel of Fig. 1, we show the map of the integrated intensity in the ^{12}CO (2–1) line wings, derived from channel maps obtained combining SMA and NRAO data. The blue- and red-shifted emissions have been averaged in the velocity intervals (–46.4, –26) km s^{-1} and (–9.2, 6.4) km s^{-1}, respectively. The outflow axis is predominantly oriented in the WE direction, with redshifted gas in the east and blueshifted gas in the west. The lobes are clearly separated and have approximately a biconical shape. The outflow center is near the position of the continuum source C1, and the exciting source can be either C1-a and C1-b. The blueshifted gas shows a fainter secondary peak to the north of the map. From geometrical considerations, this northern blue-shifted emission might be driven by a source within N, rather than C1-a or C1-b. However, as we will further discuss later, the sources eventually embedded within N are probably in the pre–stellar phase, i.e. prior to the main accretion phase in which the outflow is expected to form, so that this solution seems to us very unlikely. The outflow length, from end-to-end, is approximately $35''$ (if we do not consider the secondary peaks of the blueshifted emission), corresponding to ~ 0.28 pc at a distance of 1.8 kpc. The semi-opening angle is between about 30 and 40^o, and the spatial separation of the lobes suggests that the inclination angle with respect to the line of sight is likely to be very close to the plane of the sky (see also Cabrit & Bertout 1986).

4 Nature of the deuterated condensations

To better understand the nature of the two condensations, a detailed analysis of the gas kinematics is certainly very helpful. For this reason, here we investigate in more detail the gas kinematics in N and S by using as diagnostics the peak velocity and widths of the $\mathrm{N_2H^+}$ (1–0) and $\mathrm{N_2D^+}$ (3–2) lines. In the two left panels of

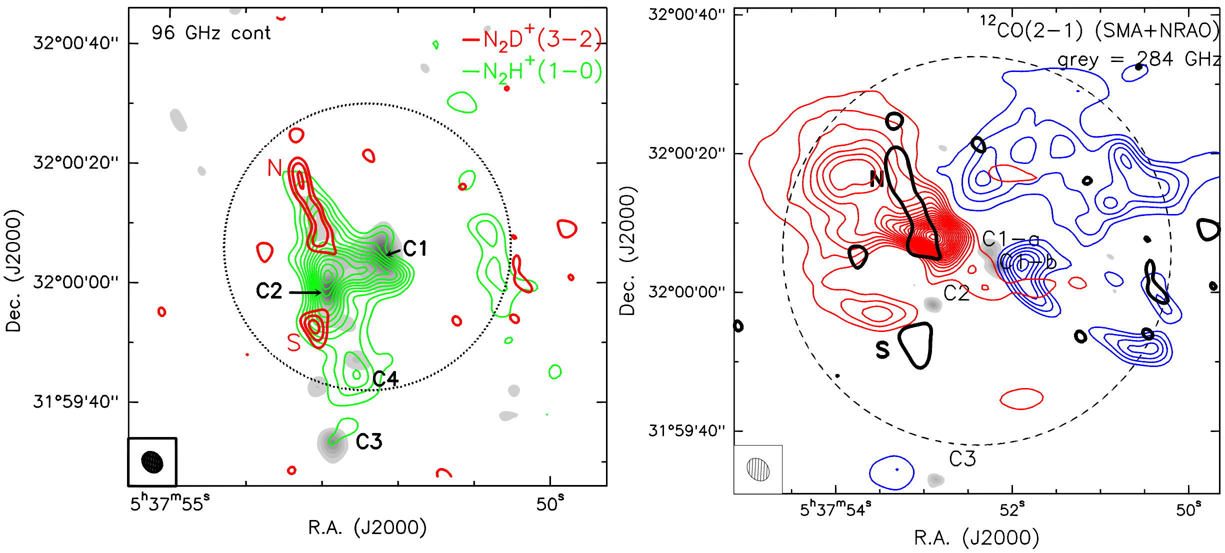

Fig. 1. Left panel: Interferometric maps obtained towards I05345 and published by Fontani et al. (2008). The green contours represent the intensity of the N_2H^+ (1–0) line, integrated in the velocity range corresponding to the main group of the hyperfine components of this line, observed with the PdBI. Levels are in steps of 3σ rms. The red contours represent the N_2D^+ (3–2) line emission integrated over the total velocity range with emission, obtained with the SMA. The two main condensations are indicated as N and S. The grey scale shows the 96 GHz continuum, in steps of 3σ. The grey scale image indicates 4 millimeter continuum peaks, called C1, C2, C3 and C4. Note that peaks C3 and C4 areoutside and at the edge, respectively, of the PdBI primary beam at 96 GHz (∼48″, dotted circle). The ellipse in the bottom left corner shows the synthesised beam of the N_2D^+ image, comparable to that of the PdBI data at 96 GHz.
Right panel: red- and blue-shifted integrated emission of the ^{12}CO (2-1) line (combined SMA + NRAO data), superimposed on the 96 GHz continuum map observed with the PdBI (grey-scale). The solid black contours represent the 3σ level of the N_2D^+ (3-2) line integrated emission, and indicate the location of the deuterated cores N and S. ¿From geometric considerations, the outflow driving source may be either C1-a or C1-b, or another source undetected in the continuum at the centre of the lobes. The dashed circle represents the SMA primary beam at the frequency of the ^{12}CO (2-1) line.

Fig. 2 we show the maps of $V_{\rm LSR}$ and ΔV, respectively, obtained for N from the N_2H^+ (1–0) line. The same plots derived from N_2D^+ (3–2) are shown in the two right panels. Both quantities are derived by fitting the hyperfine structure of the N_2H^+ (1-0) and the N_2D^+ (3-2) lines. For both tracers, the line widths are larger where the red lobe of the ^{12}CO outflow impinges core N (Fig. 1, right panel). At the same position, the gas emission is clearly red-shifted. The line broadening is ~ 3 times larger than the expected thermal broadening, indicating internal motions dominated by turbulence. For S, we find similar results. This indicates that both cores are characterised by a probable interaction with the red lobe of the ^{12}CO outflow, which can trigger turbulence in the cores themselves and can influence their evolution. Unlike the pre-stellar cores studied here, those studied in low-mass star forming regions (both isolated and clustered) have close-to-thermal line widths (see e.g. Foster et al. 2009).

In theoretical models of clustered star formation, turbulence (which in this case is generated by already formed protostars) can create density modifications across the cloud, originating several dense and cold 'seeds', which subsequently can accrete backgound gas that was initially not associated with the 'accretion domain' of the seed itself (see e.g. Bonnell et al. 2004, and McKee & Tan 2003). In this scenario, the two condensations can become more massive and form pre–stellar cores of higher mass. Alternatively, the interaction with the other cluster members, in particular with the powerful ^{12}CO outflow, could also cause the fragmentation of the condensations. For more details, see Fontani et al. (2009).

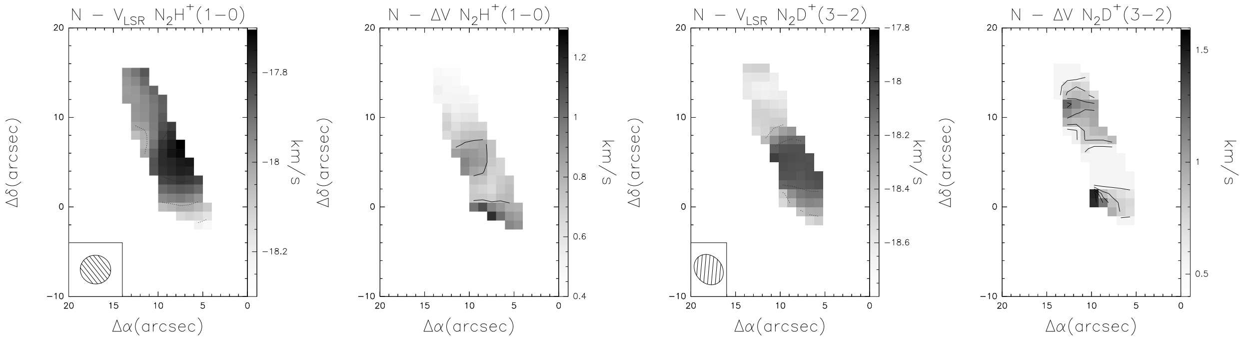

Fig. 2. Left panels: map of the peak velocity ($V_{\rm LSR}$) and line width (ΔV) derived from the N_2H^+ (1–0) line inside the 3σ level of the N_2D^+ (3–2) emission of core N. The vertical grey-scale on the right side of the two plots indicates the intensity, in km s^{-1}, of $V_{\rm LSR}$ and ΔV, respectively. In the bottom left corner, the synthesised beam of the channel maps are shown. Right panels: same as left panel for the N_2D^+ (3–2) line.

5 Summary

We have presented a millimeter high-angular resolution study of the intermediate-/high-mass star forming region IRAS 05345+3157. The main findings of this work are the following: (i) detection of two molecular condensations (called N and S) showing high values of deuterium fractionation (~ 0.1), derived from the column density ratio $N(N_2D^+)/N(N_2H^+)$; (ii) detection of three millimeter warm cores, among which one likely harbors a massive (proto-)stellar object driving a powerful CO outflow; (iii) the line widths in the pre-stellar cores indicate internal motions dominated by turbulence: this latter is likely triggered by the CO outflow, and this indicates that the kinematics of the pre–stellar core candidates in I05345 is affected by the environment; (iv) on the other hand, the deuterium fractionation is comparable to the values measured in isolated starless cores, implying that some aspects of the chemistry do not appear to be affected by the environment.

Can the results obtained for IRAS 05345+3157 be considered typical in intermediate-/high-mass protoclusters? Namely: how do the presence of intermediate-/high-mass protostars generally affect the physical/chemical properties of cores on the verge of forming stars? To answer these questions, more studies of intermediate-/high-mass protoclusters like the one presented here need to be performed.

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