Detection of a hot core in the intermediate-mass Class 0 protostar NGC 7129–FIRS 2

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Abstract. We report high angular resolution (HPBW \(\sim 0.6'' \times 0.5''\) at 1.3mm) observations of the Class 0 intermediate-mass (IM) protostar NGC 7129–FIRS 2 using the Plateau de Bure Interferometer. Our observations show the existence of an intense unresolved source in the continuum at 1.3mm and 3mm at the position of the Class 0 object. In addition, compact CH\(_3\)CN emission is detected at this position. The high rotational temperature derived from the CH\(_3\)CN lines (\(T_{\text{rot}} \approx 50\) K) as well as the enhanced CH\(_3\)CN fractional abundance (\(X(\text{CH}_3\text{CN}) \sim 7.0 \times 10^{-9}\)) show the existence of a hot core in this IM young stellar object. This is, up to our knowledge, the first IM hot core detected so far. Interferometric maps of the region in the CH\(_3\)OH \(5_{\text{kk}} \rightarrow 4_{\text{kk}}\), and D\(_2\)CO \(4_{\text{kk}} \rightarrow 3_{\text{kk}}\) lines are also presented in this paper. The methanol emission presents two condensations, one associated with the hot core which is very intense in the high upper state energy lines (\(E_u > 100\) K) and other associated with the bipolar outflow which dominates the emission in the low excitation lines. Enhanced CH\(_3\)OH abundances (\(X(\text{CH}_3\text{OH}) \sim 3 \times 10^{-8}\) – a few \(10^{-7}\)) are measured in both components. While intense D\(_2\)CO \(4_{\text{kk}} \rightarrow 3_{\text{kk}}\) emission is detected towards the hot core, the \(N_2D^+ 3\rightarrow 2\) line has not been detected in our interferometric observations. The different behaviors of D\(_2\)CO and \(N_2D^+\) emissions suggest different formation mechanisms for the two species and different deuteration processes for H\(_2\)CO and N\(_2\)H\(^+\) (surface and gas-phase chemistry, respectively). Finally, the spectrum of the large bandwidth correlator show a forest of lines at the hot core position reavealing that this object is extraordinarily rich in complex molecules. To have a deeper insight into the chemistry of complex molecules, we have compared the fractional abundances of the complex O- and N-bearing species in FIRS 2 with those in hot corinos and massive hot cores. Within the large uncertainty involved in fractional abundance estimates towards hot cores, we do not detect any variation of the relative abundances of O- and N-bearing molecules ([CH\(_3\)CN]/[CH\(_3\)OH]) with the hot core luminosity. However, the O-bearing species H\(_2\)CO and HCOOH seem to be more abundant in low and intermediate mass stars than in massive star forming regions. We propose that this could be the consequence of a different grain mantle composition in low and massive star forming regions.

Key words. Stars: formation - individual: NGC7129 – FIRS 2 – ISM: abundances – clouds – individual: NGC 7129

1. Introduction

Hot cores are compact objects near or around protostars characterized by warm temperatures (\(T_k > 100\) K) and high densities (\(n > 10^6\) cm\(^{-3}\)). These regions are also characterized by a very rich chemistry in complex molecules (CH\(_3\)OH, CH\(_3\)CN, CH\(_3\)OCHO, CH\(_3\)OCH\(_3\), C\(_2\)H\(_5\)CN ...). Hot cores are thought to be associated with high-mass protostars (M \(\geq 8\) M\(_\odot\)) and to represent an important phase in their evolution toward ultracompact and compact HII regions. Recently, regions characterized by warm temperatures and high densities have also been detected in two low-mass protostars IRAS 16293–2422 (Ceccarelli et al. 2000, Cazaux et al. 2003) and NGC 1333 IRAS 4A (Bottinelli et al. 2004). Complex molecules typical of hot cores (e.g. HCOOH, CH\(_3\)OCHO, CH\(_3\)CN, C\(_2\)H\(_5\)CN) have also been detected in these objects. However, the amount of warm material involved, as well as the chemistry, are different in the two classes of objects. For this reason, the warm regions in the inner envelope of low mass protostars are usually referred to as “hot corinos”.

The formation of complex molecules in hot cores and corinos is poorly understood. In the standard scheme, neutral molecules (CO, CS...) are frozen onto dust grains during the cold pre-stellar phase. If the dust temperature is sufficiently low during this phase, surface hydro-
genation of CO leads to the formation of solid $\text{H}_2\text{CO}$ and $\text{CH}_3\text{OH}$ (e.g. Brown et al. 1988; Charnley et al. 1992; Caselli et al. 1993). Once the star starts heating the grain surfaces, these molecules (called “parent” species) evaporate, enlarging their abundances in the gas phase. Because of the high temperature and density of hot cores and corinos, these molecules undergo fast neutral-neutral and ion-neutral reactions producing at early stages ($\sim 10^4$ yr) a second generation of complex O–bearing species called “daughter” molecules, such as methyl formate, $\text{CH}_3\text{OCHO}$. However, Horn et al. (2004) recently found that the gas–phase reaction sequence between protonated methanol and formaldehyde, crucial for the gas–phase formation of methyl formate, does not proceed in their laboratory experiments. This suggests that surface chemistry is probably playing a key role also in the formation of these species.

Regarding complex N–bearing species (e.g. $\text{CH}_3\text{CN}$, $\text{CH}_3\text{CH}_2\text{CN}$), they are observed in hot cores and corinos. In the chemical scheme of Rodgers & Charnley (2001), complex N–bearing species are thought to be formed in the gas phase about $10^3$ yr after the grain mantle evaporation, only if the gas temperature is sufficiently large ($\geq 300 \text{ K}$). On the other hand, Caselli et al. (1993) found that large abundances of ethyl cyanide ($X(\text{CH}_3\text{CH}_2\text{CN}) \sim 10^{-7}$, w.r.t. $\text{H}_2$) can be obtained on grain surfaces, if the dust temperature during the protostellar accreting is around 40 K. In the case of lower temperatures (10–20 K), the CH$_3$CH$_2$CN can still be formed on the surface, but with reduced abundances ($\sim 10^{-9}$). Thus, Caselli et al. (1993) suggests that saturated (or H–rich) complex N–bearing species (such as ethyl cyanide) are “parent” species and that they should be observable as soon as the grain mantles are released in the gas phase upon stellar heating of the dust. Later on, “H–poor” N–bearing molecules (e.g. vinyl cyanide, $\text{CH}_3\text{CHCN}$) can be formed in the gas phase from the destruction of $\text{CH}_3\text{CH}_2\text{CN}$.

Indeed, if complex species in general are not formed on grain surfaces, there are important problems for understanding the chemical composition of hot corinos: the timescale necessary to convert “parent” molecules into complex “daughter” molecules is much longer than the transit time of the gas in hot corinos (a few hundred years). Therefore, it seems that the chemistry of complex molecules must begin on grain surfaces (at least in hot corinos). However, chemists are still far from a unique interpretation of the hot core (and corino) chemistry. More observational work is needed. In particular, given the large sensitivity of surface and gas-phase chemistry on dust temperature and gas density, it will be extremely important to measure possible variations of complex molecule abundances with the physical characteristics of hot cores, which of course depend on the mass and luminosity of the associated protostar.

In this paper, we present an interferometric study of the hot core associated with the Class 0 IM protostar NGC 7129–FIRS 2. With a luminosity $\sim 500 \text{L}_\odot$ and a mass $\sim 5 \text{M}_\odot$, FIRS 2 is very likely the youngest IM object known at present (Fuente et al. 1998,2002). An energetic bipolar molecular outflow with a quadrupolar morphology is associated with it (Fuente et al. 2001, hereafter Paper I). Interferometric observations in the continuum at 1mm and the $^{12}\text{CO} \rightarrow 1$ line shows that the quadrupolar morphology of the outflow is due to the superposition of two bipolar molecular outflows FIRS 2–out 1 and FIRS 2–out 2. FIRS 2–out 1 is associated with the Class 0 protostar detected as an intense millimeter clump in the continuum image (MM1 in the nomenclature of Paper I) while FIRS 2–out 2 is associated with a more evolved infrared star (FIRS 2 - IR) undetected at millimeter wavelengths.

A quite complete chemical study of this Class 0 IM source has been carried out by Fuente et al. (2005) (hereafter Paper II) using the 30m IRAM telescope. They detected warm CH$_3$CN ($T_k > 63 \text{ K}$) towards the central position which constitutes a strong evidence for the existence of a hot core in this Class 0 IM object. However, the limited angular resolution of these observations make it very difficult to discern between the hot core emission and those of the outflow and/or the warm envelope. The new results presented in this paper confirm the existence of the hot core associated with FIRS 2 and give a first glance of the chemistry of this object. Up to our knowledge, FIRS 2 is the first IM hot core detected thus far. The intermediate kinetic temperature and mass of the FIRS 2 hot core are expected to produce a differentiated chemistry and to furnish a link between the low mass and high mass regimes.

### 2. Observations

The observations presented in this paper correspond to two different observational projects carried out with the Plateau de Bure interferometer (PdBI). The main set of data was observed on March 08, 2003. The observations were carried out with excellent weather conditions and counts 5 hr of integration time (on-source) with 6-element array in the A configuration which provides the highest angular resolution. The spectral correlator setup was adjusted to observe the CH$_3$CN $5\rightarrow4$ line with two contiguous 20 MHz units, $N_2^{13}D^+ 3\rightarrow2$ and $D_2\text{CO} 4_{33}\rightarrow3_{03}$ with two separated 20 MHz units and the remaining units were configured for maximum continuum sensitivity (see Table 1). These observations show on average system temperatures of 140 K (3mm) and 250 K (1mm), a mean atmospheric water vapour content of 1-2mm, and were made under seeing conditions of 0.3 arcsec. The RF calibrator was 0420-0414, the phase calibrators ordered by right ascension were 1928+738, 2146+608 and 2309+454, and the flux calibrator was MWC 349. The precision in the flux densities is better than 20% at 1mm and better than 10% at 3mm. Images have been created in natural weighting.

In addition, we present the CH$_3$OH $J=5_k\rightarrow4_k$ image observed within a previous project in November and December, 1998. The data corresponding to this project were partially published in Paper I. Details about the observations are given in Table 1 and Paper I.
Fig. 1. Interferometric maps of the Class 0 protostar NGC 7129–FIRS 2 in the continuum at 1mm and 3mm, and the following molecular lines: CH$_3$CN $5\rightarrow 4$, D$_2$CO $4_04\rightarrow3_03$, CH$_3$OH $5_{1,4}\rightarrow4_{1,4}$. The panel marked with “CH$_3$OH (high)” show the integrated intensity map of the lines $5_{3,1}\rightarrow4_{3,1}$, $5_{3,2}\rightarrow4_{3,2}$,$5_{2,2}\rightarrow4_{2,2}$ and $5_{3,3}\rightarrow4_{3,3}$. Contour levels are: a) 10 to 60 by 5 mJy/beam; b) 20 to 160 by 20 mJy/beam ;c) 0.6 to 2.7 by 0.3 Jy/beam km s$^{-1}$; d) 0.3 to 0.6 by 0.1 Jy/beam km s$^{-1}$; e) 1 to 4 by 0.5 Jy/beam km s$^{-1}$; f) 1 to 7.5 by 0.5 Jy/beam km s$^{-1}$.

3. Continuum data

The continuum images at 3mm and 1.3mm are shown in Fig. 1. The angular resolution of these images is 3 times better than that of the images previously published in Paper I. Both images show an intense and compact source located at RA(2000)=21:43:01.684, Dec(2000)=66:03:23.619, the position named MM1 in Paper I. There is no indication of the presence of the second and more extended source MM2 which is very likely resolved out in the high angular resolution image.

We have modeled the visibilities to have a deeper insight into the source structure. In Fig. 2 we show the 92 GHz and 230 GHz visibilities vs projected baselines in units of wavelength. In the bottom panel we show together the 92 GHz and the 230 GHz visibilities. The 92 GHz visibilities have been scaled by a factor of 10.5 to match the 230 GHz ones. The perfect match between the 92 GHz and 230 GHz visibilities suggests that both emissions arise in the same region as expected in the case of dust thermal emission.

The spectral index is $\alpha$=2.56. The fact that the 3mm and 1.3mm emission arises in the same region and the spectral index larger than 2 is consistent with dust thermal emission. We have used the high-angular resolution 1.3mm image to model the continuum emission. Several models (elliptical Gaussian, disk, $F_\nu=\nu^{-2}$, $F_\nu=\nu^{-3}$, and an elliptical Gaussian+point source) have been used to fit the visibilities. The best fit has been obtained with the elliptical Gaussian+point source model. The HPFW of the elliptical Gaussian is $\sim$650×900 AU and the flux is 0.43 Jy. The point source has a flux of 0.13 Jy. The total flux of the compact 1.3 mm component is $\sim$0.56 Jy. This implies a total (dust +gas) mass of 2 M$_\odot$ assuming a standard dust temperature of 100 K and a dust emissivity $k_\nu=0.015(1300/\lambda (\mu m))$ cm$^2$ g$^{-1}$. Taking into account the uncertainty in the value of the dust temperature which could range between 50 K and 300 K this mass is accurate within a factor of 4.
We speculate about the possibility that the point source is an accretion disk. In this case, the mass of the disk would be ~0.3–0.8 M☉. This value is 30 times larger than that found by Fuente et al. (2003) in the Herbig Be star R Mon, but it is similar to that found by Rodriguez et al. (2005) in the Class 0 low-mass protostar IRAS 16293–2422B. Thus, if our assumption is confirmed, the difference in the disk occurrence and masses between IM and low mass stars would be related to a short timescale for the disk dissipation instead of to differences in the first stages of the star formation. This interpretation is in line with Fuente et al. (2003).

4. Molecular line images

4.1. CH₃CN

The interferometric image of the Class 0 protostar NGC 7129–FIRS 2 in the CH₃CN 5→4 line shows a compact source at the same position and with the same size as the 1mm continuum source (Fig. 1). The total agreement in position and size between the continuum and the CH₃CN emissions points out to the existence of a well-differentiated compact component in the protostellar envelope.

Because of the rotational structure of CH₃CN, one can observe several lines at different energies very close in frequency. In Fig. 3 we show the interferometric spectrum of the CH₃CN 5→4 line compared to the single-dish spectrum reported in Paper II. The interferometer has recovered 100% of the flux of the highest upper state energy component (E_u=124 K) (see Fig. 3). However, only 37% of the flux of the lowest energy component (E_u=13 K) has been recovered (see Fig. 3). This suggests that while the emission of the low energy CH₃CN lines mainly arises in the cooler and more extended envelope, the emission of the high energy lines entirely arises in the hot core. In addition to the CH₃CN K-ladder we have also detected the CH₃¹⁸CN 5_0→4_0 line which allows us to have an estimate of the opacity of the CH₃CN line.

The CH₃CN column density has been estimated using the rotational diagram technique. The low energy lines are expected to be optically thick in the hot core. This is confirmed by our interferometric observations. In particular, we measure I(CH₃CN 5_0→4_0)/I(CH₃¹⁸CN 5_0→4_0)~2.4 which implies an opacity ~25 for the main isotope line assuming ¹²C/¹³C=70. We have corrected for the opacity effect and derived T_rot~54 K and a beam averaged column density N(CH₃CN)~1.1×10¹⁶ cm⁻² for the hot core component using the 5_0→4_0 and 5_5→4_5 lines. The derived rotation temperature is in agreement, within the uncertainties, with that derived from single dish data (Fuente et al. 2005). Since the low energy lines are optically thick in the hot core, we think that this agreement is fortuitous and due to the addition of two uncertainties which shift the estimated column density in opposite directions, the contribution of extended emission in the single-dish beam and the opacity effect. From our interferometric observations, we obtain X(CH₃CN)~7.0×10⁻⁹ in the 2 M☉ hot core in FIRS 2 assuming a source size of 0.72″×0.52″ (see Table 5). This fractional abundance is similar to that measured in massive hot cores and slightly larger than those derived in hot coronas.

For comparison, we have estimated the CH₃CN abundance in the cooler and extended envelope. For this aim, we have subtracted the emission of the compact component from the single-dish spectrum and analyze the result using a rotational diagram. The opacity effect are expected to be less important in the low density envelope than in the hot core. We derive T_rot=12 K and a beam averaged column density of 5.8×10¹¹ cm⁻² (HPBW=25″). Using the H₂ column density derived from single-dish continuum observations by Fuente et al. (2001), we estimate a CH₃CN fractional abundance of ~3×10⁻¹¹ in the extended component, i.e. about 3 orders of magnitude lower than in the compact component.

Summarizing, our CH₃CN interferometric data show the existence of a compact (900×650 AU) source characterized by a high kinetic gas temperature (>50 K) and enhanced CH₃CN abundance X(CH₃CN)~7.0×10⁻⁹ in the Class 0 IM protostar FIRS 2. This constitutes a definite proof of the existence of a hot core in this IM protostar which, up to our knowledge, is the first IM hot core detected so far.

4.2. CH₃OH

We have observed the CH₃OH J_k,k′=5_k,k′→4_k,k′ lines towards FIRS 2 using the 2.5 MHz wide band correlator which allows us to observe most of the CH₃OH J_k,k′=5_k,k′→4_k,k′ components simultaneously. In Fig. 1 we show the total integrated intensity map of the CH₃OH 5_1→4_1 line which is that observed with the lowest upper stage energy (E_u=35 K). The emission of this component presents two maxima, the first one is spatially coincident with the hot core while the second is located at the position (−2″,−1.5″). This position lies on the axis of the outflow FIRS 2-out 1. In Fig 1 we also show the integrated intensity map of the 5_3→4_3, 5_5→4_5, 5_2→4_2 and 5_3→4_3 lines [panel indicated as CH₃OH (high) in Fig. 1]. These lines are partially overlapped in our spectrum and all of them have upper state energies >50 K. In this case, the emission is mainly arising in the hot core.
Table 2. Gaussian fits to the line and continuum emission

|                | Position | Integrated intensity<sup>b</sup> (Jy) | Size<sup>c</sup> (arcseconds) |
|----------------|----------|--------------------------------------|-------------------------------|
| Continuum 3mm  | 21:43:01.7 66:03:23.6 | 0.0565(0.0005) | 0.66(0.02)×0.54(0.02) |
| Continuum 1mm  | 21:43:01.7 66:03:23.7 | 0.4278(0.0047) | 0.72(0.01)×0.52(0.01) |
| CH<sub>3</sub>CN <sup>5</sup><sub>k</sub>→<sup>4</sup><sub>k</sub> | 21:43:01.7 66:03:23.6 | 0.0734(0.0060) | 0.63(0.22)×0.46(0.19) |
| D<sub>2</sub>CO <sup>4</sup><sub>04</sub>→<sup>3</sup><sub>0</sub>,<sup>3</sup><sub>2</sub> | 21:43:01.7 66:03:23.6 | 0.76(0.6) | 0.58(0.24)×0.40(0.24) |

<sup>a</sup> The absolute positional precision is ≤ 0.3".
<sup>b</sup> Systematic calibration errors are not included in the error budget associated to the integrated intensity.
<sup>c</sup> Deconvolved by the synthesized interferometric beam.

Fig. 3. Comparison between the single-dish (thin histograms or red) and interferometric (thick histograms or black) spectra towards the hot core position. The interferometric spectrum has been scaled for an easier comparison. Note that we have recovered all the flux for the CH<sub>3</sub>CN line with the highest upper state energy.

With a very weak contribution of the second maximum. Thus, the morphology of the CH<sub>3</sub>OH emission shows the existence of two components, a compact one which is spatially coincident with the hot core (hereafter hot core component) and an extended one which is very likely associated with the outflow FIRS 2–out 1 (hereafter outflow component).

In Fig. 3 we compare the interferometric spectra for the hot core and outflow components with the single-dish spectrum at the central position. The two components present differences in their kinematics and excitation conditions. The emission of the CH<sub>3</sub>OH lines towards the hot core is centered at a velocity $-10\pm1$ km s<sup>-1</sup>, while the emission of the outflow component is centered at
−6±1 km s⁻¹. The ¹²CO 2→1 and SiO 2→1 maps of the outflow FIRS 2–out 1 reported in Paper II show that this velocity, -6±1 km s⁻¹, is characteristic of the high velocity bullet R1, reinforcing our interpretation of this emission as associated with the bipolar outflow.

Different excitation conditions characterize the hot core and outflow components. This is clearly seen when one compares the relative intensities of the high and low energy lines in the methanol spectra towards the two studied positions. All the CH₃OH lines have similar intensities towards the hot core. However, high energy lines are a factor of ~5 weaker than the low energy ones towards the outflow position (see Fig. 3). We have derived the rotation temperature and the beam averaged CH₃OH column density for the hot core using the rotational diagram technique (see Fig. 4). We obtain Tₚ=809 K and N(CH₃OH)=1.5 ¹⁰¹⁷ cm⁻². This temperature is quite high compared with that obtained from the CH₃CN lines. Similarly to the case of CH₃CN, the low energy lines are very likely optically thick and the derived rotation temperature is an upper limit to the actual one. To have an estimate of the uncertainty due to the unknown rotation temperature in the CH₃OH column density, we have calculated the CH₃OH column density from the flux of the 5_4,3→4_3 line (E_u=104 K) assuming Tₚ=50 K. We obtain N(CH₃OH)=4.9 ¹⁰¹⁶ cm⁻². Thus, we consider that our beam averaged column density estimate is accurate within a factor of 3. Assuming Tₚ=50 K, the derived CH₃OH fractional abundance is 3.0 ¹⁰⁻⁸ in the hot core. This abundance is similar to that measured in the prototypical massive hot core OMC1.

For comparison, we have estimated the rotation temperature and methanol column density for the outflow condensation (see Fig. 4). We have obtained Tₚ=19 K and N(CH₃OH)=2.9 ¹⁰¹⁵ cm⁻². The low rotational temperature of this component supports our interpretation of being associated with the outflow (postshocked material) instead of with the hot core. We have not detected a millimeter continuum counterpart for this condensation in our interferometric 1mm map. In principle, this could be a sensitivity problem. From our interferometric image and assuming T_dust=100 K we derive a 3×σ upper limit of ~0.01 M⊙ for the mass of the condensation associated with the methanol clump. This would imply X(CH₃OH)>3.8 ¹⁰⁻⁷ in this clump. We can alternatively think that this clump is not the result of a hydrogen density enhancement at this position. For example, it could be produced by a local enhancement of the CH₃OH abundance because of the shocks associated with the bipolar outflow. To estimate the methanol abundance in this case, we calculate the H₂ column density from the single-dish ¹³CO observations reported in Paper II. At the velocities of the bullet R1, the ¹³CO column density averaged in the 30m beam is ~3 ¹⁰¹⁵ cm⁻². If we assume a uniform distribution of the molecular gas in the beam, we obtain that the CH₃OH abundance is similar to that of ¹³CO for which we assume a standard value of ~10⁻⁶. Obviously, this is an upper limit to the actual abundance since we expect some clumpiness. Thus, the CH₃OH abundance in the outflow condensation could be larger than in the hot core and reach values close to 10⁻⁶. This large value of the methanol abundance is consistent with those found in the molecular bullets associated with low-mass bipolar outflows (see e.g. Bachiller & Pérez-Gutierrez 1997).

In addition to the CH₃OH lines, the spectrum towards the hot core show several lines that are weaker towards the outflow condensation. We have identified these lines as belonging to the complex molecules CH₃OCH₃ and C₂H₂CN. We have also a tentative detection of the sulphinic species ³⁴SO₂. The detection of complex saturated molecules corroborates the existence of a hot core in this source and reveals the rich and complex chemistry associated with it.

### 4.3. D₂CO

The interferometric map of D₂CO shows a compact source located at the position of the hot core (see Fig. 1). The size of the D₂CO emitting region is similar to that of CH₃CN. However, the linewidth of the D₂CO line is ~11 km s⁻¹, larger than those of the CH₃CN and CH₃OH lines which are typically ~6–8 km s⁻¹. Assuming the standard inside-outside collapse model, the largest linewidth of the D₂CO line is consistent with the emission arising in an inner
region of the protostellar envelope. In a simple calculation, an accretion velocity of \( \sim 5 \) km s\(^{-1} \) corresponds to a radius of \( \sim 130 \) AU assuming a dynamical age of \( \sim 10^5 \) yr and \( \dot{M} = 5 \times 10^{-5} \) M\(_{\odot} \) yr\(^{-1} \). A similar radius was found by Maret et al. (2004) for the region where the H\(_2\)CO abundance is heavily enhanced because of evaporation of the grain mantles in low-mass protostars. This suggests a similar origin for the D\(_2\)CO molecules in the hot core.

Our previous single dish spectrum was too noisy to detect this wide emission (Paper II). Recently, we have taken a good signal-to-noise ratio spectrum to compare with the interferometric observations (see Fig. 3). The single-dish spectrum shows two components, a narrow one at the velocity of the ambient cloud (already detected in Paper II) which is completely missed in our interferometric observations and a wide one with a linewidth similar to that of the PdB spectrum. Even in this wide component the interferometer recovers only the 50% of the flux, suggesting that part of them arises in a more extended area.

A narrow and wide components with linewidths similar to those of D\(_2\)CO are also detected in the single dish spectra of the H\(_2\)CO lines (Paper II). In Paper II, we have separately mapped the narrow and wide components. These maps revealed that both components are associated with the outflow. While the wide component arises in the jet, the emission of the narrow component was more intense in the interface between the jet and the molecular cloud suggesting that it is tracing the molecular gas that is being swept up by the jet. We propose that the missed flux in our interferometric D\(_2\)CO image is probably arising in a more extended component associated with the bipolar outflow similarly to the case of H\(_2\)CO.

Our interferometric image shows that, in addition to the extended component, there is an intense and compact D\(_2\)CO component associated with the hot core. We have estimated the D\(_2\)CO abundance in this component assuming \( T_{\text{rot}} = 50 \) K and obtained N(D\(_2\)CO)=3.5 \( \times 10^{14} \) cm\(^{-2} \) and X(D\(_2\)CO)\( \sim 1.4 \times 10^{-10} \). This fractional abundance is a factor of \( \sim 2 \) higher than that derived in Paper II for the whole envelope.

4.4. \( N_2D^+ \)

We have not detected the \( N_2D^+ \) 3\( \rightarrow \)2 line in our interferometric image. The rms of the image is 50 mJy/beam which is about \( \sim 2\% \) of the flux measured with the 30m telescope (Paper II). Thus, almost the 100% of the \( N_2D^+ \) emission has been missed in the interferometric observations. This implies that the emission of \( N_2D^+ \) presents a quite uniform distribution across the envelope and suggests that it mainly arises in the cooler extended envelope. This is also in agreement with our interpretation in Paper II based on kinematical arguments. The linewidth of the \( N_2D^+ \) 3\( \rightarrow \)2 line, \( \sim 1 \) km s\(^{-1} \), is at least a factor of 2–3 smaller than those of the lines arising in the warm component, and similar to those of the molecules which are thought to be good tracers of the cold envelope such as H\(_{13}CO^+ \) and N\(_2H^+ \).

5. Chemical complexity of the hot core in NGC 7129–FIRS 2

In Fig. 5 we show the observed wide band spectra in the upper side band (USB) and lower side band (LSB) of the 1mm receiver. We have detected a real forest of lines in the 1mm band. The identification of these lines is not an easy task. Since we have moderate spectral resolution (2.5

| Freq. | Molecule | Transition | Int* (K) | E\(_n\) (K) |
|-------|----------|------------|---------|------------|
| 228123.37 | CH\(_3\)OH-E | 4\( \rightarrow \)3 | -0.0003 | -3.093 |
| 228134.42 | c-C\(_3\)H\(_2\) | 2\( \rightarrow \)1 | -3.9965 | 288 |
| 228147.97 | CH\(_3\)_CHO-E | 18\( \rightarrow \)17 | -5.9576 | 114 |
| 228165.01 | CH\(_3\)_CHO-A | 18\( \rightarrow \)17 | -5.9537 | 114 |
| 228207.03 | CH\(_3\)_CHO-E | 4\( \rightarrow \)3 | -5.1294 | 220 |
| 228207.42 | CH\(_3\)_CHO-E | 1\( \rightarrow \)0 | -3.0004 | 220 |
| 228276.26 | Si\(_{18}\)O | 9\( \rightarrow \)8 | -3.9573 | 82 |
| 228286.69 | C\(_2\)H\(_2\)OH | 1\( \rightarrow \)0 | -3.0004 | 107 |
| 228285.94 | CH\(_3\)OCHO-E | 2\( \rightarrow \)1 | -4.0004 | 220 |
| 228322 | Unidentified | | | |
| 228245 | Unidentified | | | |
| 228278.96 | HCCCHO | 2\( \rightarrow \)1 | -2.6001 | 135 |
| 228310.56 | CH\(_2\)CHO | 1\( \rightarrow \)0 | -4.0004 | 36 |
| 228358.20 | CH\(_3\)_CHO-E | 2\( \rightarrow \)1 | -5.1294 | 220 |
| 228415.69 | c-C\(_3\)HD | 1\( \rightarrow \)0 | -4.5197 | 169 |
| 228434 | Unidentified | | | |
| 228467 | Unidentified | | | |
| 228483.13 | C\(_2\)H\(_2\)CN | 1\( \rightarrow \)0 | -5.4674 | 158 |
| 228494.88 | CH\(_3\)_CHO-E | 1\( \rightarrow \)0 | -6.2908 | 6 |
| 228522.71 | C\(_2\)H\(_2\)OH | 1\( \rightarrow \)0 | -4.3308 | 84 |
| 228544.17 | HCOOH | 1\( \rightarrow \)0 | -3.2324 | 62 |

* Base 10 logarithm of the integrated intensity in units of km s\(^{-1}\).MHz as appears tabulated in the JPL molecular line catalogue (Pickett et al. 1998).
Fig. 5. Spectra of the upper side band (USB) and lower side band (LSB) of the 1mm receiver obtained in our PdBI observations with our best guess for line identifications. For clarity, we have divided the molecular species in three groups. The first group is formed by the more reliable identifications and $^{18}$O. Beginning from the top, in the first line of panels we compare the observed spectra with the synthesized ones taking into account only this first group. In the second line, we add CH$_3$OCHO-A /E and show the obtained synthesized spectra. The inclusion of these compounds improve the agreement with the observational data. However, the large CH$_3$OCHO-A /E abundance we derive from these observations, raise some questions about this identification. In the third line of panels, we show the synthesized spectra after adding some other exotic compounds. In the last line, it is shown the residual spectra after subtracting our fit. Note that the agreement between the synthesized and observed one is very good in the USB but some lines remain unidentified in the LSB.
Table 5. Fractional Abundances in the hot core of NGC 7129–FIRS 2 and comparison with other hot cores

| Molecule          | NGC 7129–FIRS 2    | NGC 1333 IRAS4 A | IRAS 16293 | OMC 1 | G327.3-0.6 |
|-------------------|---------------------|------------------|----------|-------|-----------|
|                   | $T_{rot}$ (K)       | $N^a$ (cm$^{-2}$)| $X^a$    | $X^b$ | $X^c$     |
| H$_2$             | 7.9×10$^{14}$       | 1                | 1        | 1     | 1         |
| CH$_3$CN          | 54  5.5×10$^{16}$    | 7.0×10$^{-9}$    | 1.6×10$^{-9}$ | 1.0×10$^{-8}$ | 4×10$^{-9}$ | 7×10$^{-7}$ |
| CH$_3$OH          | 50$^a$  2.4×10$^{17}$ | 3.0×10$^{-8}$    | <7×10$^{-9}$ | 3.0×10$^{-7}$ | 1×10$^{-7}$ | 2×10$^{-5}$ |
| H$_2$CO           | 50$^a$  2.5×10$^{15}$ | 3.1×10$^{-10}$   | 2.0×10$^{-8}$ | 6.0×10$^{-8}$ | 7.0×10$^{-9}$ |
| D$_2$CO           | 50$^a$  3.5×10$^{14}$ | 4.4×10$^{-11}$   | 3.0×10$^{-9}$ |
| 13CS              | 50$^a$  3.4×10$^{14}$ | 4.3×10$^{-11}$   |         |
| OCS               | 50$^a$  2.4×10$^{15}$ | 3.0×10$^{-9}$    | 1.0×10$^{-6}$ | 7×10$^{-8}$ | 2×10$^{-9}$ |
| HCOOH             | 48  3.5×10$^{15}$    | 4.4×10$^{-10}$   | 4.6×10$^{-9}$ | 6.2×10$^{-8}$ | 8×10$^{-10}$ | 3×10$^{-10}$ |
| C$_2$H$_5$OH      | 75  2.0×10$^{16}$    | 2.5×10$^{-9}$    |         |
| C$_2$H$_5$CN      | 50$^a$  3.2×10$^{15}$ | 4.0×10$^{-10}$   | <1.2×10$^{-9}$ | 1.2×10$^{-8}$ | 3.0×10$^{-9}$ | 4×10$^{-7}$ |
| c-C$_3$D          | 50$^a$  2.5×10$^{15}$ | 3.1×10$^{-10}$   |         |
| c-C$_3$HD         | 50  1.8×10$^{17}$    | 2.3×10$^{-8}$    |         |

Uncertain identifications

| S$^{18}$O        | 50$^a$  2.6×10$^{16}$ | 3.3×10$^{-9}$    | 2.6×10$^{-9}$ | 3×10$^{-10}$ | >6×10$^{-13}$ |
| CH$_3$OCHO-E     | 36  4.0×10$^{18}$     | 5.0×10$^{-7}$    | 3.6×10$^{-8}$ | 2.3×10$^{-7}$ | 1×10$^{-8}$ | 2×10$^{-6}$ |
| CH$_3$OCHO-A     | 36$^a$  3.3×10$^{18}$ | 4.1×10$^{-7}$    | 3.4×10$^{-8}$ | 1.7×10$^{-7}$ | 1×10$^{-8}$ | 2×10$^{-6}$ |
| CH$_3$CHO-A      | 50$^a$  2.3×10$^{15}$ | 2.9×10$^{-10}$   | 1.9×10$^{-8}$ |
| HCCCHO           | 50$^a$  2.0×10$^{15}$ | 2.5×10$^{-10}$   |         |
| C$_2$H$_7$CHO    | 50$^a$  5.0×10$^{16}$ | 6.3×10$^{-9}$    |         |
| CH$_3$OH         | 50$^a$  1.9×10$^{15}$ | 2.4×10$^{-10}$   | <2.8×10$^{-8}$ | 2.4×10$^{-7}$ | 8×10$^{-9}$ | 3×10$^{-8}$ |
| $^{34}$SO$_2$    | 50$^a$  3.8×10$^{13}$ | 4.8×10$^{-12}$   | 2.4×10$^{-8}$ | 2×10$^{-10}$ | 4×10$^{-9}$ |
| NO$_2$           | 50$^a$  1.0×10$^{17}$ | 1.2×10$^{-8}$    |         |

* Values derived for the NGC 7129–FIRS 2 hot core assuming a size of $\sim$0.72″×0.52″. To derive the H$_2$ column density we have considered that the hot core mass (2 M$_\odot$) is uniformly distributed in an area $\sim$ab with $a=0.004$ pc (0.72″) and $b=0.003$ pc (0.52″).

$^a$ Assumed temperature.

$^b$ Values from Bottinelli et al. (2004) for a 0.0016 pc (0.5″) source.

$^c$ Values from Cazaux et al. (2003) and Wakelam et al. (2004) for a 0.0016 pc (2″) source.

$^d$ Values from Sutton et al. (1995) for a 0.004 pc (14″) source.

$^e$ Values from Gibb et al. (2000) for a 0.03 pc (2″) source.

$^f$ From Schoier et al. (2002).

$^g$ From Ceccarelli et al. (2001).

$^h$ From Gibb et al. (2000) for a 0.32 pc (20″) source.

Several lines of these species have been detected in the line. On the other hand, in most cases we have two or more lines overlapped. We have tried to identify most of them with the following procedure: In a first step we select our best candidates for the lines and estimate the column density of the carriers assuming optically thin emission and local thermodynamic equilibrium (LTE). In a few cases, we are able to estimate the rotation temperature because we have at least two “isolated” lines (see Table 3). In the other cases, we have assumed $T_{rot}=50$ K. In a second step, we synthesized the expected spectrum assuming the estimated column densities. The velocity profile is assumed to be Gaussian with a half power full width of 7 km s$^{-1}$ and centered at the ambient cloud velocity, $-10$ km s$^{-1}$. Finally, we compare it with the observed spectrum and readjust the molecular column densities to improve the fit. We list in Tables 3 and 4 the lines detected in the USB and LSB spectra with the most likely line identification.

Obviously, this identification procedure entails some ambiguity. We have classified the species according with the reliability of their identification in two groups that are differentiated in Table 5. The first group contains the most reliable identifications. In these cases, the observed frequencies are in total agreement with those calculated for these species. Moreover, the synthesized spectrum matches quite well with the observed one (see top panel of Fig. 5). Finally, the derived fractional abundances are within the range of abundances measured for these species in hot cores. Within this group, we have OCS, $^{13}$CS, C$_2$H$_5$CN, c-C$_3$D, D$_2$CO, HCOOH, and C$_2$H$_5$OH in the USB and C$_2$H$_5$OH, C$_3$HD in the LSB. The lines of the first group species are indicated by bold characters in Tables 3 and 4. The derived column densities and fractional abundances are shown in Table 5.

We have put the complex molecules CH$_3$OCHO-A and CH$_3$OCHO-E (methyl formate) in the second group. Several lines of these species have been detected in the...
USB and LSB (see second panels in Fig. 5). However, the derived fractional abundances in NGC 7129-FIRS 2 are unexpectedly high compared to those measured in hot corinos and massive hot cores (see Table 3). One possibility is that the rotation temperature is higher than that assumed. To estimate the uncertainty due to the poorly known rotation temperature, we have repeated the column density calculations with $T_{rot} = 300$ K. The derived abundance is an order of magnitude lower and then it agrees with that derived in IRAS 16293. This high rotation temperature could be explained if this complex molecule arises in an inner and hotter region than CH$_3$CN. If methyl formate cannot be produced in the gas phase (as suggested by the laboratory results of Horn et al. 2004), our findings may imply that this species is formed on grain surfaces and that its binding energy is larger than that of CH$_3$CN, thus requiring larger dust temperatures to desorb.

The rarer isotope S$^{18}$O has also been included in the group of uncertain identifications. We have only one line of this molecule, S$^{18}$O $9_8\rightarrow 8_9$ at 228.272 GHz, and the derived S$^{18}$O abundance is unexpectedly high. In this case we could have a misidentification. There is a CH$_3$OCHO-A line at 228.270 GHz, that could be an alternative identification of the tentative S$^{18}$O line if the methyl formate abundance is unexpectedly high.

The most uncertain identifications are C$_2$H$_3$CHO, CH$_3$CHO-A, HCCCHO, and NO$_2$. The observed frequencies are in agreement with those of C$_2$H$_3$CHO, CH$_3$CHO-A, and HCCCHO lines if the emission arises in gas at a velocity $v_{lsr} \approx -5$ km s$^{-1}$. This velocity is coincident with that of the bullet R1 (see Paper I) but is shifted by $\sim 5$ km s$^{-1}$ from that of the molecular cloud. Similarly, the fit to the USB spectrum improves if we include a high excitation methanol line (see Table 3) emitting at the velocities $-5$ and $-20$ km s$^{-1}$. These velocities are within the range of velocities associated with this Class 0 protostar but are shifted from that of the ambient cloud. NO$_2$ is not a common molecule in hot cores, and the three lines observed in the spectrum are overlapped with others of more common hot core species. We have kept it in the table because its inclusion improves the fit to the observed spectrum.

In Table 5 we list the derived abundances of the molecules detected in the hot core towards FIRS 2. A first look at the Table reveals that FIRS 2 is rich in deuterated species (D$_2$CO, c-C$_3$D and c-C$_3$HD), sulphur containing compounds ($^{13}$CS, OCS) and complex O- and N- molecules ($^{18}$COOH, C$_2$H$_5$OH, C$_2$H$_7$CN). Taking into account the large uncertainty in the estimated fractional abundances, we have centered our discussion in the most reliable identifications, i.e., the first group in Table 3.

6. Discussion

In Table 5 we list the derived abundances of the molecules detected in the core towards FIRS 2. A first look at the Table reveals that FIRS 2 is rich in deuterated species (D$_2$CO, c-C$_3$D and c-C$_3$HD), sulphur containing compounds ($^{13}$CS, OCS) and complex O- and N- molecules ($^{18}$COOH, C$_2$H$_5$OH, C$_2$H$_7$CN). Taking into account the large uncertainty in the estimated fractional abundances, we have centered our discussion in the most reliable identifications, i.e., the first group in Table 3.

6.1. Deuterated species

The deuterium fractionation of molecular species is a well known process in dense interstellar clouds (Watson, W.D. 1974). In the gas phase, this is mainly driven by the enhancement of the H$_2$D$^+$/H$_3^+$ ratio due to the exothermic proton–deuteron exchange reaction $H_3^+$ + HD $\rightarrow$ H$_2$D$^+$ + H$_2$ (+ 230 K), which does not proceed backwards if the gas temperature is less than about 30 K. This process is responsible for the deuteration of species such as HCO$^+$ and N$_2$H$^+$, via the reaction of H$_2$D$^+$ with the parent species CO and N$_2$, respectively, as observed in dense cloud cores (Butner et al. 1993; Williams et al. 1998).

Another phenomenon which boosts the deuterium fractionation is the freeze out of neutral species, in particular the abundant O and CO, which are efficient destruction partners of H$_3^+$ and H$_2$D$^+$ in the gas phase. Their freeze out, known to happen in dense cold clouds (Williams et al. 1998; Caselli et al. 1999; Kramer et al. 1999; Bergin et al. 2002; Tafalla et al. 2002), further enhances the H$_2$D$^+$/H$_3^+$ abundance ratio (because of the enhanced formation rate of H$_2$D$^+$, and the reduced destruction rates for H$_2$D$^+$ and H$_3^+$) and the consequent transfer of the deuteron to gas-phase species (Caselli et al. 2002; Bacmann et al. 2003; Crapsi et al. 2005). Once CO is highly depleted, multiple deuterated forms of H$_3^+$ can easily be produced (Roberts et al. 2003; Walmsley et al. 2004). Indeed, large
The abundances of H$_2$D$^+$ and D$_2$H$^+$ have been measured toward two pre-stellar cores (Caselli et al. 2003; Vastel et al. 2004). This has the consequence of enhancing the gaseous D/H ratio to values around 0.1, four orders of magnitude larger than the cosmic D abundance, which allows an efficient deuteration on grain surfaces (Tielens 1983; Charnley et al. 1997; Stantcheva & Herbst 2003).

We have detected the deuterated species D$_2$CO, c-C$_3$D and c-C$_3$HD towards FIRS 2. Moreover, the D$_2$CO interferometric image shows that the D$_2$CO emission is strongly peaked towards the hot core position. Recent theoretical and observational research suggests that the abundance of the non-deuterated species H$_2$CO is enhanced by more than 2 orders of magnitude in the inner region of the envelope, where the dust temperature is larger than 100 K (Maret et al. 2004). The size of this region (∼100 AU) is similar to that derived for the D$_2$CO emission from the linewidth of the D$_2$CO line. Assuming that evaporation is also the origin of D$_2$CO, the [D$_2$CO]/[H$_2$CO] would tell us about the gaseous D/H ratio during the pre-stellar phase of the parent clump. Unfortunately, we have not interferometric observations of H$_2$CO and cannot derive an accurate [D$_2$CO]/[H$_2$CO] ratio in the hot core. Trying to get an estimate of the deuteration degree of formaldehyde, we have compared the single dish spectra of the D$_2$CO 4$_{04}$→3$_{03}$ and H$_2$CO 3$_{12}$→2$_{11}$ lines (see Fig. 6). Both lines have similar excitation conditions and frequency. The line intensity ratio in the narrow component is lower by a factor of 2 than in the wide component suggesting a higher [D$_2$CO]/[H$_2$CO] ratio in the hot core. Assuming the same physical conditions for D$_2$CO and H$_2$CO we derive [D$_2$CO]/[H$_2$CO]∼0.14±0.03 in the hot core. This value is similar to that found in pre-stellar cores and low-mass protostars (Caselli et al. 2002; Bacmann et al. 2003; Ceccarelli et al. 2001; Loinard et al. 2003) and it implies large D/H ratios during the cold pre-stellar phase (D/H∼0.5, see Caselli et al. 2002b; Stantcheva & Herbst 2003).

Contrary to D$_2$CO, we have not detected N$_2$D$^+$ in our interferometric observations. It is interesting to note that whereas the deuteration of N$_2$H$^+$ is a gas-phase process (which proceeds from the reaction between N$_2$ and H$_2$D$^+$), the formation of D$_2$CO seems to require surface chemistry (Ceccarelli et al. 2002). Therefore, our result is not surprising. In fact, as stated above, the deuteration in the gas phase is efficient only if the gas temperature is lower than, say, 30 K. Thus, in a hot core, we do not expect to see N$_2$D$^+$ either. Moreover, in hot cores, where icy grain mantles evaporates, CO and H$_2$O molecules are abundant in the gas phase and they efficiently destroy N$_2$H$^+$ (and N$_2$D$^+$), so that one does not expect to see large abundances of N$_2$H$^+$ either. The non-detection of N$_2$D$^+$ in the hot core associated with FIRS 2 confirms the interpretation given in Paper II that N$_2$D$^+$ mainly arises in the cool envelope, and constitutes an indirect proof of this chemical scheme. On the other hand, the large D$_2$CO/H$_2$CO abundance ratio observed in the same position can be easily explained if the deuterium fractionation of formaldehyde happened on grain surfaces during the cold pre-stellar phase, and if icy mantles have recently evaporated, so that gas phase chemistry did not have the time to significantly reduce the abundance of the deuterated “parent” species.

### 6.2. Sulphuretted species

The abundances of sulphuretted molecules are very dependent on the stellar age. We have compared the observed [CS]/[OCS] ratio in FIRS 2 (∼1.1 assuming CS/$^{13}$CS=89) with the Viti et al. (2004) model for a 5 M$_\odot$ star. The measured ratio is consistent with the FIRS 2 being an evolved hot core with an age of >1.0 × 10$^5$ yr. The detection of large species like C$_2$H$_5$OH also suggests that we are dealing with an evolved hot core since these species are only formed at late times. Nevertheless, we would like to point out that the determination of the hot core age using the sulphuretted molecules is quite uncertain since other factors like the ice mantle composition and the hot core kinetic temperature can also strongly affect the abundances of these species (Wakelam et al. 2004).
6.3. Complex O- and N-bearing molecules

Theoretical models predict that the relative abundance of the N-bearing and O-bearing complex molecules is dependent on the hot core temperature (Caselli et al. 1993, Rodgers & Charnley 2001). The luminosity of FIRS 2 is a factor $>10$ larger than those of the two low mass hot corinos detected so far and a factor $\sim200$ lower than that of the massive protostar creating the Orion hot core. The intermediate kinetic temperature of the FIRS 2 hot core is expected to produce a differentiated chemistry of complex molecules. In order to have a deeper insight into the dependence of the complex molecules abundances on the protostellar luminosity, in Table 5 we compare the observed abundances towards FIRS 2 with those measured in prototypical hot corinos and massive hot cores. The luminosity of the objects listed in Table 5 varies by 4 orders of magnitude, thus one expects to detect some chemical differences between these hot cores.

However, the comparison of abundances between different hot cores (corinos) is difficult. First of all, since massive stars are usually located farther from the Sun than their low- and intermediate-mass counterparts, the abundances are derived in different spatial scales. The fractional abundances shown in Table 5 are averaged values in regions with sizes ranging from $\sim0.002$ pc in NGC1333–IRAS 4A to $0.32$ pc in OMC1 and G327. These sizes are given by the angular resolution of the current instrumentation at the hot core distance. Thus, the derived abundances in massive hot cores would be severely underestimated in the case of sizes similar to those of hot corinos. On the other hand, we can have several hot cores in the studied region, specially in massive star forming regions where clustering is more important and are located at greater distances. In order to minimize these problems, we normalize the studied abundances to those of the parent species.

As a first step, we have normalized all the molecular abundances to that of H$_2$CO and CH$_3$OH. These species are thought to be the “parent” molecules of complex O-bearing species, although some doubts are cast in the particular case of methyl formate (Horn et al. 2004). In Fig. 7a, we show the relative abundances of HCOOH, CH$_3$OH, CH$_3$CN and C$_2$H$_5$CN respect to H$_2$CO as a function of the luminosity. Since we have not interferometric observations of H$_2$CO in FIRS 2, we have estimated the H$_2$CO abundance assuming [D$_2$CO]/[H$_2$CO]=0.014. A clear trend is observed in the relative abundance of CH$_3$OH, CH$_3$CN and C$_2$H$_5$CN respect to H$_2$CO as a function of the stellar luminosity (Fig. 7a). The abundance of all these molecules increases by a factor of $\sim10$ from NGC 1333–IRAS 4A ($L=14$ L$_\odot$) to OMC1 ($L=10^4$ L$_\odot$). This trend does not present significant differences between O- and N-bearing molecules. Contrary to these molecules, the [HCOOH]/[H$_2$CO] ratio does not present a systematic behavior.

In Fig. 7b we plot the abundances of the same molecules normalized to that of CH$_3$OH. Different behaviors are found for the different molecules. The [CH$_3$CN]/[CH$_3$OH] ratio does not present any systematic trend with the protostellar luminosity, although the dispersion in the values is quite high. The same remains true for C$_2$H$_5$CN and probably for C$_2$H$_5$OH (we only have 3 points for C$_2$H$_5$OH). This suggests that the ratio between O- and N-bearing complex molecules does not seem to strongly depend on the protostellar luminosity, contrary to that expected from theoretical models. However, the relative abundance of HCOOH seems to decrease by 2 orders of magnitude from NGC 1333–IRAS4 A to G327.3. Thus, the relative abundances of HCOOH to those of CH$_3$OH, CH$_3$CN, C$_2$H$_5$CN and C$_2$H$_5$OH seem to decrease with the protostellar luminosity.

We propose that the increase of CH$_3$OH/H$_2$CO (as well as CH$_3$OH/HCOOH), CH$_3$CN/H$_2$CO, and C$_2$H$_5$CN/H$_2$CO with stellar luminosity is likely due to differences in the grain mantle composition between low and massive star forming regions. Indeed, differences in the initial conditions (in particular gas density and dust temperature) are known to strongly affect surface chemistry. For example, Caselli et al. (1993) found that complex N-bearing species are more easily formed if the dust grain temperature ($T_{dust}$) is about 40 K, during the collapse phase. Although such temperature can be found in a significant fraction of a collapsing massive clump surrounding a massive young stellar object (Fontani et al. 2002), this is not the case for low mass cores. Therefore, the observed trend (at least for N-bearing species) is consistent with theoretical predictions. But Caselli et al. (1993) also found that at $T_{dust}\sim40$ K, methanol is not efficiently formed on the surface because it requires the volatile H to stick on the grain surface (see also Charnley et al. 1992; van der Tak et al. 2000). Thus, the observed CH$_3$OH/H$_2$CO increase with stellar luminosity is not well understood, unless another surface formation mechanism for methanol (besides the CO hydrogenation) becomes important in the warmer high mass clumps, e.g. OH+CH$_3$ (see also discussion in Pontoppidan et al. 2003). However, this conclusion is only based on 4 sources and has to be confirmed with a larger and more complete sample. Observational bias such as the different spatial scale for the different objects can contribute to give this trend if the spatial extension of the emission of the observed molecules is different.

In Fig. 7c, we compare only the N-bearing molecules. The [C$_2$H$_5$CN]/[CH$_3$CN] ratio remains quite constant with a dispersion of about a factor $<10$ between all the sources. This uniform C$_2$H$_5$CN/CH$_3$CN ratio suggesting that the chemistry of both compounds is linked. Indeed, these two molecules have a common parent species: C$_2$N (see e.g. Fig. 7 in Caselli et al. 1993).

7. Conclusions: The chemistry of the IM hot core NGC 7129–FIRS 2

In this paper we present the first detection of an intermediate-mass hot core. Our interferometric observations towards FIRS 2 allow us to estimate a size of
650×900 AU and a mass of 2 M⊙ for the hot core associated with this IM object. The dimensions and mass of this IM hot core are intermediate between those measured in hot corinos (r~150 AU, M<1 M⊙) and massive stars (r~3000 AU, M>10 M⊙) and consequently one expects to find a differentiated chemistry in it.

Our interferometric observations of CH3CN, CH3OH, D2CO and N2D+ provides information on the structure and chemistry of this object. While the CH3CN emission arises mainly in the hot core, the CH3OH emission has a component associated with the bipolar outflow. The CH3CN abundance is ~7.0 10^{-5} in the hot core, which is about 3 orders of magnitude larger than in the cool envelope. The methanol abundance is enhanced (>3 10^{-8}–a few 10^{-7}) in the hot core and the outflow components. However the rotation temperature is higher in the hot core than in the outflow revealing very different physical conditions, and probably a different CH3OH desorption mechanism for the two components.

The doubly deuterated formaldehyde also presents enhanced abundances in the hot core. We estimate a [D2CO]/[H2CO]~0.14, which is 4 orders of magnitude larger than the cosmic D abundance and similar to those found in pre-stellar clumps and low-mass protostars. The enhanced [D2CO]/[H2CO] abundance in the hot core suggests that some process is responsible of the deuteration process of H2CO. In contrast to the high deuteration degree of formaldehyde, we have not detected N2D+ in the hot core. This is consistent with the chemical scheme in which the deuterium of H2CO requires surface chemistry, the deuteriation of N2H+ is a gas-phase process.

A large number of molecular lines have been detected in our interferometric spectra towards FIRS 2. Most of these lines are identified as belonging to deuterated (D2CO,c-C3D and c-C3HD), sulphuric (CH3S,COCS) and complex O-/N-bearing species (HCOOH,C2H5OH,CH3CN). Deuterated species whose deuteration requires surface chemistry, such as D2CO, present enhanced abundances in the warm regions associated with low-mass protostars. Loinard et al. (2003) searched for the doubly deuterated form of formaldehyde (D2CO) in a large sample of young stellar objects. D2CO was detected in all low-mass protostars, with [D2CO]/[H2CO] ratios of 2–40%. On the other hand, no detection was obtained towards more massive protostars (where [D2CO]/[H2CO]<0.5%). This is consistent with the results reported by Turner (1990) who detected D2CO in Orion and measured [D2CO]/[H2CO]~0.003. If the hot cores associated with massive stars are older or significantly denser than those surrounding low-mass objects, gas phase chemistry could have had the time to re-set the deuterium fractionation to values close to the cosmic D/H ratio. An alternative explanation is that the gas temperature of the material accreting high mass protostars is larger than 30 K (Fontani et al. 2002), so that the deuterium fractionation efficiency in the gas phase is strongly reduced already before the hot core phase.

The sulphuric and complex compounds are characteristic of hot cores in both the low-mass and the high-mass regimes. FIRS 2 is the first IM hot core detected thus far and presents a unique opportunity to study the link between the chemistry of hot corinos and massive hot cores. We have compared the abundances of complex molecules in FIRS 2 with those in hot corinos and the massive hot cores OMC1 and G327.3–0.6. Contrary to model predictions, we do not detect any dependence of the O-/N-complex molecules ratio on the protostellar luminosity. However, we detect differences between the behavior of the O-bearing species with the stellar luminosity. While H2CO and HCOOH are more abundant in low luminosity sources, CH3OH seems to be more abundant in massive objects. We propose that this could be due to a different mantle composition in the two kinds of region, caused by different physical conditions (mainly gas density and dust temperature) during the pre-stellar and accretion phase. However, this could also be due to other factors such as the different spatial scale of the observations or a possible contribution of the shocked gas associated with the bipolar outflow to the emission of these molecules. Differences in the hot core ages and/or cloud initial conditions could also produce these differences. The detection and detailed study of the more intermediate-mass hot cores are necessary to establish firm conclusions.

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Fig. 7. Relative abundances of the complex O- and N-bearing molecules as a function of the protostellar luminosity for the objects listed in Table 3.

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