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FIRST UNBIASED SPECTRAL SURVEY OF A YOUNG AND SINGLE MASSIVE PROTOSTAR: CYGX-N63

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Abstract. We present an unbiased spectral survey of a unique massive protostar in the Cygnus-X region: CygX-N63, performed with the 30m IRAM telescope. We identified 48 molecules over 106 GHz of bandwidth. Two prebiotic molecules were found: CH_2NH (methanimine) and NH_2CHO (formamide) and several rare molecules, such as CF^+ (fluoromethylidynium) or PN (phosphorous nitride). The spectral profiles and the population diagrams of the molecules allowed us to identify three emission regions in the protostar: the envelope, the outflow and a hot core-like region.

Keywords: star formation, chemistry, spectral survey, Cygnus-X

1 Introduction

The early phases of the massive star formation are poorly known. There are two main scenarios to explain the formation of massive stars (more than 8 solar masses). In the first one, a strong microturbulence allows the existence of large Jeans masses but T.Csengeri et al. (2010) found no clear evidence for such a microturbulence. They showed instead that small scale converging flows could initiate the formation of massive stars. This alternative scenario is supported by MHD simulations (B.Commerçon et al. 2011).

In this highly dynamical scenario, filaments play a key role. They are generated by large-scale magneto-hydrodynamic turbulence. Above a critical value of the mass per unit length, they fragment and form low-mass and intermediate mass stars (P.Palmeirim et al. 2013). In this view, high-mass stars could form where the filaments merge into ridges (M.Hennemann et al. 2012), leading to shocks. Therefore, the gas and possibly the grains undergo short temperature and density peaks. The chemical composition of the pre-collapse gas can be significantly modified by these variations. It is therefore crucial to explore precisely the chemical composition of young protostars, looking for signs of this early warm-up phase.

CygX-N63 was first discovered by F.Motte et al. (2007). This close object (1.4 kpc) is ideal to study the early phases of massive star formation. First, it is isolated enough to be observed alone in the beam of the IRAM 30m telescope. Secondly, it is very massive (M_{env}=$\sim$44 M$\odot$ within 2500 AU) (Duarte-Cabral et al. 2013) and not sub-fragmented, as showed by the dust emission, the molecular emission of ^{13}CS, OCS, D_2CO and CH_3CHO (seen with the PdBI in 2012, unpublished) and the presence of a powerful outflow, pointing to one single object. Thirdly, this protostar is still young, with a total luminosity of only 350 L$\odot$(Duarte-Cabral et al. 2013), which indicates that the accretion is not very strong yet. Besides, N63 is chemically very rich, suggesting that this object could be in a pre-hot core phase. We performed an unbiased spectral survey of this object to fully investigate its chemical composition. In a second part, we determined the spatial origin of the molecular emission, based on spectral profiles and population diagrams. Our main goal was to identify the molecules tracing the envelope, which contains the pristine gas at the origin of the massive stars.

2 Observations and data reduction

The unbiased spectral survey was made over 71 GHz at 1 mm and over 35 GHz at 3 mm with the IRAM-30m telescope in september 2012 and january 2013 toward CygX-N63, located at (δRA, δDec) = (20 40 05.2, 41 32 12.0) with respect to the phase center J2000. We used the wobbler switching mode.

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The spectra were assembled and baseline-corrected with the GILDAS* softwares. We converted the data into main-beam temperature (T_{mb}) using the interpolated forward and main-beam efficiencies (F_{eff} and B_{eff}) given by the IRAM. The spectral resolution is 195 kHz. The analysis was performed with the help of the CASSIS† software using the CDMS, JPL and VASTEL catalogues.

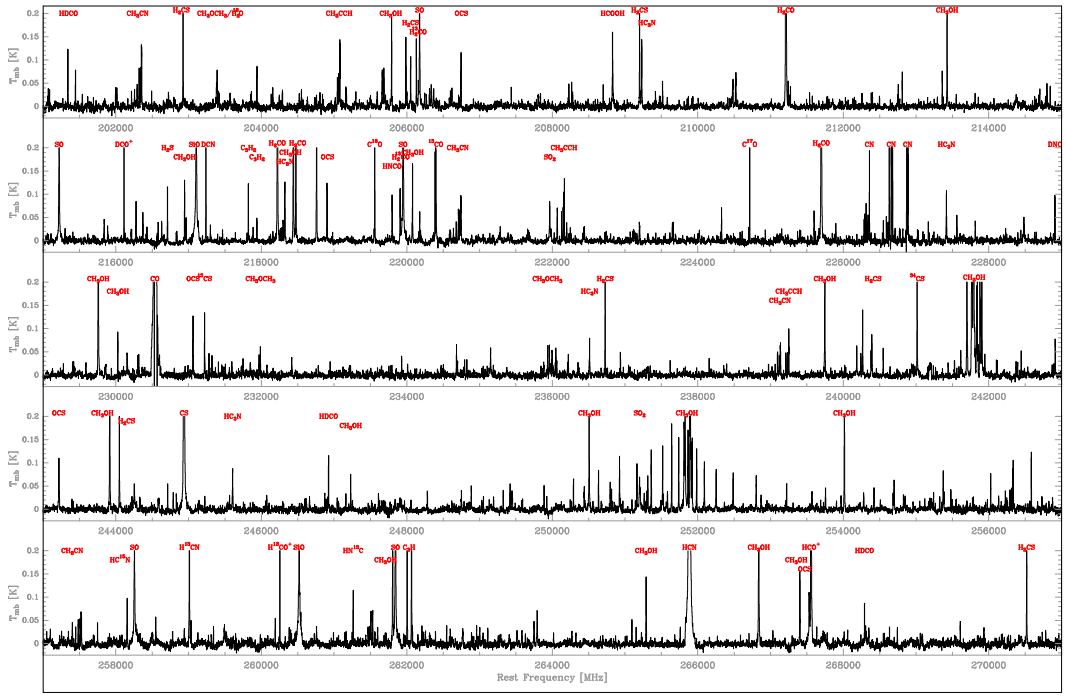

Fig. 1. Spectrum of CygX-N63 at 1mm, with some of the strongest identified lines.

3 Results

3.1 Line identification

We were able to identify $\sim$ 95% of the lines, namely 1702 identified lines. The figure 1 displays the spectrum at 1 mm. 48 molecules were found in CygX-N63, plus 35 isotopologues and 14 deuterated molecules, shown in the table 1. All families of molecules are represented: organic molecules, complex organic molecules (COMs: more than 6 atoms), N-bearing, S-bearing, carbon chains. Some rare molecules were also identified, such as the ion fluoromethyliumylidene CF^+ (see details in S.Fechtenbaum *in prep.*) or the phosphorous nitride PN. Two prebiotic molecules were also observed: the methanimine CH_2NH and the formamide NH_2CHO.

3.2 Chemical composition

We used the software CASSIS to derive the column densities and the excitation temperatures using population diagrams for the molecules for which we had at least two lines. We assumed that the local thermodynamical equilibrium (LTE) was established and that the cosmological background was negligible. For a part of the molecules, such as SO, SO_2, OCS, o-H_2CO, CS, HCO^+ or HCN, we had several isotopologues and could therefore correct the opacity effect. For the other molecules, we know that the column densities may be underestimated.

The beam dilution was taken into account. Based on previous observations of the source with the Plateau de Bure Interferometer (PdBI) at 1 mm, we chose different source size: 10" of diameter for the outflow, 1.4" for the envelope and 0.1" for the hot core-like region. The corresponding size for the hot core-like region is $\sim$ 140 AU, larger than a hot corino. Population diagrams were made by plotting $ln(N_u/g_u)$ as a function of E_u/kT_{ex}, following the relation:

*See `http:/www.iram.fr/IRAMFR/GILDAS/` for more information.
†See `http://cassis.irap.omp.eu/` for more information.

Organic molecules	CO	HCO	CH_3OH	H_2CO	H_2CCO
Complex organic molecules	CH_3OCH_3	$HCOOCH_3$	CH_3CHO	C_2H_5OH	HCOOH
CH_3COCH_3 ?	Ethylene oxide ?	Propanal ?			
Carbon chains	CCH	C_3H	C_4H	o-c-C_3H_2	p-c-C_3H_2
CH_3CCH					
N-bearing molecules	CN	HCN	HNC	HC_3N	HC_5N
C_3N	CH_3CN	C_2H_5CN	HNCO	NO	HCCNC ?
S, P and Si-bearing molecules	CS	CCS	C_3S	H_2S	H_2CS
OCS	SO	SO_2	NS	SiO	PN
Deuterated molecules	CH_2DOH	HDCS	HDCO	NH_2D	o-D_2CO
CCD	DCN	DC_3N	HDO	CH_2DCCH	C_3HD
Ions	HCO^+	$HOCO^+$	N_2H^+	DCO^+	$DOCO^+$?
N_2D^+	HCS^+	CF^+			

Table 1. Molecules detected toward CygX-N63

$$ln\frac{N_u}{g_u} = lnN_{tot} - lnQ(T_{ex}) - \frac{E_u}{kT_{ex}} \qquad with \qquad N_u = W \times \frac{8\pi k\nu^2}{hc^3 A_{ul}} \times C_{tau} \tag{3.1}$$

where N_u is the column density of the energy level u, g_u the statistical weight of this level, W the integrated area of the line and Q is the partition function[‡]. A_{ul} is the Einstein coefficient and C_{tau} the optical depth correction factor. The total column density and the excitation temperature, which is equal to the kinetic temperature if the LTE is established, are then given by CASSIS. The excitation temperatures are presented in figure 2.

To derive the column density of H_2, we used the envelope mass determined by Duarte-Cabral et al. (2013): 44 M$\odot$ within a full width at half maximum (FWHM) of 2500 AU. We took the mass contained in 1.95 σ and derived $n_{H_2} = 7.81 \times 10^{24} cm^{-2}$. We could then obtain the abundances by dividing the column densities by n_{H_2}.

3.3 Spatial origin of the molecular emission

Analyzing the spectral profiles and the rotational diagrams allowed us to find the origin of the emission for a part of the observed molecules. The spectral profiles can be divided into two groups. In the first group, the spectral profiles are well fitted by a single gaussian. The lines have a low average FWHM of (2.3 ± 0.3) km.s^{-1} and the population diagrams give an average excitation temperature of T_{ex} = (18 ± 3) K. This group contains C_4H, DC_3N, HC_5N, HDCS, $HOCO^+$, o-c-C_3H_2 and o-D_2CO. These molecules are probably tracing the envelope, where we expect such low temperature and velocity dispersion.

In the second group, the spectral profiles are better fitted with two gaussians, a narrow and a large. We plotted population diagrams for the two components separately. The features of the first component are a FWHM of (2.8 ± 0.2) km.s^{-1} and T_{ex} = (19 ± 3) K, which is very similar to the first group and therefore indicates that this narrow component may also correspond to the envelope. The large component features T_{ex} = (26 ± 3) K and a FWHM of (9.6 ± 0.5) km.s^{-1}. This group contains SiO, ^{29}SiO, SO, ^{34}SO, SO_2, HC_3N, $H^{13}CCCN$, HNCO, CCS, CH_3CN, a-CH_3CCH, e-CH_3CCH, H_2CCO, CS, CCS, OCS, o-H_2CO, HDCO, HCO^+ and HCN. CygX-N63 is known to have a powerful outflow (T.Csengeri et al. 2010) and some of these molecules, such as SiO, are recognized tracers of the outflow. We can thus infer that all molecules in this group are tracing the outflow, which is consistent with this large velocity dispersion.

On the other hand, we noticed that some molecules display population diagrams with two different slopes, which means two different excitation temperatures. It was the case for several COMs: CH_3OH, $HCOOCH_3$ and CH_3OCH_3, but also for $^{13}CH_3OH$ and CH_2DOH, which suggest that these two different temperatures are not only an effect of the opacity. The two averaged excitation temperatures are (23^{+28}_{-7}) K and (124^{+199}_{-43}) K. Note that these two components were not distinguishable in the spectral profiles, which means that they have approximately the same velocity dispersion. The two emission regions may therefore be spatially related. In addition, the COMs are known to be features of the hot core. Therefore we conclude that the cold component could correspond to the envelope or to the inner edge of the envelope and that the hot component could arise

[‡]See *Formalism for the CASSIS software on* `http://cassis.irap.omp.eu/?page=documentation`

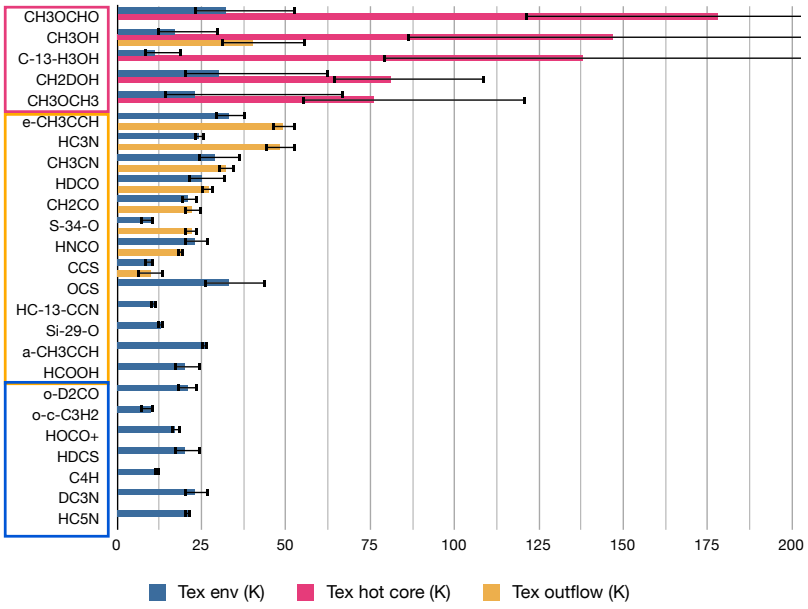

Fig. 2. Excitation temperatures derived from population diagrams. Molecules tracing the envelope are represented in blue, those tracing the outflow in yellow and those tracing the hot core-like region in pink.

from a hot core-like region. The abundances in this heated hot core-like region give a first-order idea of the composition of the grains, because a part of the ice mantle of the grains is sublimated, releasing the molecules.

The excited methanol $^*CH_3OH$ is a particular case because it displays at the same time two components in its spectral profile and two components in its rotational diagram. It traces the envelope, the hot core-like region and the outflow.

4 Conclusions

We performed a large unbiased spectral survey toward a young and massive protostellar object, revealing a very rich chemistry. Population diagrams and spectral profiles allowed us to separate the possible sources of the emission: outflow, envelope and hot core-like region. We were able to identify molecules tracing the cold envelope, which contains the pristine gas at the origin of the massive stars. The next step of our work is to compare the observed abundances, in particular in the envelope and on the grains, to the predictions given by a chemical gas-grain code called Nautilus developed in Bordeaux (U.Hincelin et al. 2013). The aim is to follow the evolution of the physical conditions in the gas which will eventually form the massive star.

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