Molecular Complexity
in
Solar-Type Star Forming Regions

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on behalf of the DOC Team

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The Beginning

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THE HOT CORE AROUND THE LOW-MASS PROTOSTAR IRAS 16293−2422: SCOUNDRELS RULE!

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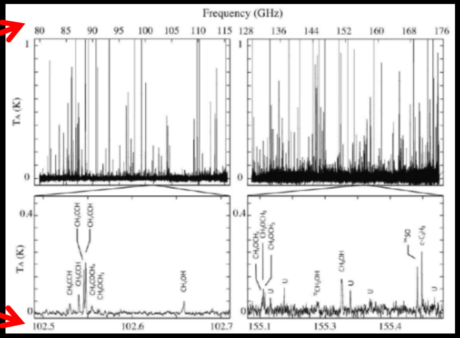
WAGOS

ABSTRACT

While warm dense gas is prevalent around low-mass protostars, the presence of complex saturated molecules—the chemical inventory characteristic of hot cores—has remained elusive in such environments. Here we report the results of an IRAM 30 m study of the molecular composition associated with the low-mass protostar IRAS 16293−2422. Our observations highlight an extremely rich organic inventory in this source with abundant amounts of complex O- and N-bearing molecules such as formic acid, HCOOH, acetaldehyde, CH_3CHO, methyl formate, CH_3OCHO, dimethyl ether, CH_3OCH_3, acetic acid, CH_3COOH, methyl cyanide, CH_3CN, ethyl cyanide, C_2H_5CN, and propyne, CH_3CCH. We compare the composition of the hot core around this low-mass young stellar object with those around massive protostars and address the chemical processes involved in molecular complexity in regions of star formation.

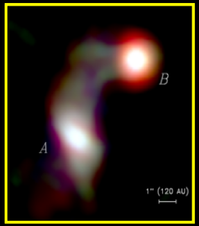
Subject headings: ISM: abundances — ISM: individual (IRAS 16293−2422) — ISM: molecules — stars: formation



Caux et al. (2011)

Key Questions

IRAS16293-2422: TIMASS, PILS : What else ?

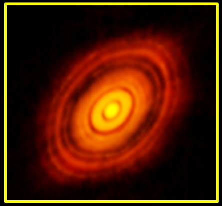


What molecular complexity can be reached in low-mass SFRs ?

Chemical differentiation: Low/High-Mass ? Other ?

When, Where, How do Complex Organic Molecules form ?

Which heritage of the earliest phases ?



The IRAM Large Program ASAI

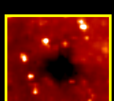
(Astrochemical Surveys At IRAM)

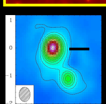
<u>Goals:</u>

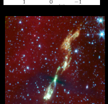
- Evolutionary view on chemistry along Solar-type Star Formation path:
- Influence of environmental conditions: feedback processes

Unbiased spectral line surveys from 70 to 280GHz: 400 hrs *(Lefloch et al. 2018)*

ASAI Source Sample: 10 templates illustrative of the different chemical stages of a sun-like protostar







Sources	Coordinates (J2000)	d (pc)	Lum. ($L_\odot$)	3 mm (mK)	2 mm (mK)	1.3 mm (mK)	$\delta\nu$ (kHz)	Comment
TMC1	$04^h41^m41.90^s$ $+25°41'27.1''$	140	–	–	4.2–4.2	–	48.8, 195.3	Early prestellar core
L1544	$05^h04^m17.21^s$ $+25°10'42.8''$	140	–	2.1–7.0	–	–	48.8	Evolved prestellar core
B1b	$03^h33^m20.80^s$ $+31°07'34.0''$	230	0.77	2.5–10.6(*)	4.4–8.0	4.2–4.6	195.3	First Hydrostatic Core
L1527	$04^h39^m53.89^s$ $+26°03'11.0''$	140	2.75	2.1–6.7(*)	4.2–7.1	4.6–4.1	195.3	Class 0 WCCC
IRAS4A	$03^h29^m10.42^s$ $+31°13'32.2''$	260	9.1	2.5–3.4	5.0–6.1	4.6–3.9	195.3	Class 0 Hot Corino
L1157mm	$20^h39^m06.30^s$ $+68°02'15.8''$	250	3	3.0–4.7	5.0–6.5	3.8–3.5	195.3	Class 0
SVS13A	$03^h29^m03.73^s$ $+31°16'03.8''$	260	34	2.0–4.8	4.2–5.1	4.6–4.3	195.3	Class I
AB Aur (†)	$04^h55^m45.84^s$ $+30°33'33.04''$	145	–	4.6–4.3	4.8–3.9	2.1–4.3	195.3	protoplanetary disk
L1157-B1	$20^h39^m10.20^s$ $+68°01'10.5''$	250	–	1.1–2.9	4.6–7.2	2.1–4.2	195.3	Outflow shock spot
L1448-R2	$03^h25^m40.14^s$ $+30°43'31.0''$	235	–	2.8–4.9	6.0–9.7	2.9–4.9	195.3	Outflow shock spot

Time

Molecular census

> 98% of lines (5 σ) are identified

2	3	4	5	6	7	8	9	10	11	12	13
H_2	C_3	c-C_3H	C_5	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	C_6H_6	c-C_6H_5CN
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HCOOCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$C_2H_5OCH_3$	$HC_{11}N$
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	
C2	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	CH_3OCOCH_3	n-C_3H_7CN	
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N	CH_3CHCH_2O			
CH^+	HCN	C_2H_2	CH_2CN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H	CH_3OCH_2OH			
CN	HCO	NH_3	CH_4	CH_3SH	c-C_2H_4O	l-HC_6H	CH_3CONH_2				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	CH_2CHOH	CH_2CHCHO	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO	CH_3NCO	NH_2CH_2CN					
CSi	H_2O	HNCS	H_2CNH	C_5N		CH_3CHNH					
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH4	H_2CCNH							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	c-SiC_3	C_4H^-	HNCHCN							
OH	N_2O	CH_3	HCOCN								
PN	NaCN	C_3N^-	HNCNH								
SO	OCS	PH_3	CH_3O								
SO^+	SO_2	HCNO	NH_4^+								
SiN	c-SiC2	HOCN	H_2NCO^+								
SiO	CO_2	C_3H^+									
SiS	NH_2	HMgNC									
CS	H_3^+	HSCN									
HF	SiCN										
HD	AlNC										
FeO?	SiNC										
O_2	CCP										
CF^+	AlOH										
SiH	H_2O^+										
PO	H_2Cl^+										
AlO,	KCN										
OH^+,	FeCN										
CN^-	HO_2										

No COMs larger than glycolaldehyde, dimethyl ether, ethanol

Complete census

First S-bearing COM detected in low-mass SFRs: **CH_3SH**

(also Majumdar et al. 2016)

Prebiotic chemistry: P-, glycolaldehyde, formamide, formic acid

C_xH_y

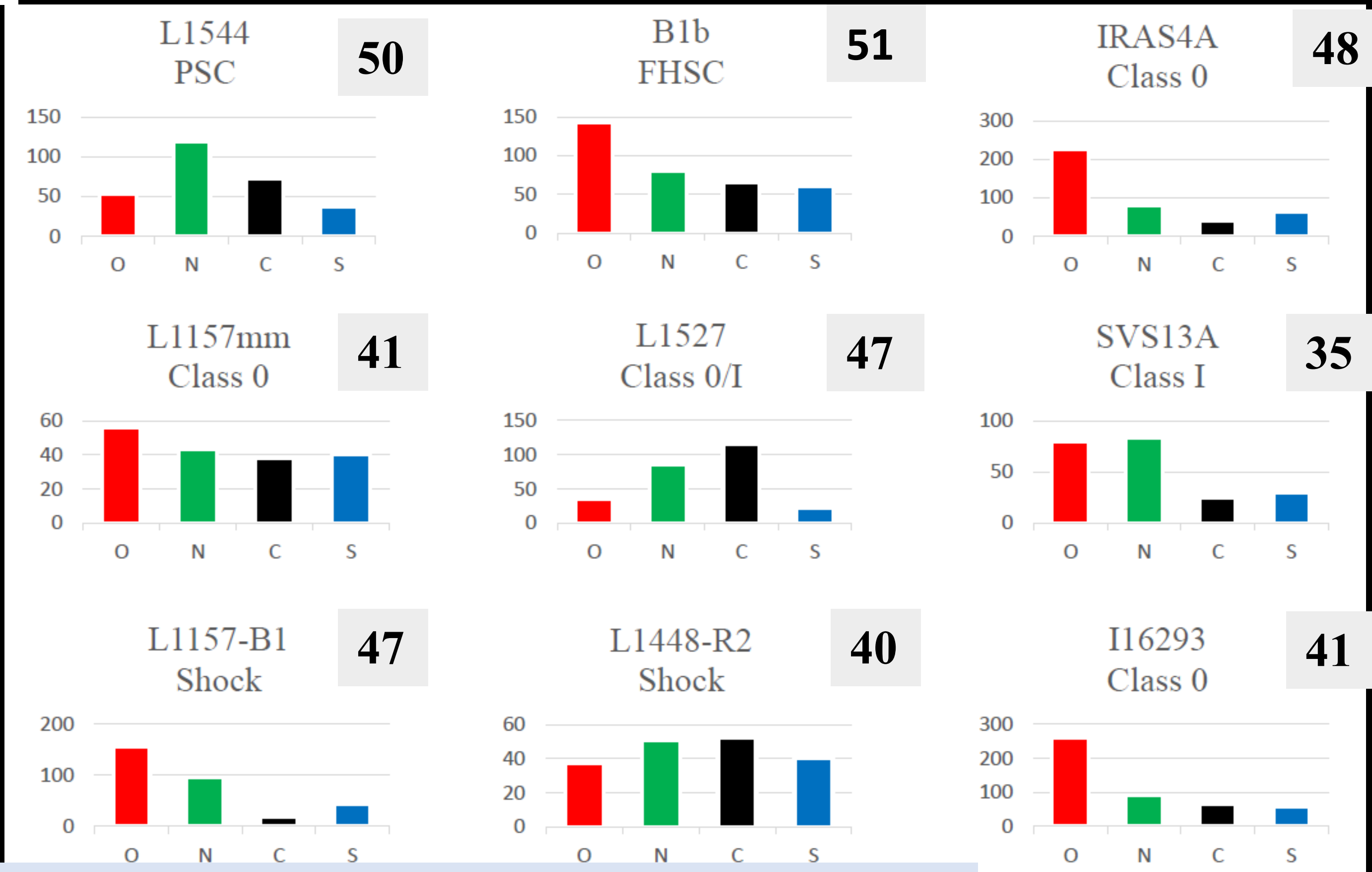
$C_xH_yO_z$

$C_xH_yO_zN_t$

$C_xH_yO_zN_tS_u$

Molecular Complexity and Evolutionary Stage

Time



ASAI sample

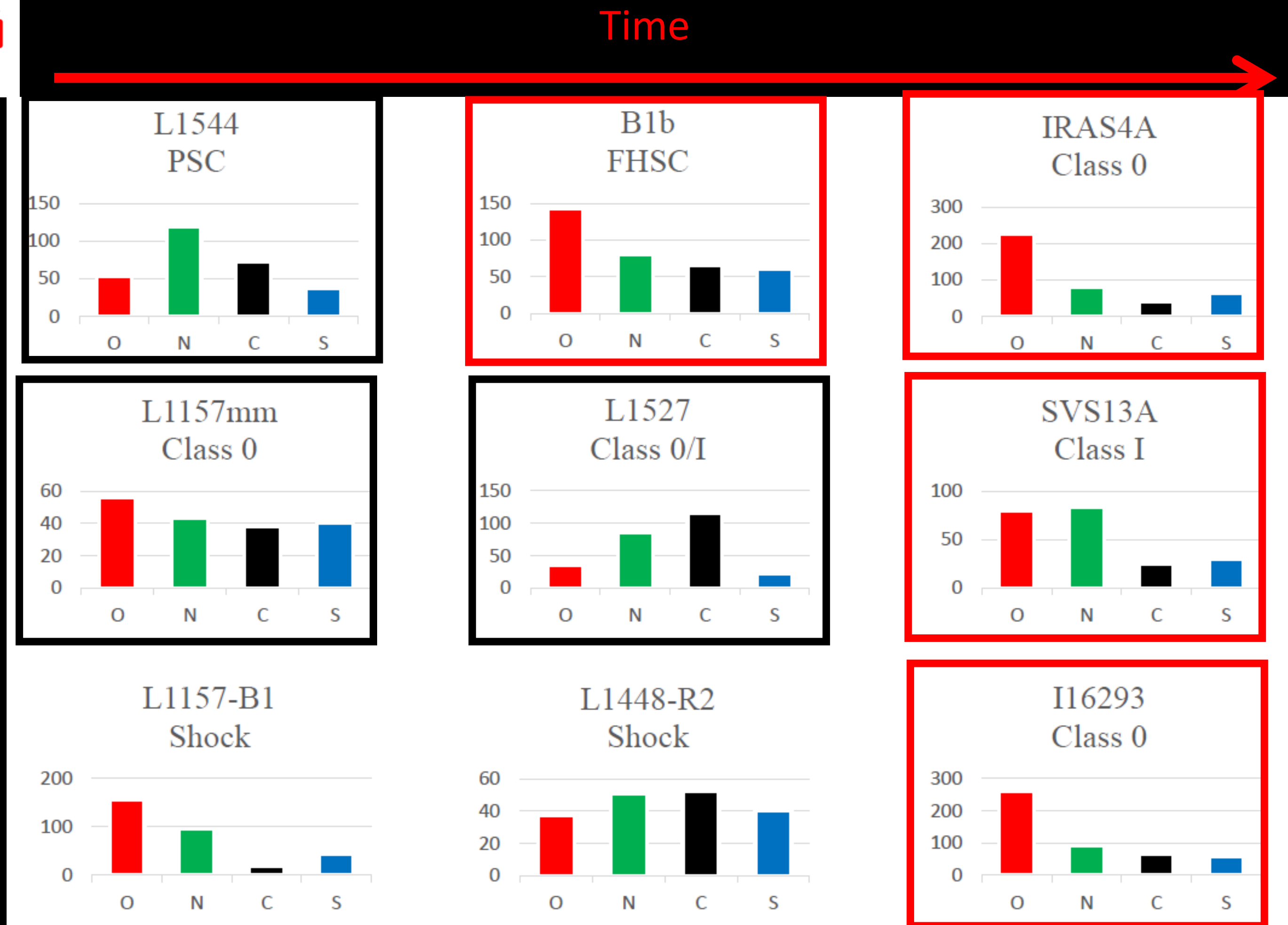
Number of *detected* molecular species : 35 – 51

Number of molecular lines : 178 – 413 (σ= 5-12 GHz^{-1})

Molecular richness is mainly independent of L_o

Orion	**SgrB2**
43	56
3200	3700

Chemical Classes



r= N(O)/N(C) = 1 defines two chemical classes:

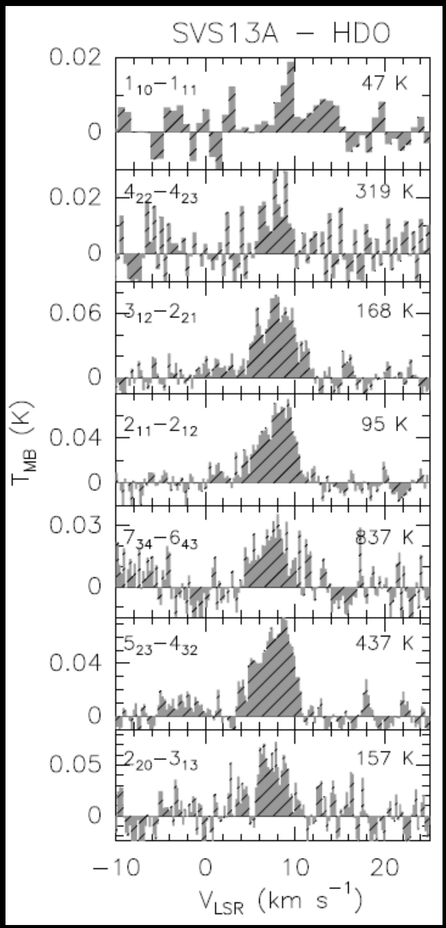
O-rich : hot corino sources : r= O/C > 1.5

C-rich : WCCC : r= O/C < 1.5

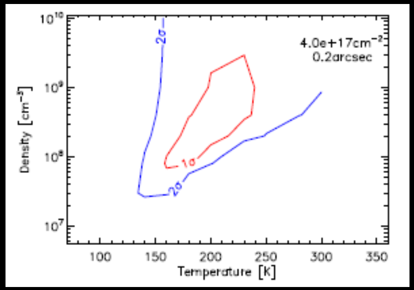
SVS13A : hot corino
L1157-mm : WCCC

Hot Corinos in the Class I stage

Strong deuteration around Class I SVS13A



Deuterated water emission from a small (25AU) region of dense and hot gas around the protostar



HDCO, D_2CO and CH_2DOH detected !

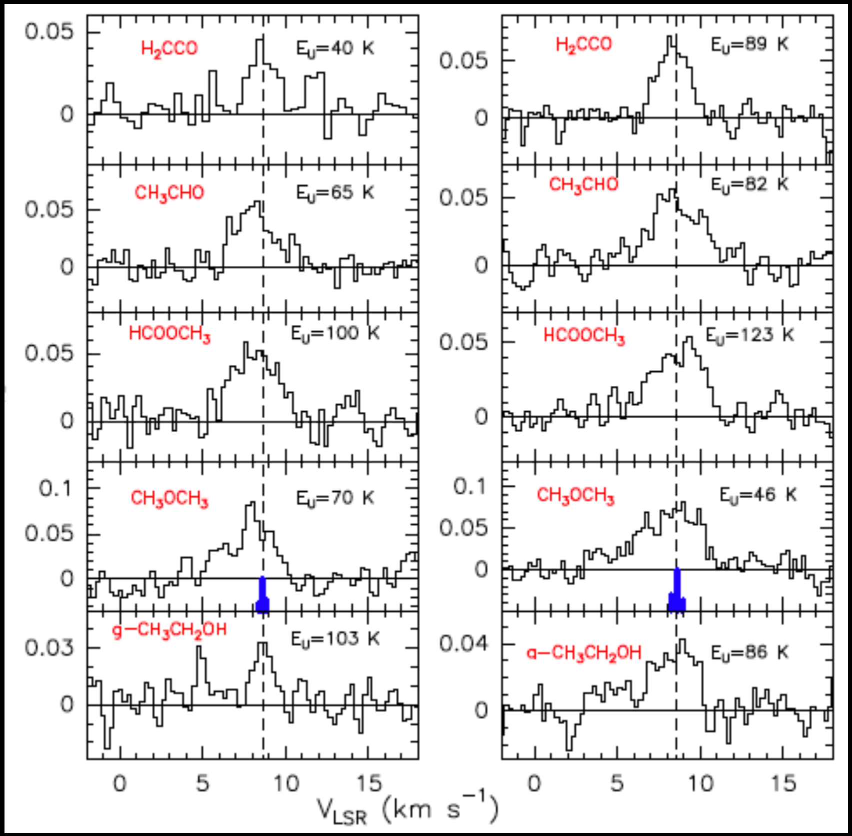
Molecular deuteration is lower by a factor of 10 to 100 in the Class I hot corino

Bianchi et al. (2017)
Codella et al (2016)

Hot Corinos in the Class I stage

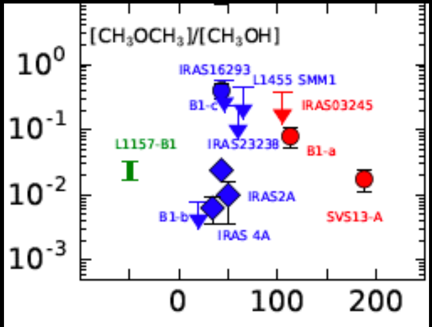
See poster by Eleonora Bianchi

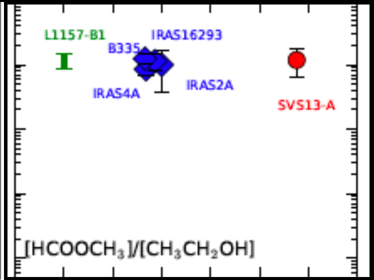
COMs around SVS13A



Bianchi et al. (2019)

Hot gas (Trot > 45 K)
High abundances: (0.1 - 1)(-8)
Size : 0.3'' (PdBI)





Same relative abundances as in hot corinos from Class 0

Prebiotic Molecules: NH_2CHO

The most simple amide and a molecule of prebiotic interest *(Saladino et al. 2012)*
A search for NH_2CHO (and HNCO) in the different stages of protostellar evolution

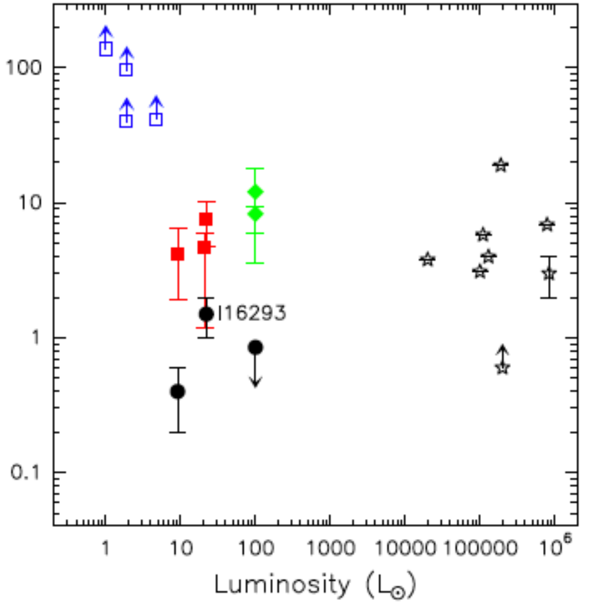
Lopez-Sepulcre et al. (2015)

ASAI: Search for NH_2CHO in solar-type environments

	Source	d (pc)	M ($M_\odot$)	L_{bol} ($L_\odot$)	Type
Not detected	TMC1	140	21	—	PSC - young
	L1544	140	2.7	1.0	PSC - evolved
	B1	200	1.9	1.9	Class 0 - early
	L1527	140	0.9	1.9	Class 0, WCCC
	L1157-mm	325	1.5	4.7	Class 0, WCCC?
Detected	IRAS 4A	235	5.6	9.1	Class 0, HC
	SVS 13A	235	0.34	21	Class 0/1
	OMC-2 FIR 4	420	30	100	IM proto-cluster
	Cep E	730	35	100	IM protostar
	L1157-B1	250	—	—	outflow shock

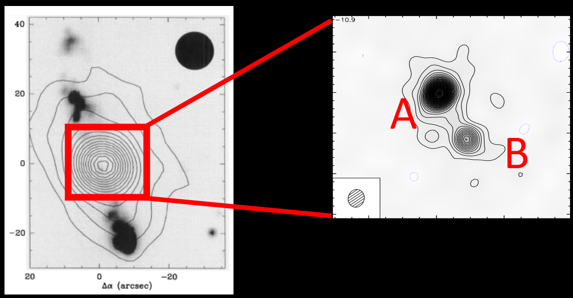
NH_2CHO is detected only in hot corinos sources and shocks

R = HNCO/NH_2CHO= 3-10



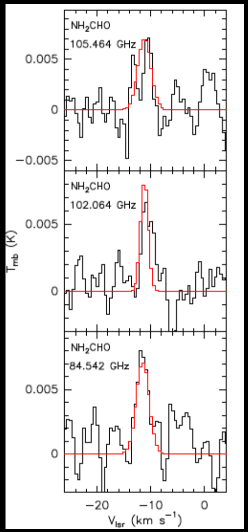
Is there a link between HNCO and NH_2CHO ?

NH_2CHO and HNCO in CepE-mm

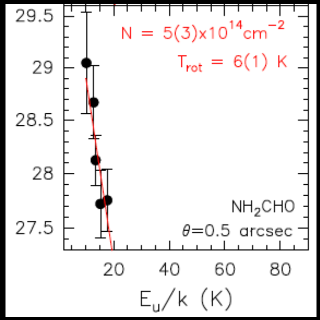


CepE-mm : L= 100 L_{sun}
M= 2-5 M_{sun}
d= 730 pc

IRAM 30m: Cold Envelope

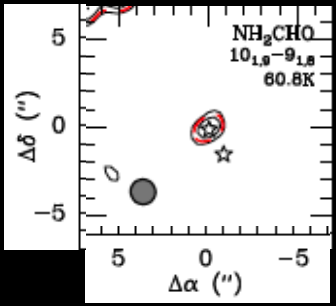


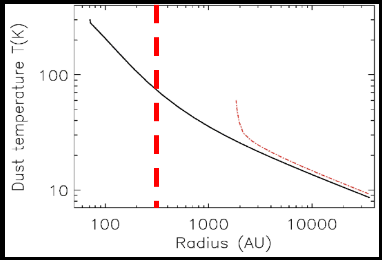
Lopez-Sepulcre et al. (2015)



Low Excitation: Trot=6K
$X(NH_2CHO)$= (4 +/- 2) $x10^{-12}$
$HNCO/NH_2CHO$= 3

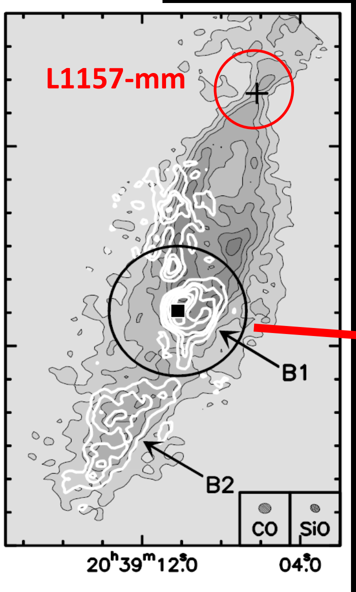
NOEMA (1.4''): Hot Corino



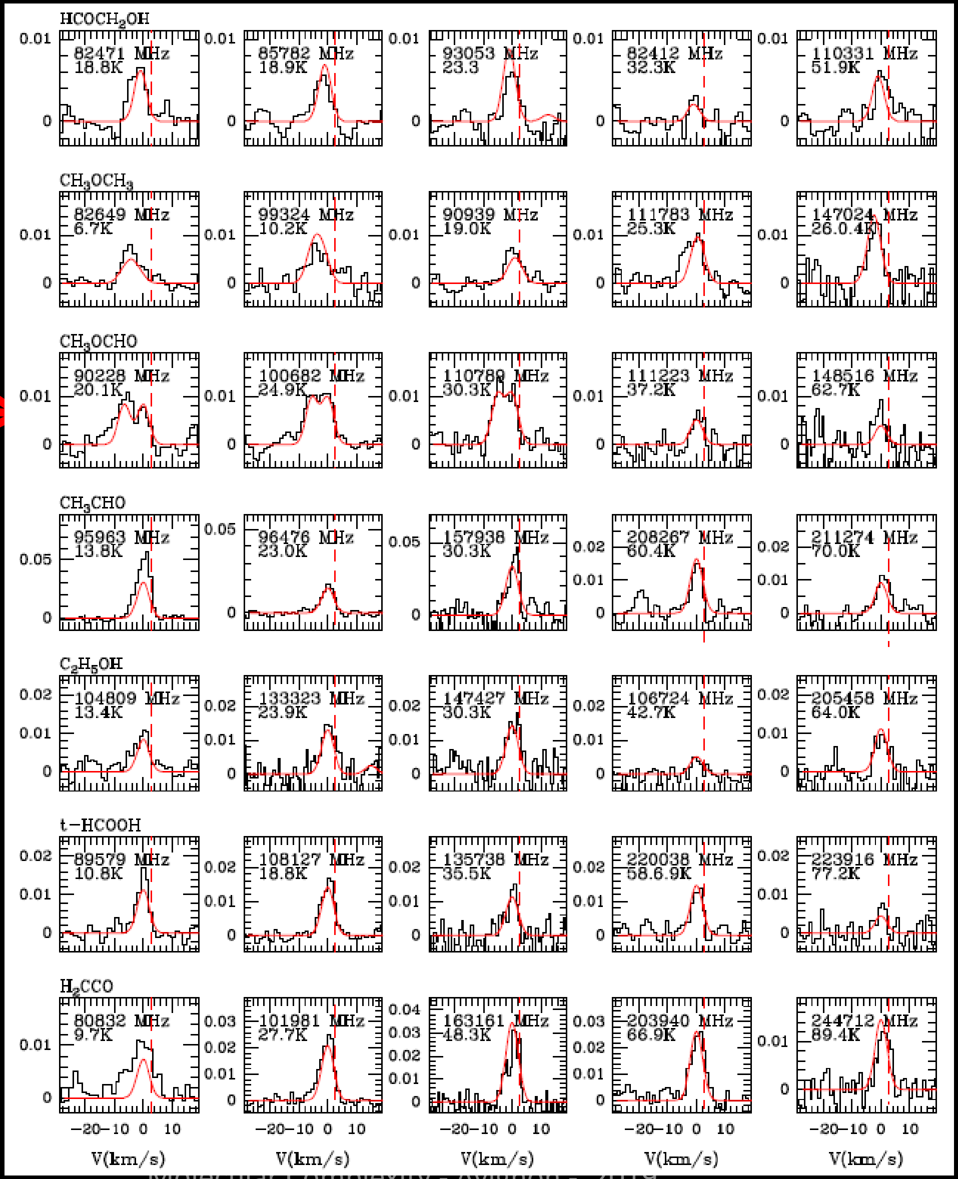


Size (FWHM)= 0.7'' = 510 AU
Td= 70 -100K
$X(NH_2CHO)$= 5 $x10^{-10}$
$HNCO/NH_2CHO$= 3

Shocks as Laboratories for COMs



Gueth et al. (1996,98)



CH_2OHCHO

CH_3OCH_3

CH_3OCHO

CH_3CHO

C_2H_5OH

$HCOOH$

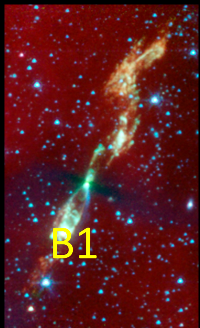
H_2CCO

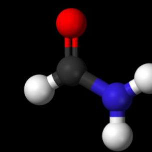
Lefloch et al. (2017)

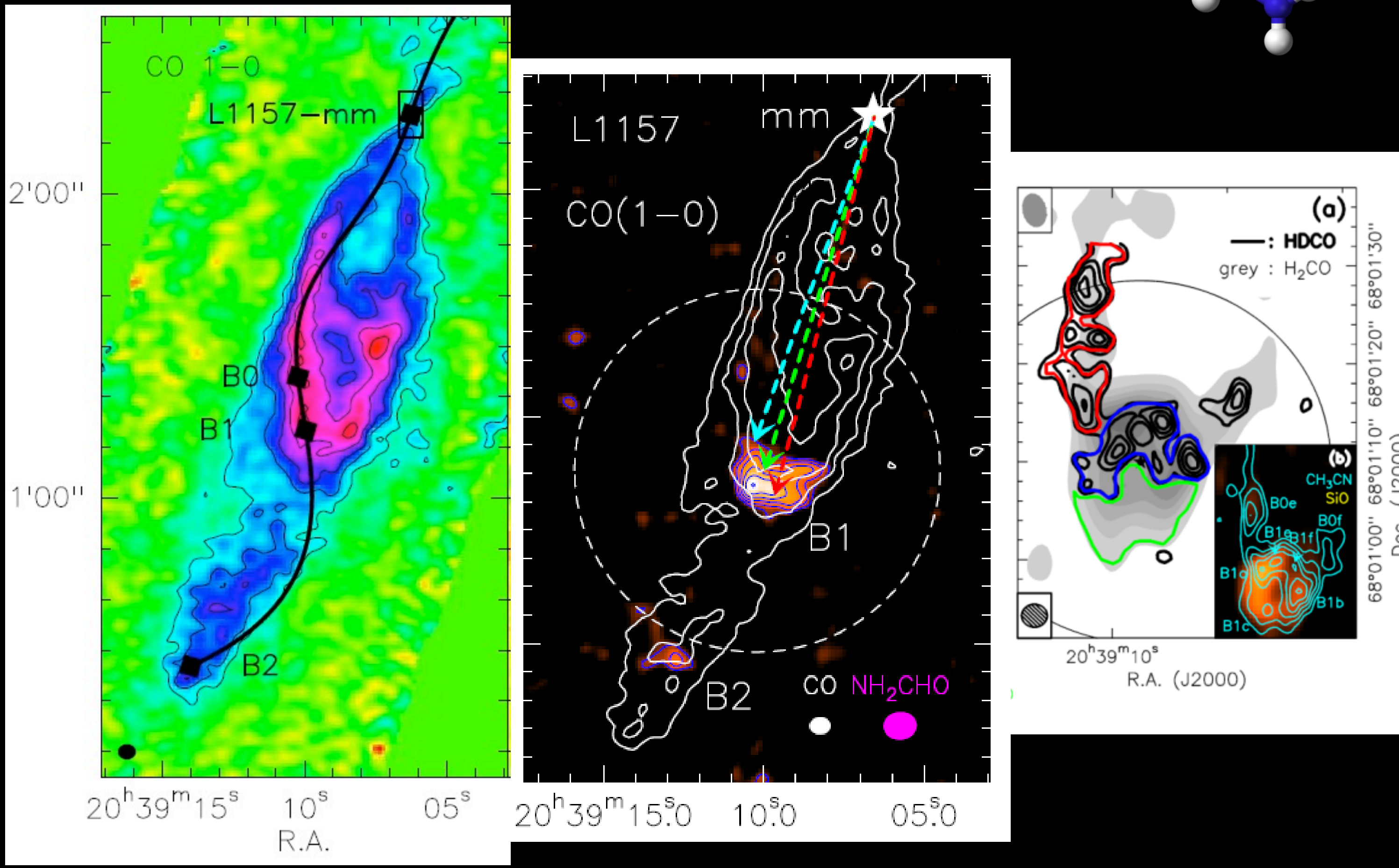
- NH_2CHO, CH_3CN, C_2H_3CN, HC_5N
- CH_3SH

Similar abundances:
X = (2-5)% X[CH_3OH]

Shocks as Laboratories for COMs



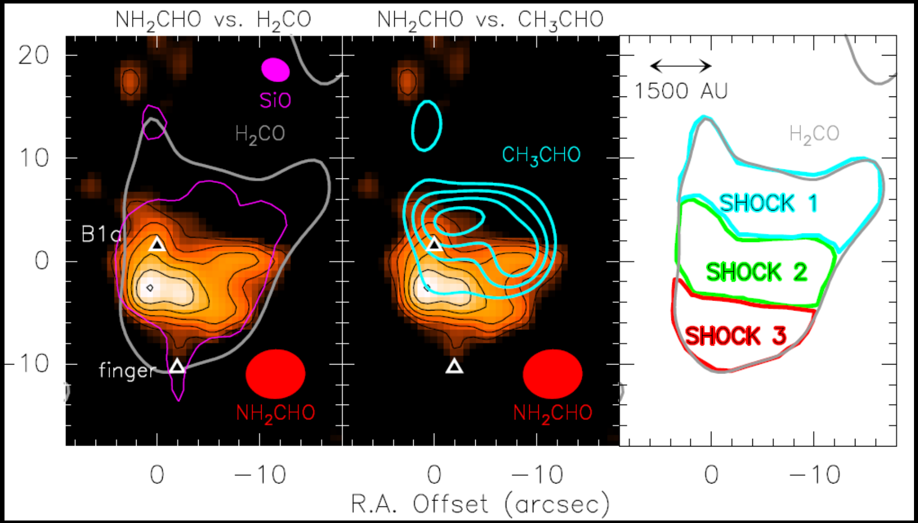




(Codella et al.2017)

New insight with SOLIS

(Codella et al.2017)



NH_2CHO is detected in the older shock #3

Spatial distribution matches with SiO

does not match with HDCO

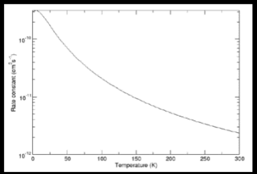
NH_2CHO: Formation route

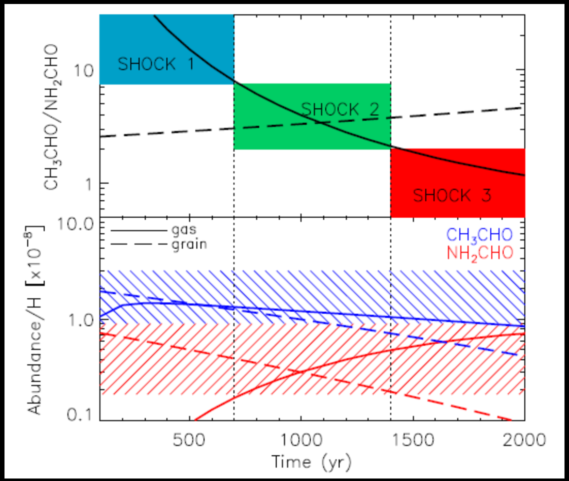
Sputtering from grain mantles (dashed)

Gas phase (solid)

$$NH_2 + H_2CO \rightarrow NH_2CHO + H$$

Barone et al. (2015)

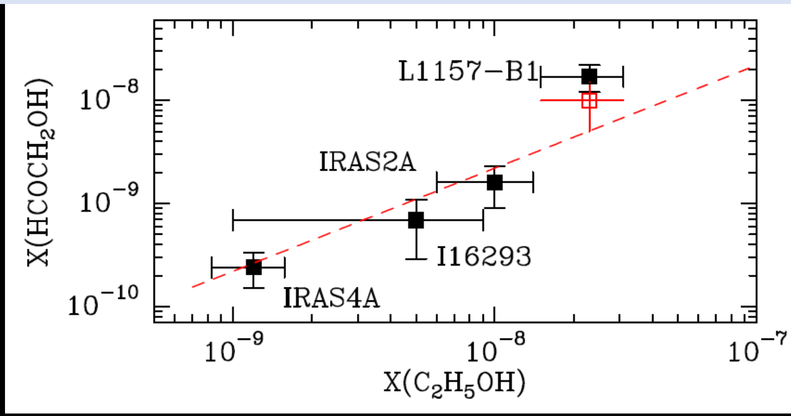




Gas phase formation route is favored

Glycolaldehyde

Linear correlations: a common origin ?



Which formation route for glycolaldehyde ?

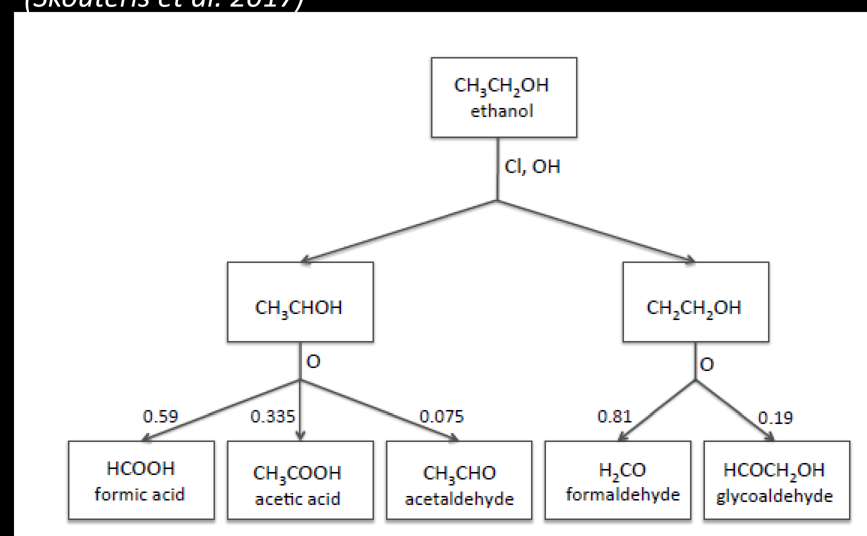
Grain surface ($CH_3OH + HCO$) ?

Gas phase ($H_2CO^+ + H_2CO$) ?

Woods et al. (2012, 2013)

A New Scheme: The Ethanol Tree

(Skouteris et al. 2017)



See Poster by Fanny Vazart

Summary and Future Prospects

Molecular Complexity

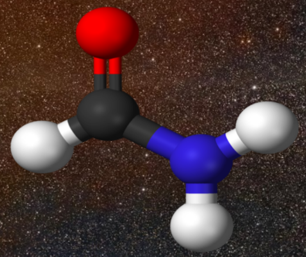
- is already present in the earliest phases of star formation
- is quite similar between low- and high-mass SFRs (N-chem.diff. ?)

Chemical differentiation is observed at large and small scales: why ?

Feedback processes (shocks) are important and drive a rich chemistry. They are true laboratories to characterize molecule formation pathways.

NOEMA and ALMA are opening a new window on Molecular Complexity.

A pluridisciplinary approach combining observations, laboratory exp. and modelling is needed to understand the chemical evolution of protostellar envelopes.



Thanks

With the help of the DOC Team and all the ASAI team collaborators for this fantastic and so successful journey

C. Kahane, C. Ceccarelli, J. Cernicharo, C. Codella, A. Fuente, A. Lopez-Sepulcre, C. Vastel, E. Caux, M. Tafalla, E. Bianchi, P. Caselli, A. Gomez-Ruiz, P. Hily-Blant, J. Holdship, I. Jimenez-Serra, E. Mendoza, J. Ospina-Zamudio, S. Pacheco, L. Podio, E. Roueff, N. Sakai, B. Tercero, P. de Vicente, S. Viti, S. Yamamoto, K. Yoshida, T. Monfredini, H. Quitian