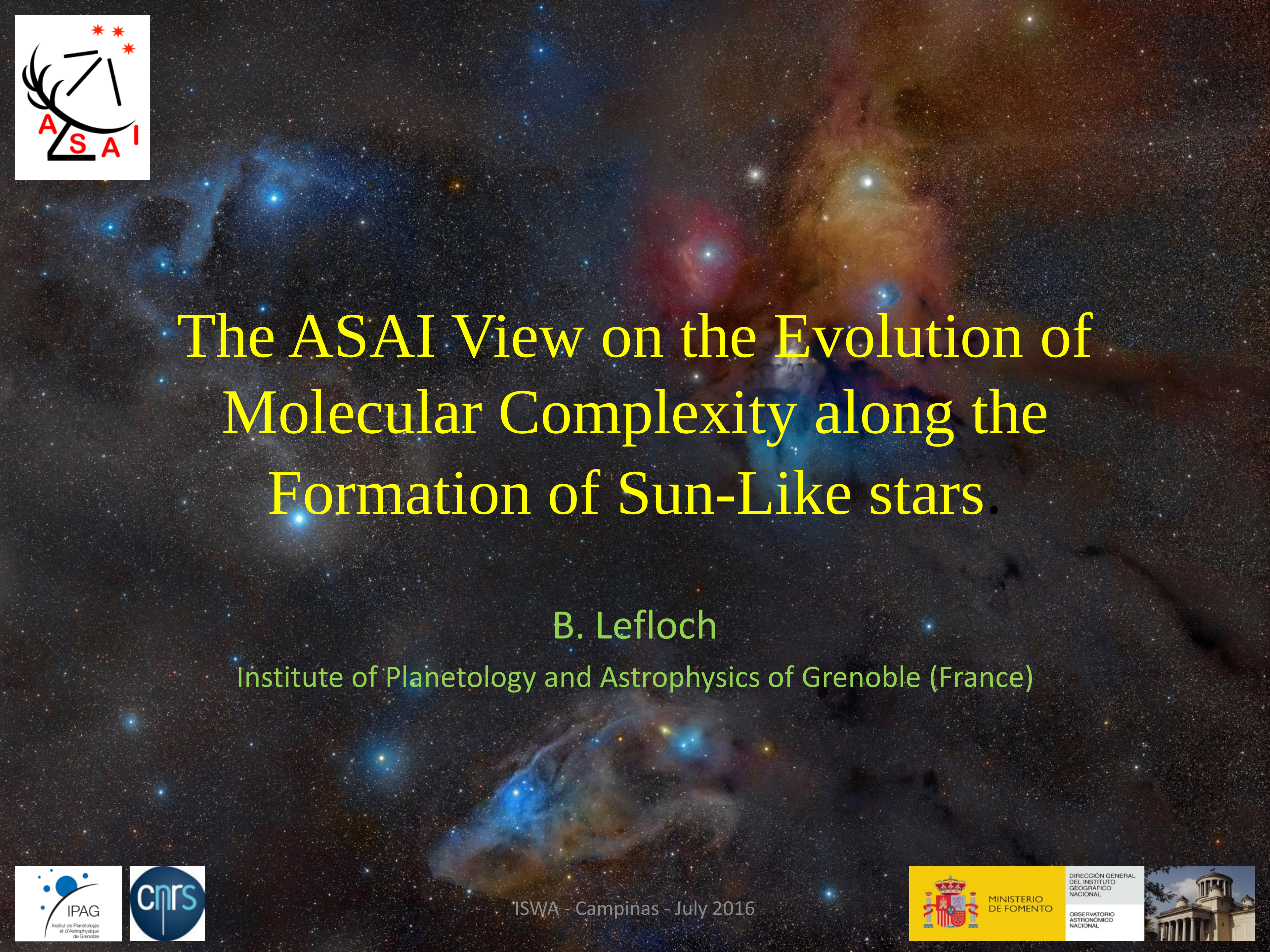


The ASAI View on the Evolution of Molecular Complexity along the Formation of Sun-Like stars.

B. Lefloch

Institute of Planetology and Astrophysics of Grenoble (France)

Outline

Introduction

Molecular complexity in the Prestellar phase

Feedback processes

Prebiotic chemistry

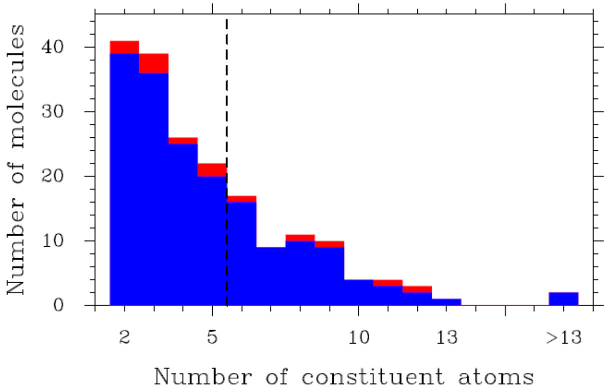
Protostars: from ASAI to SOLIS

Conclusions

Molecular Complexity in the Universe

2	3	4	5	6	7	8	9	10	11	12	13 atoms
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	$HC_{11}N$
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	$C_2H_5OCH_3$	
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH?	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	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		
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				
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		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^+										
HF	SiCN										
HD	AlNC										
FeO?	SiNC										
O_2	CCP										
CF^+	AlOH										
SiH	H_2O^+										
PO	H_2Cl^+										
AlO,	KCN										
OH^+,	FeCN										
CN^-	HO_2										

+ C_{60}, C_{70}



200 molecules discovered

Complex Organic Molecules : ≥ 6 atoms + C atoms

(Herbst & van Dishoeck, 2009)

30% of molecules are COMs, including :

Aminoacetonitrile : NH_2CH_2CN (Belloche, 2008)

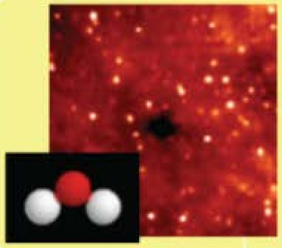
Branched alkyl molecules i-C_3H_7CN (Belloche, 2014)

Propylene oxyde CH_3CHCH_2O (McGuire 2016) ?

What about Low-Mass Star Forming Regions ?

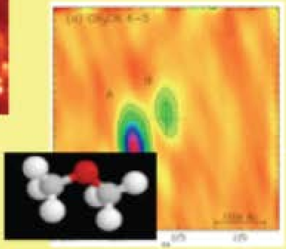
Molecular Complexity and Star Formation

An astrochemical view of solar-type star formation



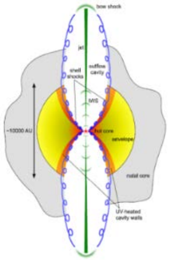
1- PRE-STELLAR PHASE: cold and dense gas
FORMATION OF SIMPLE MOLECULES

Superdeuteration

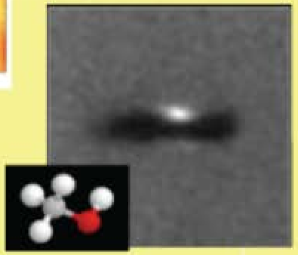


2- PROTOSTELLAR PHASE: collapsing, warm dense gas
FORMATION OF COMPLEX MOLECULES

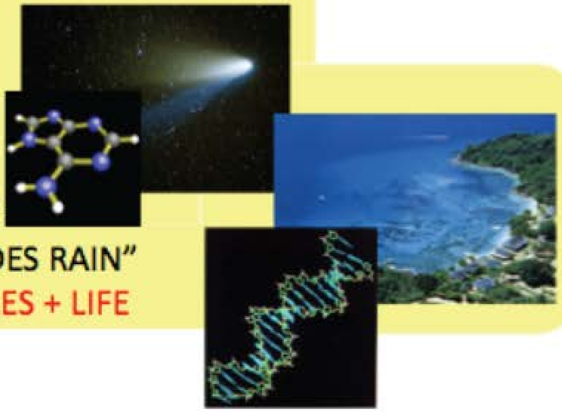
Hot Corino



Van Dishoeck et al. (2010)



3- PROTOPLANETARY DISK PHASE:
cold and warm dense gas
SIMPLE & COMPLEX MOLECULES

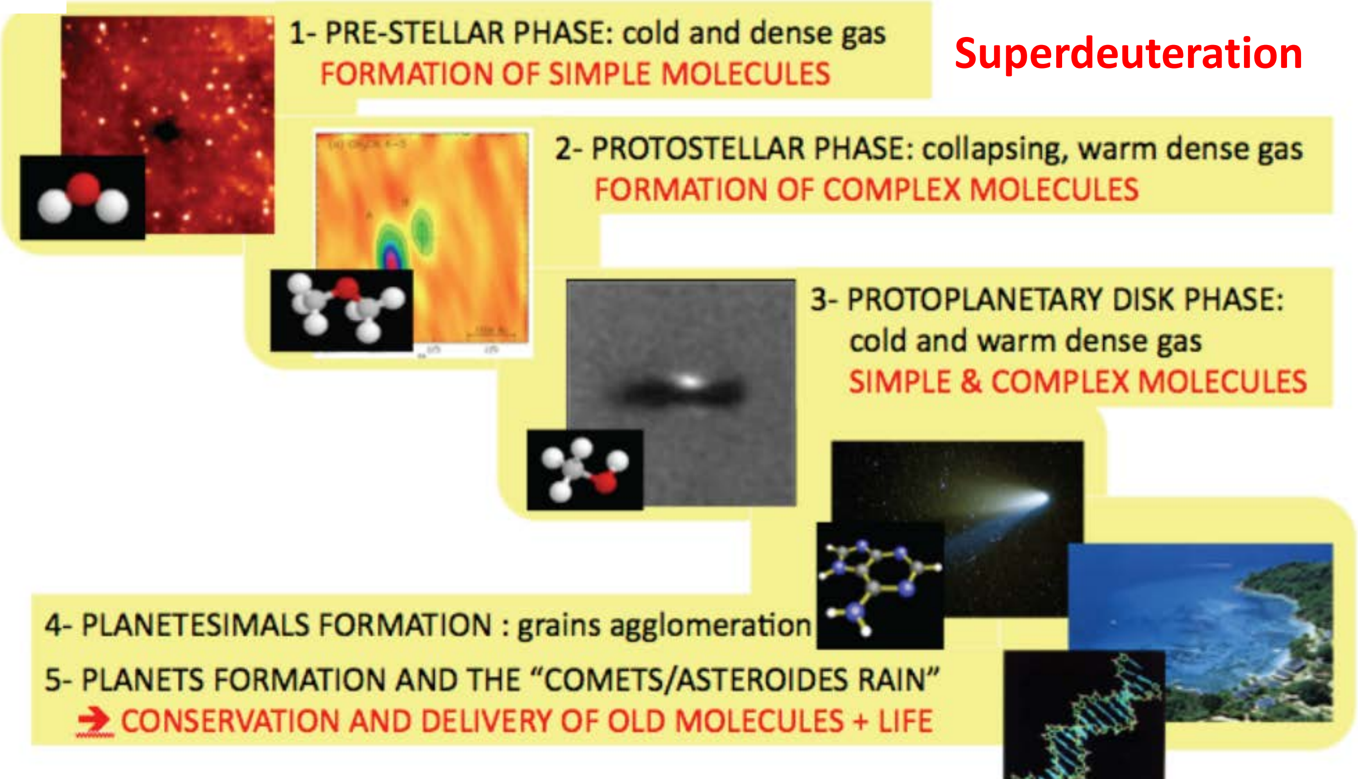


4- PLANETESIMALS FORMATION : grains agglomeration

5- PLANETS FORMATION AND THE "COMETS/ASTEROIDES RAIN"
➔ CONSERVATION AND DELIVERY OF OLD MOLECULES + LIFE

Molecular Complexity and Star Formation

An astrochemical view of solar-type star formation



1- PRE-STELLAR PHASE: cold and dense gas
FORMATION OF SIMPLE MOLECULES

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FORMATION OF COMPLEX MOLECULES

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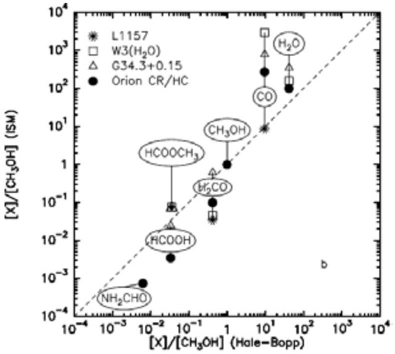
Superdeuteration

Hot Corino

Composition of Hale-Bopp // L1157

Bockelee-Morvan et al. (2000)



Open Issues

Are meteoritic and cometary amino-acids pristine interstellar molecules ?
Are such molecules widespread in the Galaxy and in star-forming regions ?
Which memory is kept by the small bodies of the Solar System ?

Our view of chemical evolution is incomplete

- Molecular composition of the prestellar phase is poorly known
e.g. : CH_3CHCH_2 was discovered as abundant as c-C_3H_2 *(Marcelino et al. 2007)*

- Some protostars do not exhibit a hot corino BUT a rich content in C-chains *Sakai et al. (2008)*
→ Is there any other "chemical class" of protostars and why ?

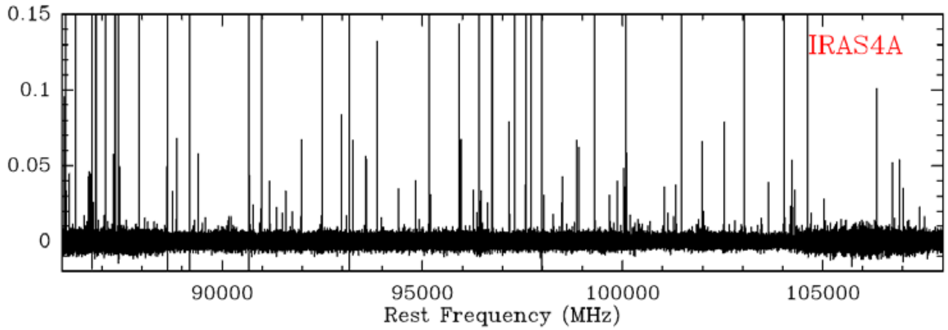
- Not many protostars are "well known" ?… Are they freaks ?

Which molecular complexity along SF can be reached and how does it evolve ?

Which role do Feedback processes play ? outflow/shocks, UV radiation

Which processes drive the formation/destruction of molecular species ?

Why Line Surveys ?



Unbiased Spectral Line Surveys

- A large number of lines: large frequency coverage to probe a wide range of A_{ij}, E_{up} n, T, **v** + isotopologues
- No (important) missing line(s) : unbiased
- Full chemical census : parent, daughter molecules, radicals, etc…

Serendipitous discoveries: CH_3COOCH_3 (Tercero et al. 2013), CH_3CHCH_2 (Marcelino et al. 2007), …

Secure identification requires

- Good knowledge of the source structure (gradients (X, T, n, v) should be consistent) Emission may be extended (filtered ?)… → Mapping
- No conflict with other molecules : model emission of various molecules (consistent relative intensities and line blending)

Recent Advances in Radioastronomy

2011 : A few GHz bandwidth ☺

Broad band Low-Trec 2SB receivers (+ backends)
IRAM 30m : Spectal range 70 – 360 GHz
Bandwidth : 32 GHz instantaneous (soon 64 GHz)
Resolution **:** 50 to 200 kHz

Observational uncertainties (rel. calibration/pointing) are less

Full mm line survey : 200hrs → 50hrs !

Spectral Line Surveys are becoming the reference tool

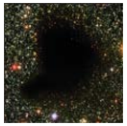
Astrochemical Surveys At IRAM

PI : B. Lefloch (IPAG) & R. Bachiller (OAN)

ASAI (400hrs) : a Legacy Chemical Survey of Solar-Type SFRs
1- to obtain an evolutive view of chemistry
2 - to constrain the influence of environmental conditions

Unbiased spectral surveys 70-272 GHz of a sample of 10 template sources of the different stages of solar-type star formation with the IRAM 30m telescope (+Herschel)

Prestellar cores: young / evolved

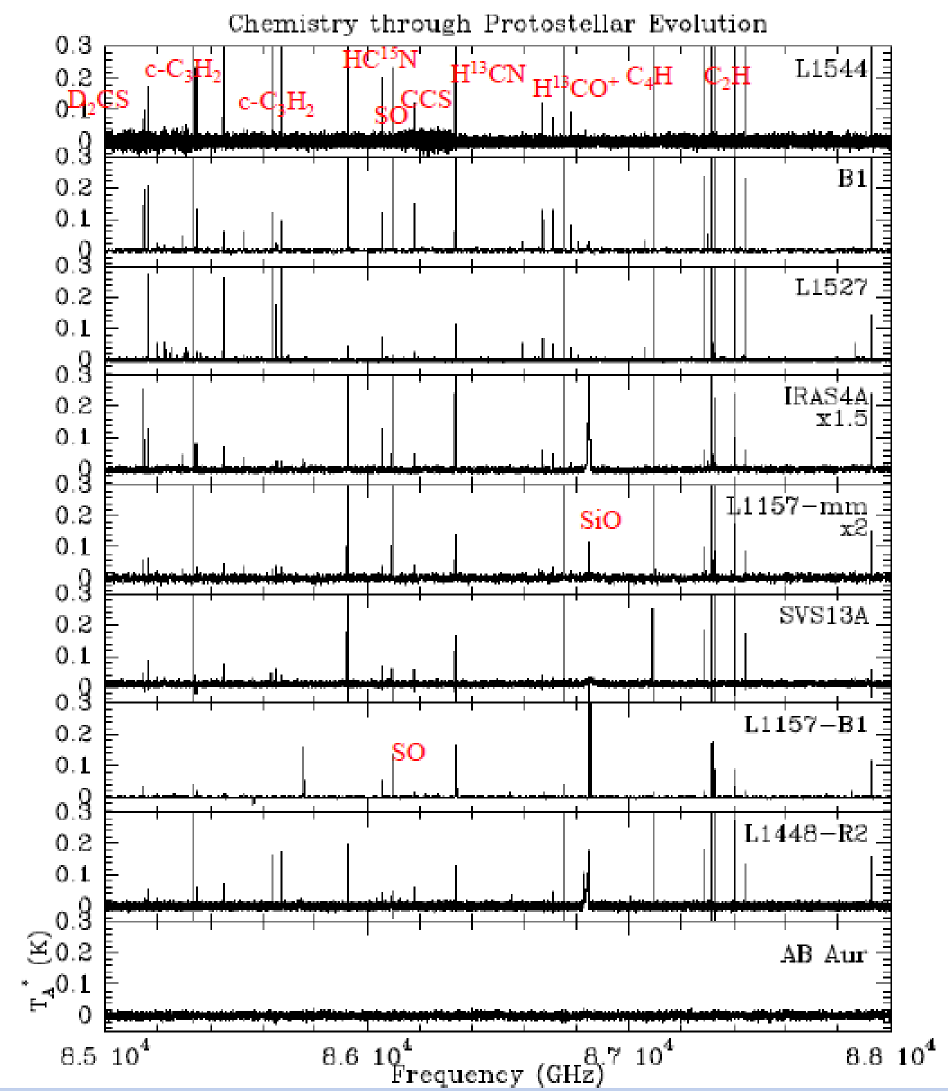


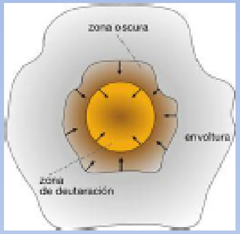
Class 0/I/II : Early / Hot Corino / WCCC
+ 2 Int. Mass protostars: Isolated/Cluster

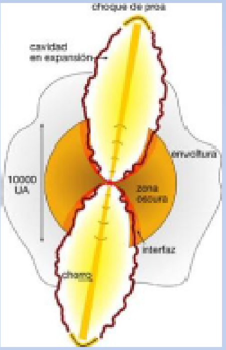
Shocks

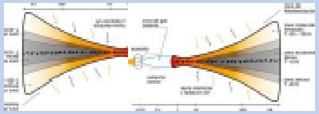
1. Census of the molecular composition: source intercomparison → time, env. conditions
2. Derive chemical composition/structure of the sources:
comparison with models → quantify chemical differentiation : how and when
3. Characterize the physical and chemical processes at work

Chemical Differentiation







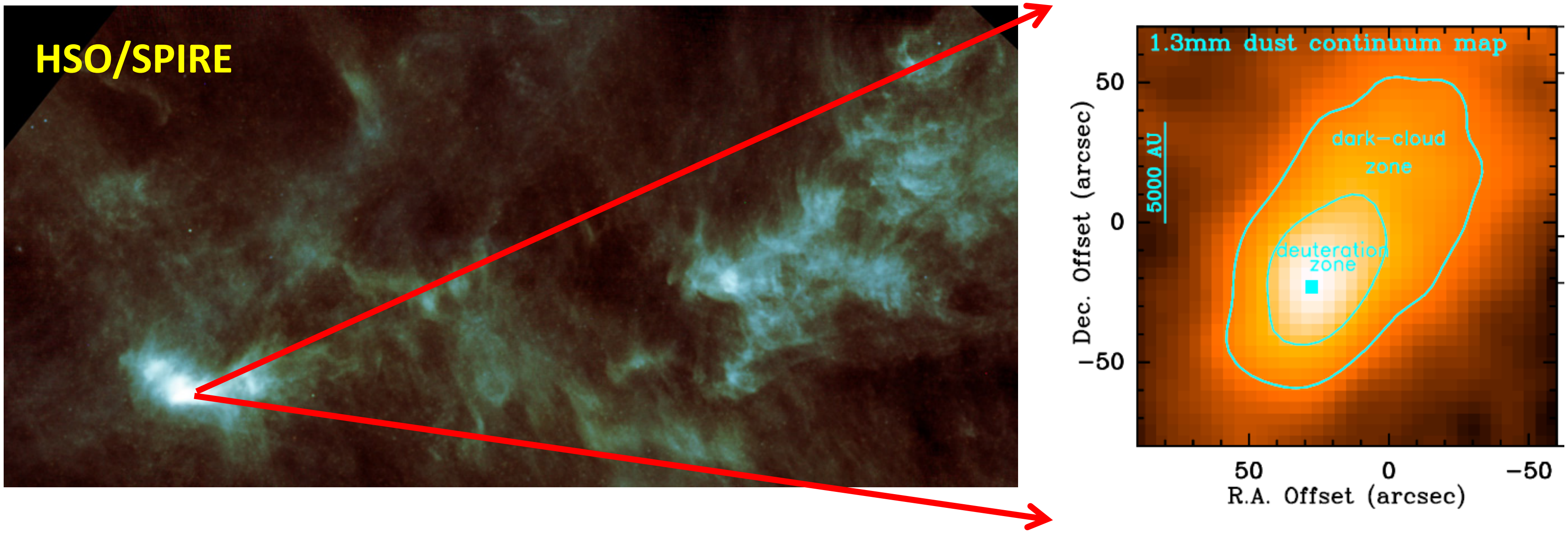


Time

The Prestellar Phase

L1544 as prototype of prestellar cores

A prestellar core in Taurus (d=140pc)

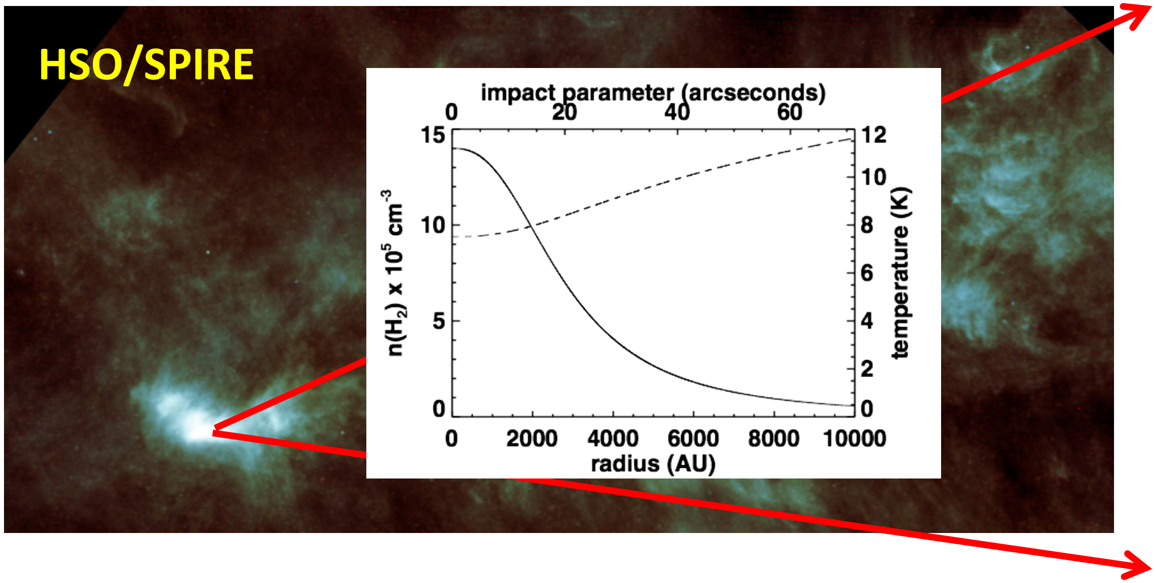


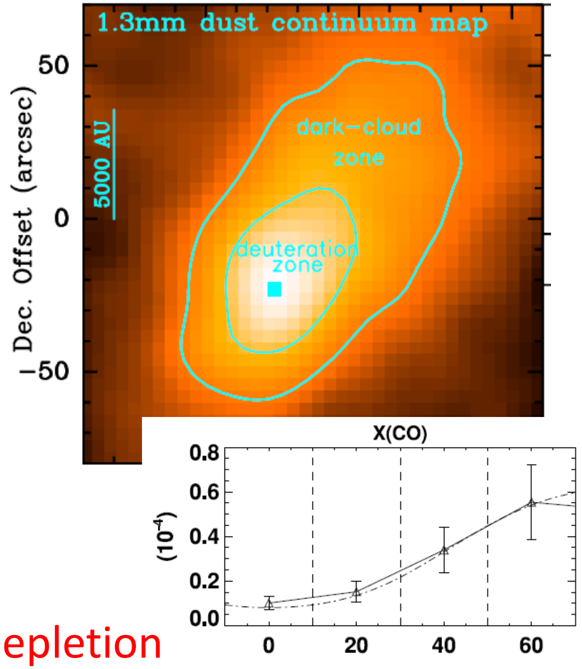
Ward-Thompson et al. (1999)

L1544 as prototype of prestellar cores

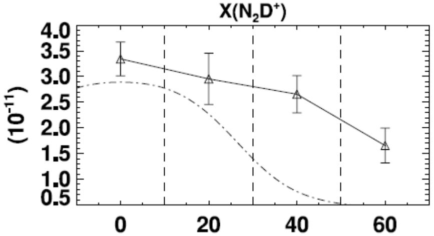
A prestellar core in Taurus (d=140pc)

Ward-Thompson et al. (1999)





Molecular depletion



Deuteration

Vastel (2006)

Density Profile

Envelope : n α r $^{-2}$:

$n(H_2) = 10^3 – 10^6$ cm^{-3} (center : r < 10^3 AU)

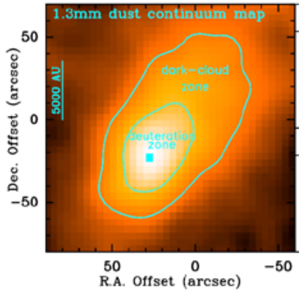
Temperature Profile

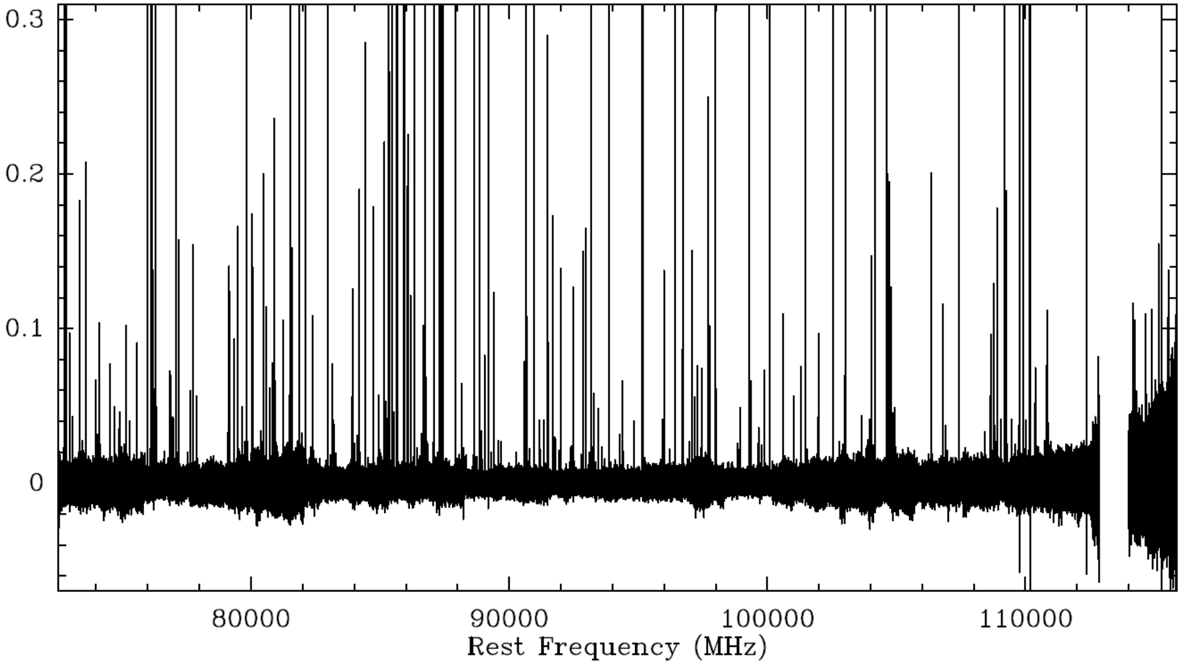
Envelope : 12K

Center : ~ 5.5-7K *(Crapsi 2007)*

The ASAI survey of L1544

Full coverage 72 – 116 GHz 50 kHz rms : 4 – 6 mK (0.15 km/s)





σ= 10 GHz $^{-1}$

C-chains

Cyanopolyynes

Deuterated species

New Molecular Species

$HOCO^+$ Vastel et al. (2016),

+ hyperfine CH_2CN Vastel et al. (2015)

(stay tuned: more is coming soon)

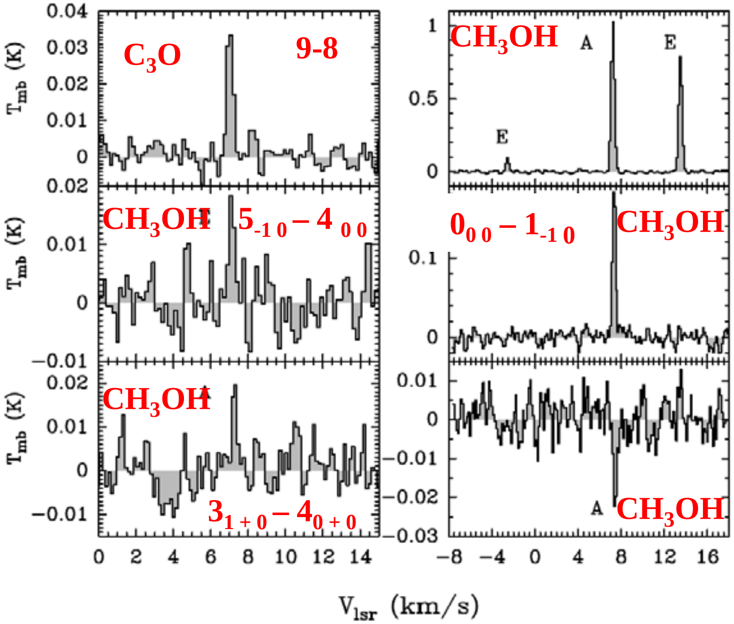
A large degree of molecular complexity degree is already present in the prestellar phase

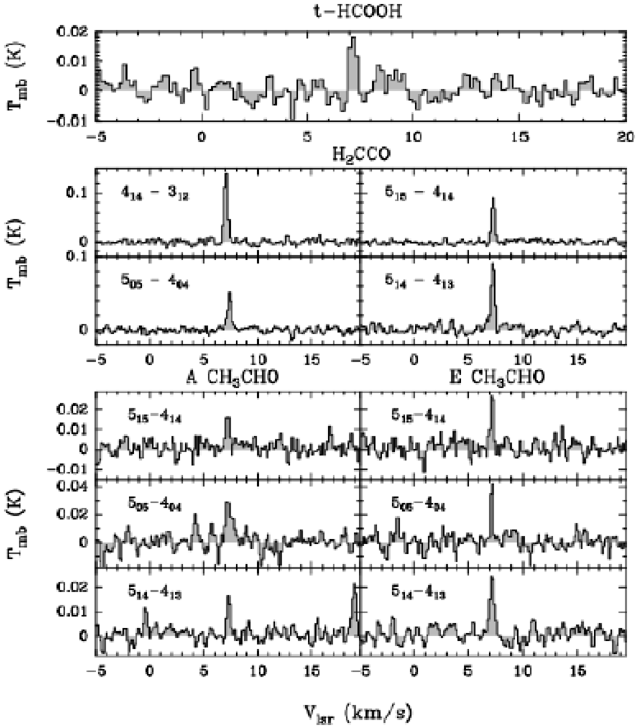
Complex Organic Molecules:

N-, C-, O-bearing

Complex Organic Molecules in L1544

Census of O-bearing COMs





Firm detections (> 5 σ)

CH_3OH (7)

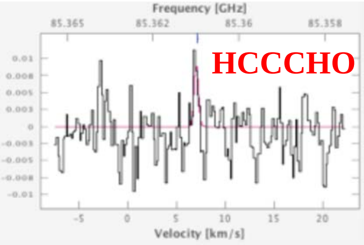
CH_3CHO (8)

t-HCOOH (1)

H_2CCO (4)

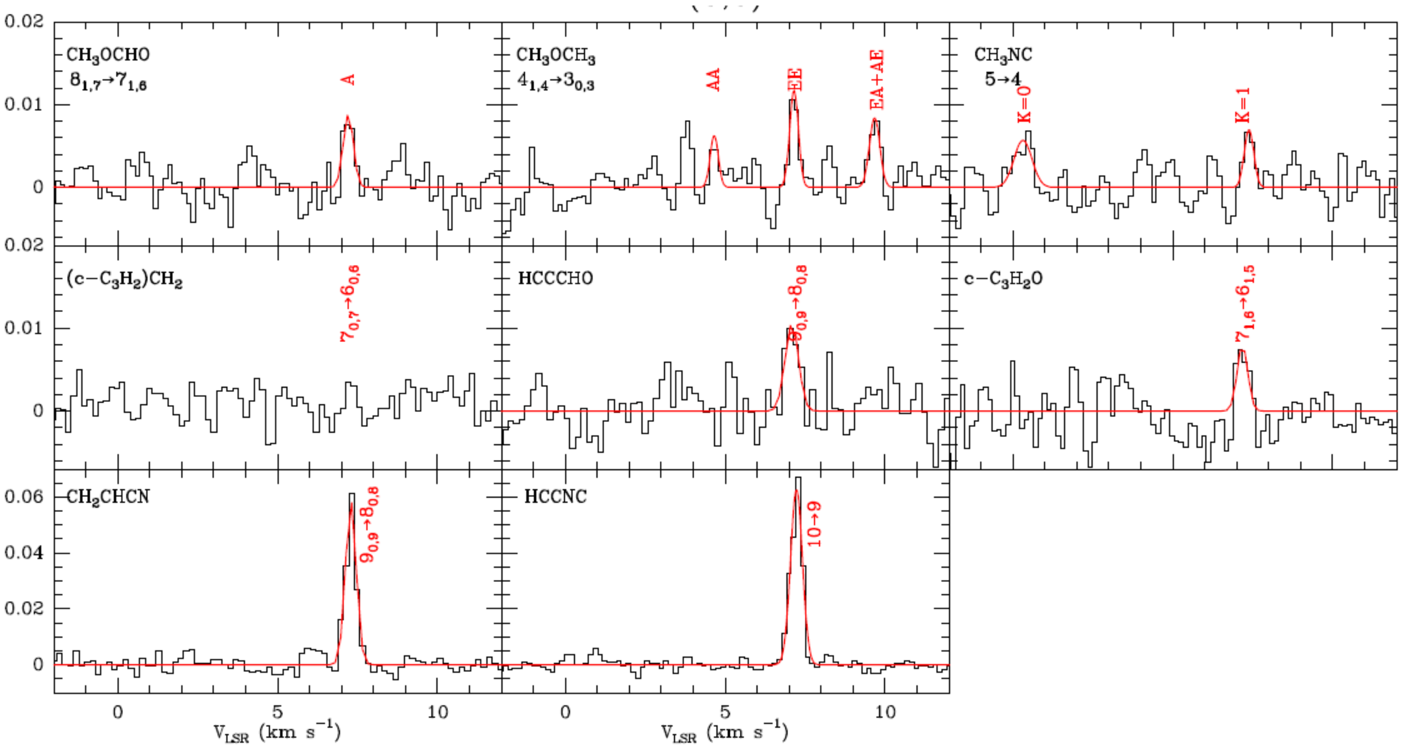
HCCCHO (3)

+ C_3O (3), HCO(4)



E_{up}= 5 – 30K

Complex Organic Molecules in L1544

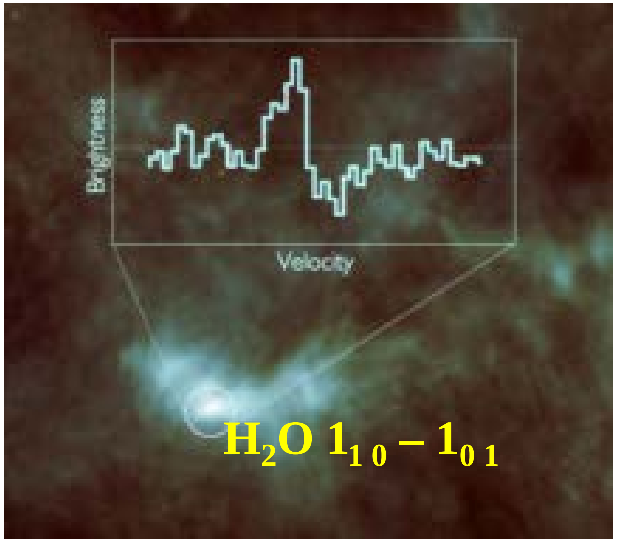


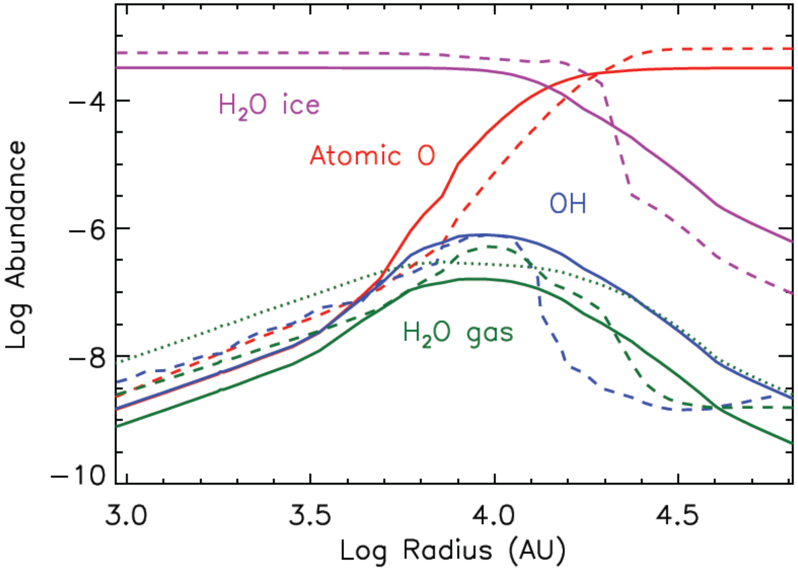
Jimenez-Serra et al. (2016)

Deeper integration (1 mK rms) : CH_3OCHO, CH_3OCH_3
+ N-bearing COMs

Water Emission in L1544

Caselli et al. (2012) Keto et al. (2014)





Gravitational contraction of the envelope

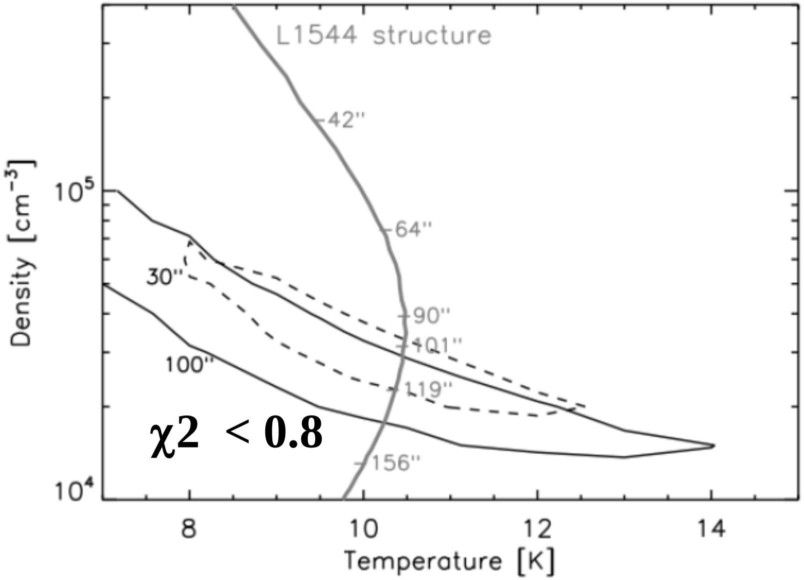
H_2O : Abundances Xi ≈ 10^{-9} Xe ≈ 10^{-7}

Photodesorption of H_2O ices due to :

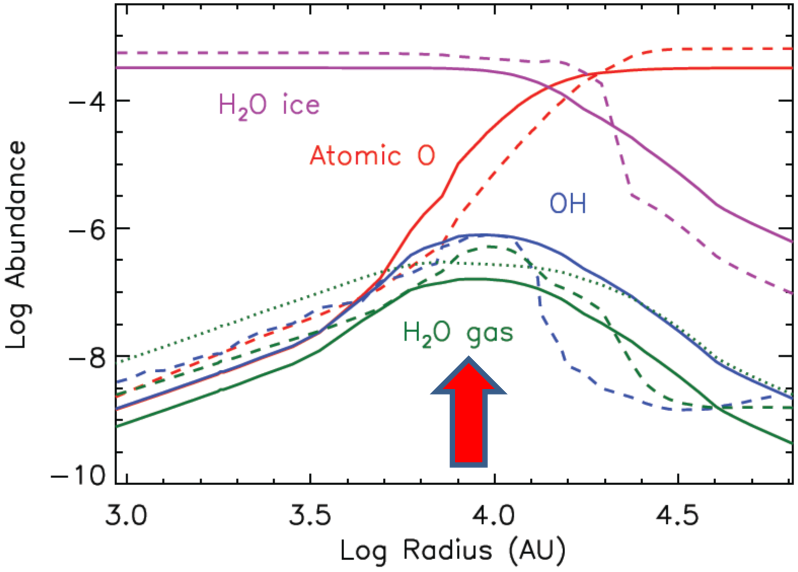
FUV photons in the external envelope (r > 5000 AU)
CR-H_2 interaction → dim FUV field ≈ 10^{-3} G_0

CH_3OH Emission

Comparison with the radial structure of L1544 *(Caselli et al. 2012)*



$\chi2 < 0.8$



Keto et al. (2014)

CH_3OH arises

- from the low-density, outer layers at 7000-10000 AU from the core center
- from the region of strong water ice UV-photodesorption

CH_3OH is produced in the outer layers of L1544: likely to be (photo?)desorbed from the ice mantles of dust grains

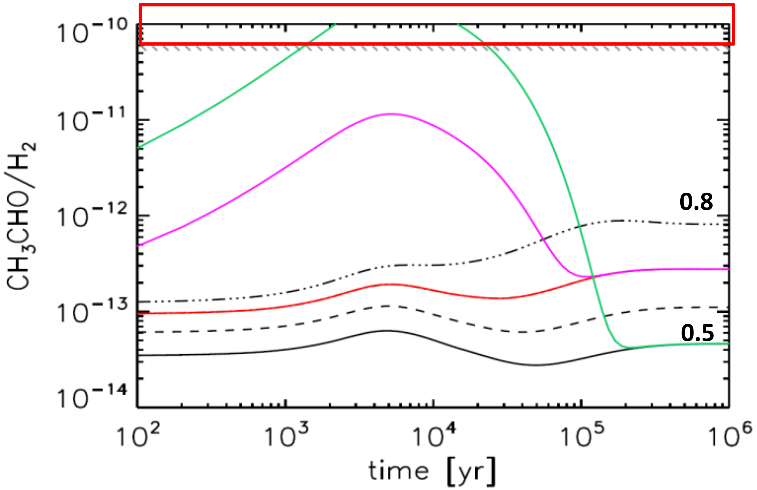
A simple model

The detection of COMs at T=10K is a challenge for models

NAHOON: time-dependent gas phase chemistry code ***(Wakelam et al. 2012;*** *Loison et al. (2014)*

[CH_3OH] and [C_2H_4] are increased and released in the gas phase

CH_3CHO



Non-thermal desorption of CH_3OH and C_2H_4 from grain mantles + gas phase reactions could account for the formation of some COMs *in the gas phase* : CH_3OH, H_2CCO

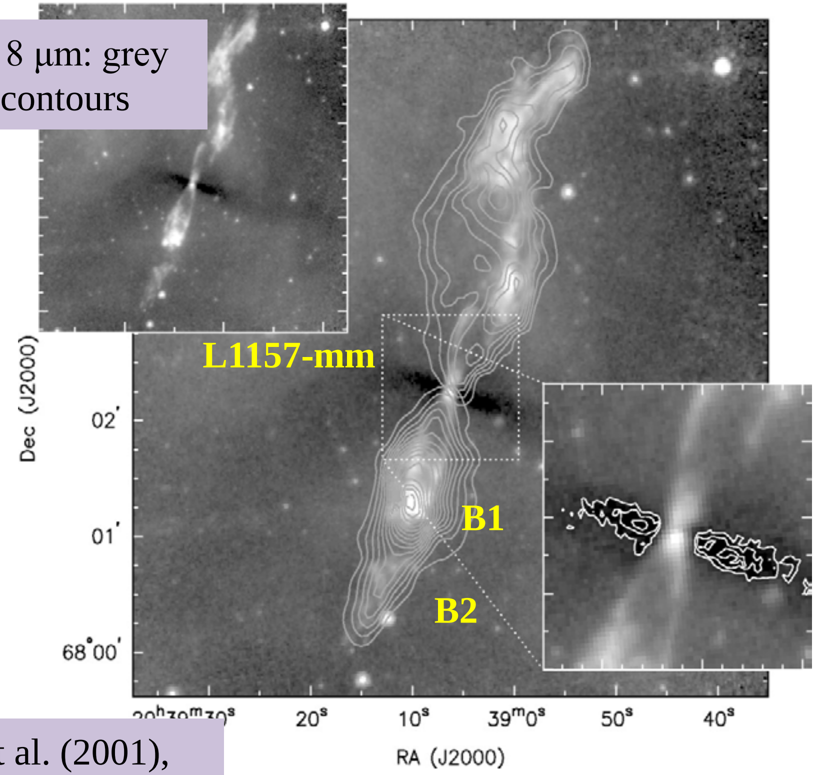
CH_3OH : 1(-8)
C_2H_4 : 5(-9)

➡ **Non-Thermal desorption mechanism ?**

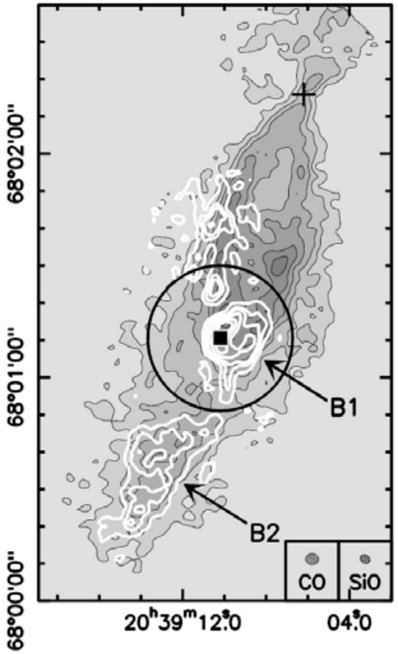
Feedback processes

Outflow Shocks

Spitzer 8 µm: grey
CO: contours



Bachiller et al. (2001),
Looney et al. (2007),
Neufeld et al. (2009)



Gueth et al. (1996,98)

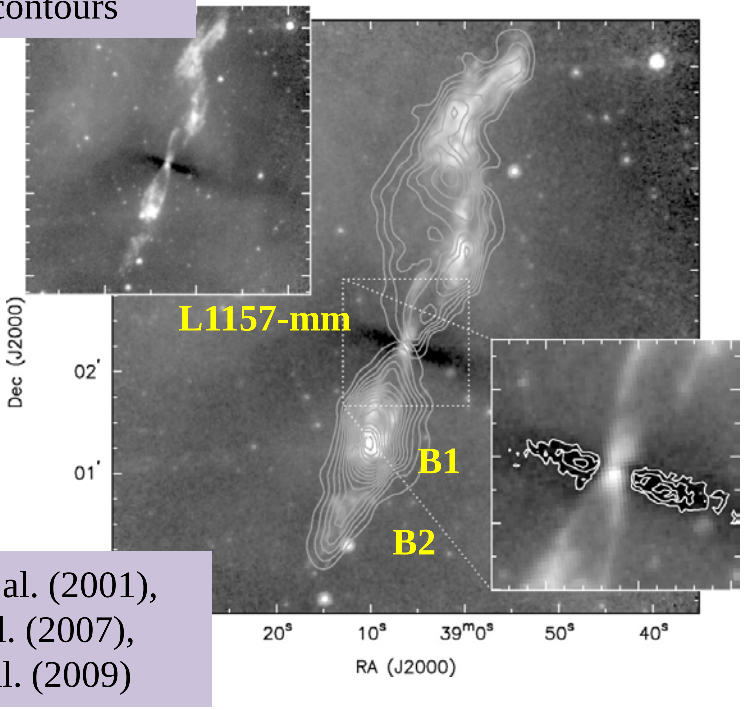
Outflows interact with the parental cloud through *shocks*

L1157 : Distance: 250 pc
Driving source: Class 0 L1157-mm (L= 4-11 L_o)
Precessing molecular outflow associated with several bow shocks seen in CO and in H_2.

Outflow Shocks

L1157 is the prototype of Chemically Active Outflows

Spitzer 8 µm: grey
CO: contours



Bachiller et al. (2001),
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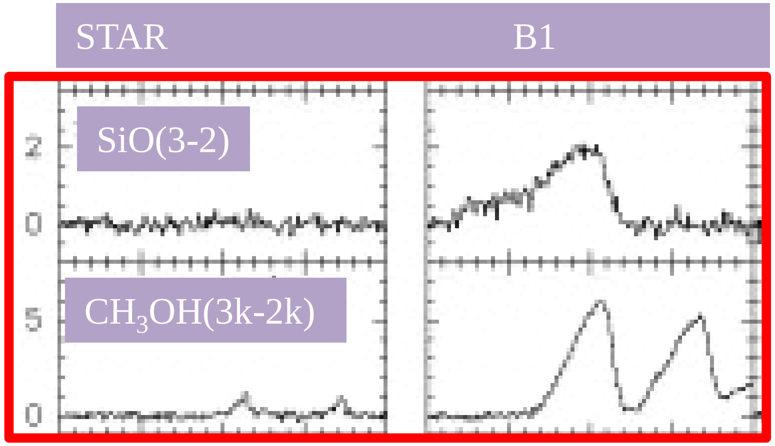
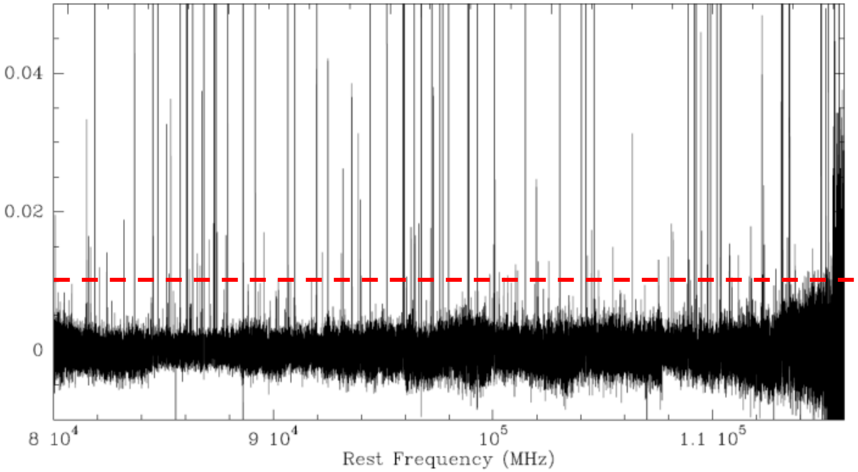


L1157-B1 : bright molecular shock
→ Evidence for grain mantle/core sputtering and dust shattering : CH_3OH/SiO
→ high-temperature gas phase reactions : HCN

Chemically active outflows are ideal laboratories to study shock chemistry.

Environmental Effects

L1157-B1 : Prototype of chemically active outflow shock (Bachiller et al. 2001)



80 – 116 GHz **:** 1σ ≃1.5mK
330 lines detected (3 σ)
spectral line density <s> = 9 GHz $^{-1}$

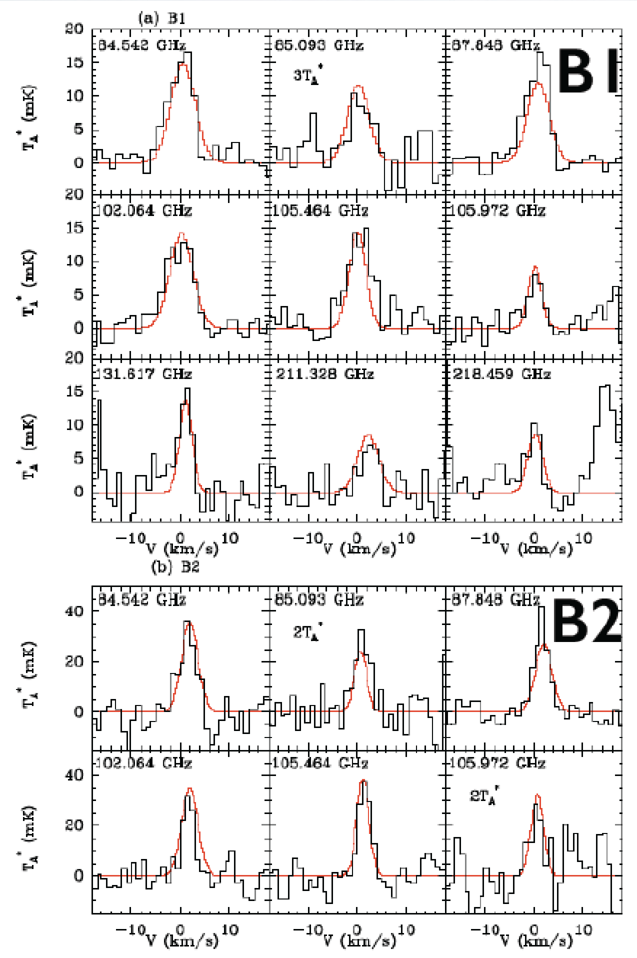
45 molecular species identified
(+ rare isotopologues)
10% of U lines

A New View on outflow shock gas
Physical conditions : n, T, ζ
pre-shock dust and gas composition

Full Census of Molecular Ions (Podio et al. 2014; Codella et al. 2014)
HCO^+, HOCO+, SO^+, HCS^+, N_2H^+

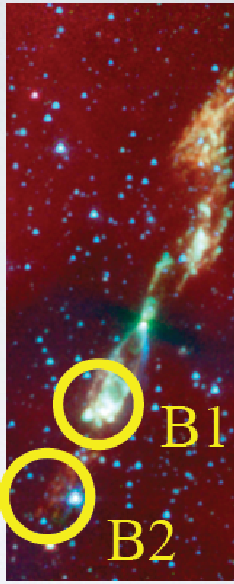
Cyanopolyynes : *Talk by E. Mendoza*

NH_2CHO around solar-type protostars



Detections:
B1: 23 lines
B2: 6 lines

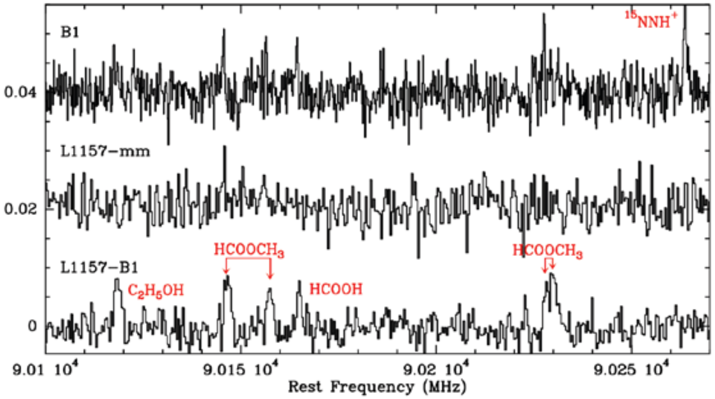
$X \sim 10^{-9} - 10^{-8}$
similar to high-mass!

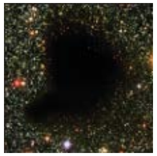


First discovery of NH_2CHO in protostellar shocks

Mendoza et al. (2014)

COMs in L1157-B1





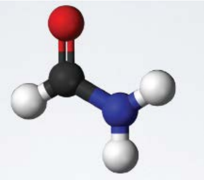
Species	L1157-B1	I16293in	I16293out	L1544
CH_3OH	1.5(-6)	3(-7)	4(-9) ?	6(-9)
H_2CCO	0.9(-8)	1(-10)	3(-11)	1(-9)
NH_2CHO	3.5(-9)	6(-10)	3(-12)	< 1(-11)
C_2H_5OH	1.7(-8)	< 5(-9)	< 0.8(-9)	?
HCOOH	0.7(-8)	< 3(-10)	< 0.8(-10)	1(-10)
CH_3CHO	2.9(-8)	3(-9)	1(-10)	1.6(-10)
$HCOOCH_3$	2.2(-8)	0.9(-8)	0.3(-10)	7(-10)
CH_3OCH_3	2.5(-8)	4(-8)	2(-10)	1(-10)

Shocks are an excellent laboratory to study COMs

- a chemical diversity comparable to hot corinos !
- Abundances are higher by x10 or more
- Mixed “cold/hot” abundance ratios…

Prebiotic Chemistry

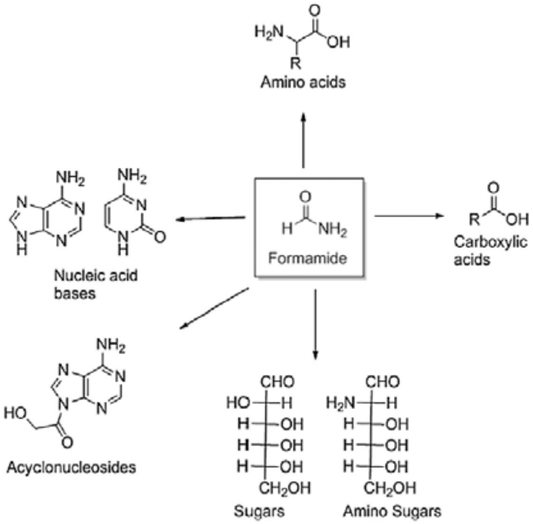
NH_2CHO



An important molecule for prebiotic chemical processes:

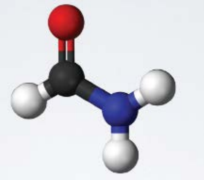
the simplest molecule with a peptide bond
with the four most abundant elements of biological systems: C,N,O,H

NH_2CHO could drive the synthesis of more complex, pre-biotic molecules involved in pre-genetic and pre-metabolic processes (Saladino et al. 2012; *Ferus et al. 2015)*

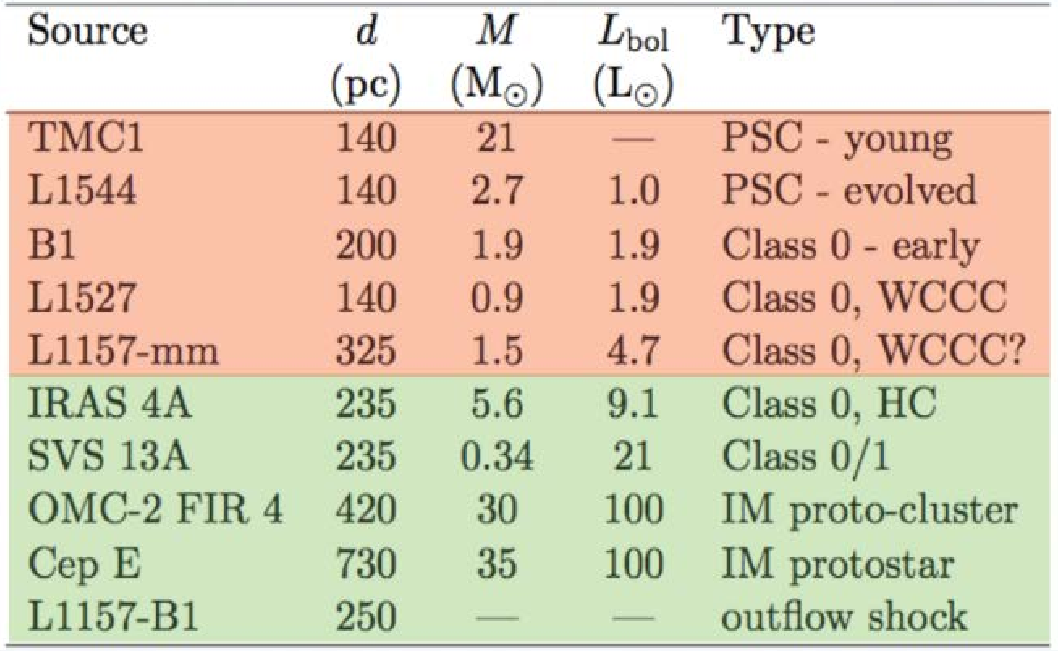


Detected in Comets: Hale-Bopp (Bockelee-Morvan et al. 2000), **81P/Wild2 (**Elsila 2009):
Exogeneous delivery on Earth (Ferus et al. 2014) ?
Detected in high-mass SFRs (Bisschop et al. 2007) and **IRAS16293-2422** (Kahane et al. 2013).

NH_2CHO in solar-type SFRs



ASAI: Systematic search for NH_2CHO in solar-type environments



	Source	d (pc)	M ($M_\odot$)	$L_{\rm bol}$ ($L_\odot$)	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

cold sources

$X <$ a few 10^{-12}

hot sources

Lopez-Sepulcre et al. (2015)

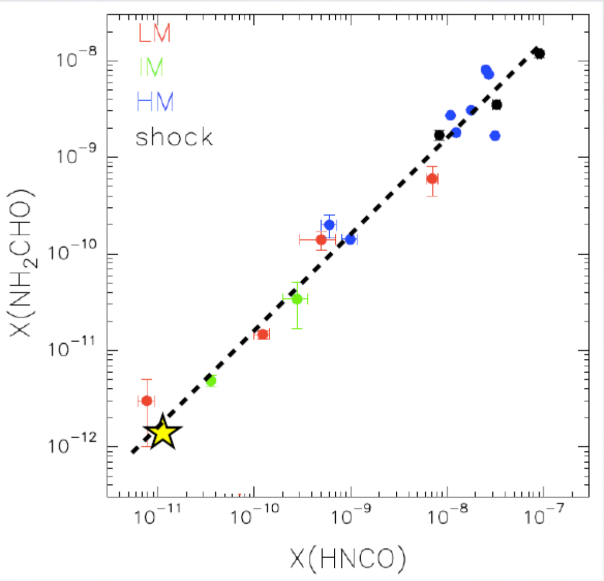
NH_2CHO is detected only in hot corino protostars and shocks.

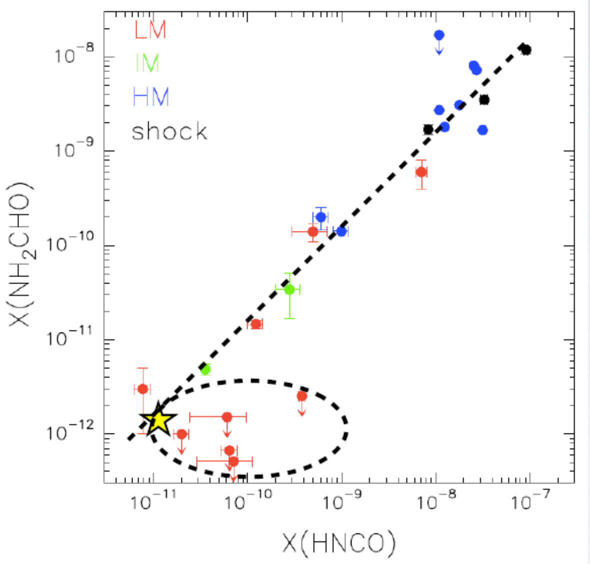
Other Molecules with a peptide bond

Search for NH_2COCH_3 ☹ : $X(NH_2COCH_3)/X(NH_2CHO) < 0.15$ in L1157-B1

> 1 in SgrB2 (Halfen 2011)

Search for HNCO ☺

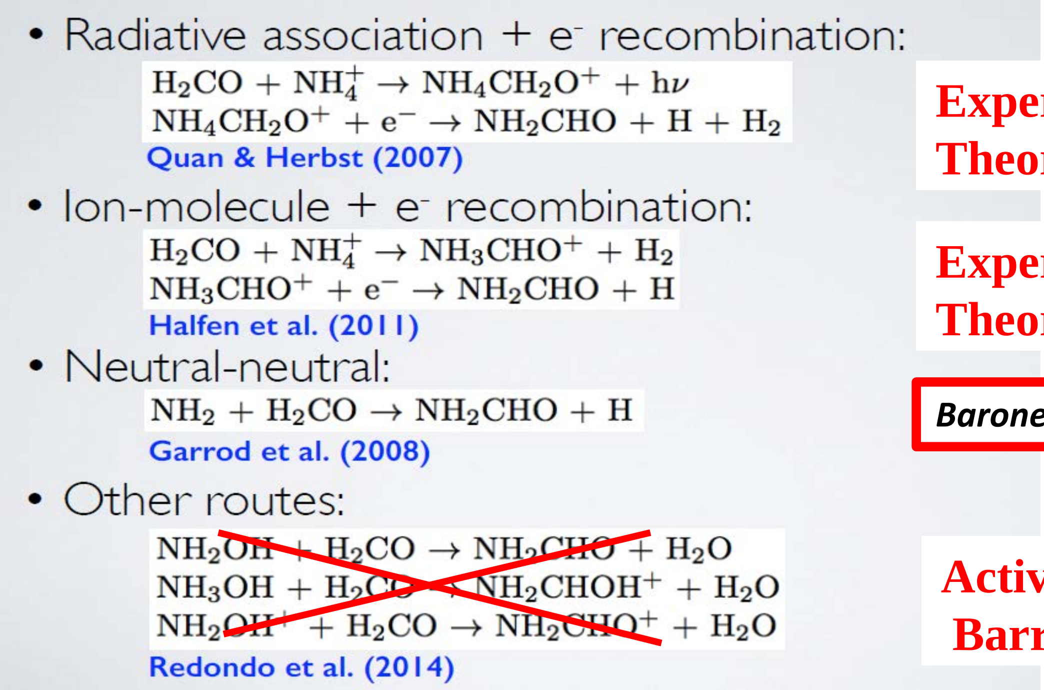




NH_2CHO and HNCO are chemically related (α=1)
HNCO is *also* detected in cold sources *(see Marcelino et al. 2009)*

NH_2CHO formation routes

Gas Phase



- Radiative association + e⁻ recombination:

$$H_2CO + NH_4^+ \rightarrow NH_4CH_2O^+ + h\nu$$
$$NH_4CH_2O^+ + e^- \rightarrow NH_2CHO + H + H_2$$

Quan & Herbst (2007)

- Ion-molecule + e⁻ recombination:

$$H_2CO + NH_4^+ \rightarrow NH_3CHO^+ + H_2$$
$$NH_3CHO^+ + e^- \rightarrow NH_2CHO + H$$

Halfen et al. (2011)

- Neutral-neutral:

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

Garrod et al. (2008)

- Other routes:

~~$NH_2OH + H_2CO \rightarrow NH_2CHO + H_2O$~~
~~$NH_3OH + H_2CO \rightarrow NH_2CHOH^+ + H_2O$~~
~~$NH_2OH^+ + H_2CO \rightarrow NH_2CHO^+ + H_2O$~~

Redondo et al. (2014)

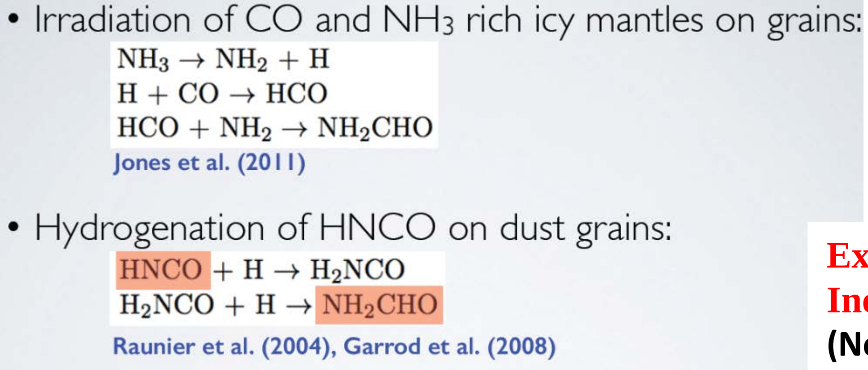
Experiments/ Theory Needed

Experiments/ Theory Needed

Barone et al. 2015

Activation Barrier

Grain Mantles



- Irradiation of CO and NH_3 rich icy mantles on grains:

$$NH_3 \rightarrow NH_2 + H$$
$$H + CO \rightarrow HCO$$
$$HCO + NH_2 \rightarrow NH_2CHO$$

Jones et al. (2011)

- Hydrogenation of HNCO on dust grains:

$$HNCO + H \rightarrow H_2NCO$$
$$H_2NCO + H \rightarrow NH_2CHO$$

Raunier et al. (2004), Garrod et al. (2008)

Experimentally Inefficient

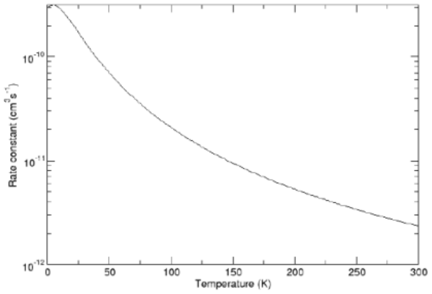
(Noble et al. 2015)

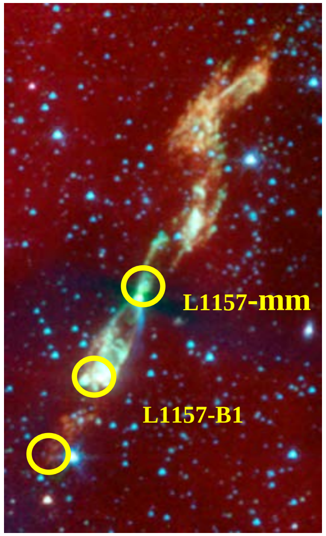
NH_2CHO formation route

Gas phase scenario

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

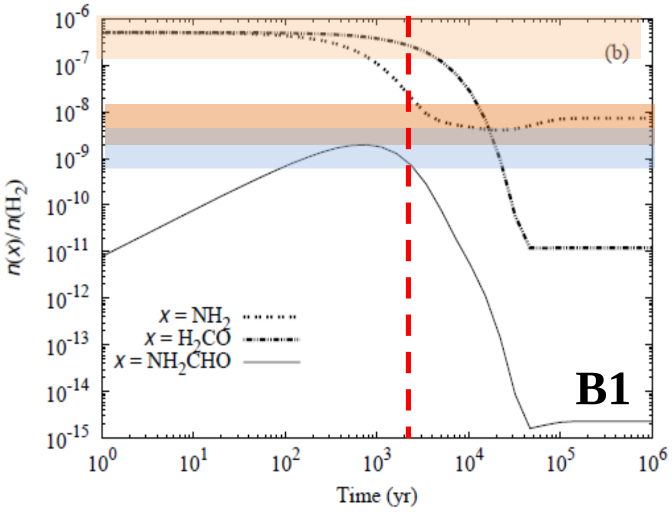
Garrod et al. (2008)
Barone et al. (2015)





L1157-B1 : 2000 yrs
L1157-B2 : 4000 yrs
(Gueth et al. 1996)

Step 1 : cold cloud chemical abundances
Step 2 : Passage of the shock → increase of (n,T)
→ release of H_2CO and NH_2 in the gas



H_2CO (ASAI)

NH_2 (CHESS)

NH_2CHO (ASAI)

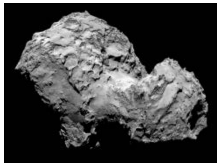
Reasonable agreement

L1157-B2, I16293-2422 : OK
((*Barone et al. 2015*)

P- Chemistry in Solar-type SFRs

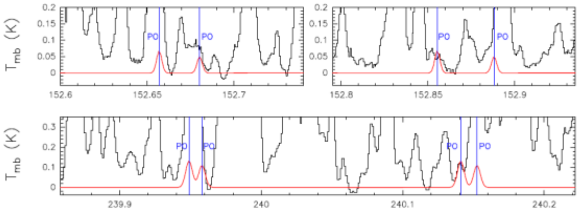
Phosphorus is one of the main biogenic elements CHONPS: [P]= 3×10^{-7}

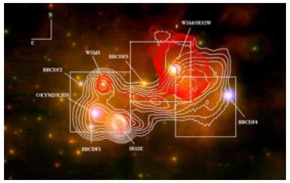
Solar system:
Ubiquitous in meteorites (Macia 2005)
Identified in comet 67P/Churuymov-Gerasimenko (Altwegg et al. 2016)



Interstellar Medium:
Thorne (1984) : *PO is the main gas phase reservoir of Phosphorus in molecular clouds ?*
Very few (sometimes uncertain) detections:
→ Evolved stars: HCP, PH_3, CP, CCP, PO, PN (Agundez et al. 2007; DeBeck)

→ High-Mass SFRs: PN (Ziurys et al. 1987; Fontani et al. 2016),
PO (Rivilla *in press*) .

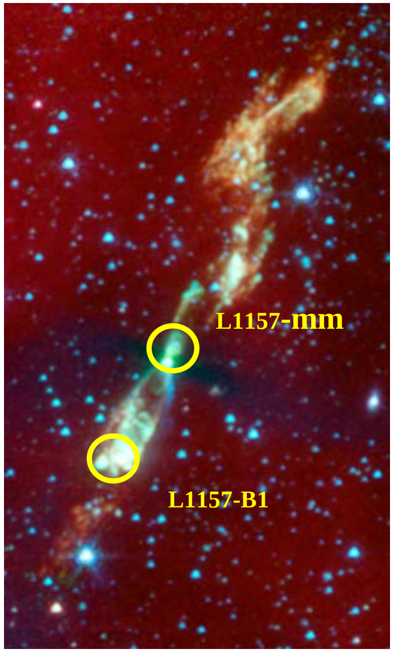




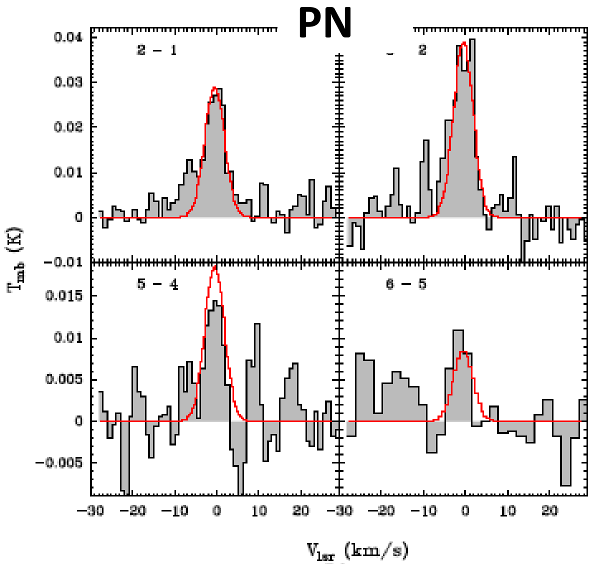
P- Chemistry in Solar-type SFRs

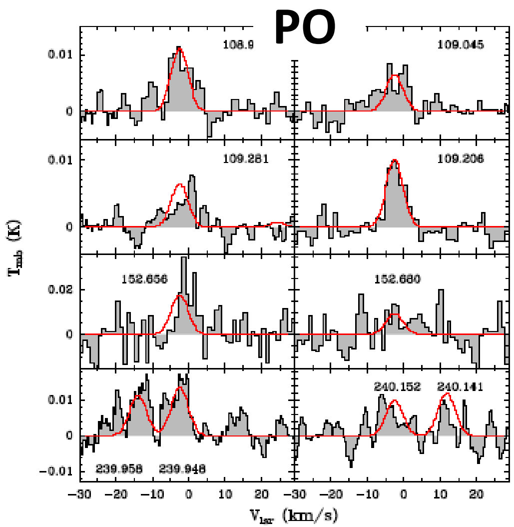
Systematic search for P-bearing species between 80 and 350 GHz with the IRAM 30m towards solar-type protostars and associated outflow/shocks

First detection of PO and PN in solar-type star forming region L1157



Emission from molecular-rich shock B1





Lefloch et al. (2016)

PO and PN are produced in the shock (from sputtered PH_3): PO/PN= 3
X ~ 10^{-9} : Phosphorus depleted by 100
Modelling (UCL_CHEM) : atomic N plays a key role in the chemistry of PO and PN

Protostars: from ASAI to SOLIS

COMs around Solar-Type Protostars

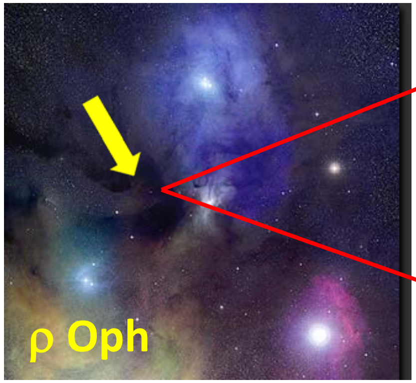
One solar-type protostar investigated in detail: IRAS16293-2422

3 mm surveys since 1994 (also interferometric): Blake et al. (1994), Jorgensen et al. (2011), Caux et al. (2011)

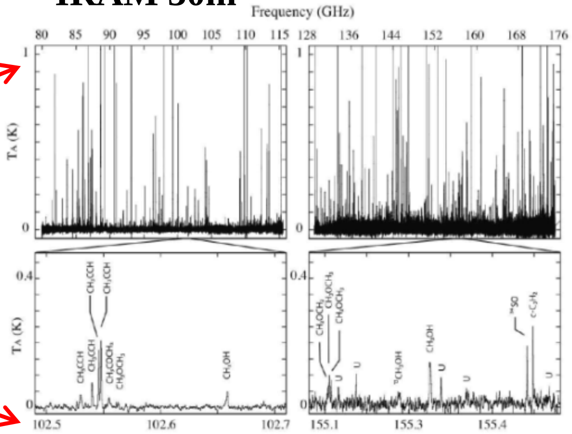
TIMASS (Caux et al. 2011): 300 hrs of telescope time : IRAM 30m + JCMT : 80 - 365 GHz : 10" – 30"

CHESS (Ceccarelli et al. 2010): HIFI/Herschel : 480 – 1900 GHz : 10" – 40"

IRAS16293-2422



IRAM 30m



Cazaux et al. (2003), Caux et al. (2011) Jaber et al. (2014)

Spectral Line Density :
s= 20 GHz^{-1}

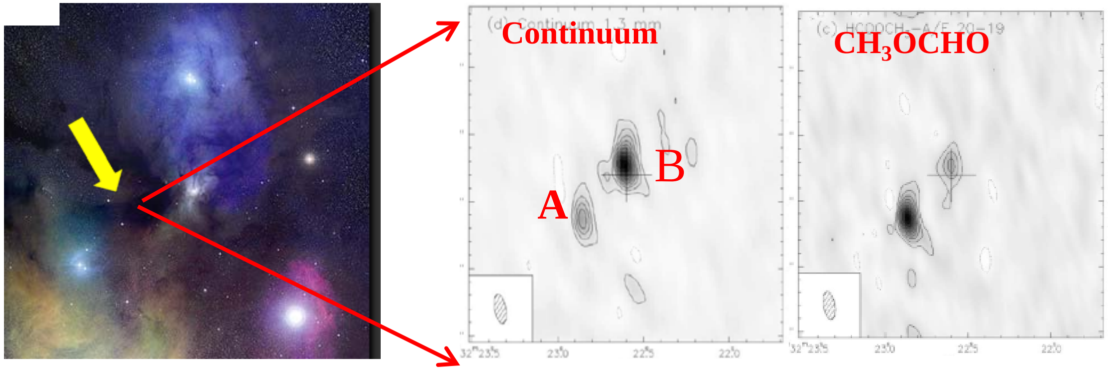
1000 Lines identified
32 chemical species

Line forest : CH_3CN, CH_3CCH, $HCOOCH_3$

Comparable to High-Mass SFR

Chemical Differentiation in I16293-2422

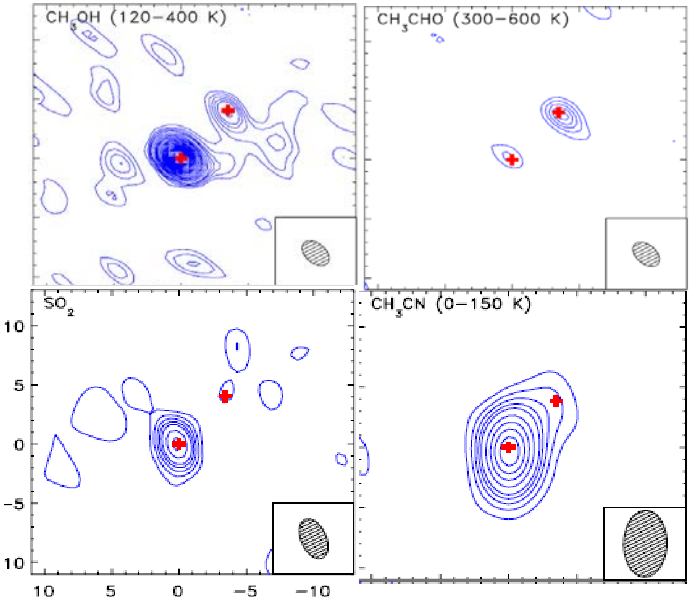
I16293, PdBI (Bottinelli et al. 2007)



A multiple system
different signatures/sources

A rich content in COMs in the hot corino region

: size ≈ 1.5” : Td ≥ 100K



I16293, SMA (Jorgensen et al. 2011)

2.5” – 5” resolution
Acetaldehyde and Ketene peak at B
S-bearing, N-Bearing peak at A

Outflow influences chemistry

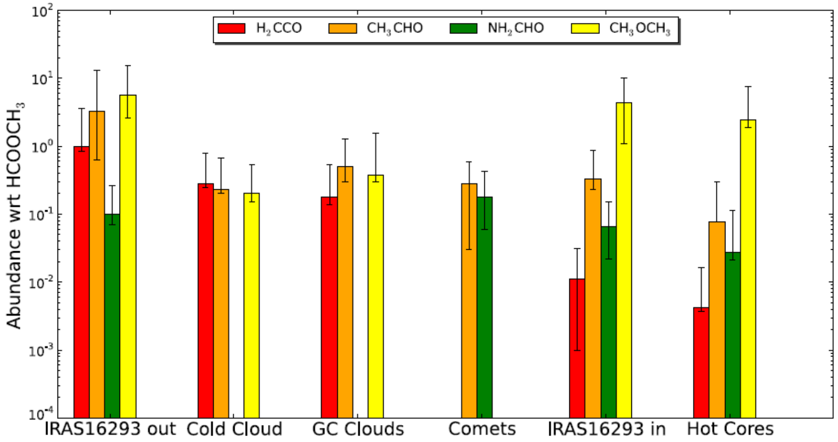
No significant excitation gradients

Chemical differentiation studies will benefit a lot from ALMA and NOEMA

COMs around Solar-Type Protostars

IRAS16293-2422

(Jaber et al. 2014, Kahane et al. 2013, Jorgensen et al. 2012)



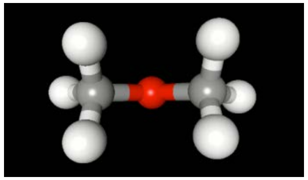
Ketene/Methyl Formate : Cold / Hot objects

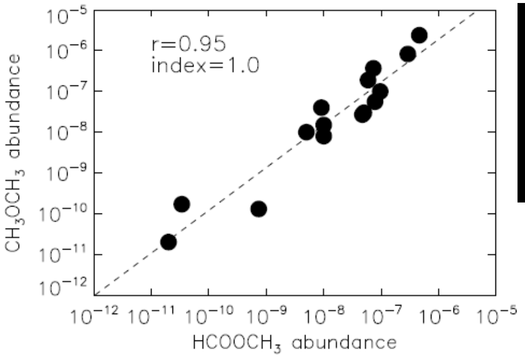
A rich content in COMs and pre-biotic material

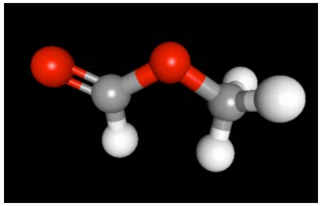
H_2CCO, CH_3CHO, **NH_2CHO**, $HCOOCH_3$, CH_3OCH_3, CH_3CN, ***$HOCH_2CHO$***
($E_{up} < 150K$)

Two components:

Hot corino (Td ≥ 100K) : X= 1(-9) – 1(-8)
Cold envelope : X= 3(-12) – 2(-10)



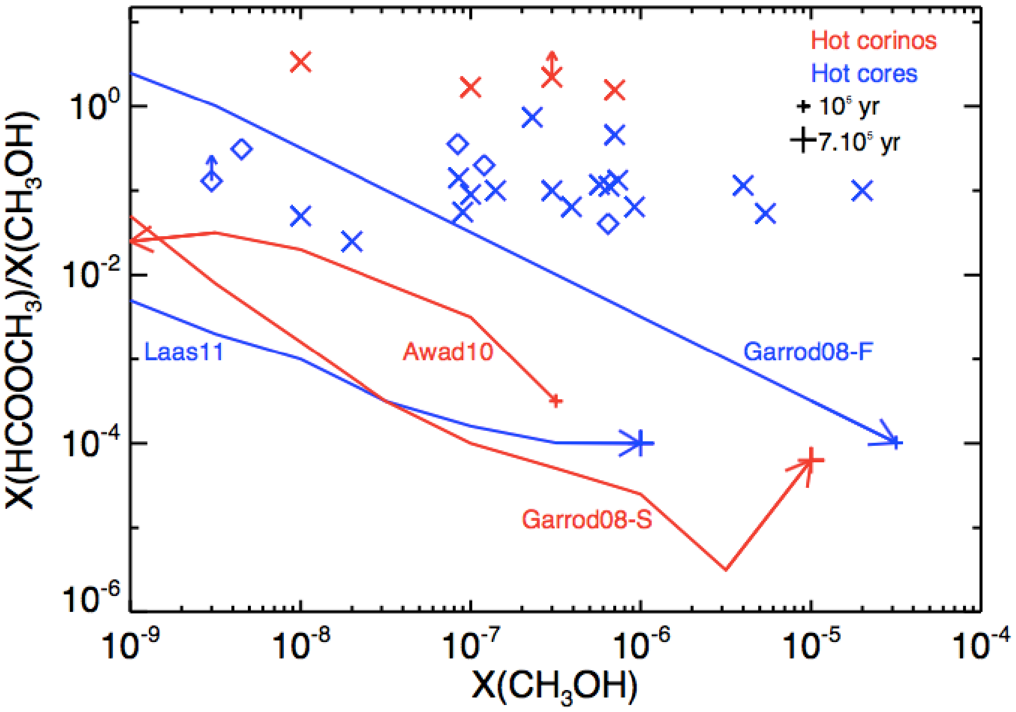




Correlation between species abundant in Hot objects

Tight linear correlation between MF and DME

Formation of MF and DME ?



Taquet et al (2012)

Models (<2012) are unable to reproduce the observed abundances

Are they synthesized through gas phase chemistry or at the icy surface of grain mantle?

SOLIS

http://solis.osug.fr

First Galactic Large Program with NOEMA

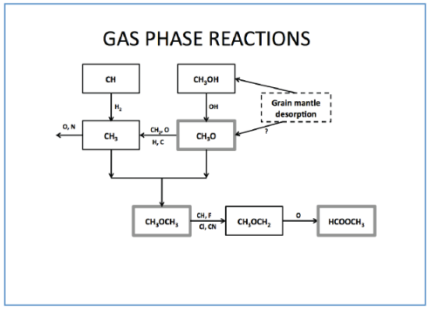
375 hrs - PIs : C. Ceccarelli (IPAG) & P. Caselli (MPE)
Summer 2015 – 2017

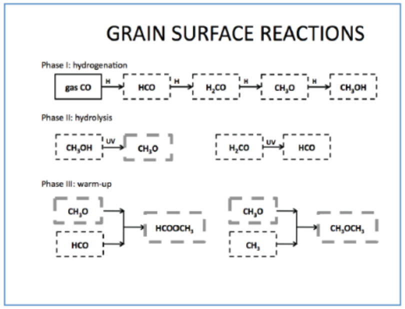
(1) Understanding organic chemistry in space and (2) how it evolves during the process of formation of Solar-type systems are the two complementary goals of the proposed project, SOLIS.

Observing COMs down to 0.3 ” resolution (40AU) in ASAI sources

- prestellar to evolved protostars (cold/warm gas/dust)
- environmental conditions (shocks, UV radiation)

Five “key” COMs : CH_3O, CH_3OH, CH_3OCH_3, $HCOOCH_3$, NH_2CHO

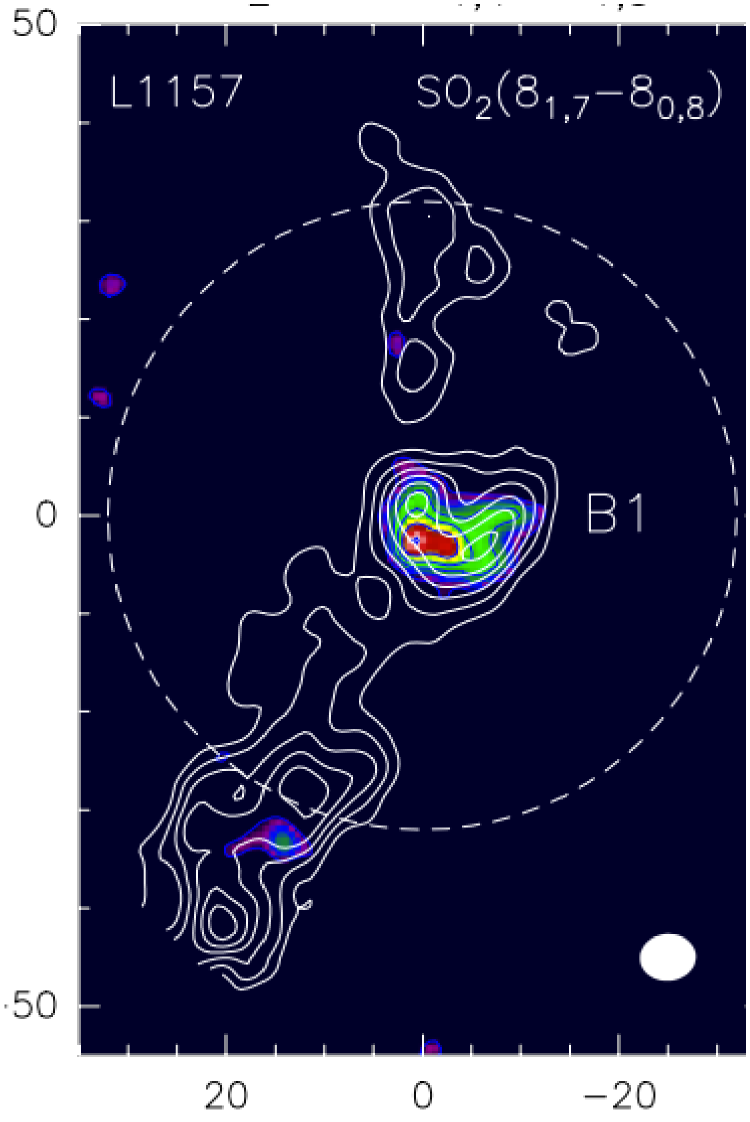




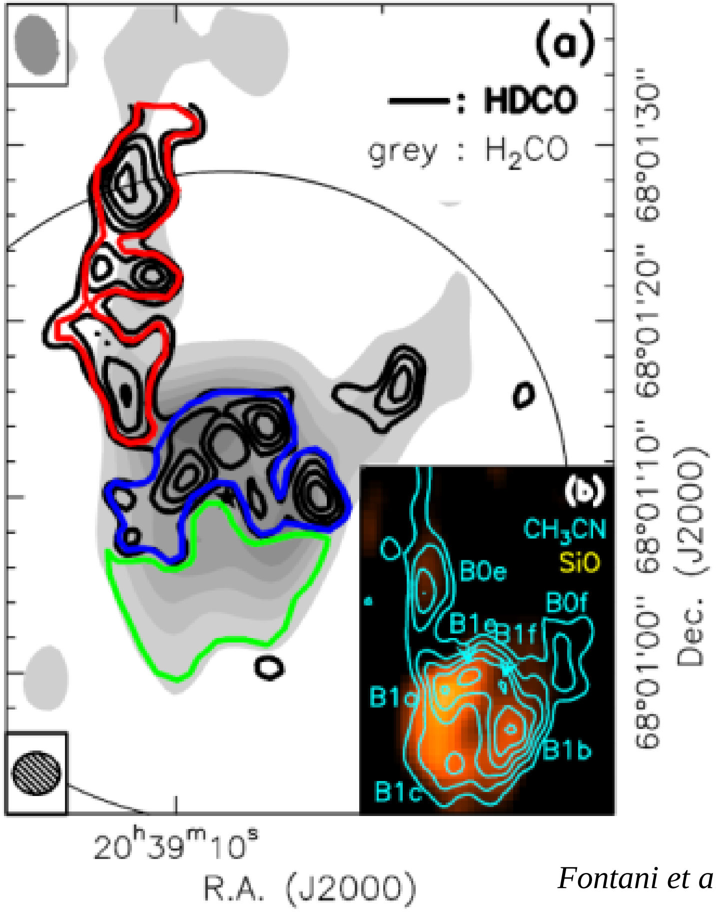
Abundance maps of COMs in each source

→ Test gas phase vs grain surface chemistry
→ Assess formation/destruction routes
→ Desorption mechanims : UV/CR/thermal

New insight from SOLIS



(Codella et al. in prep)



Fontani et al. (2015)

Conclusions

ASAI illustrates the power of unbiased line surveys

- New molecular species were detected : NO^+, p-CH_2CN, PO, PN.
- 10% of U lines in the database : more to come !
- Families of chemically related species are evidenced: DME/MF, NH_2CHO/HNCO, …
- More work is needed to establish their formation routes: SOLIS

Molecular Complexity:

- is present to a wide degree in the prestellar phase. A scenario combining non-thermal desorption of simple species on icy mantles + subsequent gas phase reactions is proposed
- is widespread (enhanced) by feedback processes such as shocks

Many results to come out in the next months !

SOLIS is taking over: we will map the distribution of COMs at excellent sensitity level down to x10 AU scale

Thank You

The ASAI Team:

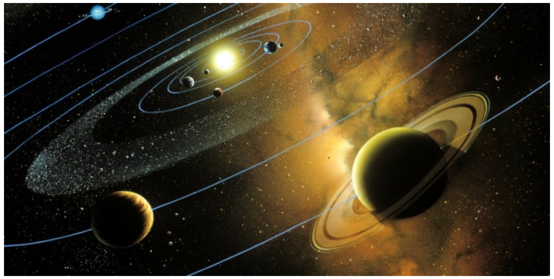
M. Benedettini, R. Bachiller, E. Bianchi, G. Busquet, S. Cabrit, P. Caselli, C. Ceccarelli, J. Cernicharo, C. Codella, A. Faure, F. Fontani, A. Fuente, A. Gomez-Ruiz, M. Gonzalez, P. Hily-Blant, I. Jimenez-Serra, C. Kahane, A. Lopez-Sepulcre, E. Mendoza, K. Yoshida, T. Monfardini, L. Podio, E. Roueff, N. Sakai, M. Tafalla, M. Vasta, S. Viti, S. Yamamoto

Beyond ASAI

Molecules in Meteorites and Comets

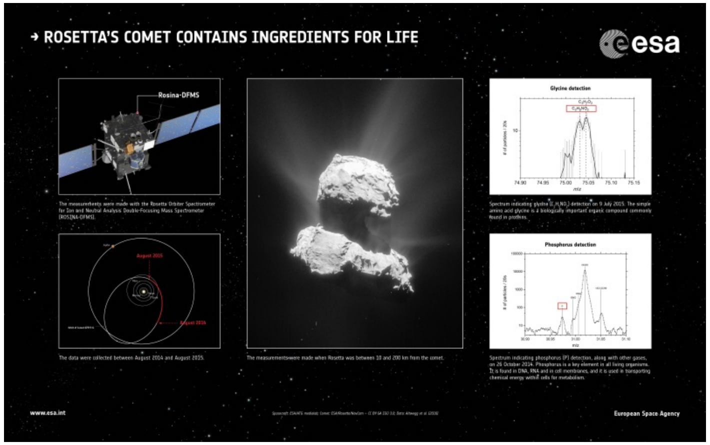
Meteorites and Comets

More than **80 amino acids** were found in meteorites on Earth, with specific isotopic composition and racemic distribution: extraterrestrial origin (Botta & Bada 2002)



+ several other classes of organic compounds:
carboxylic acids, , alcohols, amines, amides, …
High D fractionation ratio.

Stardust: **glycine** (NH_2CH_2COOH) and amines were detected in samples returned from comet 81P/Wild 2 (Elsila, 2009) *despite evidence for terrestrial contamination*



→ ROSETTA'S COMET CONTAINS INGREDIENTS FOR LIFE

The measurements were made with the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis Double-Focusing Mass Spectrometer (ROSINA-DFMS).

The data were collected between August 2014 and August 2015.

The measurements were made when Rosetta was between 10 and 200 km from the comet.

Spectrum indicating glycine ($C_2H_5NO_2$) detection on 9 July 2015. The simple amino acid glycine is a biologically important organic compound commonly found in proteins.

Spectrum indicating phosphorus (P) detection, along with other gases, on 26 October 2014. Phosphorus is a key element in all living organisms. It is found in DNA, RNA and in cell membranes, and it is used in transporting chemical energy within cells for metabolism.

www.esa.int

European Space Agency

Altwegg et al. (2016)

Glycine detected in the coma with Rosina
→ UV photochemistry of CH_3NH_2 and CO_2 ice on grain mantles (e.g. Bossa 2010) ?
→ Gas phase formation in the ISM ?

COM Properties

Species	Tex (K)	N (cm^{-2})	X
C_3O	10	2(11)	5(-11)
CH_3CHO	17 ± 1	5(11)	1(-10)
t-HCOOH	10	5(11)	1(-10)
H_2CCO	27 ± 1	5(12)	1(-9)
HCCCHO	12 ± 1	2.7(11)	7(-11)
E-CH_3CCH	11 ± 2	2(13)	5(-9)
CH_3OCH_3	11	1(12)	1(-10)
$HCOOCH_3$	4	≤ 6(12)	7(-10)
CH_3OH	*10*	**3(13)**	**6(-9)**

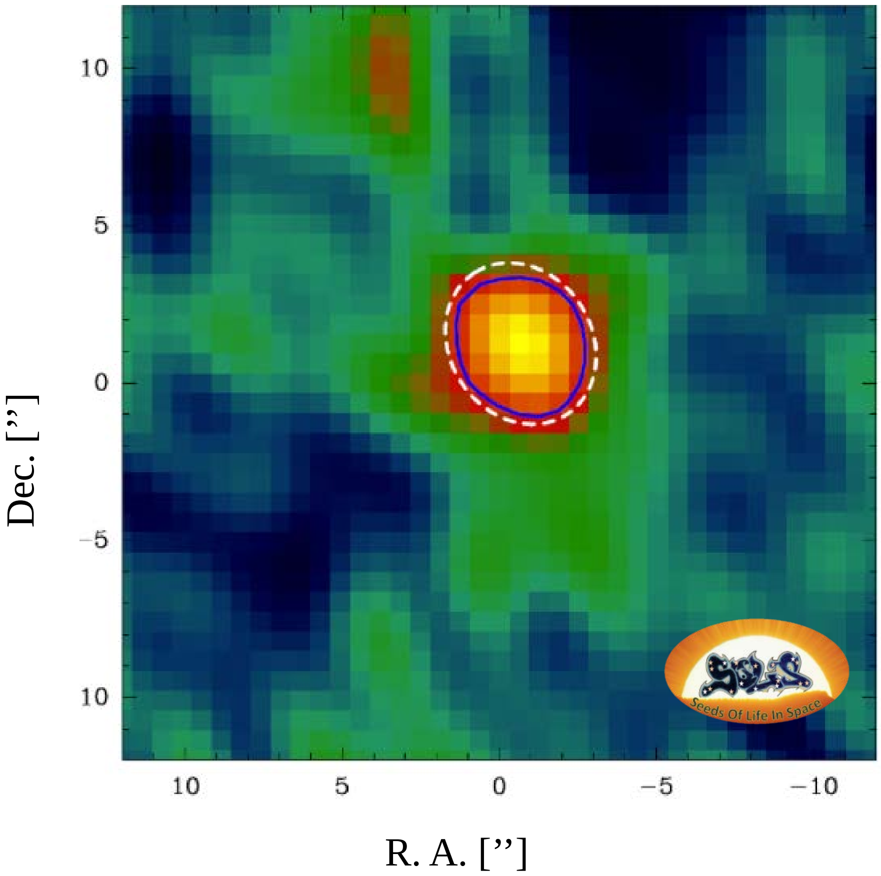
Excitation and physical conditions are similar to those of CH_3OH

The emission of Complex Organic Molecules probably arises from the same region as CH_3OH and H_2O

Seeds Of Life In Space (SOLIS)

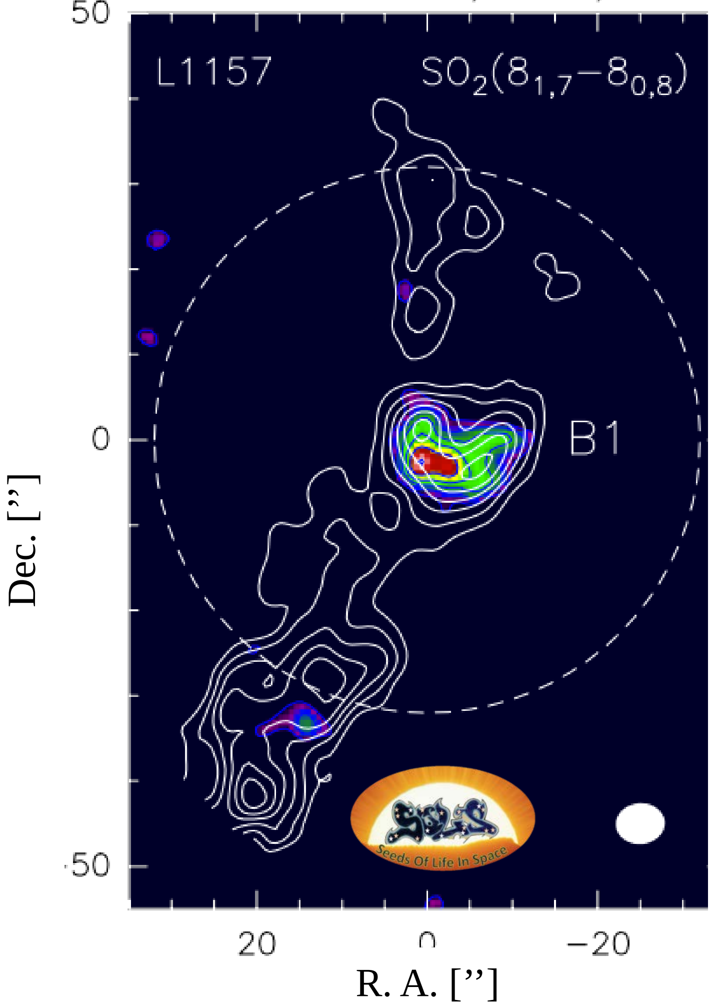
Formamide NH_2CHO (prebiotic molecule)

IRAS 4A



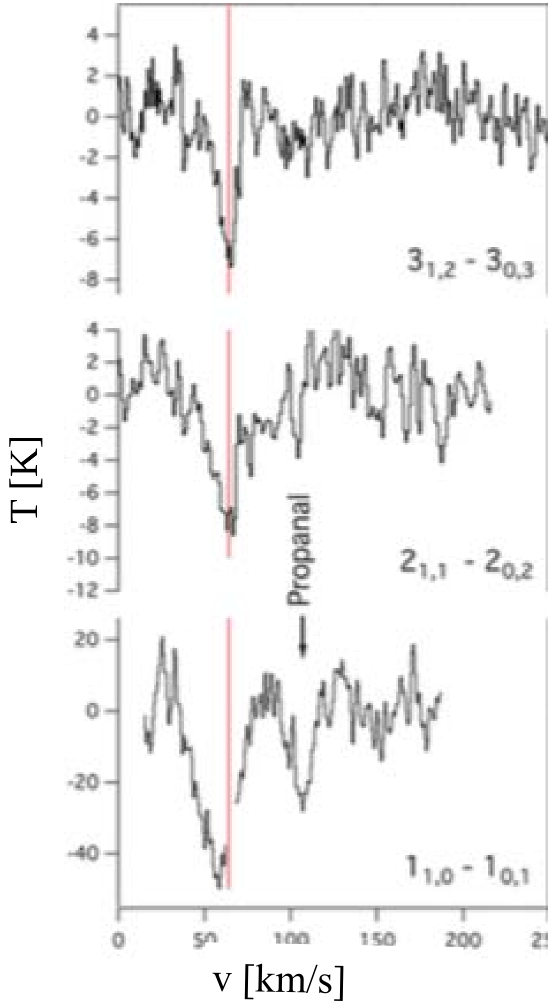
Lefloch et al. (in prep.)

L1157



Codella et al. (in prep.)

IMS chiral molecule: propylene oxide (CH_3CHCH_2O)



McGuire et al. (2016)

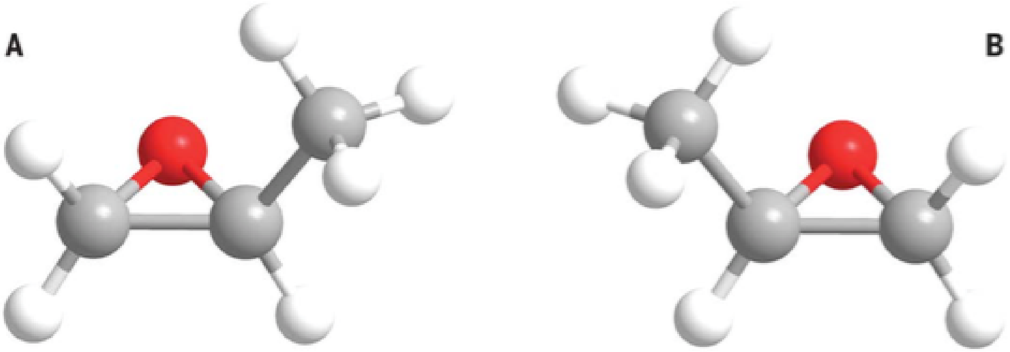
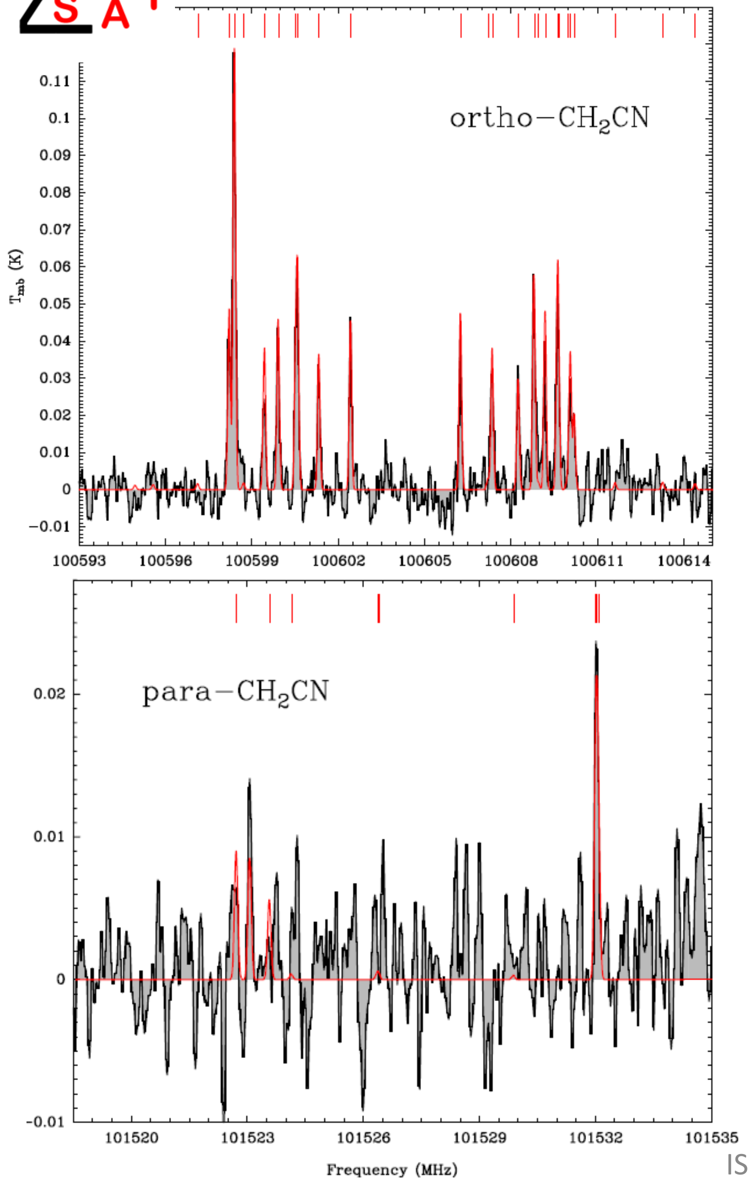


Fig. 1. The molecular structure of *S*-propylene oxide and *R*-propylene oxide. (**A**) *S*-propylene oxide. (**B**) *R*-propylene oxide. Carbon, hydrogen, and oxygen atoms are indicated by gray, small white, and red spheres, respectively.

amino acids are chirals (S-form)!

The Hyperfine Structure of CH_2CN



U Lines at 106 GHz ?

Vastel , Yamamoto, Lefloch, Bachiller (2015)

Full hyperfine transition series of CH_2CN identified in L1544

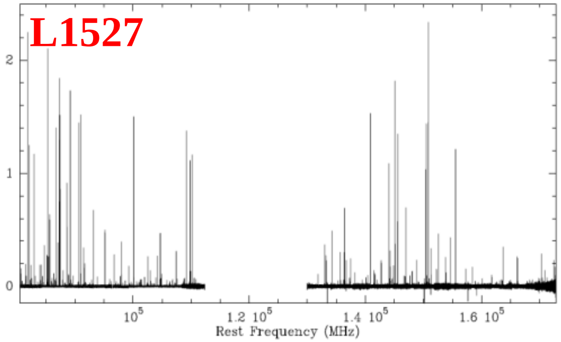
LTE analysis :
Tex= 10 – 12K
$X(CH_2CN) \simeq 10^{-12}$ to 10^{-11}
OPR = 1

Dark cloud : TMC1 : $X \simeq 10^{-9}$

A tracer of chemical evolution ?

WCCC protostars

ASAI : L1527, L1157-mm



Early-type protostar (Class 0/I)

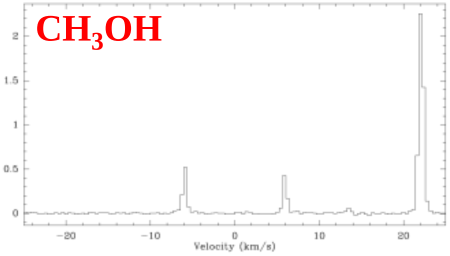
Complex Organic Molecules in the cold envelope

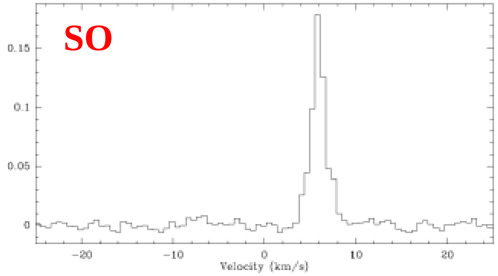
CH_3OH, H_2CCO, CH_3CHO, HC_2CHO (propynal), CH_3CN : seen in I16293
c-H_2C_3O, C_2H_3CN : not seen in I16293
CH_3OCH_3, $HCOOCH_3$: not detected

Strongly differs from hot corino

Two class of line profiles :

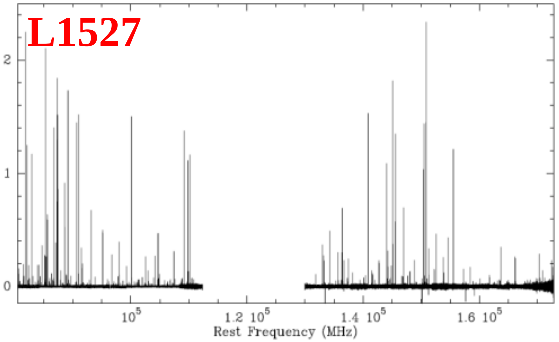
narrow (< 1km/s) : COMs
broad (> 1.5 km/s) : SO, CH_3CN





WCCC protostars

ASAI : L1527, L1157-mm



Early-type protostar (Class 0/I)

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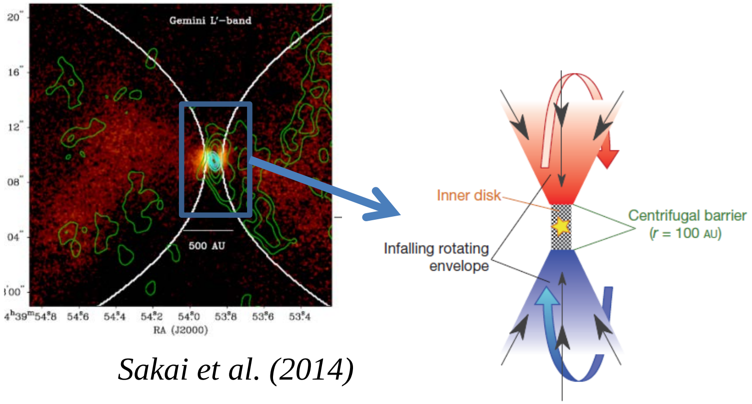
ALMA (0.6” resolution)

Chemical differentiation at the centrifugal barrier



Sakai et al. (2014)

- SO and CH_3OH emission at the centrifugal barrier, in the disk?
- c-C_3H_2 in the envelope