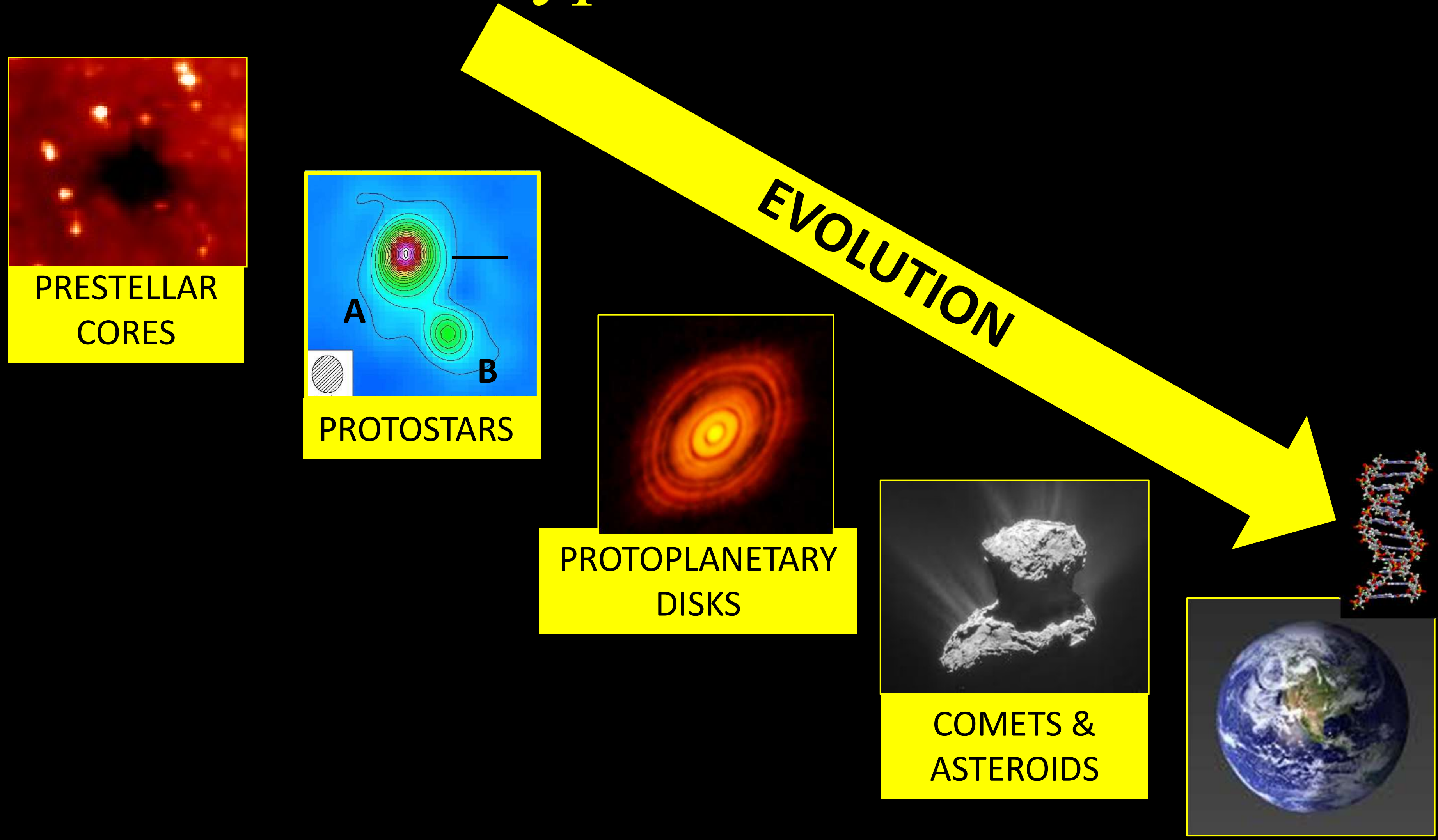
Prebiotic Chemistry in Sun-like Star Forming Regions: Where is Phosphorus ?

B. Lefloch
(IPAG, Grenoble, France)

The Astrochemical View on Solar-type Star Formation



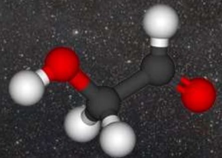
Prebiotic Chemistry in Star Forming Regions

Terrestrial life is based on CARBON chemistry

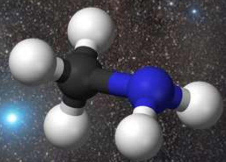
Complex Organic Molecules (COMs)

$(CH_2OH)_2$
Ethylene Glycol

NH_2CHO
Formamide

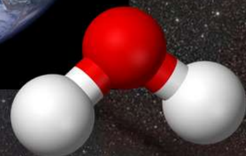


CH_2OHCHO
Glycolaldehyde



CH_3NH_2
Methylamine

Water



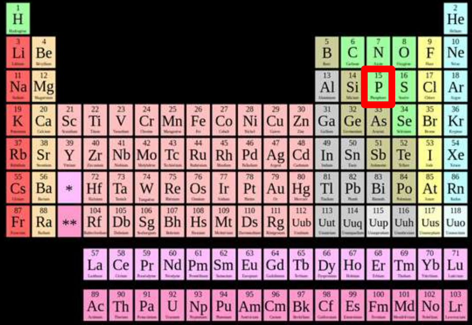
efficient solvant (liquid on large T range)
—> facilitates formation of COMs

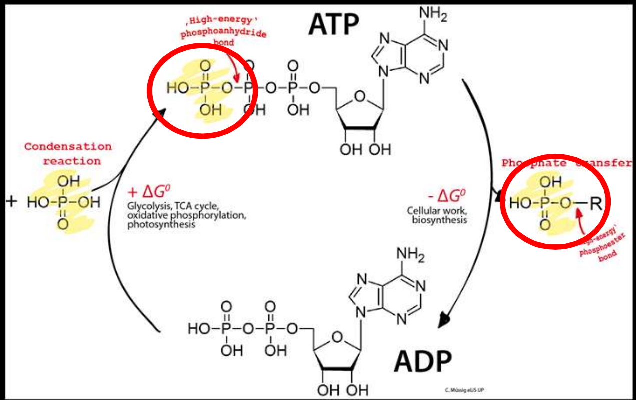
H,O,C,N are
the most abundant elements in Space
the simplest elements able to form (multiple) bonds

Prebiotic Chemistry in Star Forming Regions

Phosphorus : a Key Player

- capacity to form multiple bonds
- PO bond





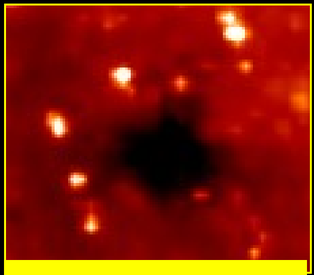
Adenosine tri/di/monophosphate:
Energy storage/consumption process
in all life forms *Schwartz (2006)*

ATP is also involved in biochemical processes: DNA, RNA synthesis

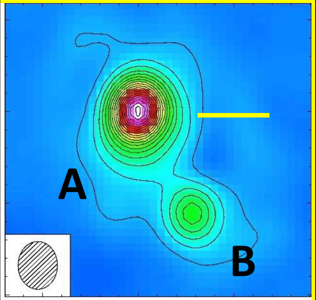
Urey-Miller experiment: PH_3 facilitates amino-acid synthesis

Phosphorus in the ISM

[P] Solar abundance is low *(Asplund 2009):* 3 x 10 $^{-7}$



PRESTELLAR CORES



PROTOSTARS

PROTOPLANETARY DISKS

PH_3

Bregman et al. (1975)
Ridgway et al. (1976)

COMETS & ASTEROIDS

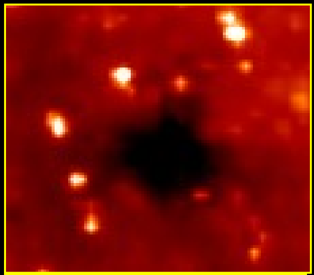
Minerals
(Macia 2005)

Diffuse clouds
P^+ : [P]/[H] ~ 10 $^{-7}$
(Jura & York 1978; Dufton et al.1986)

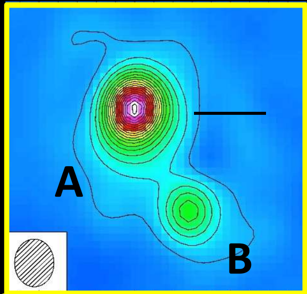
Massive molecular clouds: PN
Depletion onto dust grains ?
(Turner 1990)

Evolved stars: IRC+10216
PN, PO, HCP, CP, CCP
(Agundez et al. 2007)

Phosphorus in the ISM



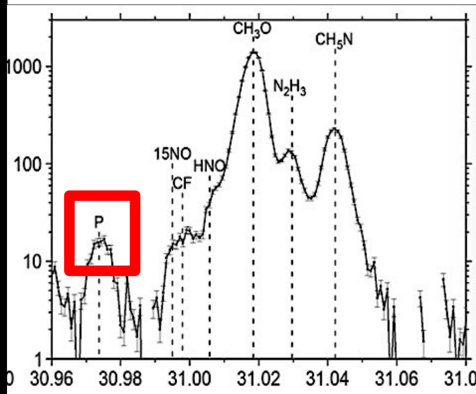
PRESTELLAR CORES



PROTOSTARS

PROTOPLANETARY DISKS

Altwegg et al. (2016)



COMETS & ASTEROIDS

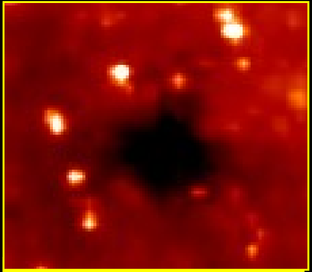
Rosetta: 67P

- P^+ in the coma

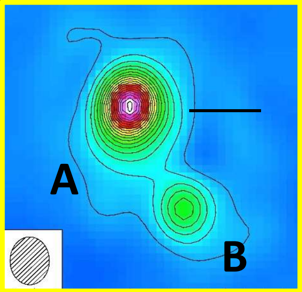
- Carrier: ~~PN, CP, HCP, PO~~

PH_3 ?

Phosphorus in Solar-Type Star Forming regions



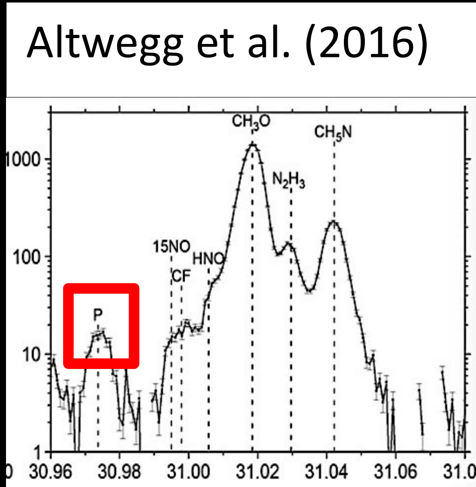
PRESTELLAR CORES



PROTOSTARS

PROTOPLANETARY DISKS

?



COMETS & ASTEROIDS

Searching for P-bearing species with ASAI

(Astrochemical Survey At IRAM)

Unbiased spectral line surveys covering the full 3, 2, 1.3 mm bands
along the main chemical stages of Solar type star formation

(Lefloch et al. 2018)

Time

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

An ideal Tool to obtain
the census of P-bearing species

The ASAI Results

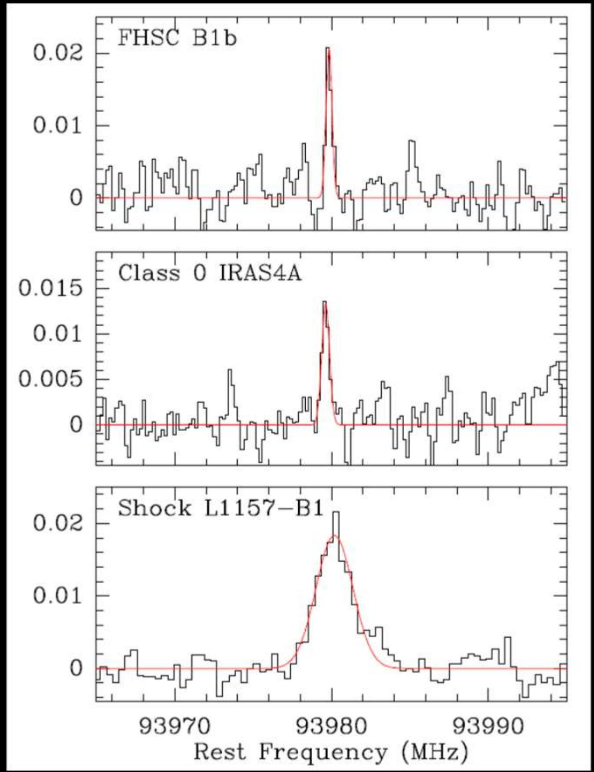
PO and PN are detected *only*

Source	Type	PN	PO	PH_3
TMC1	Early Prestellar Core	-	-	-
L1544	Late Prestellar Core	-	-	-
B1b	Early Class 0 (FHSC)	Y	-	-
IRAS4A	Class 0 (hot corino)	Y	-	-
L1157-mm	Class 0 (WCCC)	-	-	-
L1527	Late Class 0 (WCCC)	-	-	-
SVS13A	Class I (hot corino)	-	-	-
L1157-B1	Shock	Y	Y	-
L1448-R2	Shock	-	-	-

Time

PH_3 undetected: $[PH_3] < 1.5 – 4 \times 10^{-12}$

PN J=2-1

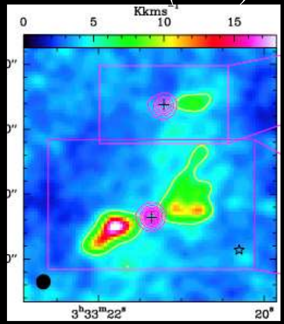


Lefloch et al. (2019)

PN in Protostars: B1b & IRAS4A

Gerin et al. (2015)

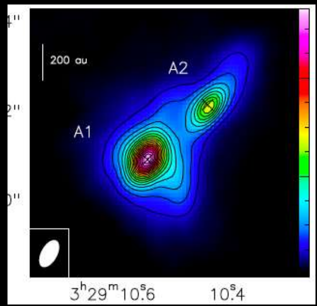
10''



B1b: 0.8 L_o – 230 pc

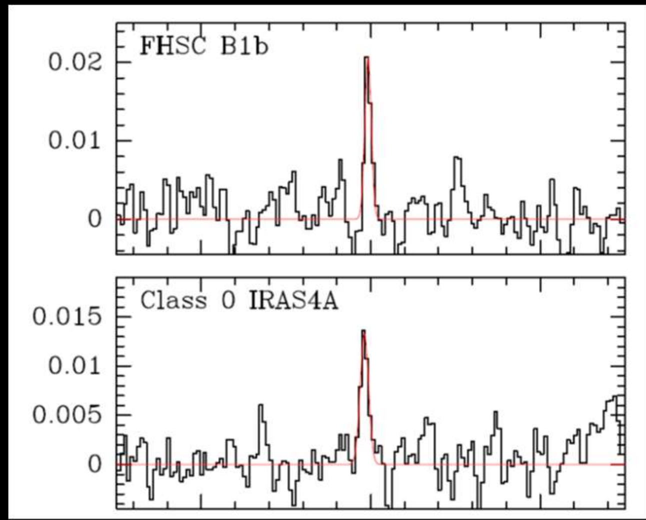
Lopez-Sepulcre et al. (2015)

2''



IRAS4A: 9 L_o - 260 pc

PN J=2-1



Lefloch et al. (2019)

- Weak Line Emission
- FWHM ~ 1 km/s
- Only Low-Excitation Transitions
  J=2-1 and J=3-2 (E_{UP}= 13.5K) are detected

➔ PN traces the Cold Envelope

Non-LTE modeling

B1b: T=13 K → **[PN] ≈ 4x10^{-13}**

IRAS4A: T=35 K → **[PN] ≈ 2x10^{-13}**

[PN]/[P] ~ 10^{-6}

PN in Protostars: Open Questions

- Why is only PN detected in protostars ?
- Why is PN detected only in cold gas around protostars?
- What is the major reservoir of Phosphorus ?

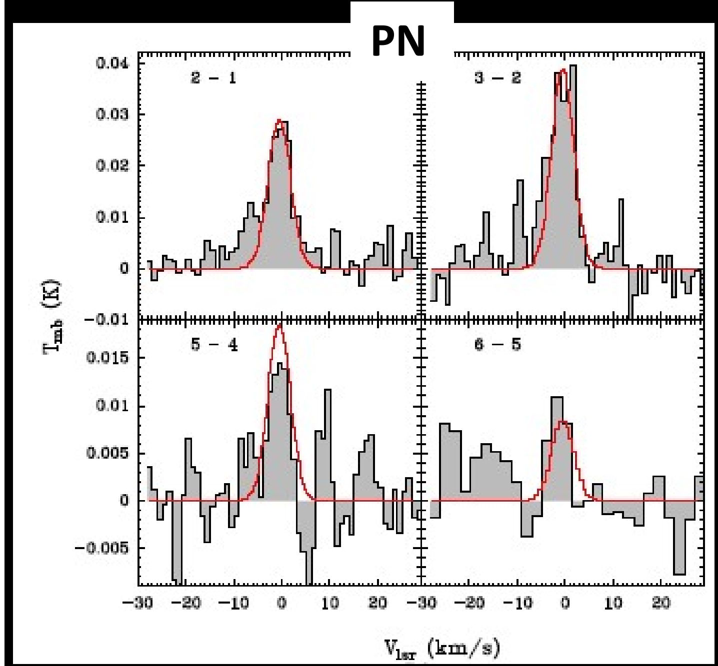
→ NEW P-BEARING CHEMISTRY UNDER STUDY

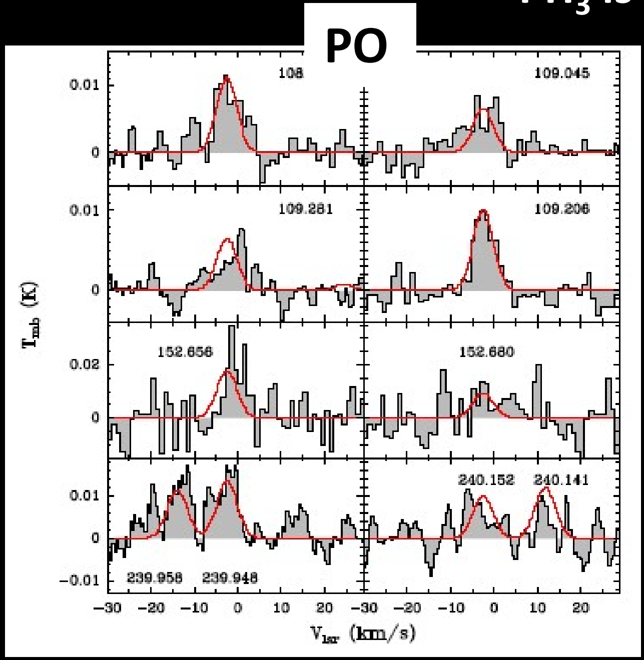
P- Chemistry in the shock L1157-B1

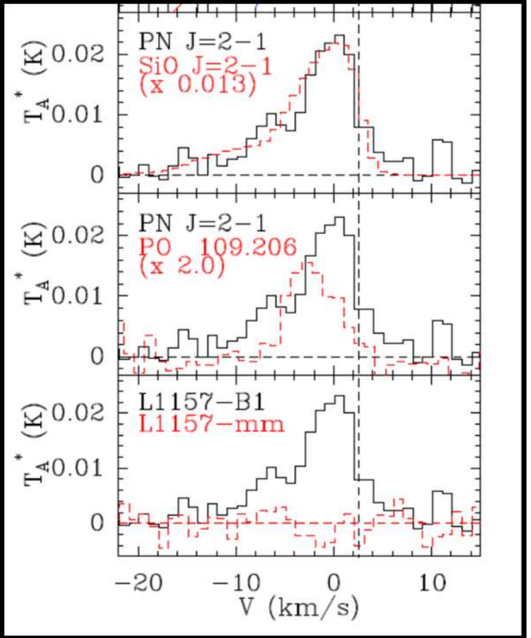
First detection of PO and PN in Sun-like star forming region L1157

Lefloch et al. (2016)

PH_3 is undetected $X(PH_3) \leq 10^{-9}$



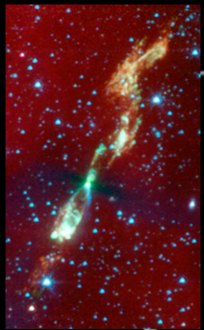


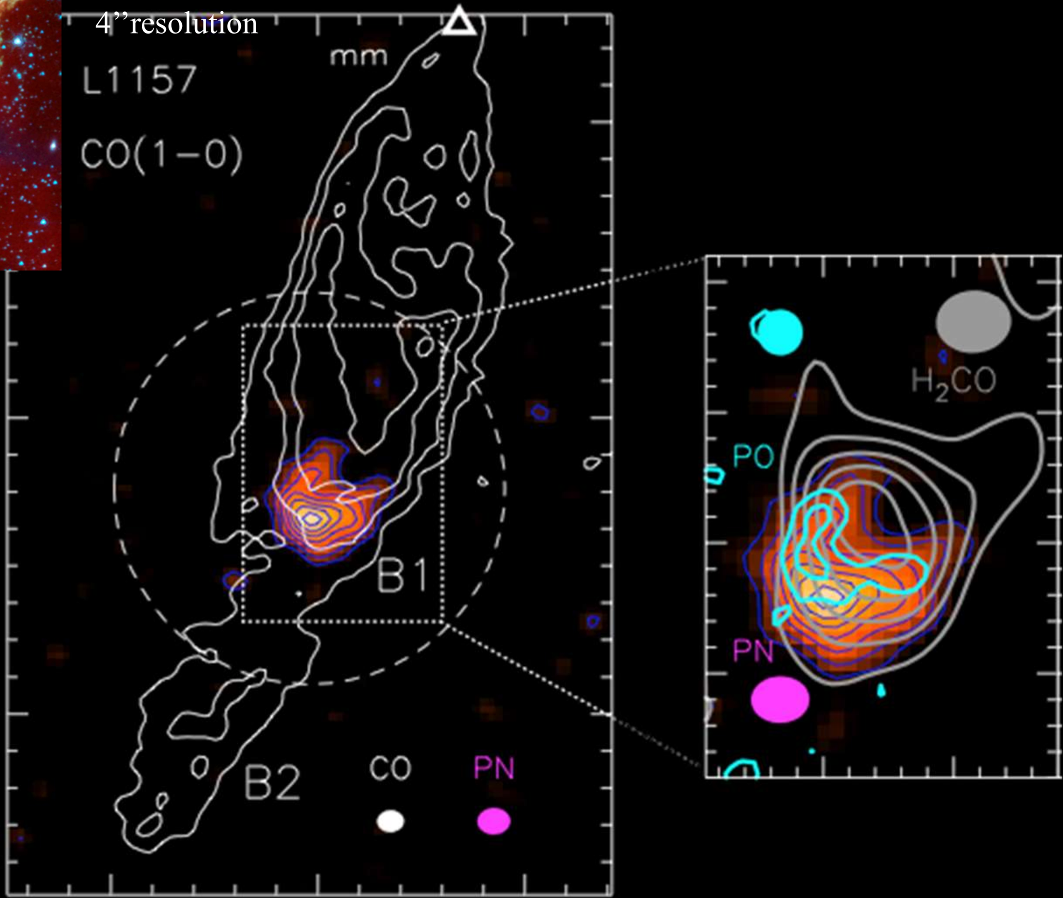


$X(PO) = 2.5 \times 10^{-9}$: PO/PN= 3
Phosphorus depleted by 100

PO and PN are produced in the shock
They are tracing different layers

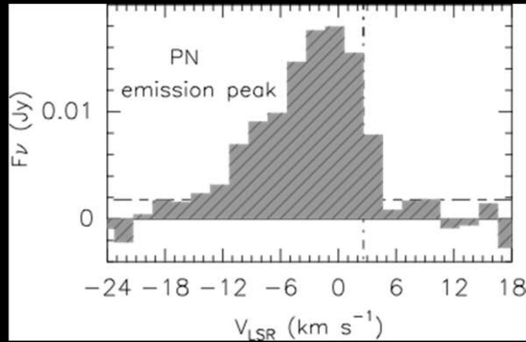
The NOEMA view of L1157-B1

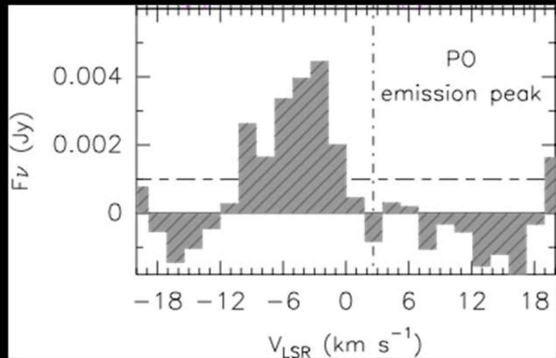




PN J=2-1 93979 MHz

PO $^2\Pi_{1/2}$ J=5/2 – 3/2 109 GHz

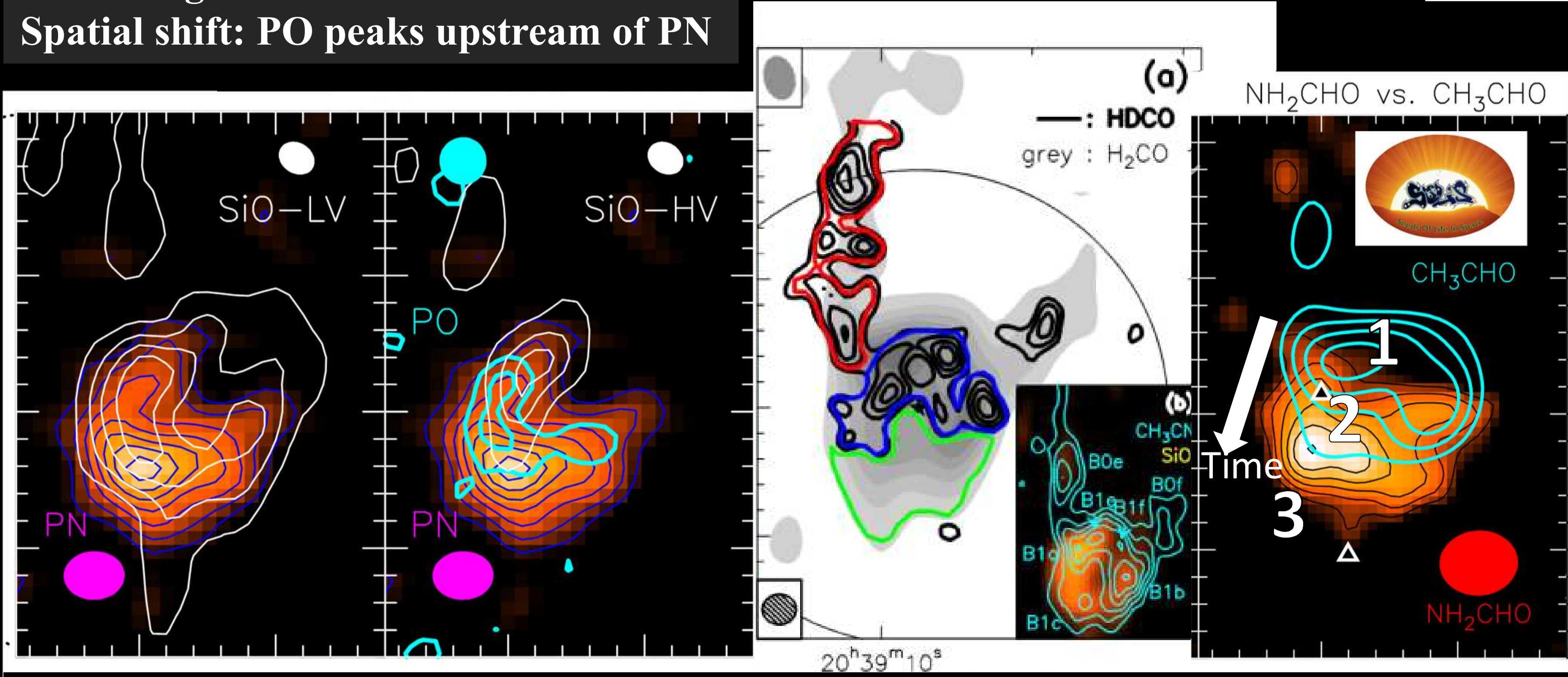




PO and PN are tracing the apex of the cavity

Shock's Anatomy

Overall agreement with SiO
Spatial shift: PO peaks upstream of PN



SiO production in gas phase
$Si + OH \rightarrow SiO + H$
$Si + O_2 \rightarrow SiO + O$

PO and PN are gas phase products
They are present in the early phase of the shock then PO disappears earlier than PN

P-Modelling in Shocks

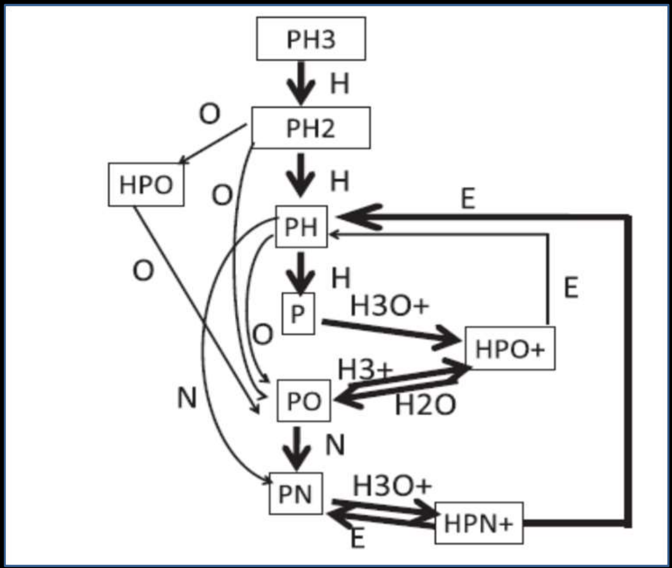
UCL_CHEM *(Viti et al. 2011)* + Parametric shock code *(Jimenez-Serra et al. 2008)*

Step 1 : pre-shock gas and dust conditions.

Main assumption: P is depleted and hydrogenated on the dust grains: PH, PH_2, PH_3 (Charnley & Millar 1994)

Step 2: chemical gas and dust evolution across the shock.

→ density n0, shock velocity, X_i[P], duration of pre-shock phase



Aota & Aikawa (2012)

A poorly explored chemistry

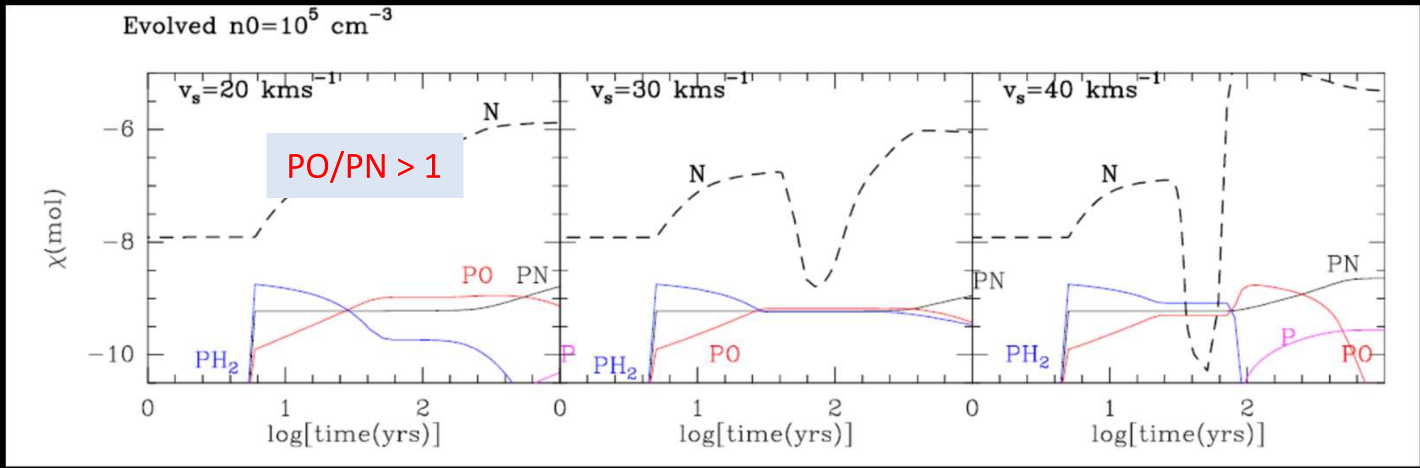
A few (partial) networks have been proposed:

- Charnley and Millar (1994)
- Aota & Aikawa (2012)
- Vasyunin & Herbst (2013)

P- and N- are coupled

Shock Modelling

P must be depleted by a factor 100 in order to reproduce the observations
Good fits when the pre-shock density is at least 10^5 cm^{-3}



Stage 1: Destruction routes of PH_n

$H + PH_2 \rightarrow PH + H_2,$

$O + PH_2 \rightarrow PH + OH,$

$O + PH_2 \rightarrow HPO + H.$

$O + PH \rightarrow PO + H,$

$O + HPO \rightarrow PO + OH$

$H + PH \rightarrow P + H_2$

Stage 2: Formation of PN / destruction of PO

$N + PO \rightarrow PN + O$

$N + PO \rightarrow P + NO.$

$PH + N \rightarrow PN + H.$

$n(H_2)= 10^5$ cm^{-3}
PO/PN > 1 : yes
Spatial shift: yes

Agreement is encouraging. BUT
Missing reactions → PO/PN> 1 ? e.g.: P + OH → PO + H
(Jimenez-Serra et al. 2018; NO: Codella et al. 2018)

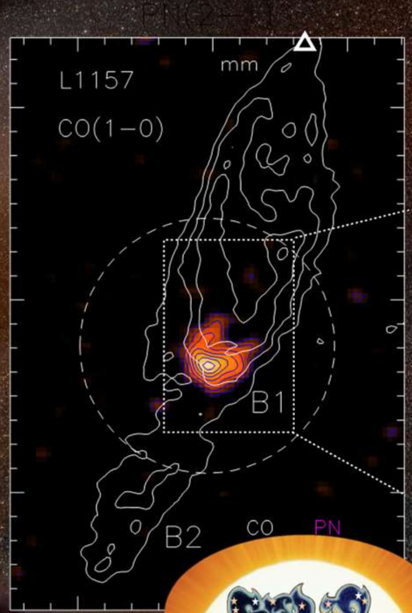
More work is needed !

Conclusions and Prospects

PO and PN (only) have been detected so far in solar-type star forming regions:

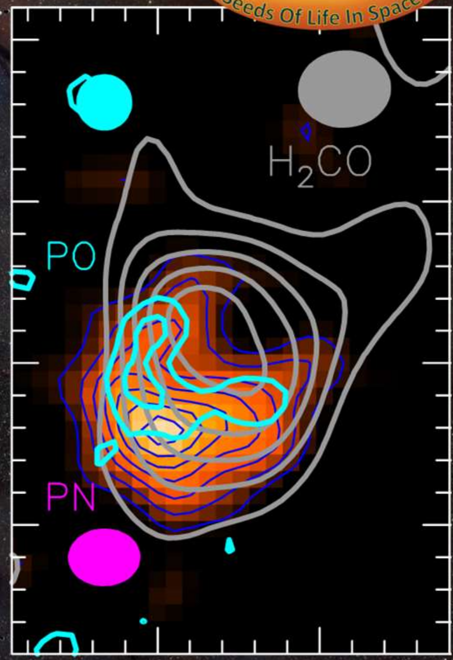
Strong P depletion is found

What is the main P carrier on dust grains ?



PN is detected towards cold protostellar envelopes and shock regions → multiple formation mechanisms ?

PO and PN are early gas phase products in shocks:
PO disappears earlier than PN.



Preliminary chemical modelling succeeds in accounting for PO and PN emission in shocks but

→ MORE WORK IS NEEDED TO MODEL THE P + N CHEMISTRY

→ UNDERSTAND THE ROLE AND FATE OF PH_3