Observational Facilities in the Time of LLAMA

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Observers should work in close contact with modellers and lab. experiments.

The Method of Astrochemistry

1. Observations

2. Derived Chemical Composition

3. Chemical Model

Molecular Collisions

Lab. Spectroscopy

Ab initio Calculations

Line catalog

Radiative Transfer

New Species

Physical Conditions

Abundances

\( \phi - \chi \) Processes

Gas and Grain Chemistry

Theory

Lab Experiment

Chemistry

Abundances

Physical Conditions

New Species

Collisions

Radiative Transfer

Molecular

Lab. Spectroscopy

Ab initio Calculations

Line catalog
Current Observational Facilities

Herschel

HIFI: 490 – 1900 GHz: 10” – 40”
PACS: 200 – 58 μm: 6” – 14”

CHESS (Ceccarelli et al)

SOFIA

CO \( J_{\text{up}} = 11 - 22 \)
C+ 158, OI 63μm

6” – 20”

ASAI (Lefloch, Bachiller, et al)

IRAM 30m

7” – 30”
70 - 360 GHz

ASAI (Lefloch, Bachiller, et al)

NOEMA

0.1” – 4”
70-360 GHz

SOLIS (Ceccarelli, Caselli et al.)

ALMA

EmoCA (Belloche et al.)
PILS (Jorgensen et al.)

+ APEX, ASTE, …
Preparing for LLAMA

Complementarity

→ Angular resolution:
  IRAM 30m : telescope beam at 3mm ≈ 1mm with LLAMA
  Multi-scale approach : avoid to jump from 30” to 0.3” …

→ Frequency: Multi-transition/Multi-wavelength approach are now very common
  LLAMA will be unique (or almost) in the submm domain
  mm domain : H$_2$O line maser (183 GHz)

0.8mm band : Is IRAM 30m OK ?
Main-beam efficiency is low (35%); beware of the error lobe (Orion, Gal. Center)
The Future Evolution of the IRAM 30m Telescope

(K. Schuster)

- EMIR with high resolution backends for up to 64 GHz total bandwidth
- NIKA II, a dual band continuum imager with 6 arcmin FOV and polarization option.
- The 50 pixel 3mm Heterodyne array
- SHERA the 98 Pixel successor of HERA at 1.3 mm.
Unbiased Spectral Line Surveys
- A large number of lines: large frequency coverage to probe a wide range of $A_{ij}$, $E_{up}$
- No (important) missing line(s): unbiased
- Full chemical census: parent, daughter molecules, radicals, etc…

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)

Serendipitous discoveries: $\text{CH}_3\text{COOCH}_3$ (Tercero et al. 2013), $\text{CH}_3\text{CHCH}_2$ (Marcelino et al. 2007), …
The IRAM line survey of Orion Irc2 (Cernicharo et al., Favre et al.)

2006: 15137 lines identified : 8000 “U”known

2013 : Collaboration with spectroscopy groups (U. Lille, IPSL,CSIC) → 4000 U

$^{13}$C, $^{15}$N isotopologues from CH$_3$CH$_2$CN , CH$_2$CHCN
Line Identification

Public Catalogs: CDMS, JPL + Spectroscopic collab.

\[ \text{HCNH}^+ (3-2) : 148221.46371 \text{ MHz} \]

Blended with \( \text{NH}_2\text{CHO} \) \( 7_{26} - 6_{25} \) 148223.14338 MHz!

One line is not sufficient to identify a species...
Accurate Spectroscopic predictions are needed

Vastel, Yamamoto, Lefloch, Bachiller (2015)

Full hyperfine transition series of CH$_2$CN computed identified in L1544 for both o- and p- species.

LTE analysis (CASSIS):
Tex = 10 – 12K
X(CH$_2$CN) $\simeq$ 10$^{-12}$ to 10$^{-11}$
OPR = 1
Line Identification

Accurate spectroscopic predictions are needed: NO$^+$ in Barnard 1 (Cernicharo 2012)

Line spectroscopy can be tricky: Observations can help

EmoCA: Survey of SgrB2(N) with ALMA (PI: Belloche et al.)

LTE Model of Ethanol with official JPL entry (Belloche, priv. comm)

New predictions with revised parity for gauche a-dipole components (Muller, priv. comm)
Multi-transition approach

CO J=2-1 @ PdBI 1” res.

What are the physical conditions in outflows and jets?

→ Feedback into the cloud
→ Probe the jet launching region at 10 AU scale
Multi-transition approach

CO J=2-1 @ PdBI 1” res.

IRAM 30m + JCMT + Herschel + SOFIA

Astrochemistry workshop - LLAMA - 2016
Multi-transition approach

(n,T, N) derived from J=1-16 line analysis
Spatial Information needed : maps!

Comparison with Paris-Durham shock model predictions

Two components in the jet:
Internal shocks revealed?

Radiative Transfer Modelling
Deuteration at 20” scale

Codella et al. (2012)

CH$_2$DOH, HDO, HDCO, HDCS, NH$_2$D, DCN, HDO

Deep Integration: rms = 1 mK

Shock age: 2000-4000 yr

→ A record of ice mantle formation
Deuteration at 3” scale

HDCO is associated with shocks in the cavity walls and the arch

Extended $\text{H}_2\text{CO}$: gas phase formation

D-fractionation: 0.04 (arch) to 0.15 (walls)
D-fractionation on mantle grains ~ 0.11
NOEMA

NOrthern Extended Millimeter Array of IRAM

Northern Hemisphere Sources : Dec > -20

NOEMA: Currently 8 antennas – 15m diameter
70 to 373 GHz (ALMA: 30 to 900 GHz)
Angular resolution: 4” -- 0.2”
Currently: one band of 3.7 GHz

Ultimate goal: 12 antennas (15m diam): 40% collecting area of ALMA
angular resolution down to 0.1” (ALMA: 0.01”)

Survey mode: 2SB receivers - 16GHz bandwidth @ 256 kHz res.
⇒ Perfect machine for line surveys
NOEMA

NOEMA with 8 antennas
(PIs: C. Ceccarelli & P. Caselli)

SOLIS: 0.10 mJy/beam
(3.5”x2.7”)

ALMA-Cycle 3
(PI C. Ceccarelli)

ALMA: 0.15 mJy/beam
(2.9”x2.0”)

Astrochemistry workshop - LLAMA - 2016
Aim: To understand how, when and where complex organic molecules form during the early stages of solar-type stars formation.

Systematic survey of a set of key COMs (and many other molecules) toward a sample of low- and intermediate mass objects

- L1544
- L1521F
- IRAS 4A
- Cep E
- SVS 13A
- OMC2-FIR4
- L1157 B1
Chemical differentiation in IRAS4A

Pineda, Lefloch et al. (in prep)

Santangelo et al. (2015)

Sensitivity
6mJy / beam in 1 km/s
The Intermediate-Mass Protostar CepE-mm

First Hot Corino around an IM protostar
COM-rich line spectrum *resolved*: 0.8”-1”

\[
\text{NH}_2\text{CHO} \ 10_{19} - 9_{18}
\]
Conclusions

Astrochemistry is a multidisciplinary field: different expertise (and experts) are needed.

Multi-wavelength, multi-transition approach: both chemical and physical conditions must be determined.
→ Spatial information (mapping) is needed
→ Several spectral bands (instruments?) are required

A good knowledge of the Source structure for RT and chemical modelling.

Close collaboration with spectroscopists and laboratory experiments is needed.
As a First Step

OI 63 µm towards HH377 with SOFIA

PACS: OI 63 µm

Lefloch et al. in prep
New insight from SOLIS

(Codella et al. in prep)

Fontani et al. (2015)