ExTernal Molecules and the Emergence of Life

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The Kepler Orrery II

\[ t[BJD] = 2455879 \]

D. Fabrycky 2012
Looking for Goldilocks

$\eta(\text{Earth}) = 1/5$, Kepler mission
Exoplanet atmosphere

Hell on Earth

Cyano Bacteria in Grand Prismatic Spring Yellowstone
Lakebed Fossils under the Ice

Bacterial colonies in Antarctica
Life in the driest spot on Earth

Microbes grow on salt crystals in the Atacama desert
Life quickly evolved once the Solar System was formed.
Key Questions

• Building new worlds: What are the key processes in planet formation? How do they depend on the environment? What is the inventory of planets, particularly in the habitable zone?

• Planetary habitats: What are the primordial sources of organics and volatiles and the processes that play a role in their formation and delivery?

• Setting the stage for life: What are the conditions on the early Earth & newly formed planets and what are the key processes that set the stage for life?
Building Planetesimals One Grain at a Time
From Embryo to Planet

from embryo’s to planets
Late Heavy Bombardment

Heritage Shows

“reduced” initial composition

“oxidized” initial composition

H chondrite

Cl chondrite

The Hadean Period

Moon forming event

Magma ocean: H$_2$O & CO$_2$ degassing

Warm, wet early Earth and subduction of CO$_2$
Late Heavy Bombardment

LHB: Ocean Vaporizing Impact

Does life have an interstellar heritage?

How did the Earth & terrestrial planets get their volatile and organic inventory?
Building the Solar System’s Organic Inventory

- From small to big: Protective environment of dense clouds
- Chemical growth: a few atoms at a time

- From big to small: Stars as sooting candles
- UV and energetic particle processing

Tielens 2011
Building the Solar System’s Organic Inventory

gas:
- ion-molecule reactions
- cosmic-ray photolysis

ices:
- hydrogenation
- photolysis
- thermal polymerization
- ice-ion-molecule
- ice segregation

comets:
- energetic processing

CO reservoir

PAH reservoir

stars:
- soot chemistry
- shock chemistry

asteroids:
- aqueous alteration

nebula:
- UV & X ray photolysis
- radical reactions
- hydrocarbon chemistry
- Fischer-Tropsch
- shocks, intermittent
- accretion, diffusion

hot core:
- ice evaporation
- ion-molecule reactions

Tielens 2011
Gas-Grain Interaction

- Depletion in dense cores (i.e., B68)
- Interstellar ice
- Gas phase HO$_2$ & H$_2$O$_2$ (i.e., r Oph)
- High deuterium abundances of CH$_3$OH/H$_2$CO in protostellar envelopes
- Hot Core/Corino composition & deuterium fractionation

Grain Surface Reactions

- Hydrogenation & oxidation
- Tunneling
- Deuteration

H$_2$CO/CH$_3$OH

H$_2$O


Simple Organic Molecules ("SOM")

- Warm dense gas with rich organic inventory: of relatively simple organic molecules
  - \( \text{CH}_3\text{OH}, \text{CH}_3\text{CH}_2\text{OH}, \text{CH}_3\text{OCH}_3, \text{H}_2\text{CO}, \text{CH}_3\text{CHO}, \text{HCOOH}, \text{NH}_2\text{CHO}, \ldots \)
  - \( \text{HCN}, \text{CH}_3\text{CN}, \text{CH}_3\text{CH}_2\text{CN}, \ldots \)
- Large deuterium fractionations
- Driven by evaporation of ice mantles formed in cold phase

Ceccarelli et al, 2007, PPV, 47
Origin of “SOM”

Deuterium fractionation implies formed from cold-reservoir-progenitors

- Surface chemistry in cold regions
- Photolysis of ices
- Evaporation followed by gas phase reactions
- Ion molecule chemistry in ices


Grain surface chemistry: Charnley & Rodgers 2007 Bioastronomy


Grain Surface Chemistry

“SOM” molecules require ‘free’ carbon
Evaporating Ices

- Evaporating ice molecules drive rich chemistry
- Protonated methanol & methyl transfer
- Issues:
  - Experimental studies disagree
  - formation of intermediaries inhibited
  - Recombination leads to fragmentation
  - Role of ammonia as proton scavenger
  - Chemical clock $\sim 3 \times 10^4$ yr incompatible with hot corinos

Geppert et al, Faraday discussions, 133, 177
UV photolysis/ion bombardment & warm up

- Radical production (CH₃ & others)
- Recombination

- Issues:
  - Chemical specificity
  - Polymerization

Ices are charged & charges are localized:
- Na, PAHs
- OCN⁻
- Polarization charge

Warm-up leads to segregation

H-bonding
Stereochemistry
Methanol drives chemistry
Near evaporation, “droplets” may conduct methyl transfer without fragmentation

Warm organics in protoplanetary disks

Photo-Chemistry in Warm Surface Layers

Chemistry in warm, UV/X-ray irradiated gas

Building the Solar System’s Organic Inventory

From small to big:
- Protective environment of dense clouds
- Chemical growth: a few atoms at a time

Comets

From big to small:
- Stars as sooting candles
- UV and energetic particle processing

Asteroids
The incredibly rich spectrum of interstellar PAHs

Orion
PAHs in Orion
M51: The Whirlpool Galaxy
M51: The Whirlpool Galaxy
PAHs and Herbig Stars

Source | Sp T | Size        | Location                        
--------|------|-------------|--------------------------------- 
TY Cra  | B7-B9 | ~2000 AU    | HAeBe in cloud                  
HD 97048| B9-A0 | ~100-1000 AU | HAeBe cloud edge                
HD 100546| B9    | ~150 AU     | isolated HAeBe star             

PAHs & C$_{60}$ in NGC 7023

Berne & Tielens, 2012, PNAS, 109, 401
PAHs & $C_{60}$ abundance

Berne & Tielens, 2012, PNAS, 109, 401
PAH photolysis

• Dehydrogenation & isomerization

• Stable intermediaries: cages & fullerenes

• Fragmentation products: hydrocarbon chains & radicals
Multiphoton absorption leads to fragmentation in a laser pulse
Many pulses strip the molecule down
Loss of all H followed by loss of $\text{C}_2$ and C units (magic numbers)

From PAHs to $C_{60}$

UV photolysis at 355 nm

From PAHs to $C_{60}$

UV photolysis at 532 nm

From Graphene to $C_{60}$

Transformation of graphene to $C_{60}$, driven by electron irradiation
Imagine Brazil as Soccer Champions of the molecular Universe!!
The Organic Inventory of Comets

Comets, and hence the Earth, sampled many reservoirs with a diverse chemical history

- ice chemistry
- Hot Core chemistry
- Warm gas photochemistry
- PAHs

Tielens, 2013, Rev Mod Phys and refs therein
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Future of Astrochemistry

- Paradigms have been developed which provide precise descriptions of the various stages in the formation and early evolution of planetary systems.

- Goal for the near future:
  - Review these paradigms & determine how accurate are
  - Predict the composition of terrestrial exoplanets & exomoons
  - Predict biosignatures of exoplanets
Kepler, TESS & Plato

ALMA

SOFIA

James Webb
Space missions cost 1 Billion euro and up!

Grad students: Any study is relevant somewhere in the Universe. Your challenge is to find out where!
Molecular Astrophysics

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