Quantifying lightning as source of prebiotic molecules

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Miller-Urey experiment (1952)

Energy source: lightning
Reducing atmosphere

More than 20 different amino acids produced
Nitrogen Fixation:

Start with:

\[ N_2 + O_2 + H_2O (+CO_2) \]

Nitric oxide:

\[ N_2 + O_2 \rightarrow 2NO \]

Nitrite:

\[ 2NO + O_2 \rightarrow 2NO_2 \rightarrow 2NO_2^- \text{ (in water)} \]

Nitrate:

\[ NO_2 + OH \rightarrow HNO_3 \rightarrow NO_3^- \text{ (in water)} \]
History of Earth’s atmosphere

Goldblatt et al. 2017
Nitrate production during history of Earth’s atmosphere

- **1 N$_2$ | 0 O$_2$ | 0 CO$_2$**
- **0.99 N$_2$ | 0.01 O$_2$ | 0 CO$_2$**
- **0.9 N$_2$ | 0.1 O$_2$ | 0 CO$_2$**
- **0.7 N$_2$ | 0.3 O$_2$ | 0 CO$_2$**
- **0.9 N$_2$ | 0 O$_2$ | 0.1 CO$_2$**
- **0.78 N$_2$ | 0.21 O$_2$ | 400ppm CO$_2$**
- **Air: 0.78 N$_2$ | 0.21 O$_2$ | 400ppm CO$_2$ + traces**

O$_2$ fraction in gas vs. Mass NO$_3^-$ [mg]

- **N$_2$ + O$_2$**
- **N$_2$ + CO$_2$**
- **N$_2$ + O$_2$ + CO$_2$**

- **4 Gyr**
- **2 Gyr**
- **0.5 Gyr**
- **today**
Problem: Scale

~ 20 cm

~ 12,000 km
High-energy radiation

- Protons
- XUV radiation
- Cosmic rays

https://www.spaceweatherlive.com/de/hilfe/der-sonnenwind
Atmospheric C/H/N/O chemistry
Complete up to 2C, 6H, 2N, 3O

XUV = X-Ray + UV radiation
SEP = Stellar Energetic Particles
The Planet: HD 189733 b

Substellar Point

Antistellar Point

West terminator

East terminator

Substellar Point

Equator

Star: HD189733

Atmospheric profiles from 3D Met Office Unified Model

Lines et al. 2018

Top of atmosphere

Pressure (bar)

Height

Base of atmosphere

Temperature (K)

HD 189733 b

Antistellar

Substellar
XUV = X-Ray + UV radiation

SEP = Stellar Energetic Particles

CR = Cosmic Rays

XUV (Bourrier et al. 2020)
SEP (scaled from Rab et al. 2017)
CR (Rimmer & Helling 2013)
Substellar point

XUV ✓
CR ❌
SEP ✓

XUV
SEP
Thermal
Ionization rates for different processes
Ionization rates for different processes

- Thermal Ionization
- Cosmic Ray
- Photochemical (XUV)
- SEP
Prebiotic molecules: Amino acid Glycine (C$_2$H$_5$NO$_2$)
Conclusion

• Nitrate production increase with oxygen abundance
• CO₂ possible oxygen source for nitrate in early Archean
• Energy input needed for prebiotic molecules
• XUV/SEP/CR: important energy source for prebiotic chemistry
• Tracer for SEP/CR ionisation: NH₄⁺, HCN

Outlook

• Reproduce nitrate production experiments
• Measure nitrogen isotope fraction
• Include lightning in model
• Add aqueous chemistry