# The origin of life as a planetary phenomenon

Dimitar D. Sasselov, John P. Grotzinger and John D. Sutherland, 5th February 2020

Paul Waldmann and Kyeong Ro Lee
05.06.2020

Seminar: Physics of Early Evolution and Emergence of Life

# Table of contents

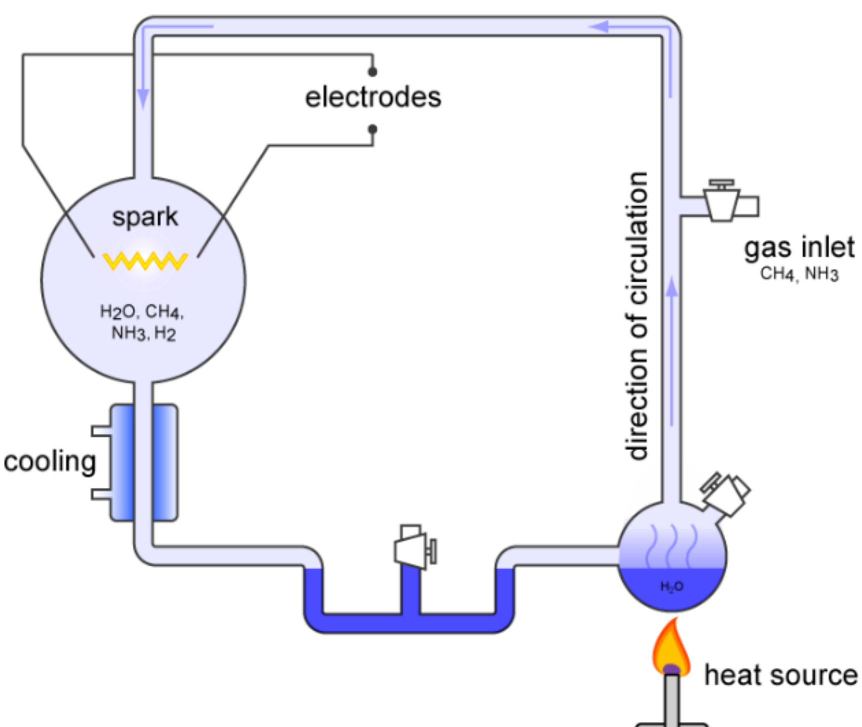
# The origin of life as a planetary phenomenon

**Cyanosulfidic chemistry**

(chemistry ↔ geological and planetary aspects)

**Unselctive Chemistry**

(e.g.formose reaction in primordial soup)




**Miller-Urey**

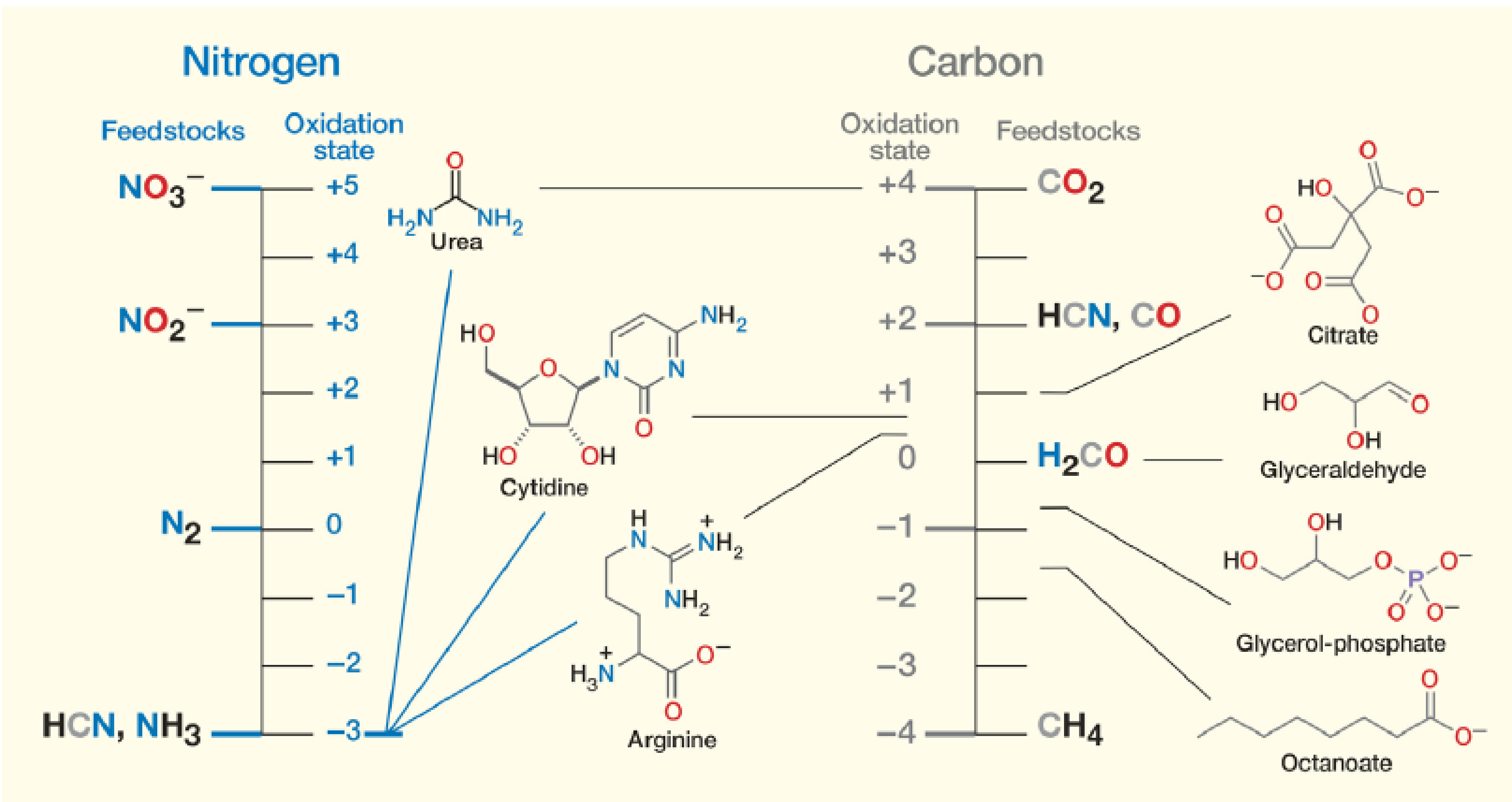
(assumption of atmosphere)

# The prebiotic cyanosulfidic chemistry - Assumptions

- Emergence of life is linked to planetary conditions
- Vestiges of prebiotic chemistry are present
- Panspermia is not taken into account
- There are key builiding blocks wich then assembly into higher order structures

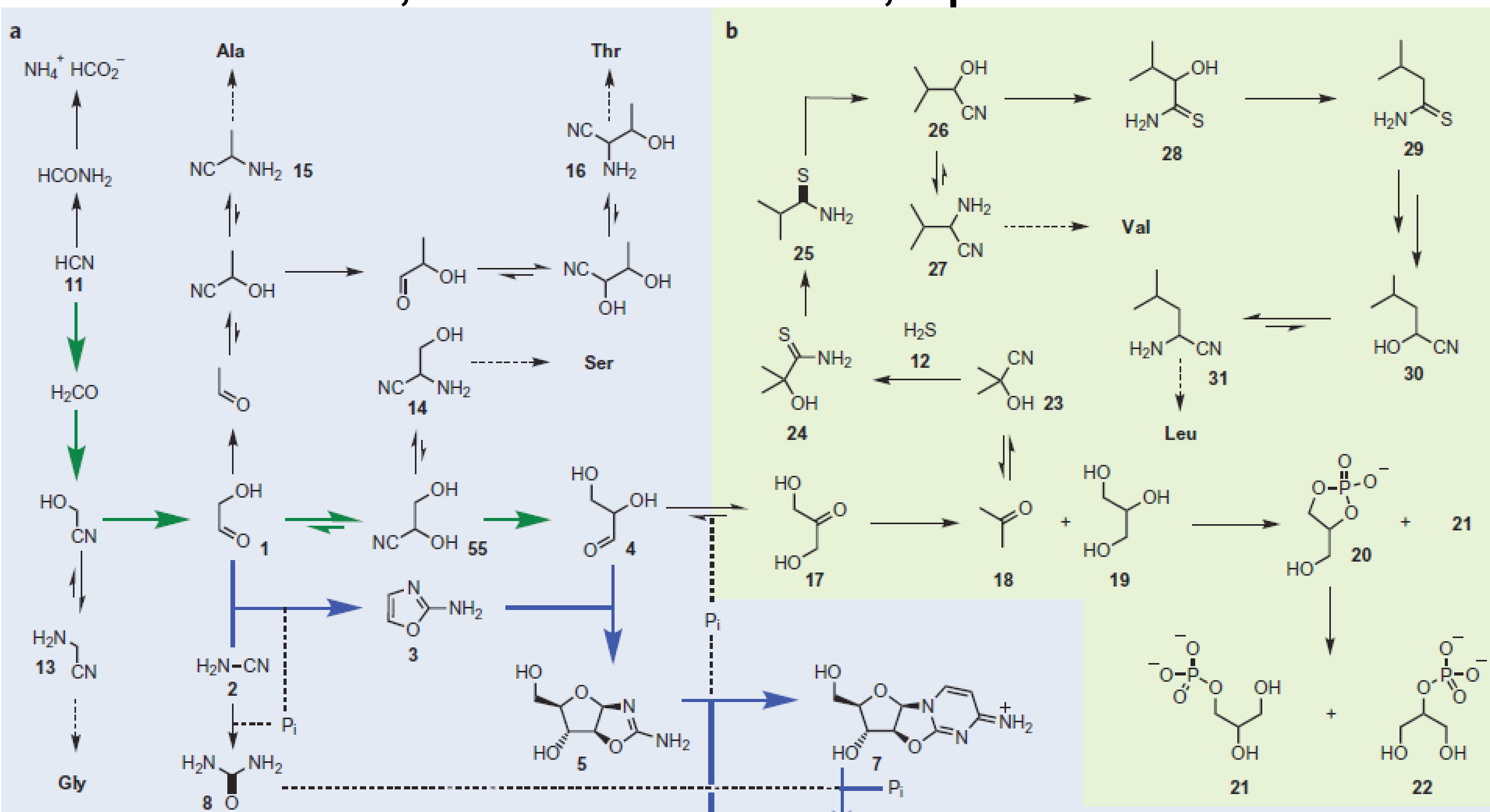
# The prebiotic cyanosulfidic chemistry - Assumptions

- Preferred feedstock: Hydrogen cyanide (HCN)



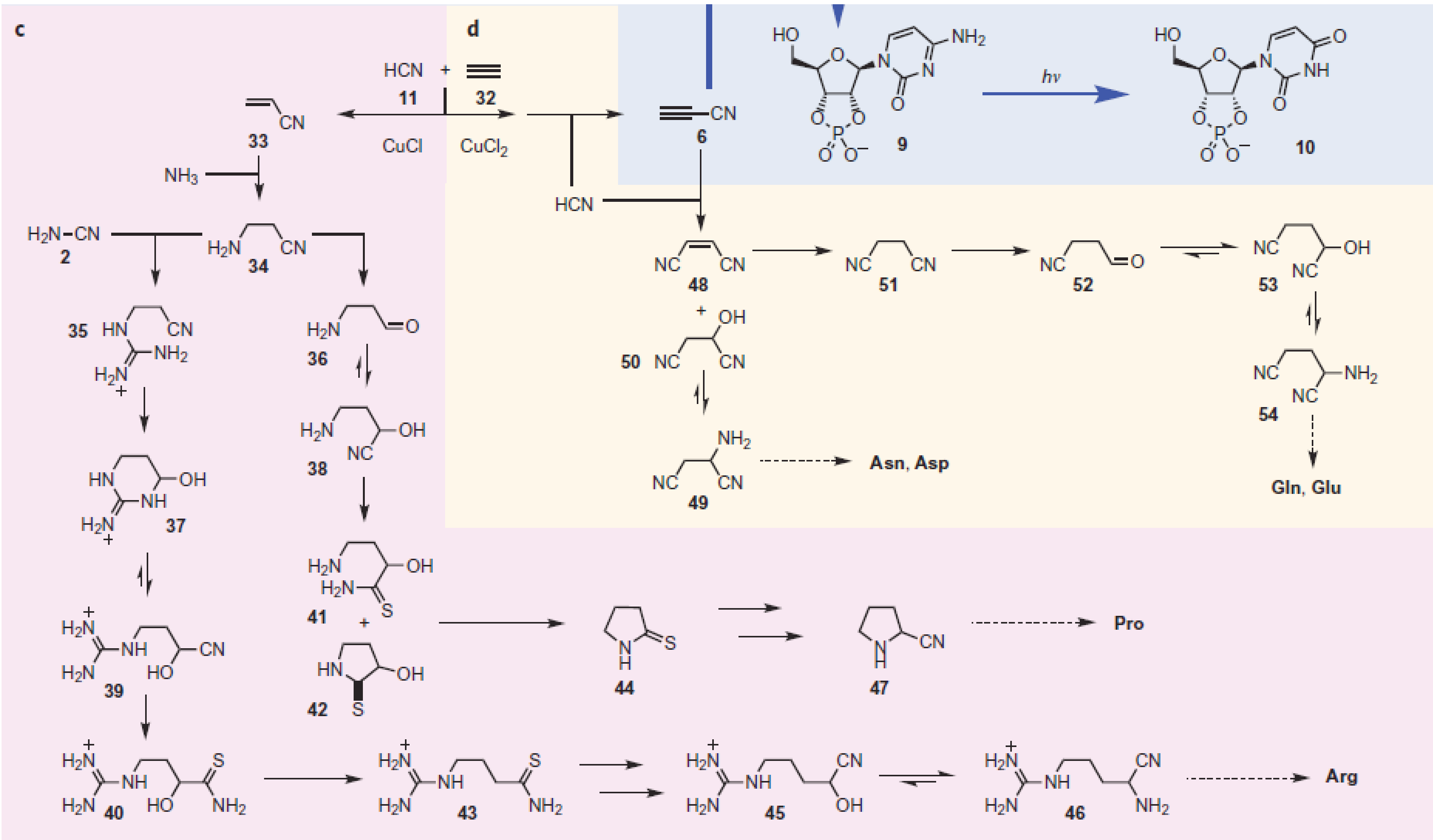
# The prebiotic cyanosulfidic chemistry - HCN

- HCN (and Hydrogen sulfide) produces sugars, amino acids, ribonucleotides, lipids



# The prebiotic cyanosulfidic chemistry - HCN

- HCN ( copper catalysed ) produces amino acids, ribonucleotides



# The prebiotic cyanosulfidic chemistry - Mechanism

- Assumption: Atmosphere containing C, H, O and N
- Energy input can produce CO, NO•, CN•
- By cooling, CN• needs a hydrogen atom → HCN
- HCN must be transported to the surface and concentraded there

# The prebiotic cyanosulfidic chemistry - Mechanism

- $H_2O$-Lakes with $Fe^{2+}$ convert gaseous HCN to ferrocyanide salts
- $CaK_2[Fe(CN)_6]$ and $MgNa_2[Fe(CN)_6]$ sink and mix with sediment bottom
- Lakes protect the salts from UV radiation
- Drying cycles can concentrate these salts

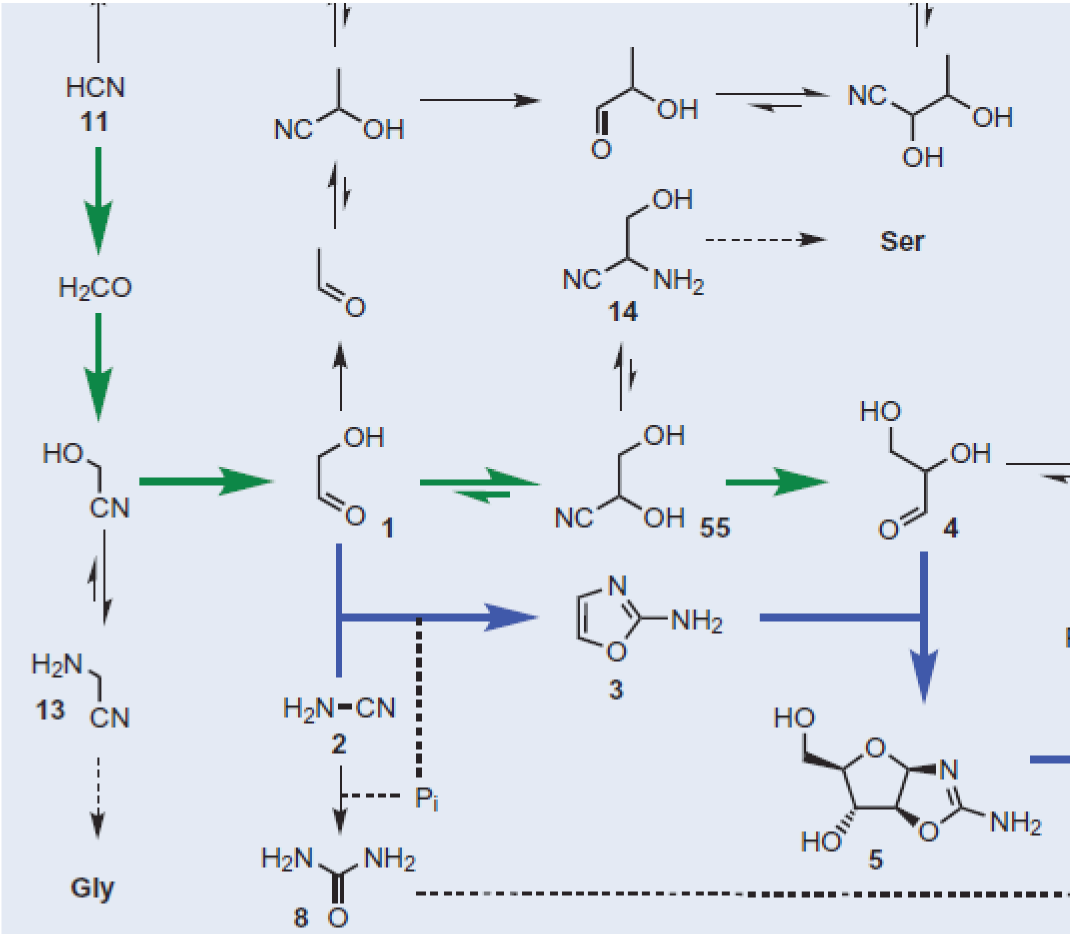
# The prebiotic cyanosulfidic chemistry - Mechanism

- Heating ferrocyanide salts (700°C):
  - $CaK_2[Fe(CN)_6] \rightarrow CaCN_2$ and KCN
  - $MgNa_2[Fe(CN)_6] \rightarrow Mg_3N_2$ and NaCN
- In solution with water:

  HCN, $H_2CN_2$, $NH_3$

# The prebiotic cyanosulfidic chemistry - Reduction

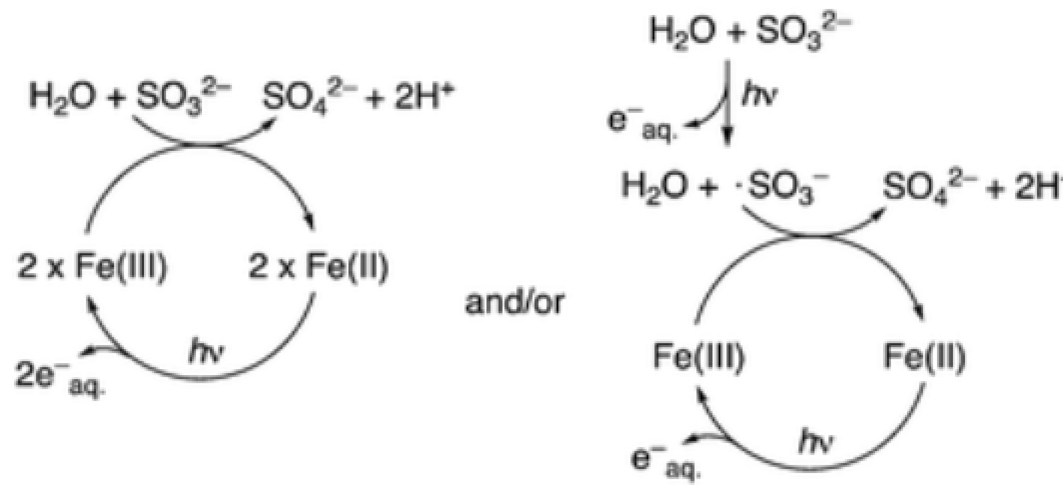
- Making biological molecules, HCN reduction is needed
- Radiolytic hydration of water produces HO•
- Mid-range UV can effectively produce e⁻ by irrdiation of mutliple anions

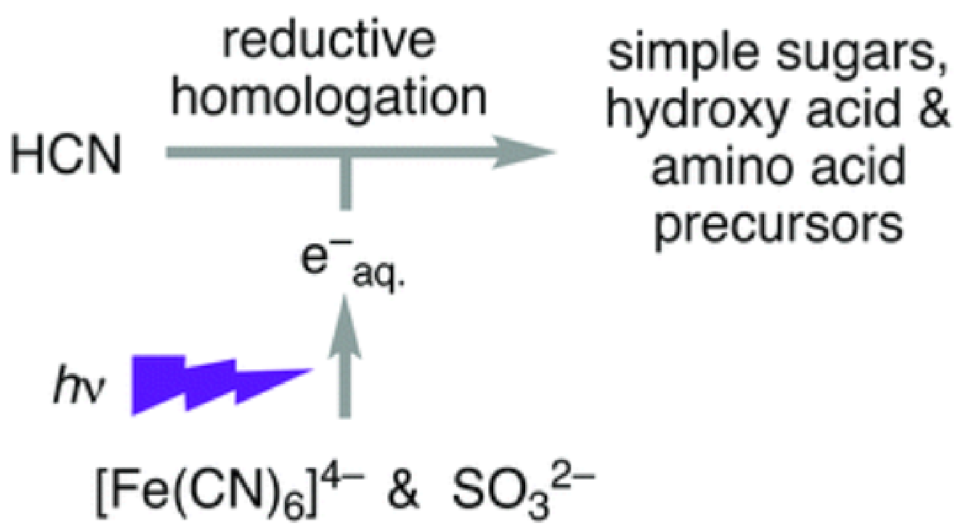


# The prebiotic cyanosulfidic chemistry - Reduction

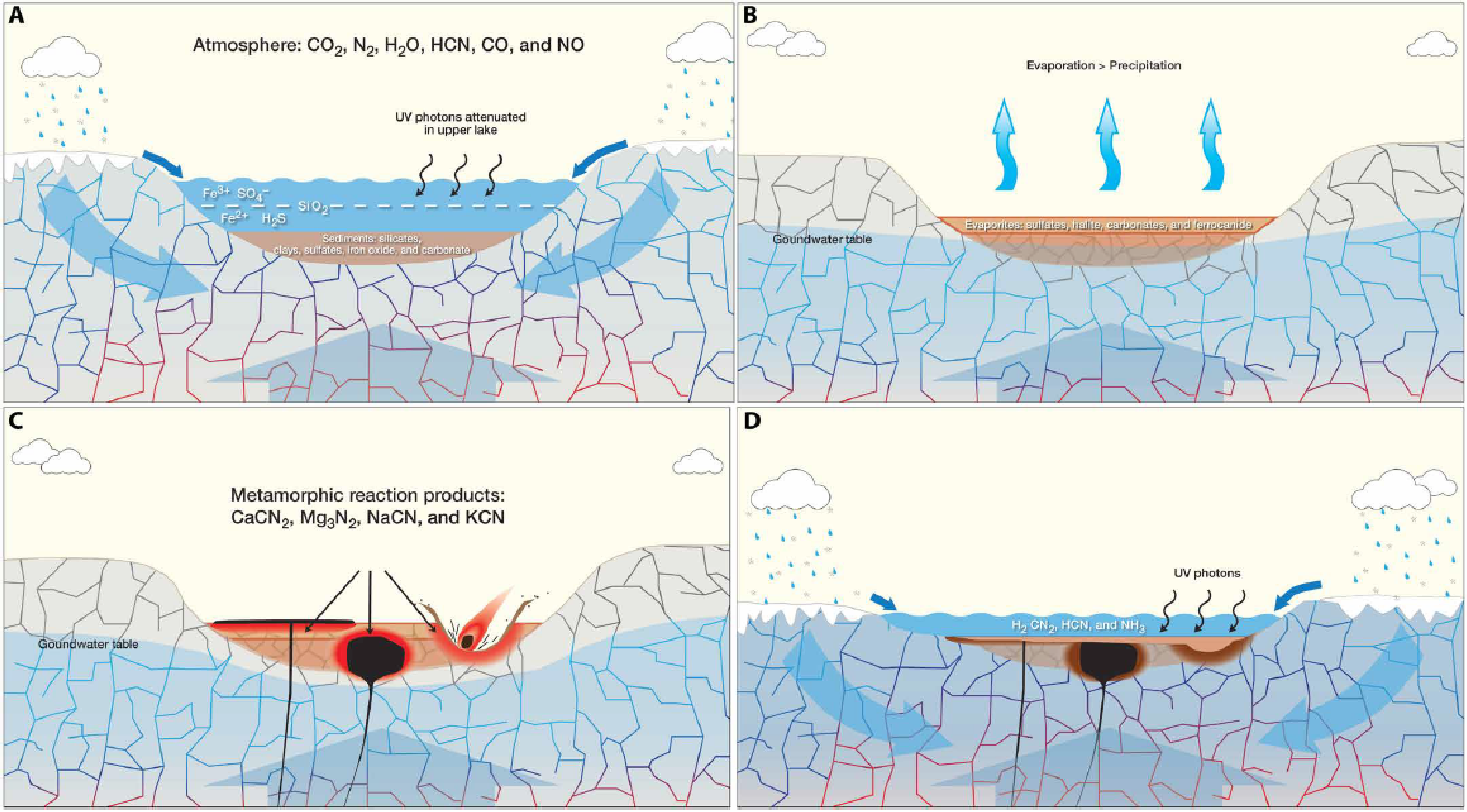
Volcanism produces

$SO_2 \xrightarrow[H_2O]{} SO_3^{2-}$



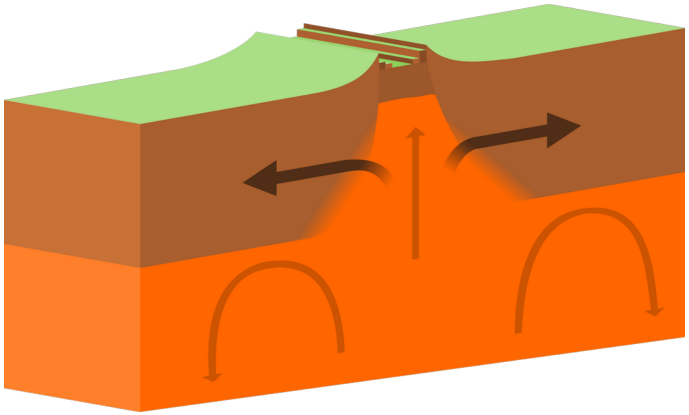



# The prebiotic cyanosulfidic chemistry - Mechanism

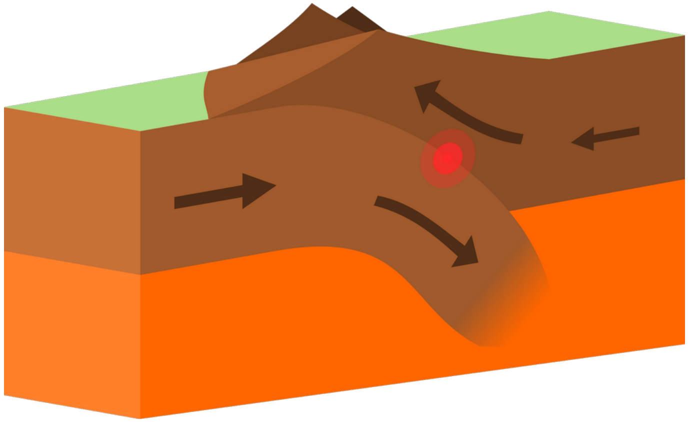


# Earth-Mars Comparison

- Mars: “frozen” early Earth
- Geologically “dead” - absence of plate tectonics
- Lack of radioactive isotopes
- Not enough liquid iron → weaker magnetic field
- Can’t hold atmosphere against solar wind



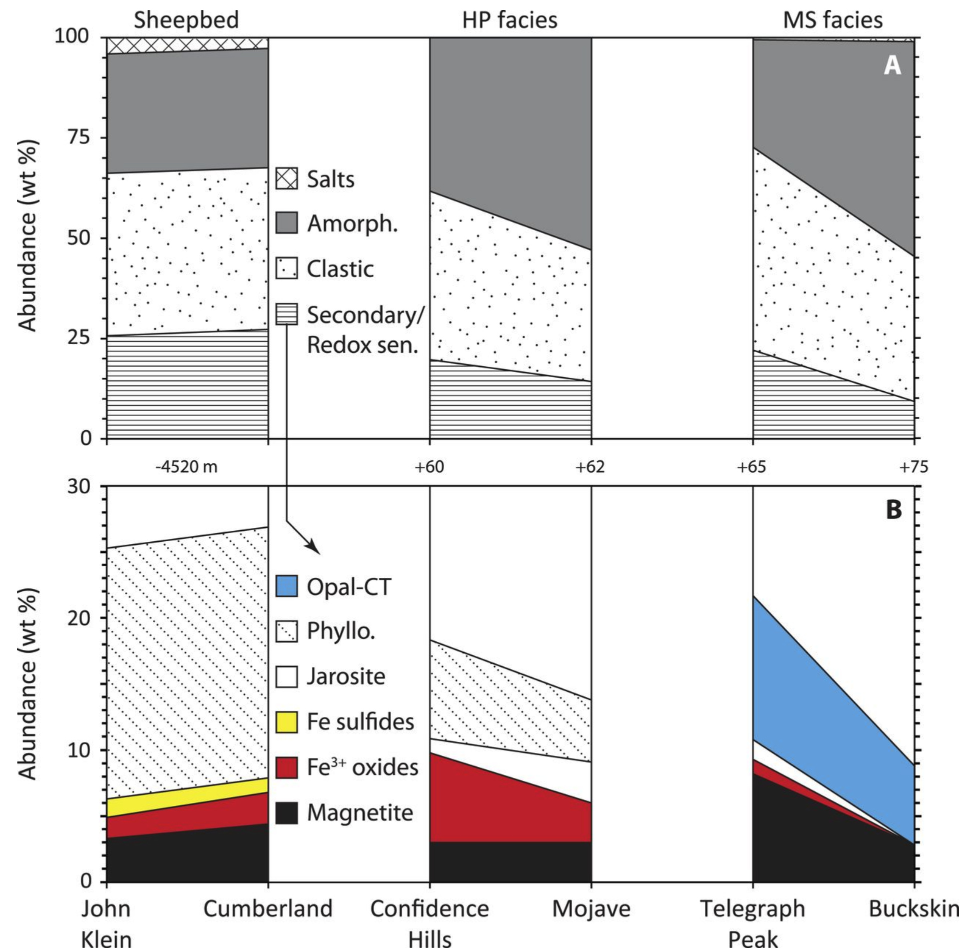
Divergent boundary
https://commons.wikimedia.org/wiki/File:Continental-continental_constructive_plate_boundary.svg



Convergent boundary
https://commons.wikimedia.org/wiki/File:Continental-continental_destructive_plate_boundary.svg

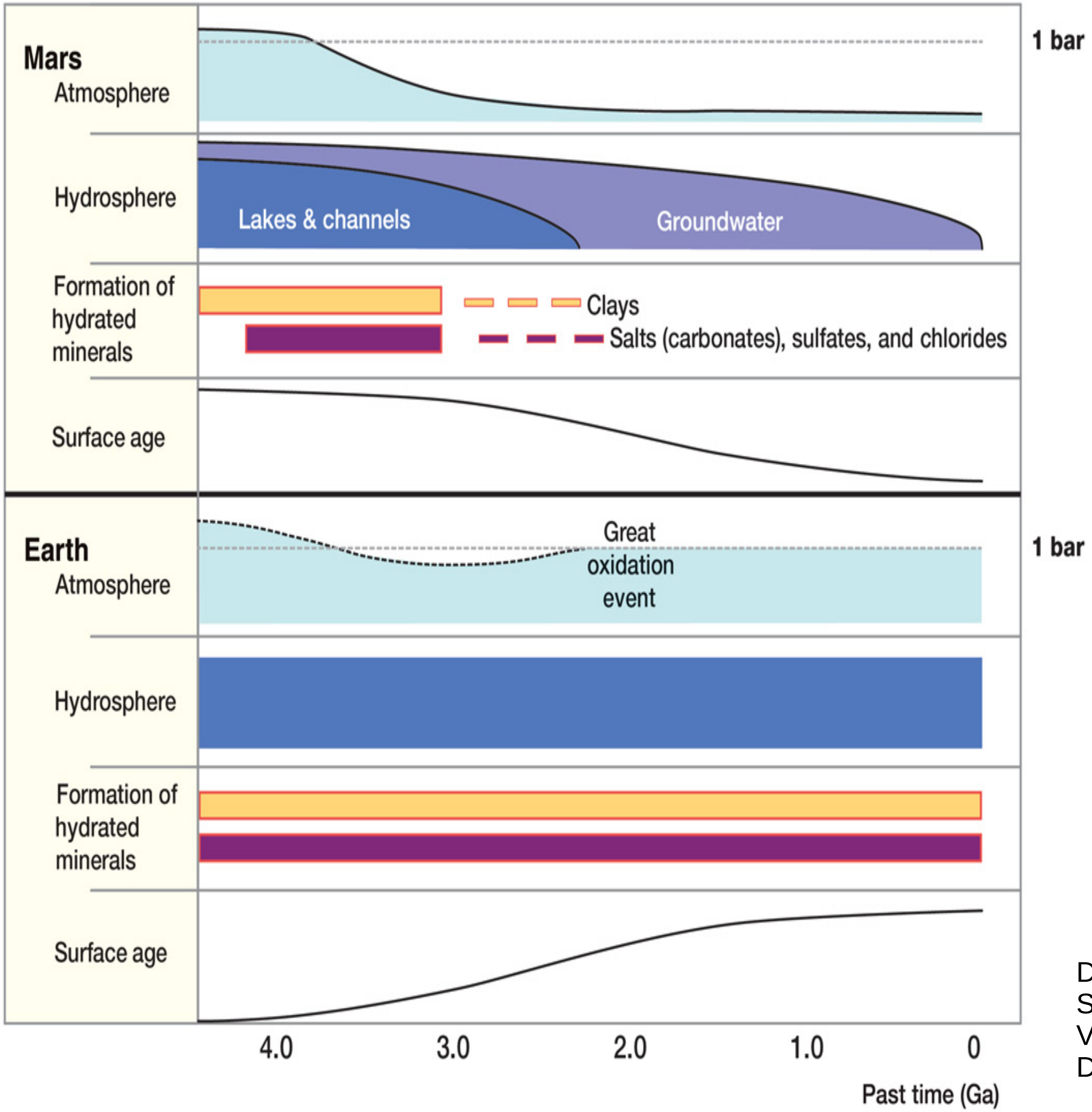
# Earth-Mars Comparison

- Abundance of **sedimentary rocks**
- Chemical concentration from evaporation or shallow burial → authigenic minerals
- Deeper burial and conversion of sediment into rock → diagenetic minerals
- **Thermal metamorphism**




J. A. Hurowitz et al.,
Science 02 Jun 2017:
Vol. 356, Issue 6341, eaah6849
DOI: 10.1126/science.aah6849

# Earth-Mars Comparison

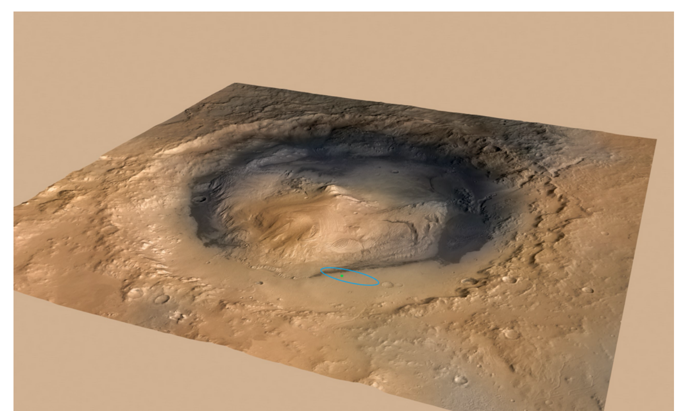



D. D. Sasselov et al.,
Science Advances 05 Feb 2020:
Vol. 6, no. 6, eaax3419
DOI: 10.1126/sciadv.aax3419

# Earth-Mars Comparison

- The Curiosity Rover: launched in Nov. 2011, landed on Gale crater of Mars Aug. 2012
- Found sulfates, chlorides, clay minerals
- Iron, manganese, boron, phosphorous and nitrogen compounds

The Curiosity rover,
http://photojournal.jpl.nasa.gov/catalog/PIA19920



Gale crater of Mars,
http://photojournal.jpl.nasa.gov/catalog/PIA16058

# Earth-Mars Comparison

- Heating mechanism is essential for cyanosulfidic synthesis
- Traces of heating mechanism → Metamorphic rocks found in Mars (CRISM, MRO and OMEGA)
- Signs of igneous events
- Shock heating (impacts)

# Earth-Mars Comparison

- Evidences of lake environment on Mars found by Curiosity rover
- Neutrally to mildly acidic pH
- Low to high salinity
- C, H, O, S, N, P, Fe, Mn, B have been found

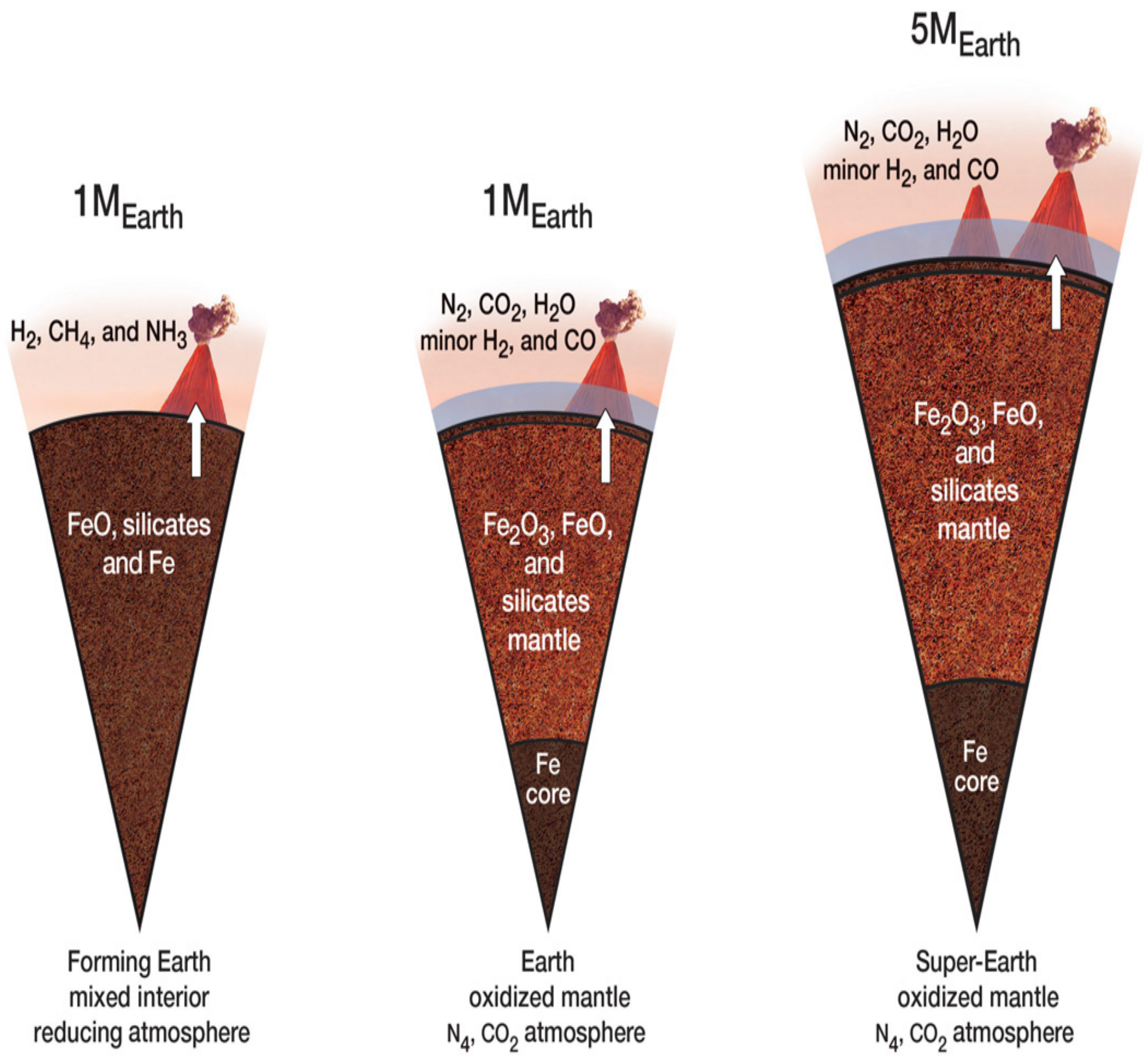
# Planetary Conditions in General

- “Rocky planets” with bulk Si/Fe interior, up to $10M_{Earth}$
- Currently numerous exoplanets have been found (4,164 have been confirmed as of 04/06/2020, more than 1000 are terrestrial)
- Long-lived liquid $H_2O$
- C, N, S, P, Fe
- Mid-range UV
- Redox gradients, vents and volcanoes
- Stable climate

# Atmosphere

- Metal-sillicate partitioning
- Photolysis of $CH_4$, $NH_3$ and $H_2$ → H escapes  and $N_2$-$CO_2$ atmosphere is generated

# Atmosphere




D. D. Sasselov et al.,
Science Advances 05 Feb 2020:
Vol. 6, no. 6, eaax3419
DOI: 10.1126/sciadv.aax3419

# Hydrospheres

- “Habitable zone”
- Liquid water belt
- Pressure of atmosphere
- Question: did Mars’ hydrosphere last long enough to allow prebiotic chemistry?

# Hydrospheres

### List of exoplanets in the conservative habitable zone [ edit ]

In astronomy and astrobiology, the circumstellar habitable zone (CHZ), or simply the habitable zone, is the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure. Note that this does not ensure habitability, and that ∗ represents an unconfirmed planet or planet candidate. Earth is included for comparison.[10]

| Object | Star | Star type | Mass ($M_{\oplus}$) | Radius ($R_{\oplus}$) | Flux ($F_{\oplus}$) | $T_{eq}$ (K) | Period (days) | Distance (ly) | Ref |
|---|---|---|---|---|---|---|---|---|---|
| Earth | Sun (Sol) | G2V | 1.00 | 1.00 | 1.00 | 255 | 365.24 | - | |
| Proxima Centauri b | Proxima Centauri | M6Ve | ≥1.3 | 0.8 – 1.1 – 1.4 | 0.65 | 234 | 11.186 | 4.22 | [11] |
| Gliese 667 Cc | Gliese 667 C | M3V | ≥3.8 | 1.1 – 1.5 – 2.0 | 0.88 | 277 | 28.143 ± 0.029 | 23.62 | [12][13] |
| Kepler-442b | Kepler-442 | K?V | 8.2 – 2.3 – 1.0 | 1.34 | 0.70 | 233 | 112.3053 | 1291.6 | [13] |
| Kepler-452b | Kepler-452 | G2V | 19.8 – 4.7 – 1.9 | 1.50, 1.63 | 1.11 | $265^{+15}_{-13}$ | 384.8 | 1402 | [13][14] |
| Wolf 1061c | Wolf 1061 | M3V | ≥ 4.3 | 1.1 – 1.6 – 2.0 | 1.36 | 275 | 17.9 | 13.8 | [13] |
| Kepler-1229b | Kepler-1229 | M?V | 9.8 – 2.7 – 1.2 | 1.4 | 0.49 | 213 | 86.8 | 769 | [13] |
| Kapteyn b | Kapteyn | sdM1 | ≥ 4.8 | 1.2 - 1.6 - 2.1 | 0.43 | 205 | 48.6 | 13 | [13] |
| Kepler-62f | Kepler-62 | K2V | 10.2 – 2.8 – 1.2 | 1.41 | 0.39 | 244 | 267.291 | 1200 | [13][15] |
| Kepler-186f | Kepler-186 | M1V | 4.7 – 1.5 – 0.6 | 1.17 | 0.29 | 188 | 129.9459 | 561 | [13] |
| Luyten b | Luyten's Star | M3.5V | 3.15 - 2.89 - 2.63 | ~1.35 | 1.06 | 206-293 | 18.650 | 12.36 | [16] |
| TRAPPIST-1d | TRAPPIST-1 | M8V | 0.30 | 0.78 | 1.04 | 258 | 4.05 | 39 | [17][18] |
| TRAPPIST-1e | TRAPPIST-1 | M8V | 0.77 | 0.91 | 0.67 | 230 | 6.1 | 39 | [17][18] |
| TRAPPIST-1f | TRAPPIST-1 | M8V | 0.93 | 1.046 | 0.38 | 200 | 9.2 | 39 | [17][18] |
| TRAPPIST-1g | TRAPPIST-1 | M8V | 1.15 | 1.15 | 0.26 | 182 | 12.4 | 39 | [17][18] |
| LHS 1140 b | LHS 1140 | M4.5V | 6.6 | 1.43 | 0.46 | 230 | 25 | 40 | [19] |
| Kepler-1638b | Kepler-1638 | G4V | 45 – 6 – 1 | 1.60 | 1.17 | 304 | 259.365 | 2491.83 | [20] |
| Teegarden c* | Teegarden's Star | M7V | 1.11 | | 0.37 | | 11.4 | 12.58 | [21] |

https://en.wikipedia.org/wiki/List_of_potentially_habitable_exoplanets

# UV irradiation

- High-energy UV → attenuated
- **Mid-range UV** → synthetic photochemistry
- Source of energy and selection agent
- Prevents formation of isomers and tautomers
- Can be blocked by $H_2S$ and $SO_2$

# Conclusions & Outlook

- Open questions → to be answered by Mars 2020 rover
- Other possibilities of prebiotic chemistry
- Confirmation of $N_2$-$CO_2$ atmosphere in exoplanets
- History of $H_2O$ acquisition and distribution
- The explanation in prebiotic chemistry already fits observation

# References


- **The origin of life as a planetary phenomenon**

  Dimitar D. Sasselov, John P. Grotzinger and John D. Sutherland

- **Common origins of RNA, protein and lipid precursors in a cyanosulfidic protometabolism**

  Bhavesh H. Patel, Claudia Percivalle, Dougal J. Ritson, Colm D. Duffy and John D. Sutherland*

- **Photochemical reductive homologation of hydrogen cyanide using sulfite and ferrocyanide**

  Jianfeng Xu, Dougal J. Ritson, Sukrit Ranjan, Zoe R. Todd, Dimitar D. Sasselov and John D. Sutherland

# References


- **Redox stratification of an Ancient Lake in Gale Crater, Mars**

  J. A. Hurowitz et al., Science 356, eaah6849 (2017)

- **Hydrous minerals on Mars as seen by the CRISM and OMEGA imaging spectrometers: Updated global view**

  J. Carter et al., J. Geophys. Res. 118, 831-858 (2013)