

Plein ecran

Stellar Energetic Particle-driven Production of Biologically Relevant Molecules in Atmospheres of Young Earth-like Exoplanets

Guillaume Gronoff (SSAI/NASA LaRC/SEEC), V. Airapetian (NASA GSFC/SEEC), B. Hayworth (Penn St University), B. Hegyi (SSAI/NASA LaRC), J. Kasting (Penn St University)



Young stars, active stars, and astrobiology

The Solar System 4 Gyr ago

- Sun radiative output $\approx 70\%$ (compared to current Sun)
- Earth and Mars had liquid water at the surface (standing bodies of water).

The Prebiotic Chemistry

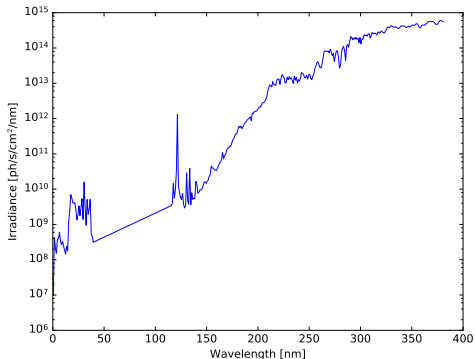
- Are prebiotic molecules, the building blocks of life of extraterrestrial origins? For example brought by comets!
- Are they created in-situ, like in a Urey-Miller experiments, which created lots of prebiotic molecules but had a reducing atmosphere?

Effect of an active star

- In Airapetian et al 2016, we proposed the activity of the Young Sun as a solution for these problems
- We show an improved solution here; with better photochemical models; more realistic stellar fluxes; and a wider range of planetary atmospheres for a better application to extrasolar planets

The magnetic activity of the Young G-K stars

Young Stellar Flares: SuperFlares



- Observed by Kepler
- Very energetic Stellar Flares ($>5 \cdot 10^{34}$ erg)
- Frequent superflares (0.1 per day)
- Spectra assumed equivalent to current flares

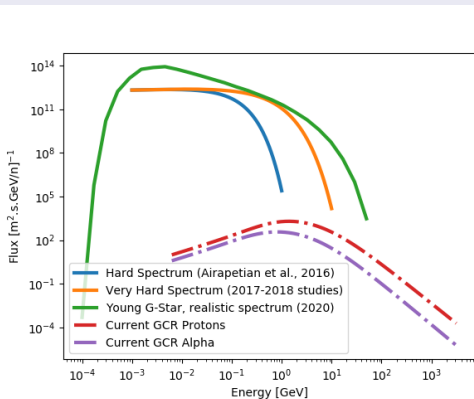
The magnetic activity of the Young G-K stars

SuperFlares effects

The superflares are associated to energetic coronal mass ejections (CME), themselves driving shocks that accelerate particles, forming Stellar Energetic Particle (SEP) events!

The SEP events from active stars

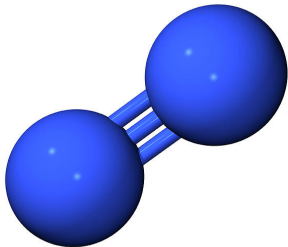
Average Flux of an active star Energetic Particle Events



- Flares are associated with CME. (Airapetian et al. 2021, ApJ, 916, 96)
- SEP events linked to the CME. (Hu, Airapetian et al. 2021, Science Advances, 2021)
- Super-Carrington like SEP events.
- Green Spectra: realistic with stellar wind at 7300km/s

Pathway to BioMolecules and Potential for Life

Prospects for prebiotic chemistry



- The dominant molecule in the Atmosphere 80-90%
Extremely hard to dissociate
- Triple bonds: 10 eV/atom vs 5.2 eV/atom for O₂
- Prebiotic chemistry needs to break $N_2 \rightarrow 2 N$:
 - UV emission at $\lambda < 100$ nm (early Sun, M dwarfts)
 - Lightning discharge
 - Energetic particles (e, p)

Simulation of the hard SEP interaction with a Earth-like planet, part 1 – magnetosphere

The Simulation Framework

- Active solar-like star with a mass loss rate of $1.7 \cdot 10^{-12} M_{\odot}$ (Airapetian, Usmanov 2016)
- Slow component of wind speed: 700 km s^{-1}
- Carrington-type CME cloud propagating at a radial speed of 1800 km s^{-1} with a total energy of $2 \cdot 10^{33} \text{ erg}$
- BATS-R-US code running on the SWMF/CCMC (Airapetian et al., Nat. Geo. 2016)
- The magnetic field of a Earth-like planet

Simulation of the hard SEP interaction with a Earth-like planet, part 1 – magnetosphere

Earth Magnetic Field Under the Super-Carrington scale CME (Airapetian et al., Nat. Geo. 2016)

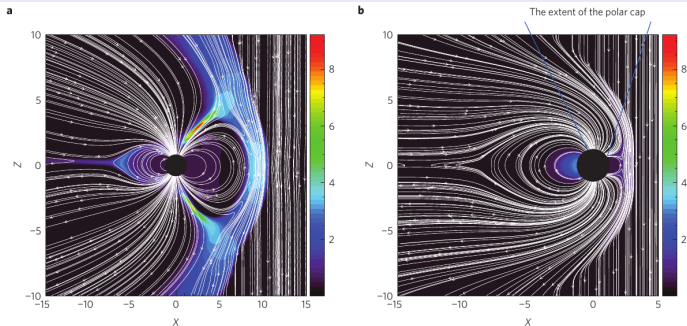
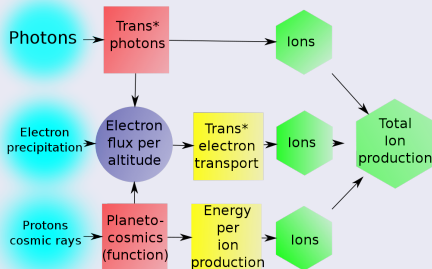


Figure 1 | Simulation of the magnetic field lines and plasma pressure in the Earth's magnetosphere due to a CME event. **a**, Initial state. **b**, Final state. Magnetic field lines (white) and plasma pressure in nPa (colour map)¹⁴. Axes represent distance from the Earth's centre in units of Earth radius.

The Aeroplanets model: simulating SEP energy deposition in the atmospheres

Aeroplanets



- The GEANT4 Planetocosmic models computes the ionization by cosmic rays and high energy proton
- A multi-stream equation is solved for the electrons

The Photochemical model: PHOTOCHEM

Simplified chemistry diagram

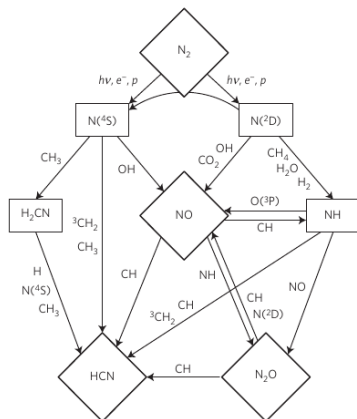
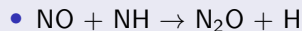


Figure 3 | The pathway diagram of abiotic production of odd nitrogen and nitrogen-bearing compounds including nitrous oxide and hydrogen cyanide due to photo and collisional dissociation and ionizations caused by XUV solar flux and SEP particle flux. Symbols e^- and p represent electrons and protons respectively.

Destruction of N_2 , CO_2 & CH_4
 N_2O production:



HCN production:

- $NO + CH \rightarrow HCN + O$
- $CH_2 + N(^4S) \rightarrow HCN + H$
- $CH_3 + N(^4S) \rightarrow HCN + H + H$
- $CH + CN \rightarrow HCN + H$
- $N_2O + CH \rightarrow HCN + NO$

Modeling cases

Atmospheric pressure variation

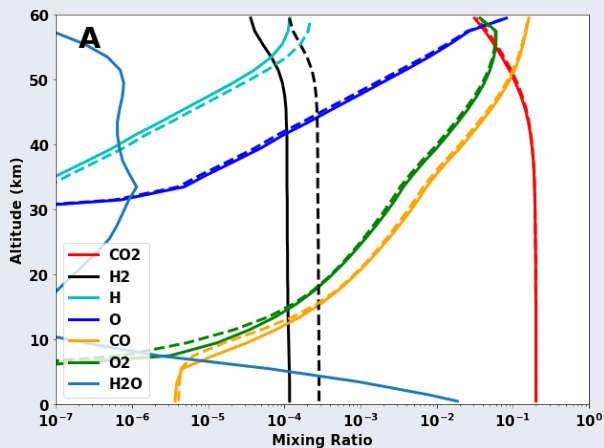
- Different pressure at the ground on the Young Earth have been proposed
- Exchange of N_2 between the crust and the atmosphere could have led to pressure varying between 0.5 and 1 bar
- We explore these different pressure at the ground in our calculations
- We use a N_2 , CO_2 rich atmosphere which corresponds to our best estimation for a Young Earth atmosphere

CH_4 level variation

- CH_4 levels should change greatly in function of the different conditions
- A low CH_4 level would corresponds to its creation by serpentinization
- Methanogens would create a higher level (not shown in this presentation)

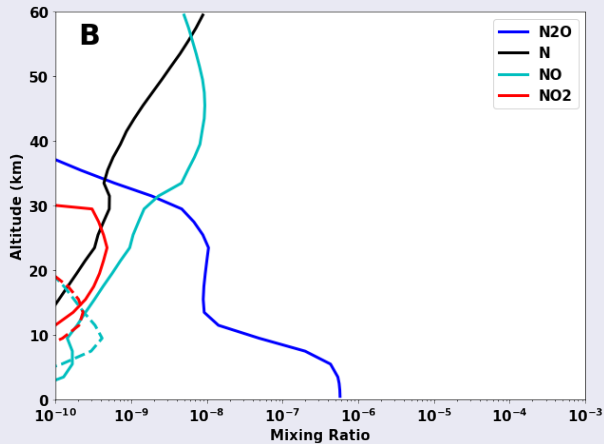
Simulation of the hard SEP interaction with a Earth-like planet, part 3 – bio-molecule production

0.5 bar: Production of species with and without stellar activity



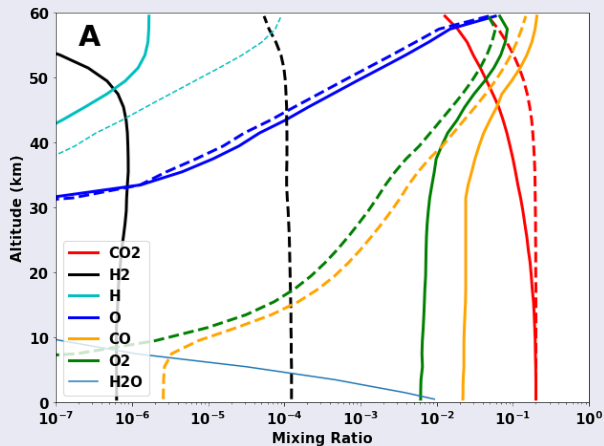
Simulation of the hard SEP interaction with a Earth-like planet, part 3 – bio-molecule production

0.5 bar: Production of species with and without stellar activity



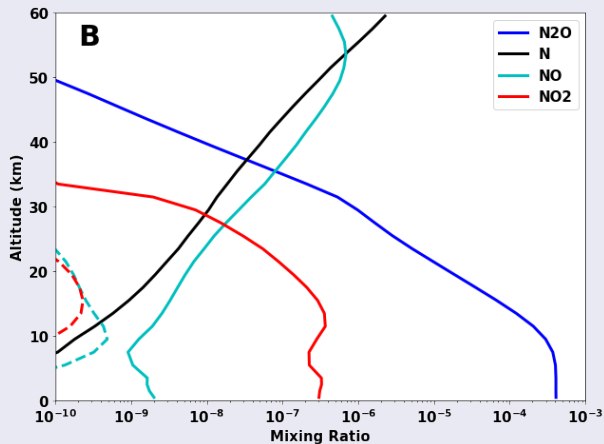
Simulation of the hard SEP interaction with a Earth-like planet, part 3 – bio-molecule production

1 bar: Production of species with and without stellar activity



Simulation of the hard SEP interaction with a Earth-like planet, part 3 – bio-molecule production

1 bar: Production of species with and without stellar activity



Simulation of the hard SEP interaction with a Earth-like planet, part 3 – bio-molecule production

Fluxes ($\text{cm}^{-2}\text{s}^{-1}$) in the Ocean (No SEP vs SEP)

Species	0.5 bar; Low CH_4	1 bar; Low CH_4	1 bar; High CH_4
NO-X	$1.1 \cdot 10^7 - 1.1 \cdot 10^8$	$3.1 \cdot 10^7 - 2.2 \cdot 10^{10}$	$2.2 \cdot 10^7 - 5.4 \cdot 10^8$
HCN	$2.2 \cdot 10^3 - 2.0 \cdot 10^7$	0 - 0	$2.6 \cdot 10^4 - 3.3 \cdot 10^9$

Conclusions

Conclusions

- We show that the SEPs have a major impact on the production of certain prebiotic molecules and greenhouse gases.
- These flux could be sufficient to provide the building blocs of life on Earth according to Airapetian 2019 and ref therein
- Greenhouse gases could provide a clue to the FYS paradox.
- The impact of the space weather on the atmospheric photochemistry should not be neglected when assessing the factors of habitability of the environments of young rocky (exo)planets.

Future work

- Publication of our results for the different cases of CH_4 and different pressures
- Publication of updated computation for the Earth