climate change initiative

LONG-LIVED GREENHOUSE GAS
PRODUCTS PERFORMANCES

The impact of Space Weather on Earth's atmospheric chemistry and climate

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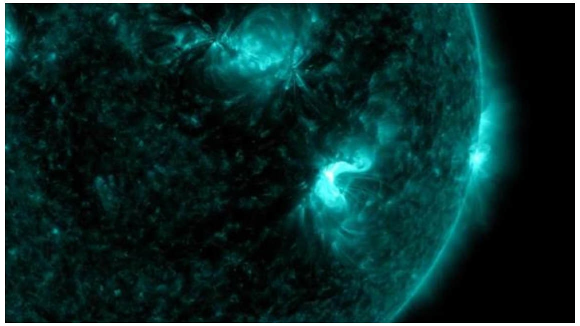
Introduction: Space Weather

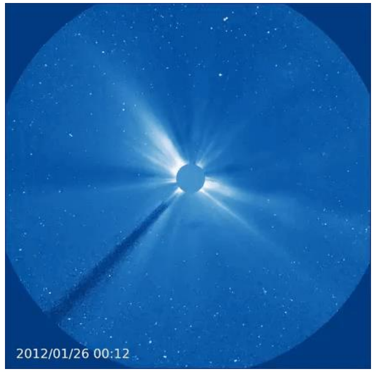
ESA definition: “Space weather refers to the environmental conditions in space as influenced by solar activity … the conditions within the Earth's magnetosphere, ionosphere and thermosphere … as dynamic changes in the environment caused by the Sun and the solar wind can influence the functioning and reliability of spaceborne and ground-based systems and services, thereby potentially endangering human health and wellbeing through impact on this infrastructure.”

(no mention to the alteration of atmospheric species)

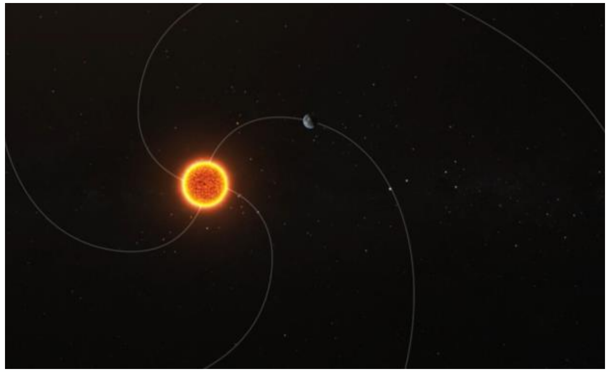
Solar flares



Coronal mass ejections (CMEs)

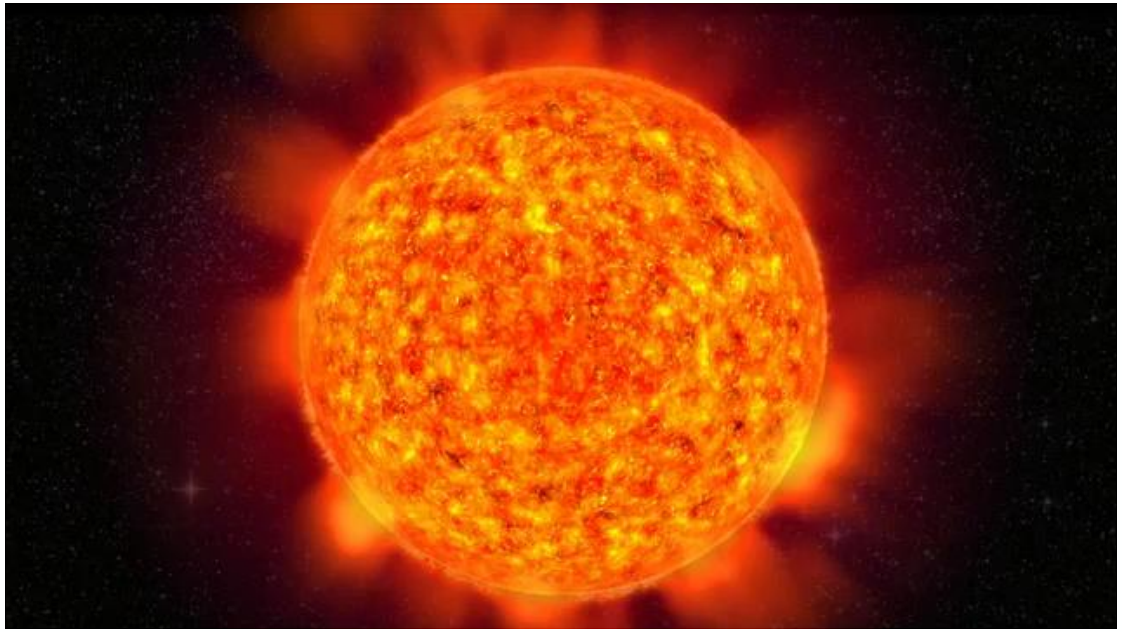


Solar energetic particles (SEPs)

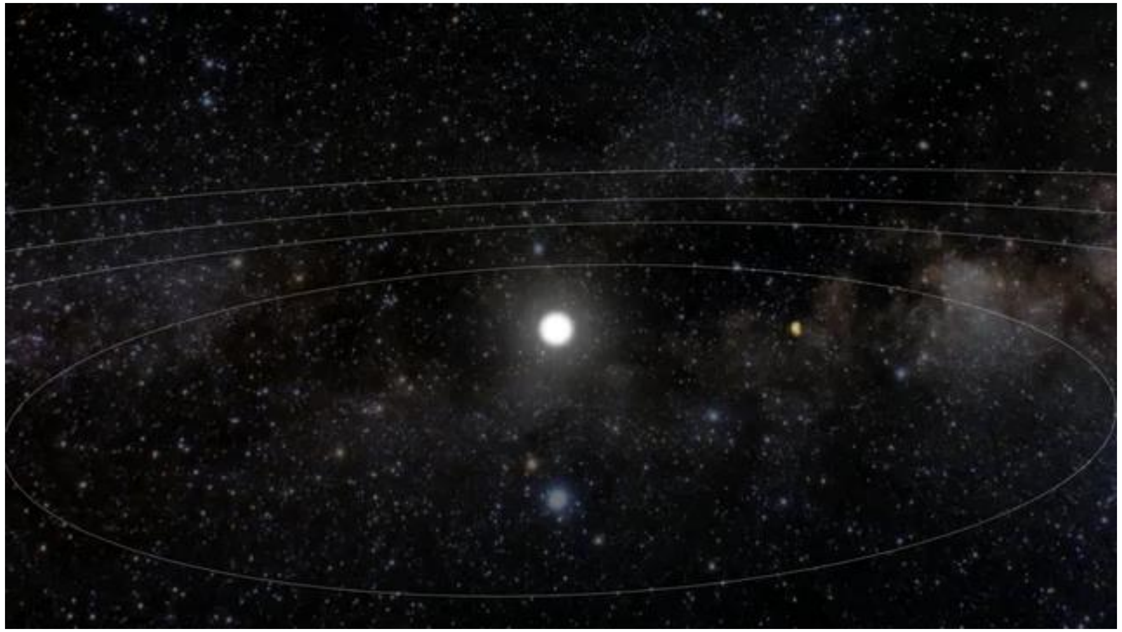


Introduction: Space Weather

Ejection of the solar flare's associated CME

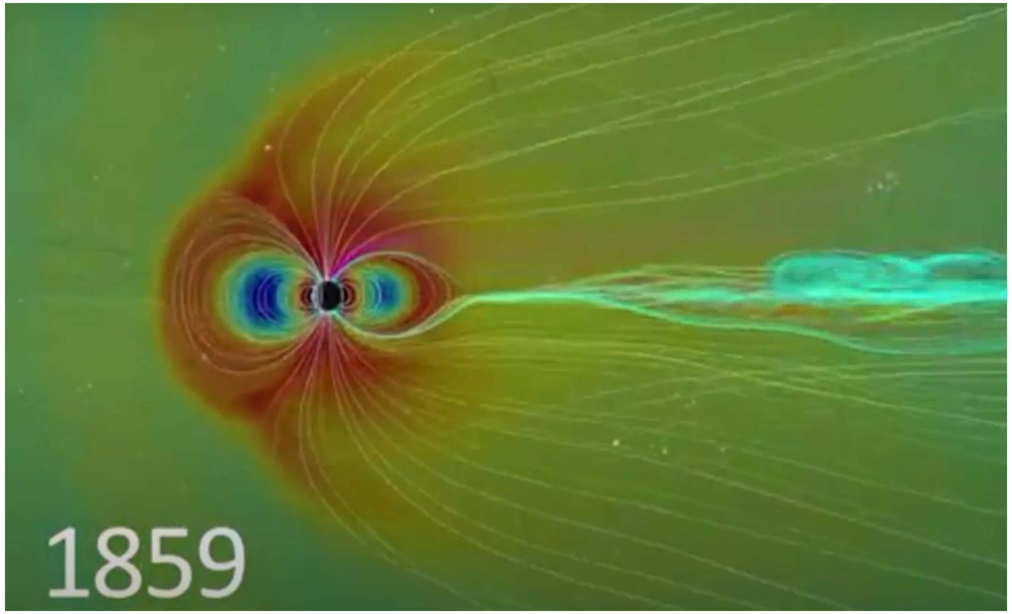


Interaction between the ICME and the Earth's magnetic field

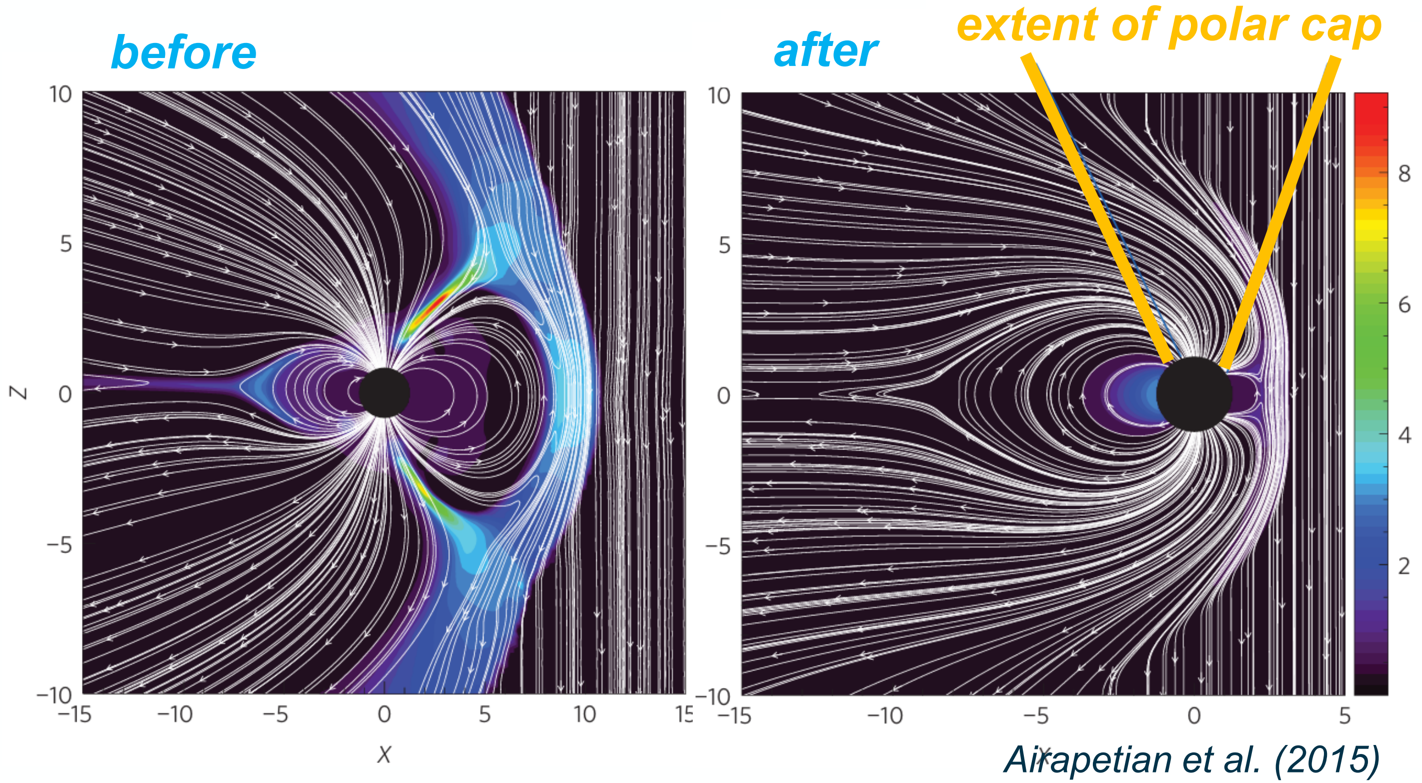


Introduction: Carrington (and Hudgson) event

- The most intense event in recorded history (by R. Carrington & R. Hudgson) – 1 september 1859
  - Solar flare: ~X45 (±5); CME: v = 2356 km/s; Dst: ~-900 nT (Cliver & Dietrich, 2013)
  - Frequency: Δt ~ 445 years (Love 2024); [0.46, 1.88]% for current solar cycle (Moriña et al. 2019)
- 2003 Halloween solar storms: ~X25-45; v = 2240 km/s; Dst: -383 (Gopalswamy 2005)



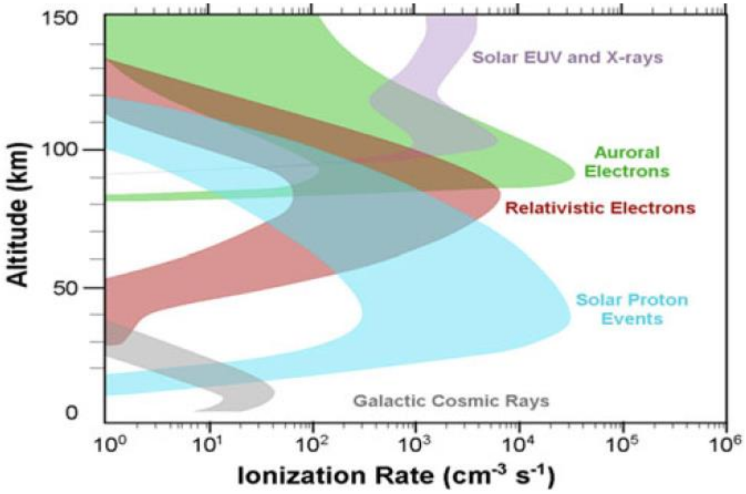
NASA Goddard



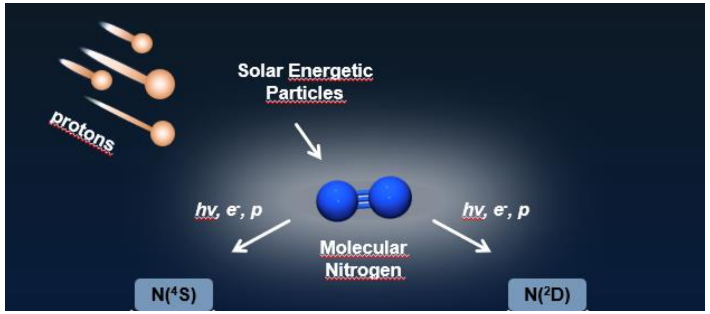
Airapetian et al. (2015)

Ion chemistry triggered by SEPs (1/2)

- SEPs are **accelerated**, at the flare reconnection sites and by CME-driven shocks, to energies of up to **GeV level**
- The higher the energy, the more significant the penetration into the Earth's atmosphere
- High-energy protons can **penetrate** into the polar regions where they collide with the Earth's atmospheric gases, producing fast secondary electrons. These electrons can dissociate N2, producing both the electronic ground state N(4S) and the electronic first excited state N(2D) of the nitrogen atom, which in turn readily react with ambient atmospheric gases to form **odd hydrogen HOx** (H, OH, HO2) and **odd nitrogen NOx** (N, NO, NO2) gases
- **HOx and NOx contribute to catalytic O3 destruction cycles**

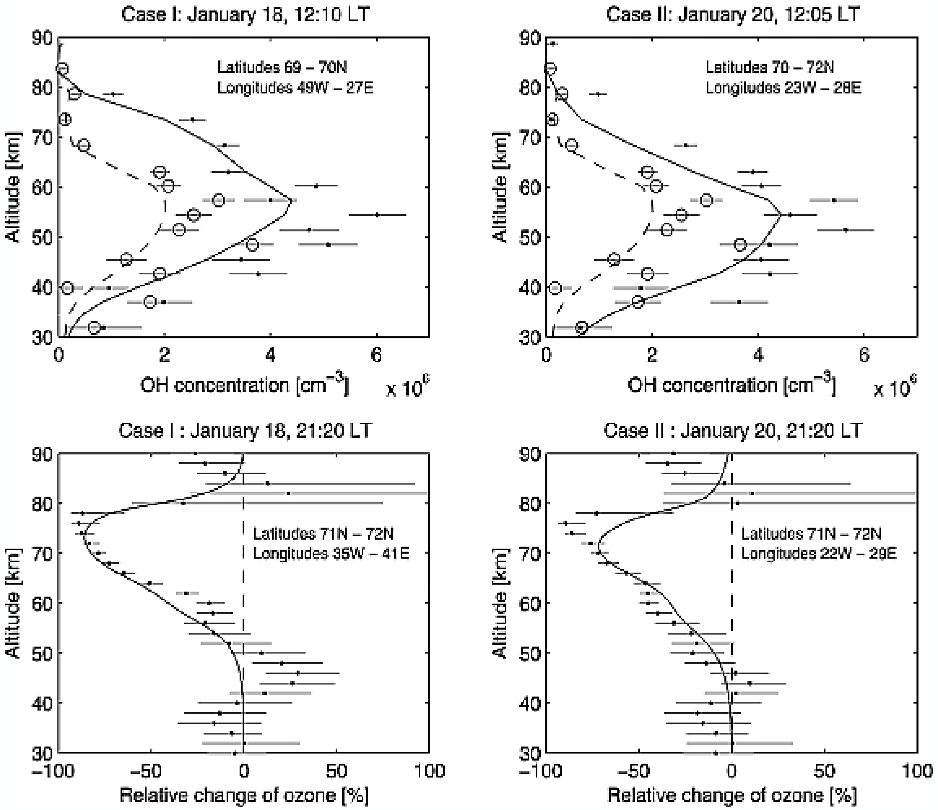


Airapetian et al. (2019)



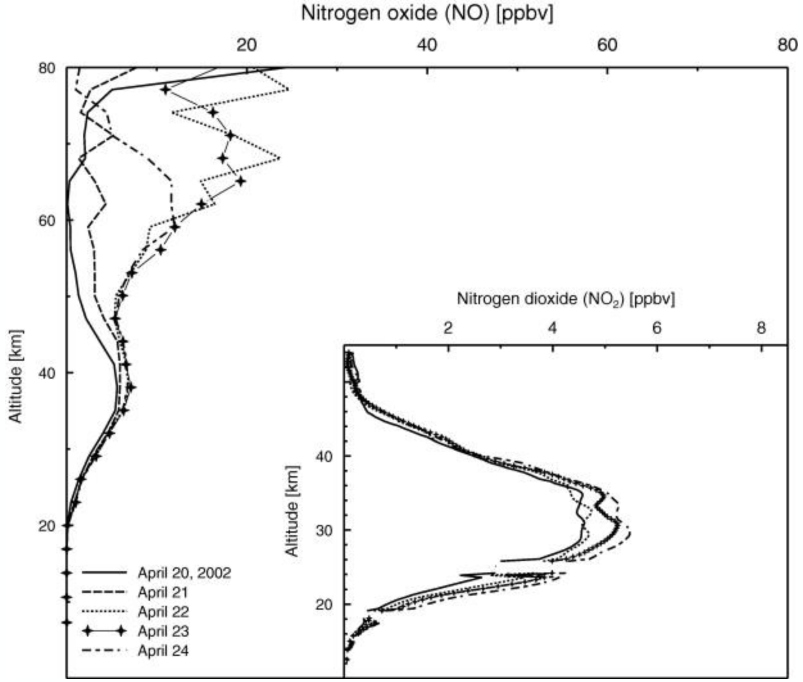
Ion chemistry triggered by SEPs: observations

Production of **odd hydrogen** during the January 2005 solar proton event (GOMOS satellite, 65° N -75° N)



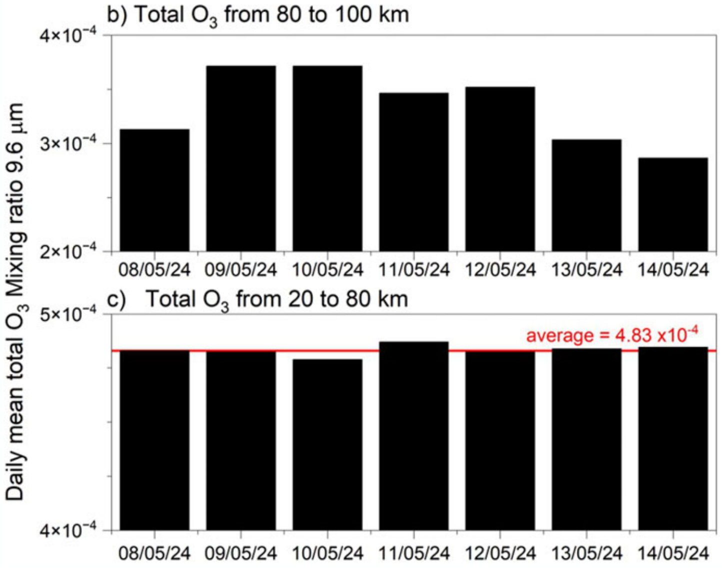
Verronen et al. (2006)

Production of **nitrogen oxide** and **nitrogen dioxide** during the April 2002 solar proton event (UARS satellite, 67° N -76° N)



Damiani et al. (2009)

Reduction of ~15% in the daily total **ozone** on 11 May 2024 (TIMED satellite, SAMA)



Verronen et al. (2006)

Ion chemistry triggered by SEPs (2/2)

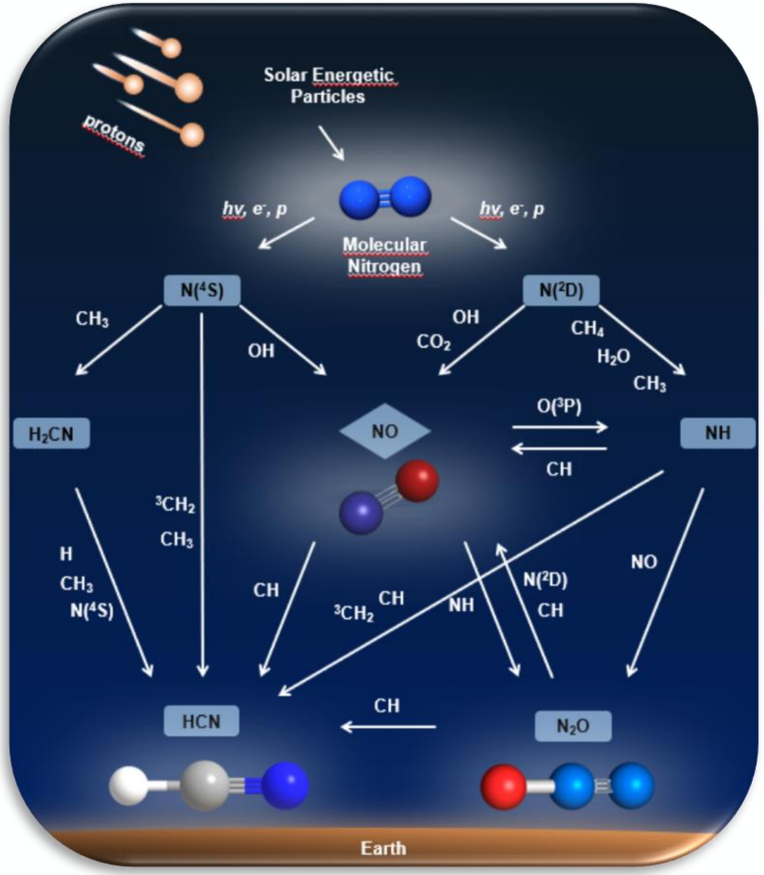
- **HOx** species (*short lifetime* of a few days) are an effective catalyst in the mesosphere (Pikulina et al. 2022):

  $OH + O_3 \rightarrow HO_2 + O_2$ and $HO_2 + O \rightarrow OH + O_2$

- **NOx** species (*longer-lived,* months to years) deplete mesospheric and stratospheric ozone
  - mesospheric O3 is destroyed via:

    $NO + O_3 \rightarrow NO_2 + O_2$ and $OH + O_3 \rightarrow HO_2 + O_2$

  - Stratospheric O3 destroyed by NOx descent through polar vortices

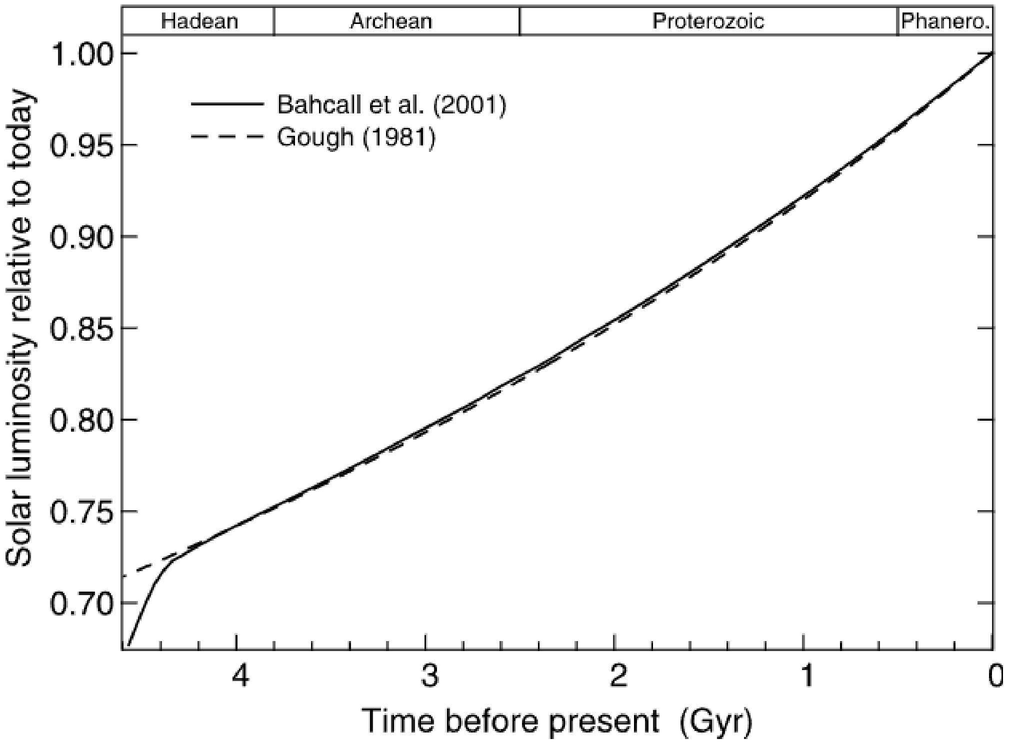


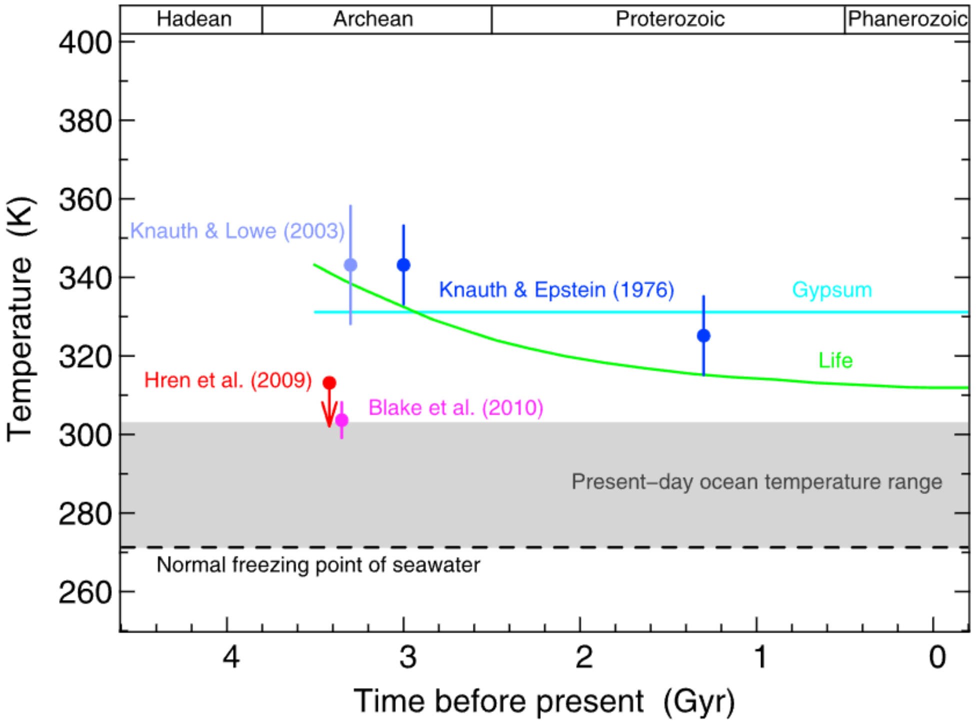
- Airapetian et al. (2020): **nitrous oxide (N2O)** efficiently produced through frequent energetic particle precipitation

  $N(^4S) + NO_2 \rightarrow N_2O + O$ and $NO + NH \rightarrow N_2O + H$.

Faint young Sun Paradox

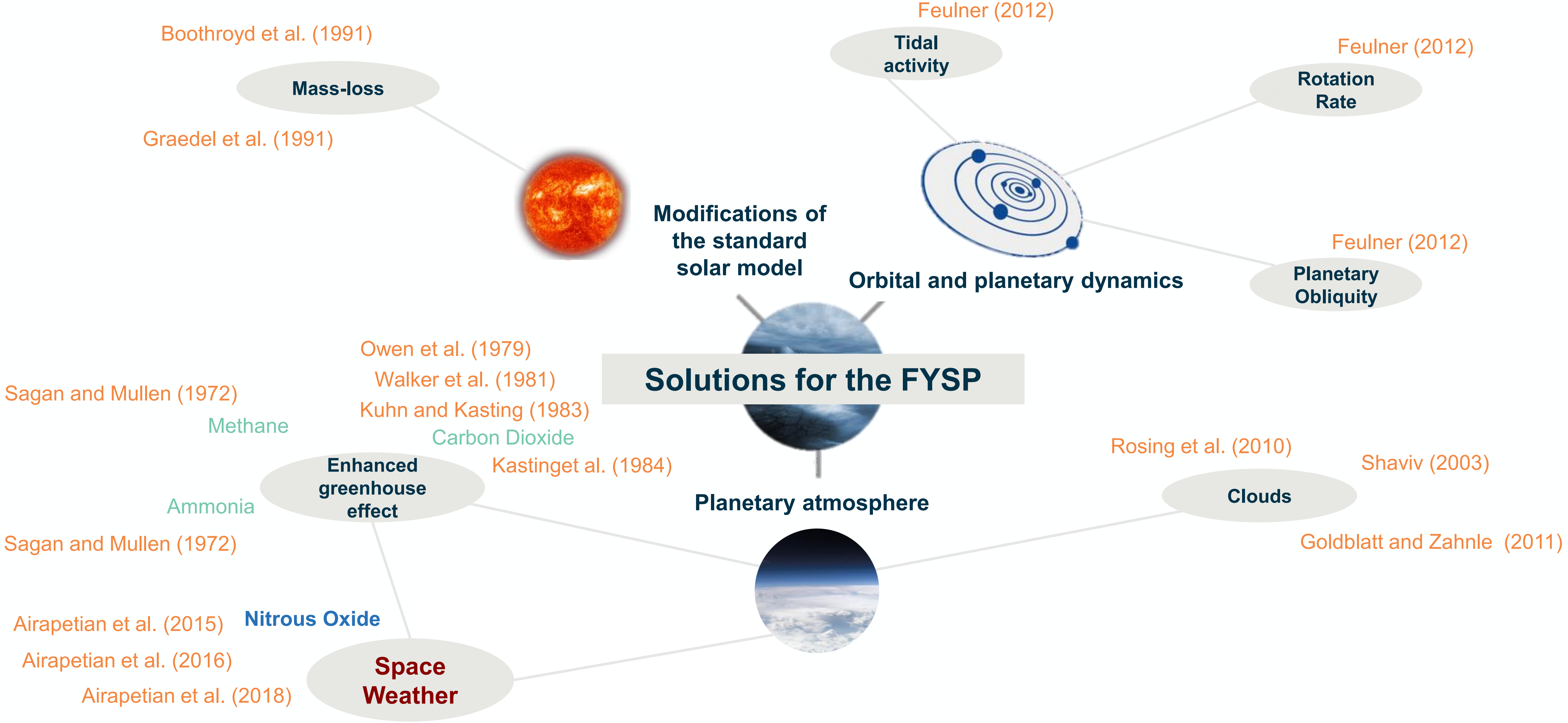
- For a N2-dominated atmosphere (with 10% CO2), N2O production in the lower atmosphere could increase by more than 300 times compared to previous predictions.
- **N2O production as a solution for the faint young Sun paradox (3.8 Ga)**





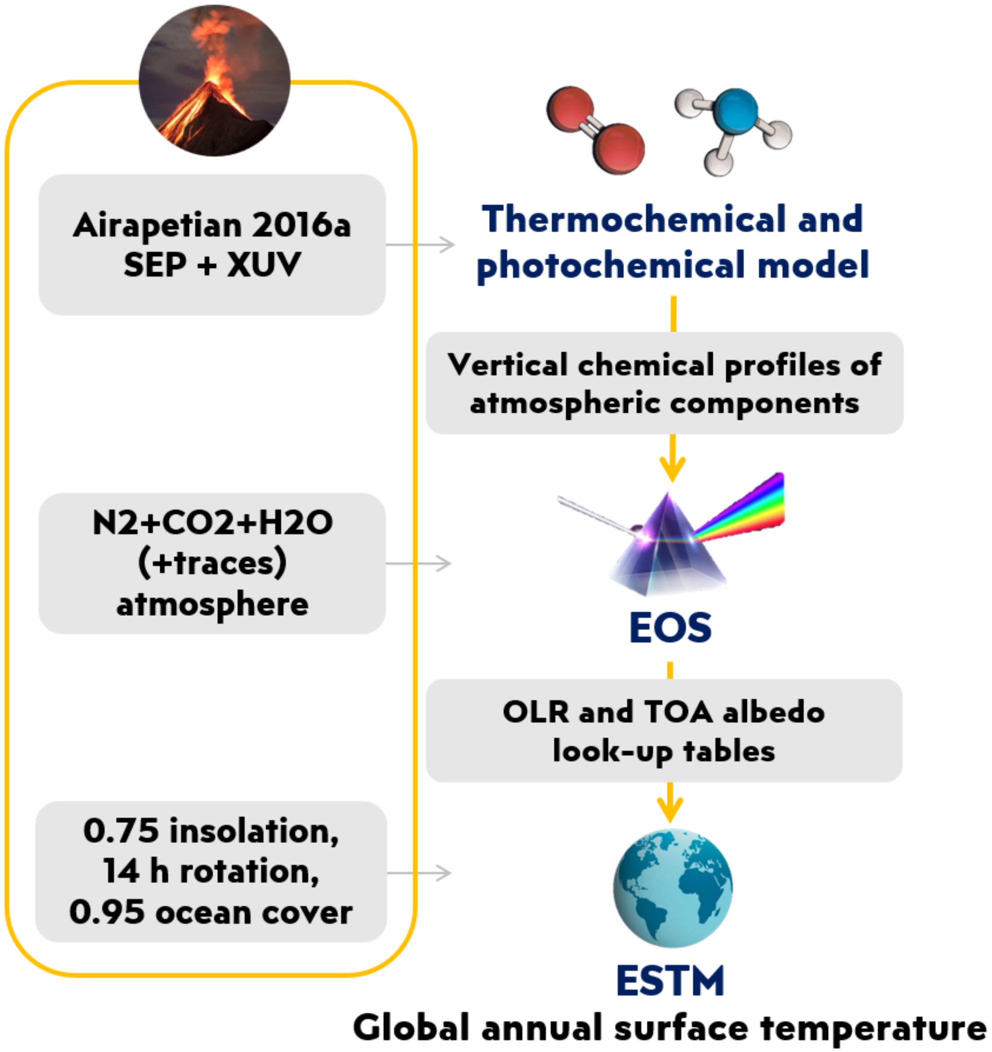
Adapted from Feulner et al. (2012)

Faint young Sun Paradox: solutions

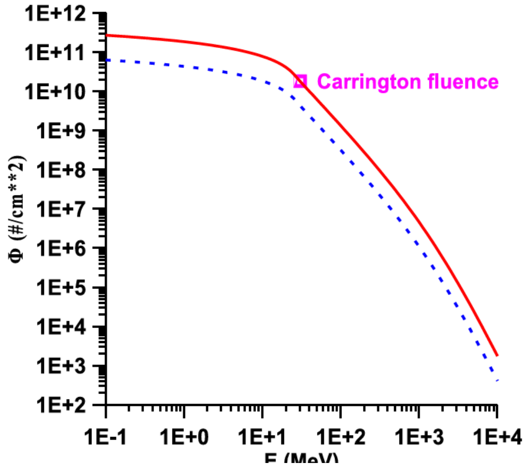


Pipeline of models

ARCHEAN EARTH

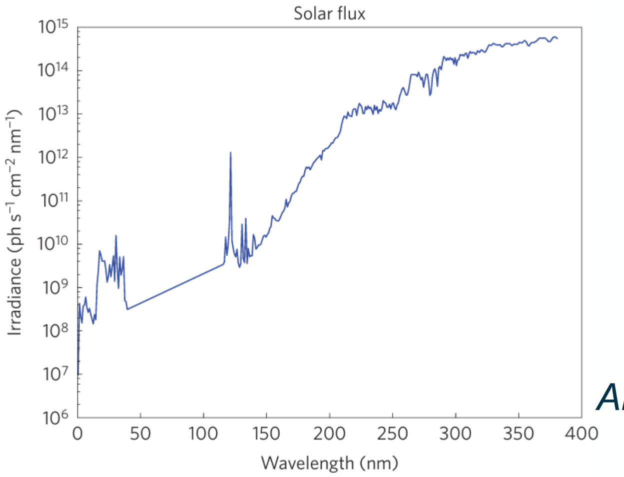


energy spectrum of proton fluences



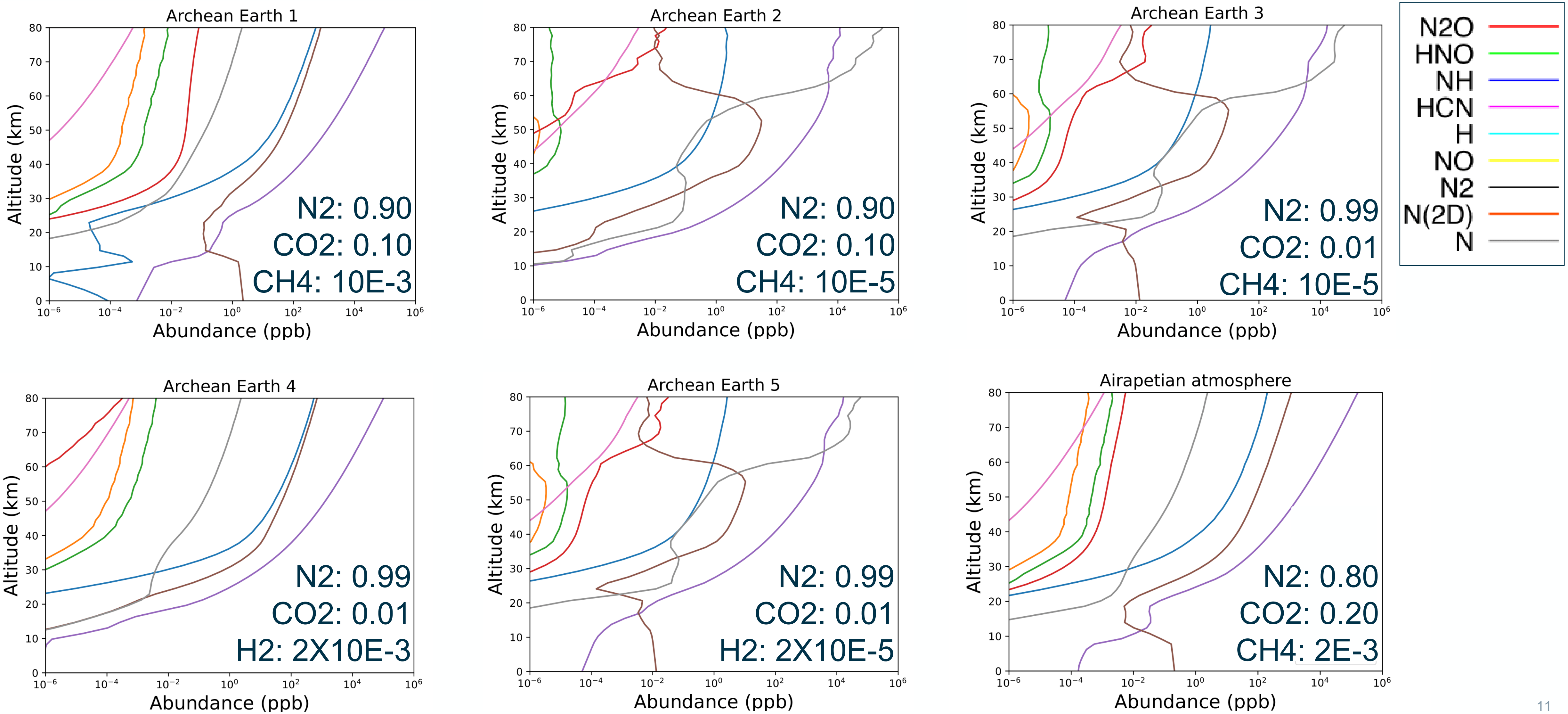
Miroshnichenko & Nymmik (2014)

XUV flux of the young Sun



Airapetian et al. (2016)

Results AE: atmospheric vertical profiles (1/2)



Results AE: atmospheric vertical profiles (2/2)

Name		N_2 Fraction	O_2 Fraction	CO_2 ppm	CH_4 ppm	CO ppm	H_2 ppm	N_2O ppm	HCN ppm	NH_3 ppm
Archean Earth 1	unprocessed	0.900	no	100 000	10	no	no	no	no	no
	equilibrium	0.900	0	99 775	0.39	1.21×10^{-5}	0.02	0	3.00×10^{-20}	2.26×10^{-3}
	processed	0.900	0	99 700	0.39	71.45	0.03	8.44×10^{-8}	1.00×10^{-15}	1.01×10^{-8}
Archean Earth 2	unprocessed	0.900	no	100 000	0.1	no	no	no	no	no
	equilibrium	0.899	2 100	98 820	0	3.70×10^{-39}	7.20×10^{-38}	2.80×10^{-14}	5.1×10^{-15}	0
	processed	0.901	0	98 860	0	145.90	3.85×10^{-14}	9.23×10^{-17}	0	0
Archean Earth 3	unprocessed	0.990	no	10 000	0.1	no	no	no	no	no
	equilibrium	0.990	0	9 890	3.97×10^{-4}	3.80×10^{-6}	7.40×10^{-4}	0	5.70×10^{-21}	1.35×10^{-5}
	processed	0.990	0	9 807	0	82.47	7.63×10^{-4}	1.34×10^{-15}	6.63×10^{-20}	3.58×10^{-11}
Archean Earth 4	unprocessed	0.990	no	10 000	no	no	20	no	no	no
	equilibrium	0.990	1 058	98 721	0	5.20×10^{-39}	1.01×10^{-35}	2.04×10^{-14}	0	2.04×10^{-35}
	processed	0.991	0	98 670	0	141.70	1.88×10^{-10}	7.69×10^{-17}	0	0
Archean Earth 5	unprocessed	0.990	no	10 000	no	no	0.2	no	no	no
	equilibrium	0.990	0	9 890	3.97×10^{-4}	3.80×10^{-6}	7.40×10^{-4}	0	5.68×10^{-21}	1.40×10^{-5}
	processed	0.990	0	9 809	0	81.32	7.63×10^{-4}	1.41×10^{-15}	6.63×10^{-20}	3.68×10^{-10}
Airapetain atmosphere	unprocessed	0.800	no	200 000	3	no	no	no	no	no
	equilibrium	0.800	0	200 395	0.02	1.71×10^{-5}	4.94×10^{-3}	0	1.31×10^{-20}	2.09×10^{-4}
	processed	0.800	0	200 300	0.02	71.36	5.34×10^{-3}	5.85×10^{-10}	4.99×10^{-20}	3.56×10^{-7}

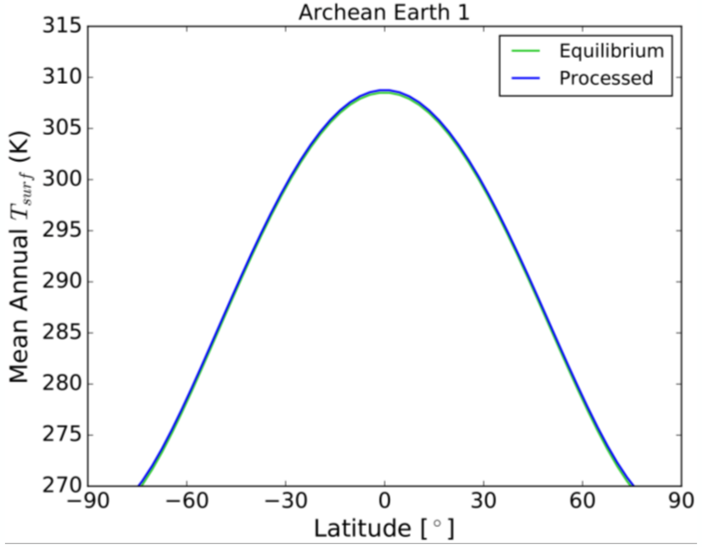
Results AE: variation of surface temperature (1/3)

CO: 71 ppm (H2+0.01 ppm)

N2O: 8.44 x 10^{-8} ppm

0.29 K

Quantity	Description (Units)	Archean 1		Archean 2		Archean 3		Archean 4		Airapetian atm.	
		EQ.	PR.	EQ.	PR.	EQ.	PR.	EQ.	PR.	EQ.	PR.
$< T >$	Global surface temperature (K)	295.37	295.66	294.57	294.89	224.94	225.17	224.94	224.95	303.64	303.83
ΔT_{PE}	Pole–Equator temperature difference (K)	41.58	41.43	42.45	42.22	36.63	36.67	36.36	37.16	36.44	36.34
$< A >$	Global top-of-atmosphere albedo	0.33	0.33	0.33	0.33	0.56	0.56	0.56	0.56	0.32	0.32
$< OLR >$	Global outgoing longwave radiation (W m^{-2})	178.2	178.3	177.5	177.6	114.0	114.3	114.0	114.0	180.2	180.3



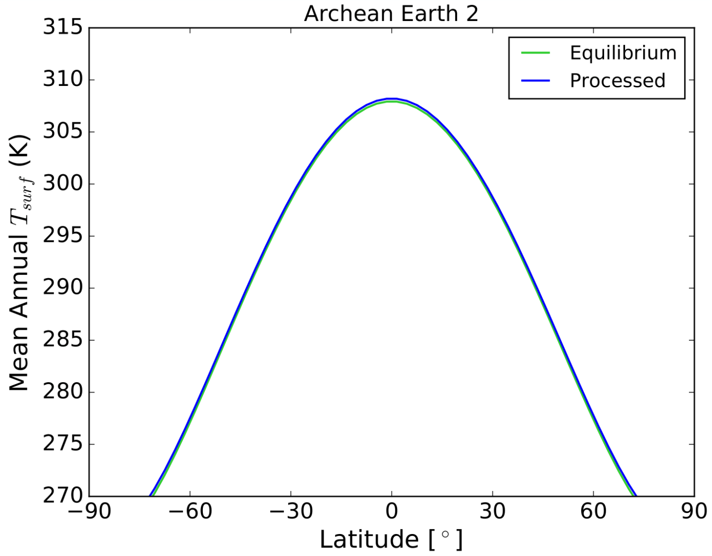
Results AE: variation of surface temperature (2/3)

CO: 145.9 ppm

N2O: 9.23×10^{-17} ppm

0.32 K

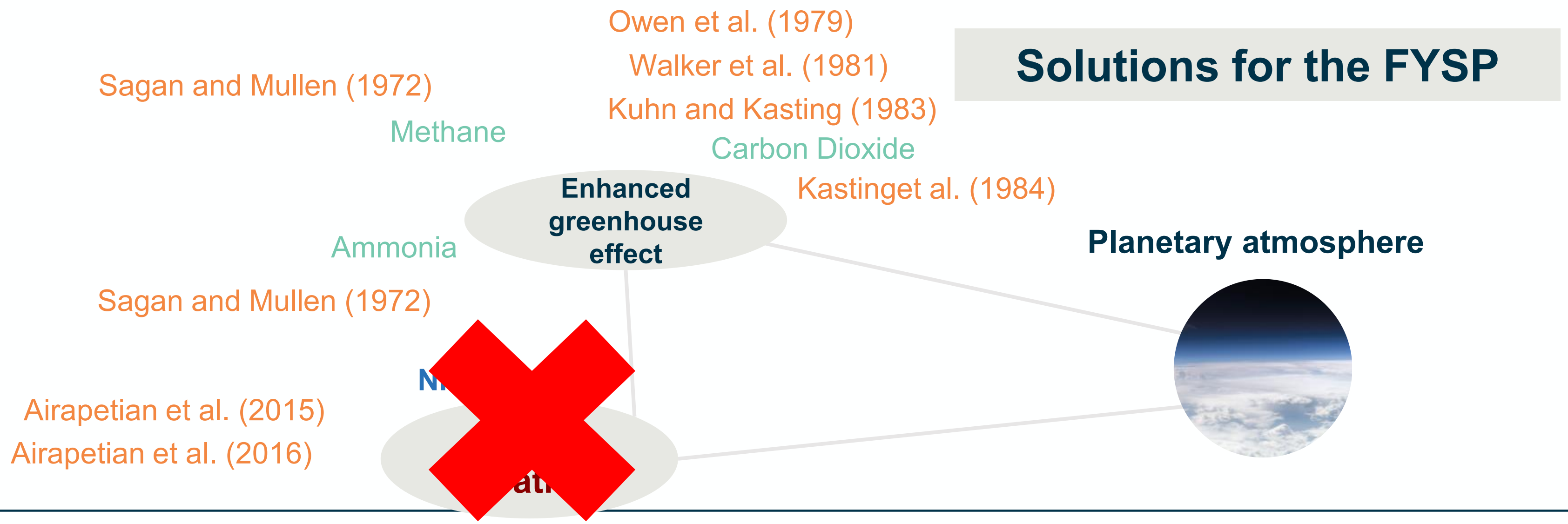
Quantity	Description (Units)	Archean 1		Archean 2		Archean 3		Archean 4		Airapetian atm.	
		EQ.	PR.	EQ.	PR.	EQ.	PR.	EQ.	PR.	EQ.	PR.
$< T >$	Global surface temperature (K)	295.37	295.66	294.57	294.89	224.94	225.17	224.94	224.95	303.64	303.83
ΔT_{PE}	Pole–Equator temperature difference (K)	41.58	41.43	42.45	42.22	36.63	36.67	36.36	37.16	36.44	36.34
$< A >$	Global top-of-atmosphere albedo	0.33	0.33	0.33	0.33	0.56	0.56	0.56	0.56	0.32	0.32
$< OLR >$	Global outgoing longwave radiation (W m^{-2})	178.2	178.3	177.5	177.6	114.0	114.3	114.0	114.0	180.2	180.3



Results AE: variation of surface temperature (3/3)

N2: 99%
CO2: 1%, CH4: 0%
Snowball state

Quantity	Description (Units)	Archean 1		Archean 2		Archean 3		Archean 4		Airapetian atm.	
		EQ.	PR.	EQ.	PR.	EQ.	PR.	EQ.	PR.	EQ.	PR.
$< T >$	Global surface temperature (K)	295.37	295.66	294.57	294.89	224.94	225.17	224.94	224.95	303.64	303.83
ΔT_{PE}	Pole–Equator temperature difference (K)	41.58	41.43	42.45	42.22	36.63	36.67	36.36	37.16	36.44	36.34
$< A >$	Global top-of-atmosphere albedo	0.33	0.33	0.33	0.33	0.56	0.56	0.56	0.56	0.32	0.32
$< OLR >$	Global outgoing longwave radiation (W m^{-2})	178.2	178.3	177.5	177.6	114.0	114.3	114.0	114.0	180.2	180.3

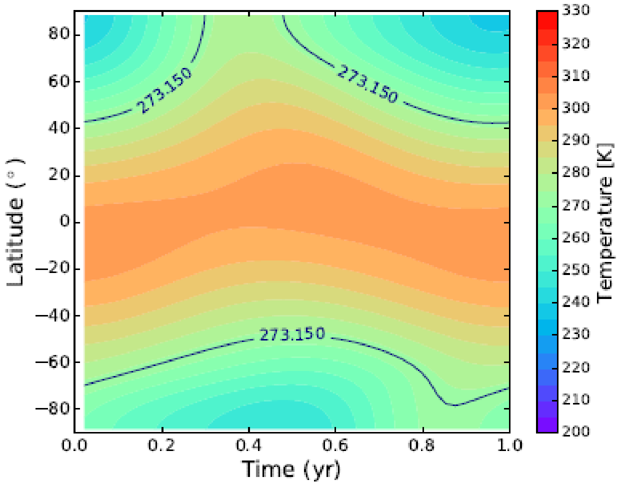


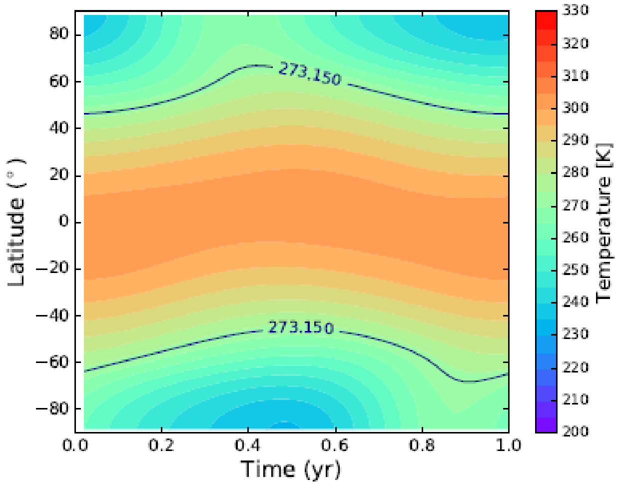
Results PE: continuos Carrington-like events

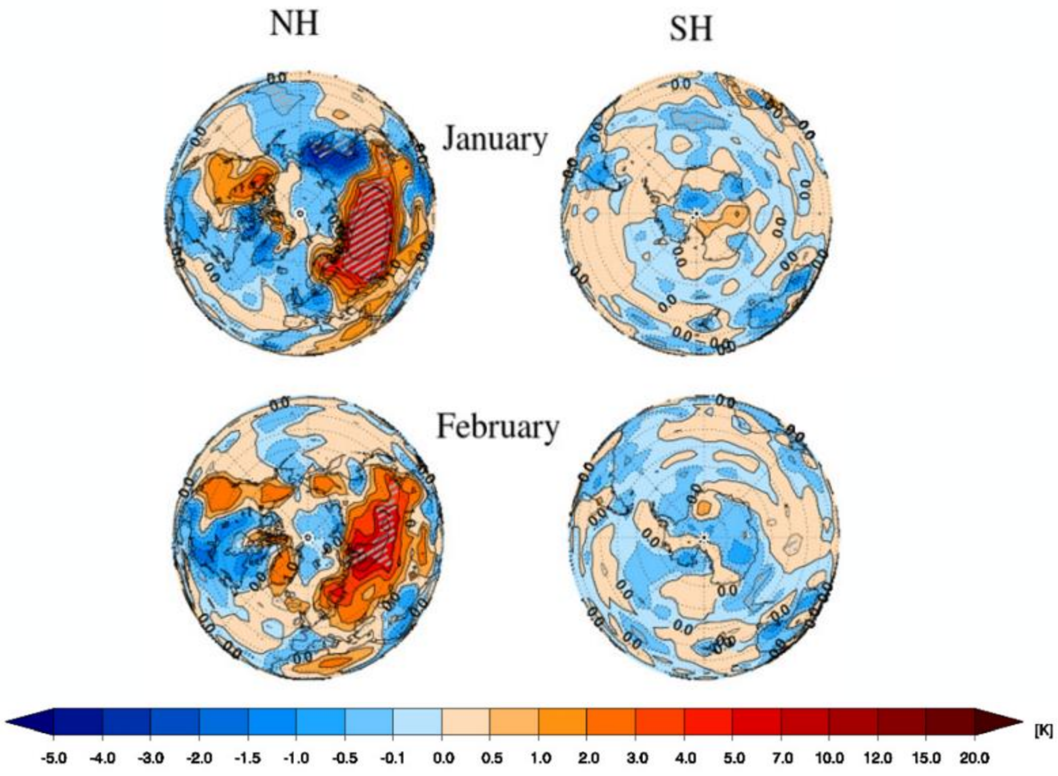
Present-day Earth	N_2 Fraction	O_2 Fraction	CO_2 Fraction	CH_4 Fraction	CO ppm	H_2 ppm	N_2O ppm	HCN ppm
unprocessed	0.79	0.21	360×10^{-6}	1.8×10^{-6}	0.1	0.55	0.33	/
processed	0.79	0.21	360×10^{-6}	1.1×10^{-6}	0.0004	0.004	0.000001	0.9×10^{-12}

Quantity	Units	UNPR.	PR.
$< T >$	K	288.15	284.40
ΔT_{PE}	K	44.26	48.38
$< A >$		0.35	0.36
$< OLR >$	$W\ m^{-2}$	241.7	227.3

3.75 K







Calisto et al. (2013)

Conclusions

Archean Earth:

- Due to the dissociation of N_2 by SEPs, N(2D) is produced, giving rise to a rich chemistry that results in the production of greenhouse gases such as N_2O and HCN. H_2 and CO are also produced.
- In the case of secondary atmospheres, the chemical abundances of the species are dominated by SEP-driven chemistry, while high-energy radiation plays a marginal role.
- If the amount of CO_2 and CH_4 - in the initial gas mixture - is 10% and 10 ppm, respectively, then the two most abundant species produced are CO (71 ppm) and H_2 (0.03 ppm).
- However, this condition does not result in a significant increase in global temperature, with a **maximum warming** of only **~0.3 K**.
- The contribution provided by nitrogen species, such as N_2O and HCN, is **negligible**, in contrast to what previously proposed by A16a.

Present-day Earth:

- The cumulative effects on the present-day Earth of a prolonged period of intense solar activity (Carrington-like SEP events) would decrease a global surface temperature decrease of nearly 4 K, due to the decrease in concentration of minor greenhouse gases

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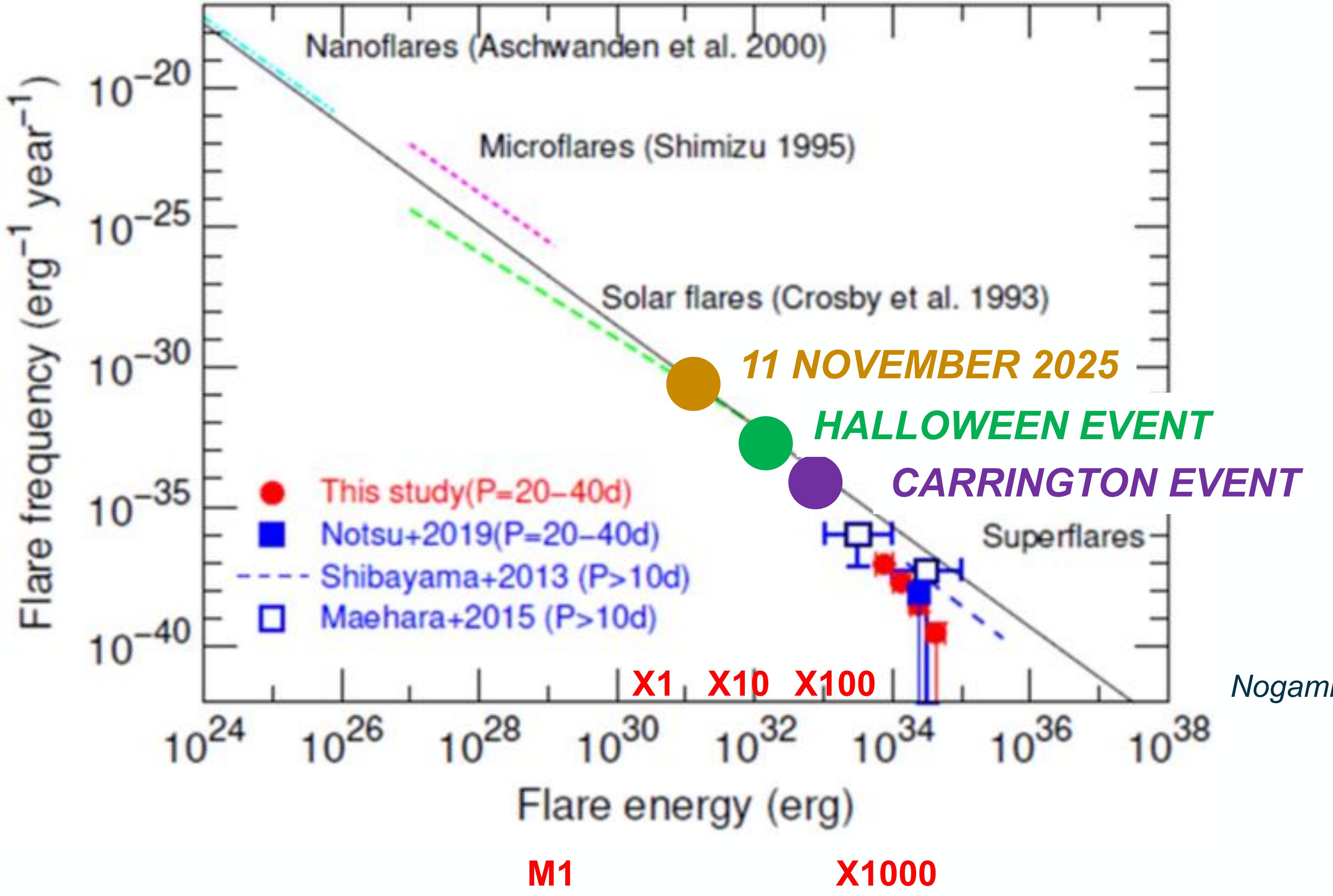
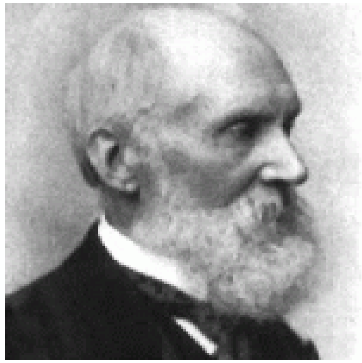
Solar flare intensity



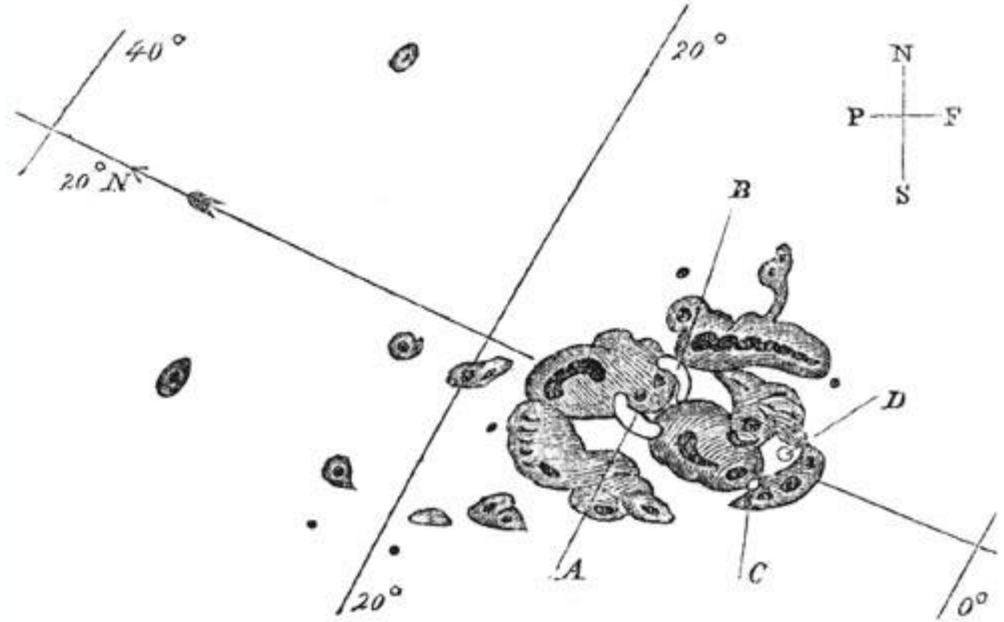
Nogami (2014)

Carrington (and Hudgson) event



R. Carrington

R. Hudgson



JOURNAL ARTICLE

Description of a Singular Appearance seen in the Sun on September 1, 1859 FREE

R. C. Carrington, Esq.

Monthly Notices of the Royal Astronomical Society, Volume 20, Issue 1, November 1859, Pages 13–15, https://doi.org/10.1093/mnras/20.1.13

Published: 11 November 1859

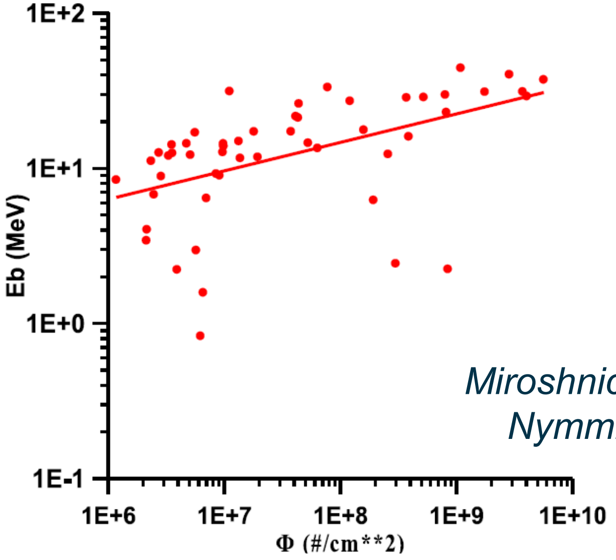
*"when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My first impression was that by some chance **a ray of light had penetrated a hole in the screen** attached to the object-glass..."*

*"While observing a group of solar spots on the 1st September, I was suddenly surprised at the **appearance of a very brilliant star of light, much brighter than the Sun's surface**"*

integral energy spectrum for the 1859 Carrington Event

- **No direct measurements** were available in 1859; the spectrum was reconstructed using **proxy data and modeling**
- **Nitrate anomalies in Greenland ice cores** (McCracken et al., 2001) were used to estimate the **integrated proton fluence** for E ≥ 30 MeV: $\Phi \approx 1.88 \times 10^{10}$ cm^{-2}.
- The **spectral shape** was inferred by **scaling empirical models** derived from modern SEP events (e.g., 1956, 1972, 2005).
- From spacecraft data it has become clear that SEP spectra form two segments that may be approximated by **two power-law functions**, with an intermediate break-point (or bend-point, “knee”) at a typical energy of **Eb ≈ 30 MeV** (e.g., Mewaldt et al., 2005a,b, 2007, 2009; Nymmik, 2011a)
- Such a double power-law (or two-segment) shape seems to be consistent with “**an exponential turnover of the power-law spectrum**”:

$$\frac{dF}{dE} = C \cdot E^{-\gamma} \cdot \exp\left(\frac{E}{E_0}\right)$$



Miroshnichenko & Nymmik (2014)