Cosmic Showers: How Particle Space Weather Affects Planets

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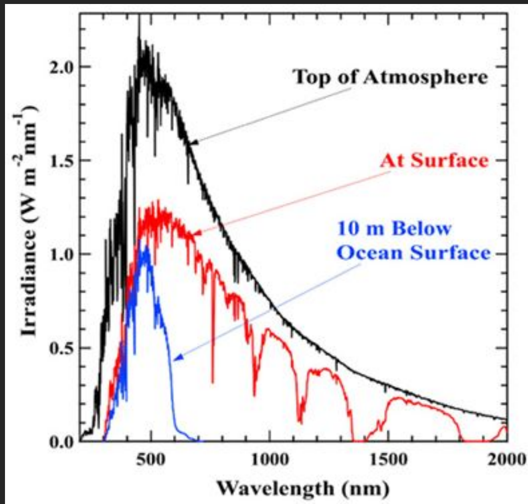
University of Colorado

KISS Short Course

06 November 2023

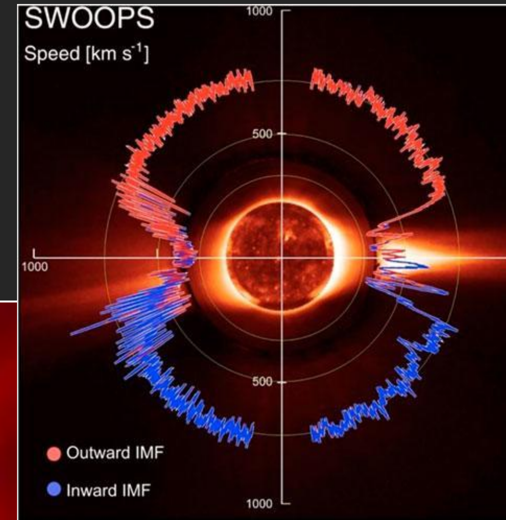
Our Sun spits lots of stuff at planets

Sunlight

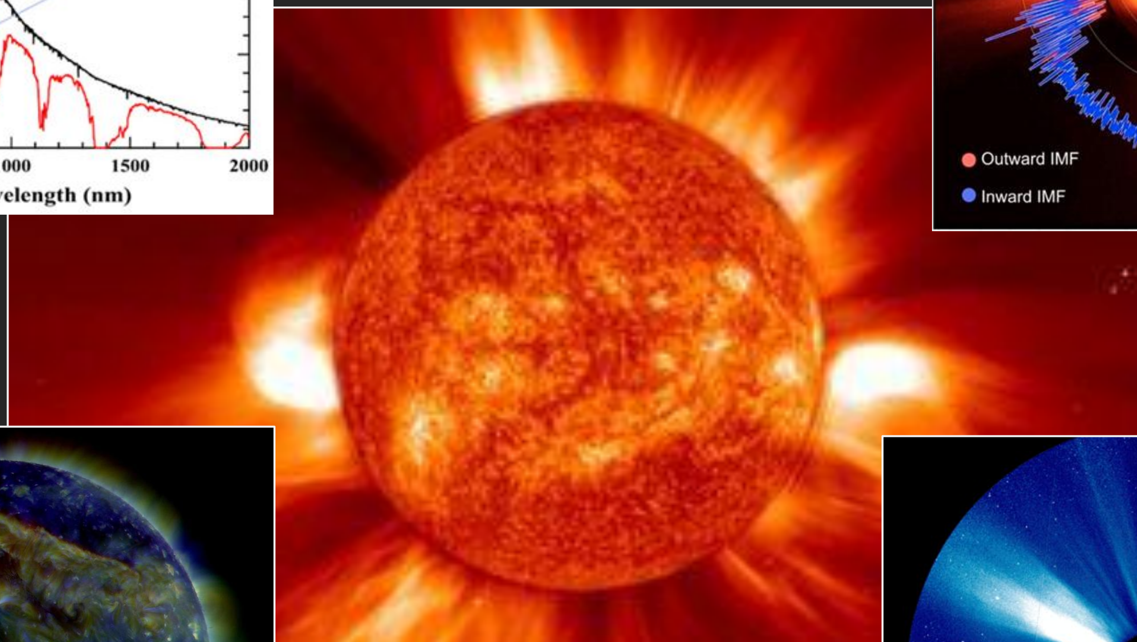


NASA / LASP / SORCE

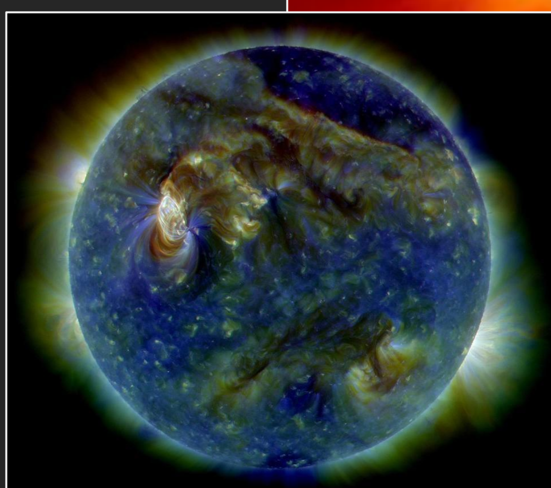
Solar Wind



McComas et al., 2013

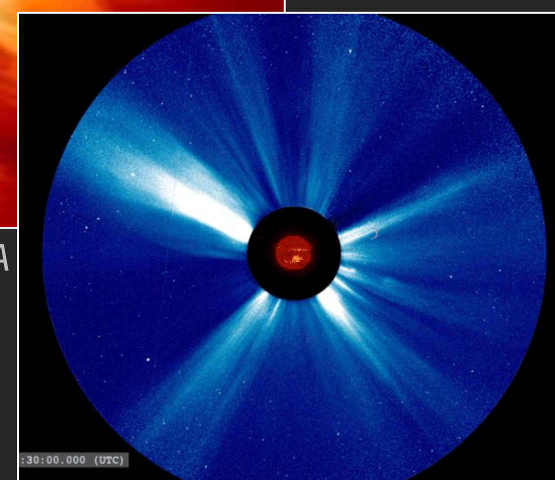


ESA



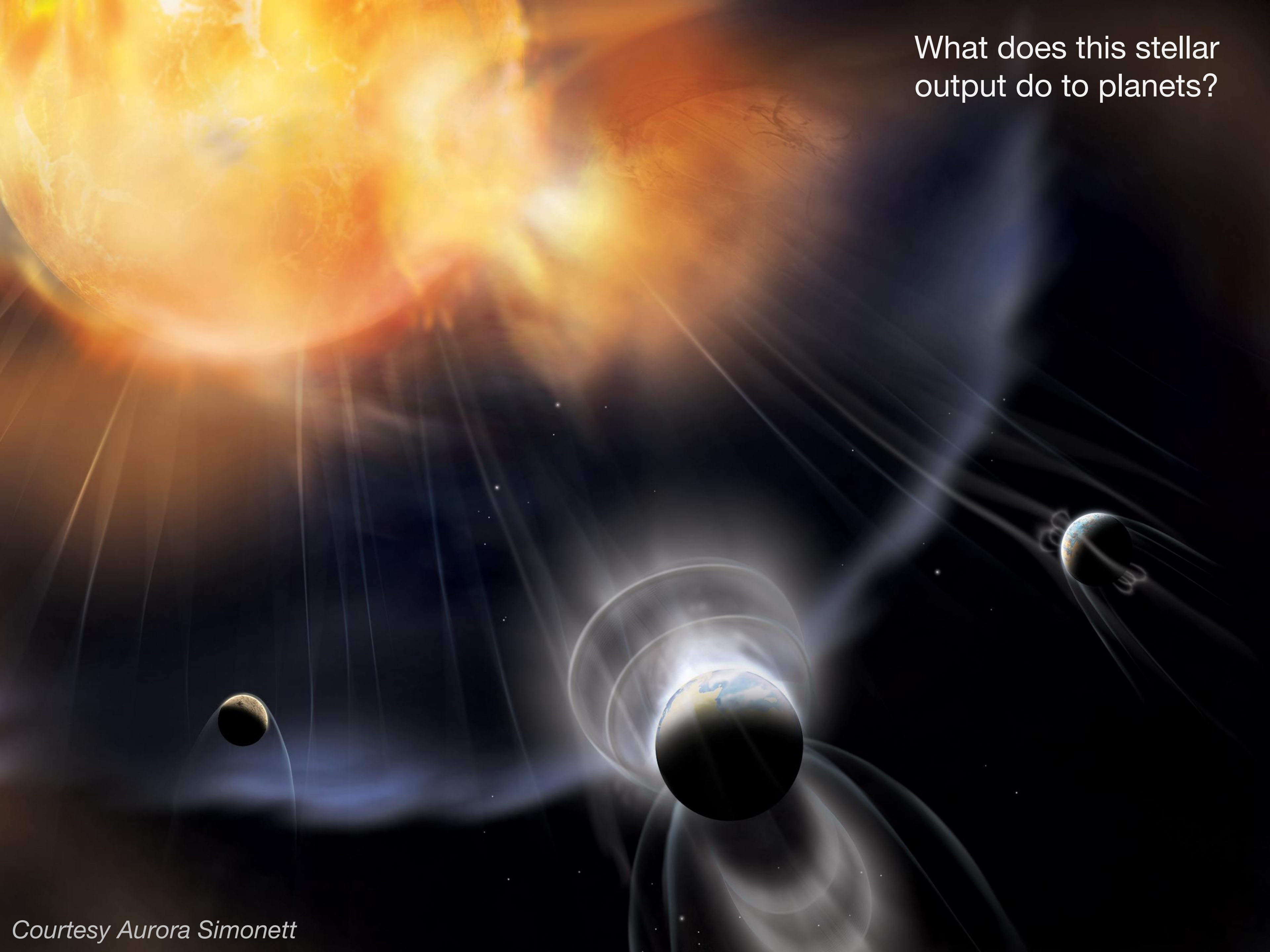
NASA / SDO / AIA

Solar Extreme Ultraviolet (EUV)



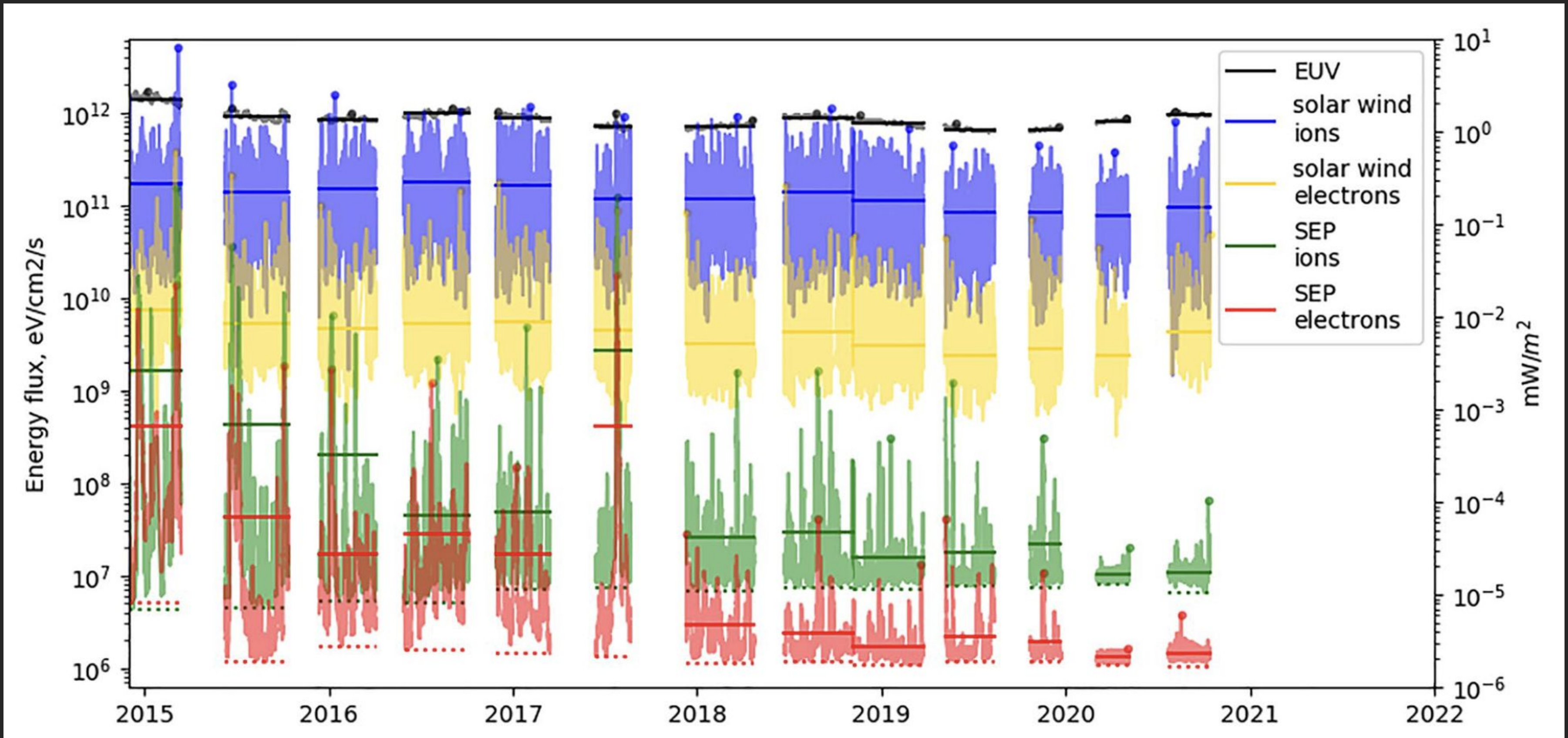
NASA STEREO

Solar Energetic Particles (SEPs)



Courtesy Aurora Simonett

Solar input energy fluxes at Mars

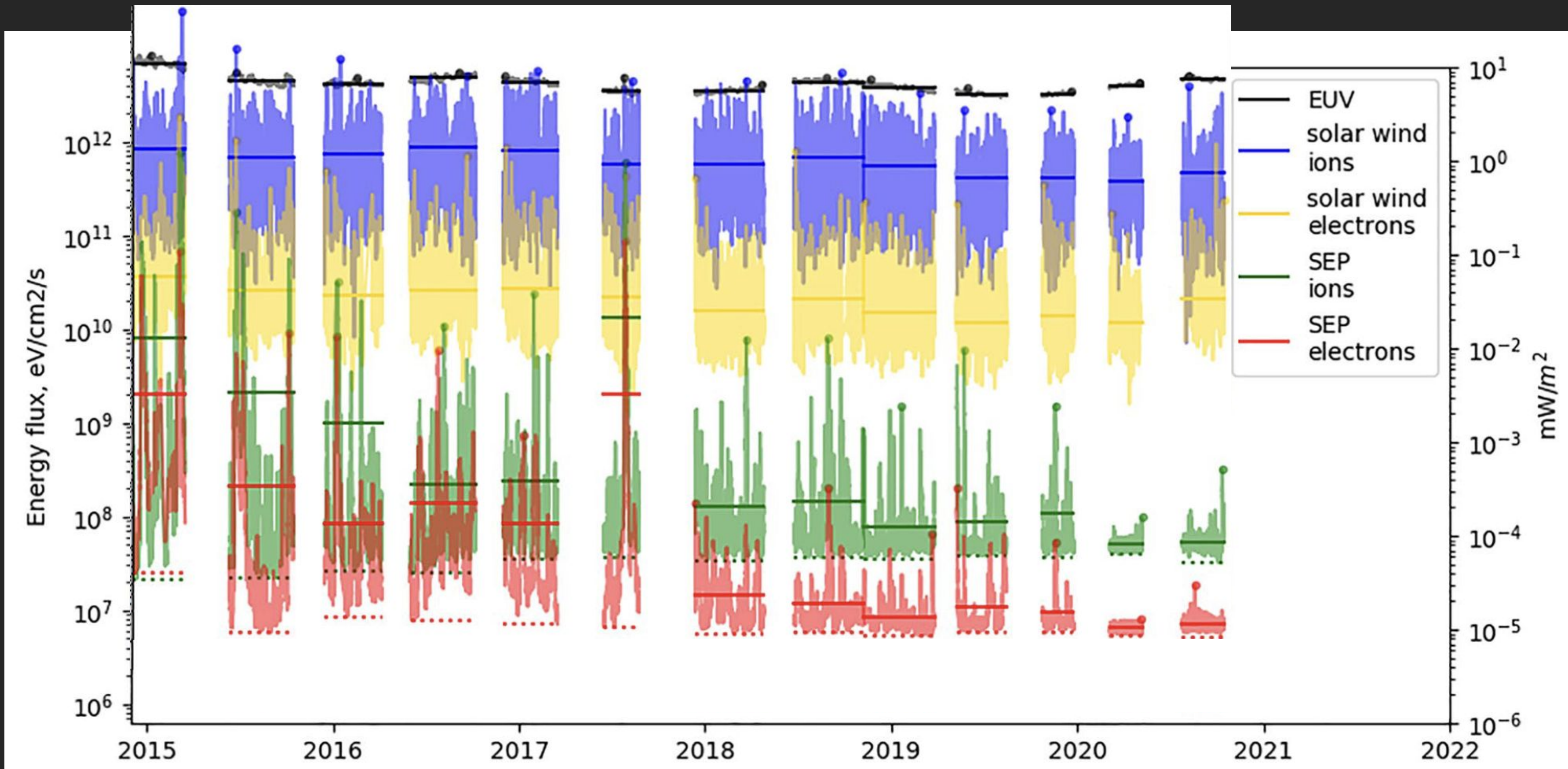


Jolitz et al., 2022

+ Solar irradiance ~ 6×10^5 mW/m^2

Particles carry much less energy to Mars than light

What about Venus or Earth?



Venus

Jolitz et al., 2022

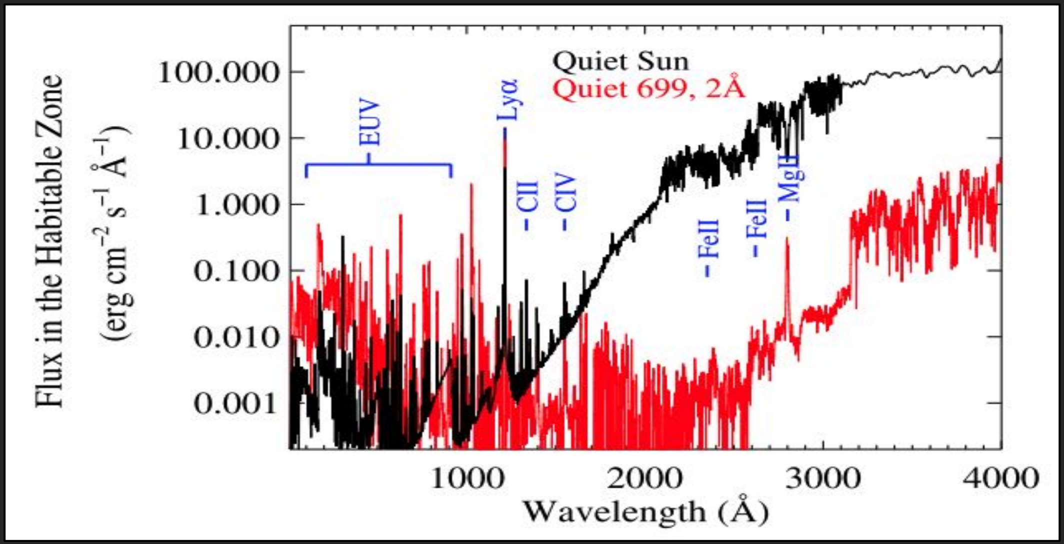
Particles carry much less energy to solar system planets than light

Short course and workshop cancelled due to insignificance of particles relative to photons?

Not so fast…

No star is the same

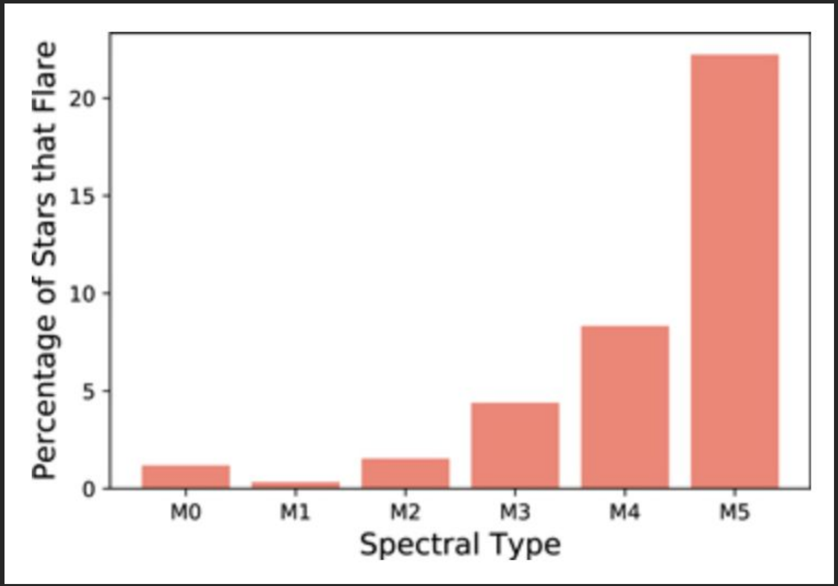
M Dwarfs are less luminous, with higher EUV and stellar activity



France et al., 2020

Spectrum of Barnard's Star relative to the Sun

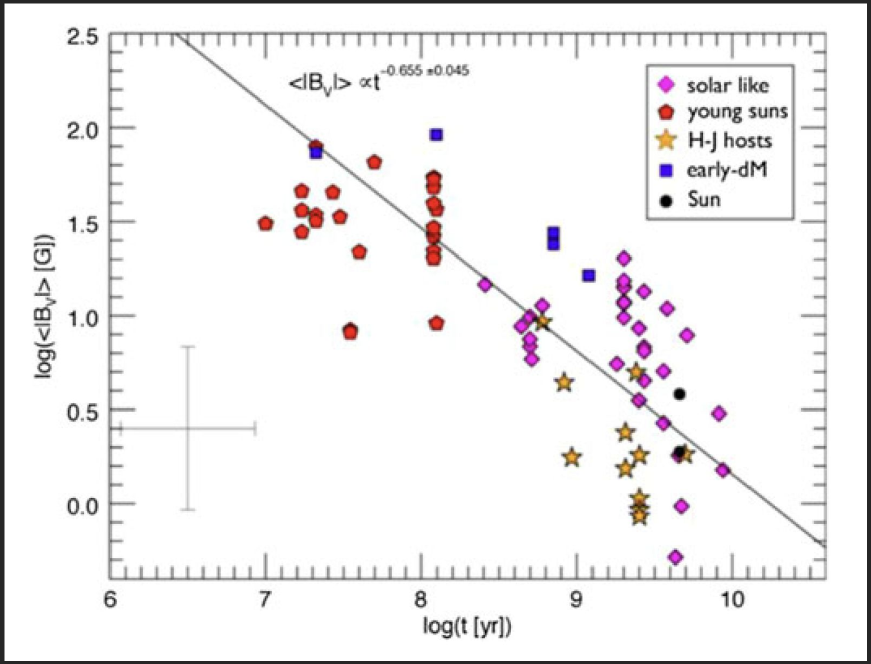
Martínez et al., 2020



Smaller M Dwarfs are more likely to flare

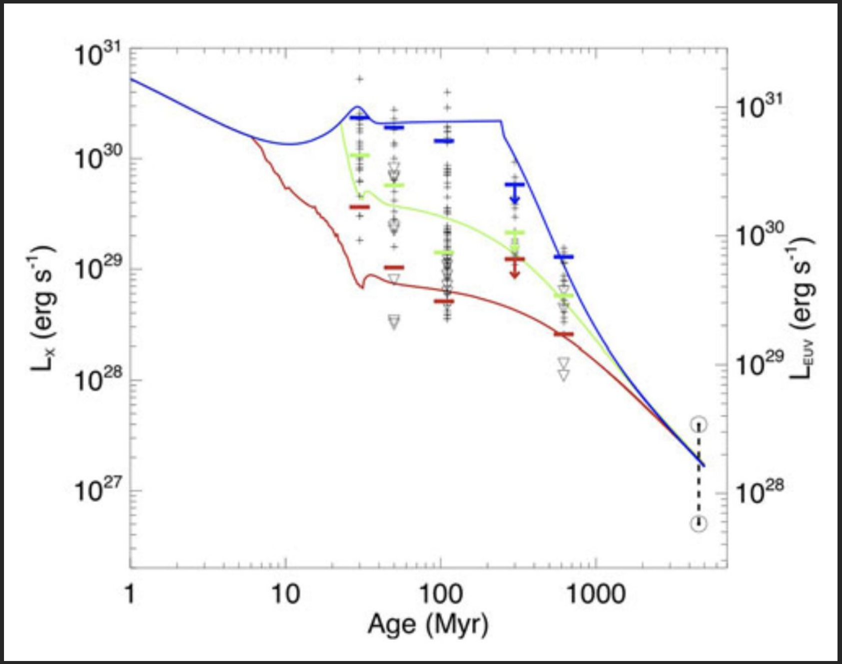
Stars change as they age

Magnetic field



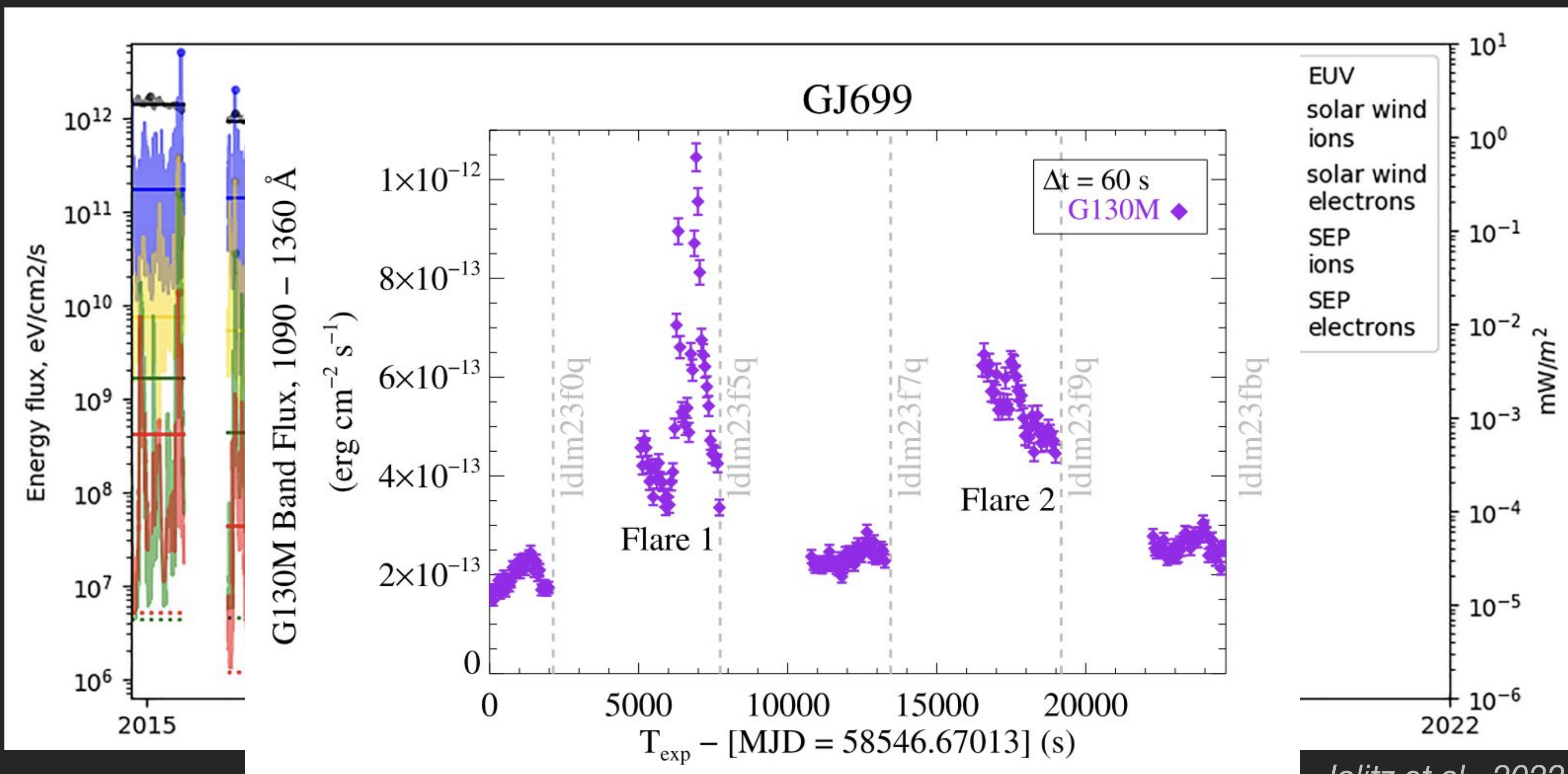
Vidotto et al., 2014

X-ray luminosity



Tu et al., 2015

Understanding the cadence and energy of extreme events (flares, CMEs) is very important since SEPs are associated with both



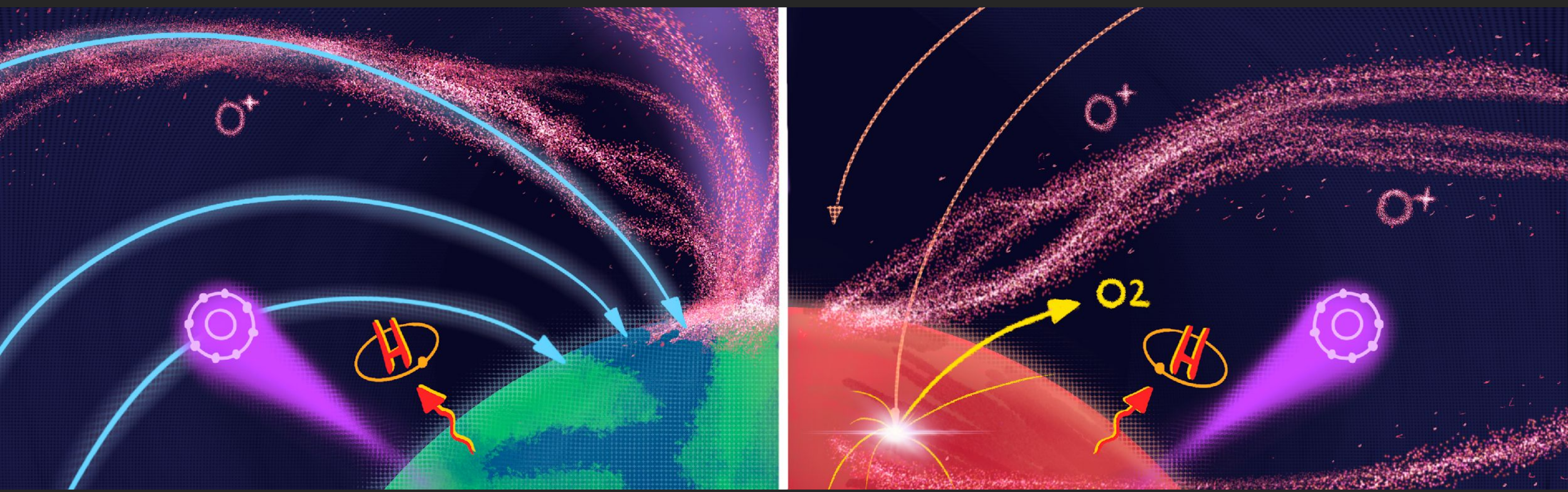
Jolitz et al., 2022

France et al., 2020

Stars drive atmospheric escape from planets

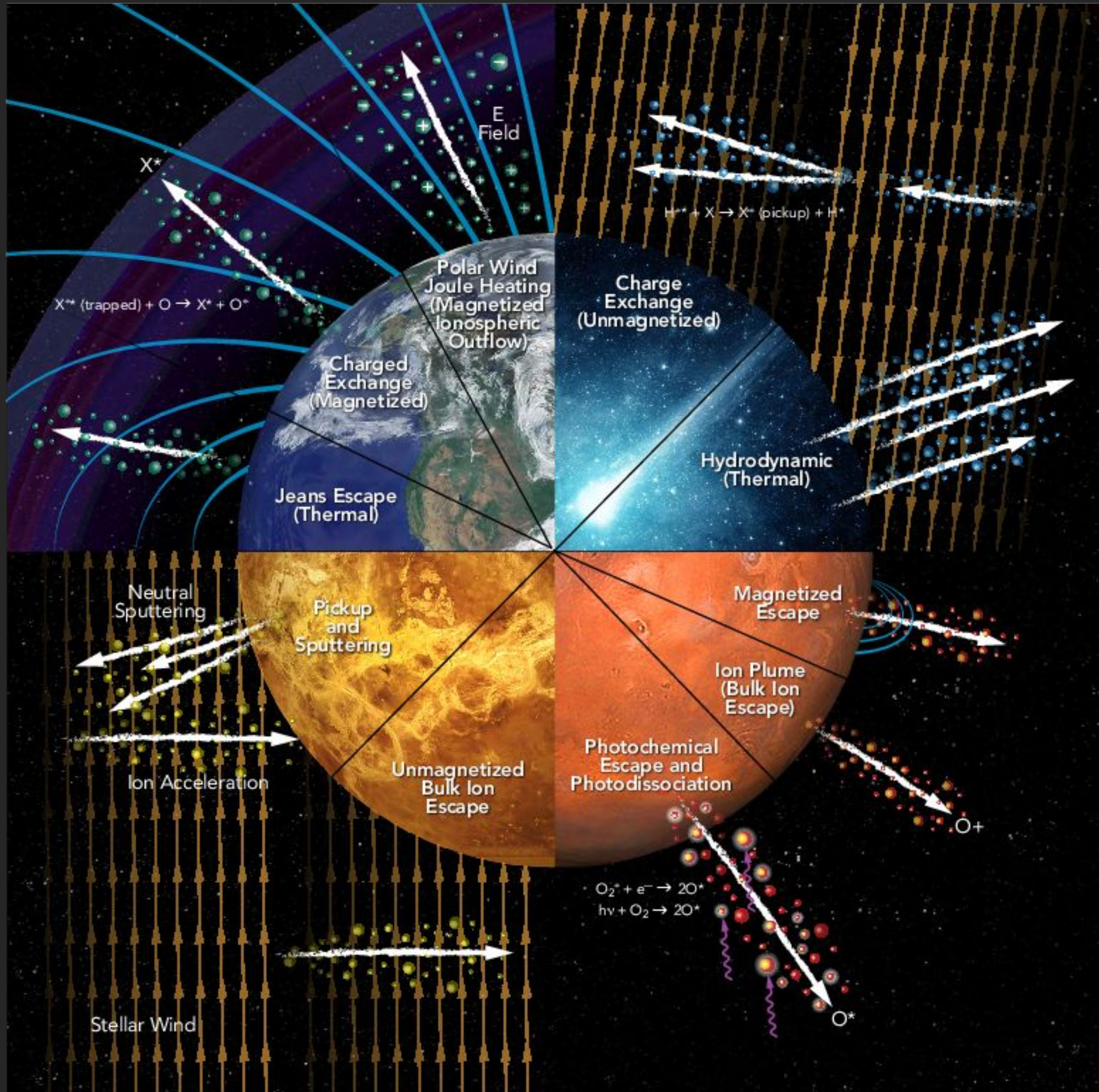
‘Atmospheric escape’ results from a suite of physical processes

- Some processes are influenced by stellar particles; some are not
- Different atmospheric species can be stripped by different processes
- Different processes can be dominant at different times in stellar history



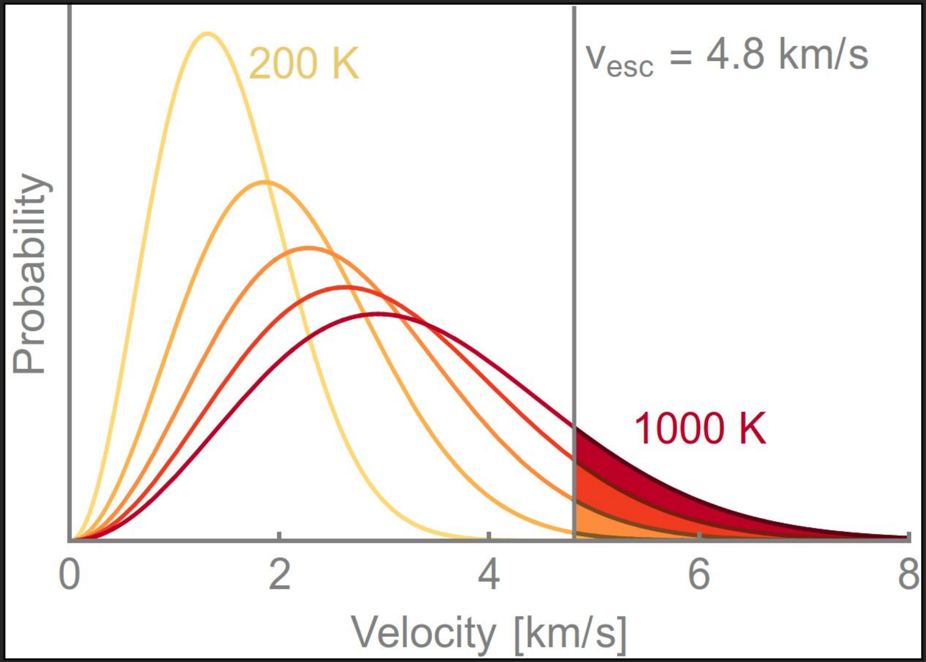
Courtesy C. Pazol

The physics is rich



Gronoff et al., 2020

The thermal distribution of particle energies can lead to escape…

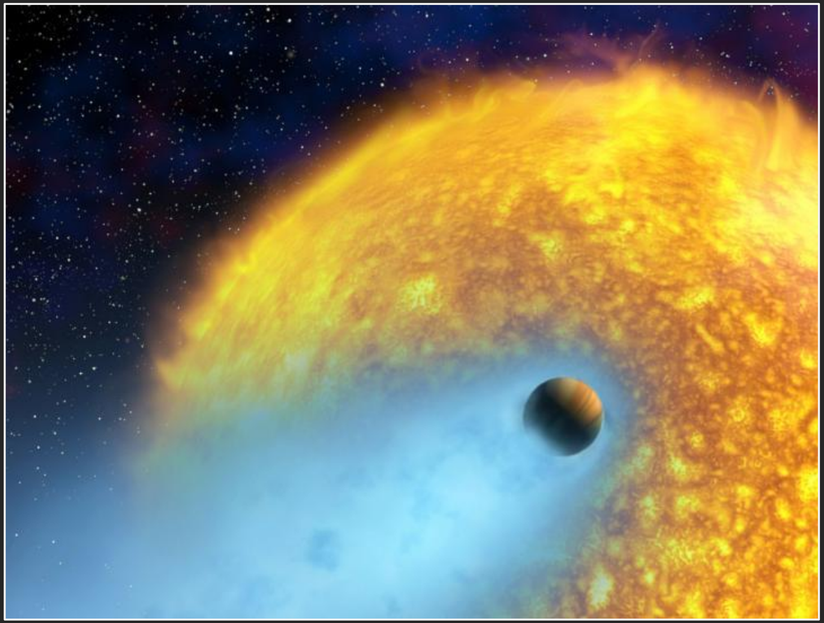


Courtesy M. Chaffin

Thermal escape
or Jeans escape
or
photoevaporation?

$$\lambda_{esc} = \frac{E_{escape}}{E_{thermal}}$$

NASA / ESA / Vidal-Madjar



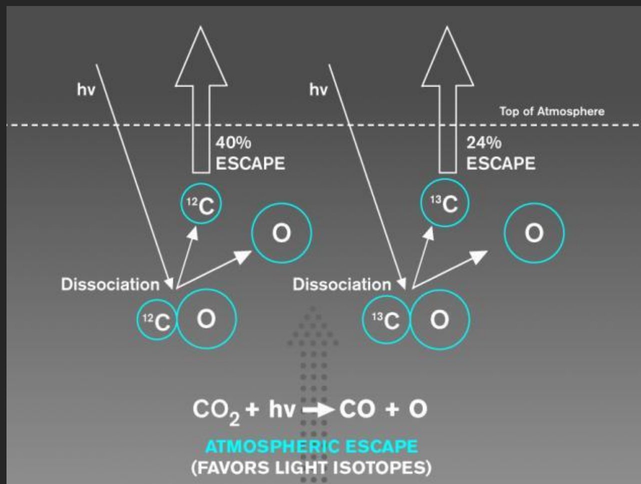
$\lambda_{esc} < \sim 3$

Hydrodynamic escape
or Blowoff / outflow
or photoevaporation

…sometimes lots of escape

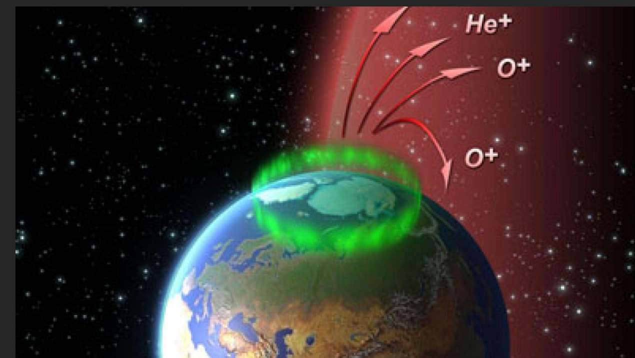
Atmosphere can escape via non-thermal processes, too

Photochemical escape



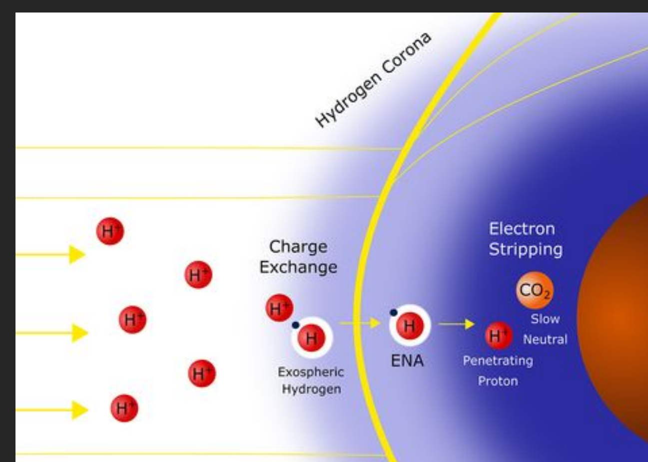
Lance Hayashida / Caltech

Ion escape



ESA

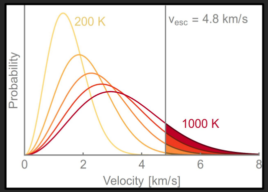
Sputtering



Henderson et al., 2021

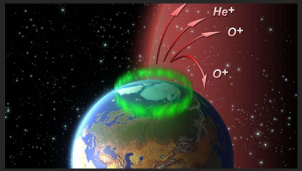
Charge Exchange

Particle space weather can influence escape in several ways



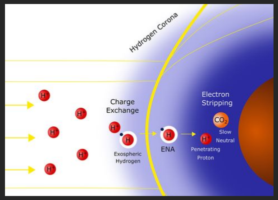
Thermal escape

Stellar particles deposit energy, so can alter the thermal distribution. Under what conditions is this important?



Ion escape

Stellar particles carry energy flux (kinetic, Poynting) that can ionize, energize, and deflect escaping atmospheric particles.

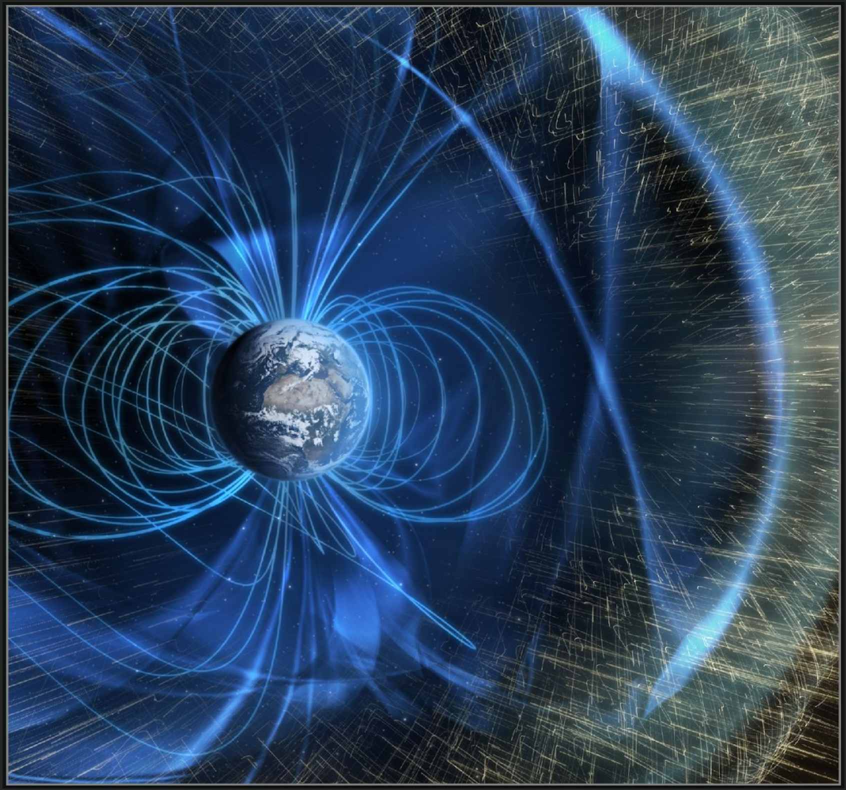
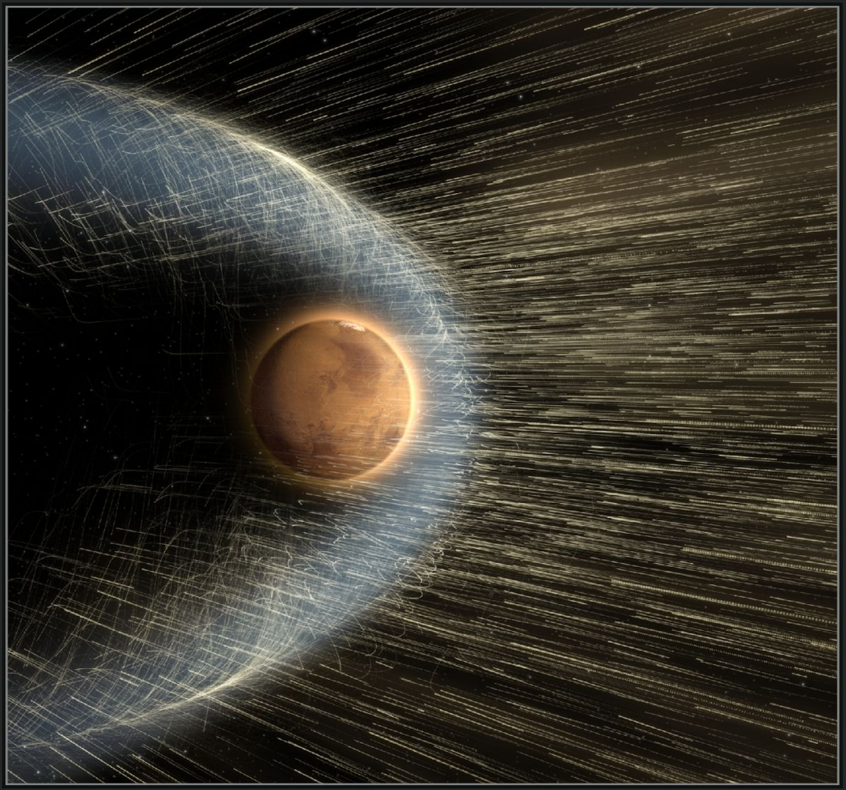


Charge exchange

Stellar particles are the source of charge exchange. When particle fluxes / energies increase, so should charge exchange.

Sputtering

Sufficiently energetic stellar particles can reach a planet's exobase. When is this significant compared to other processes?

NASA GSFC / MAVEN

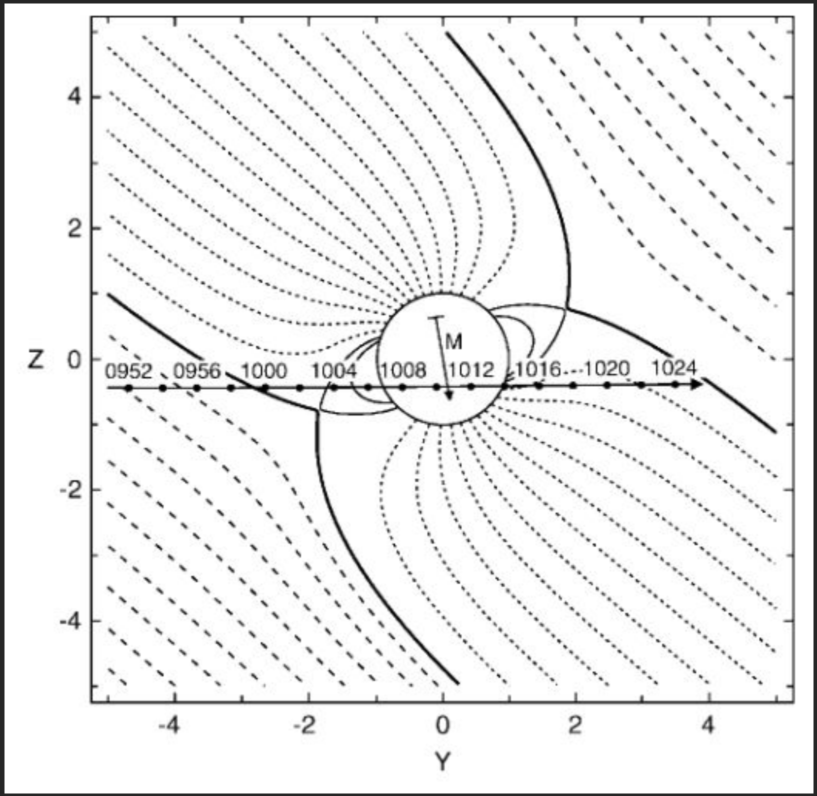
It's not clear whether magnetic fields shield atmospheres from escape driven by stellar winds

Magnetic fields prevent stellar winds and SEPs from accessing an atmosphere

But magnetic fields can transfer energy from the particles to an atmosphere

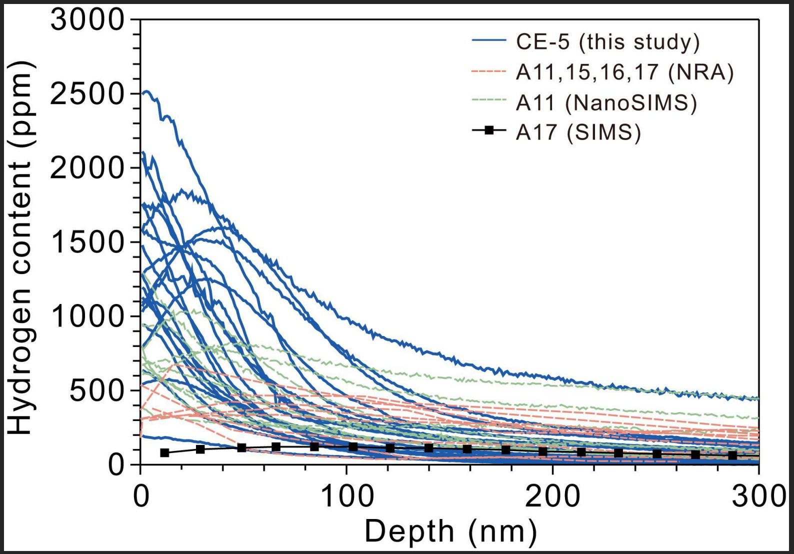
Stellar particles can be absorbed by planets

NASA / JPL / DLR

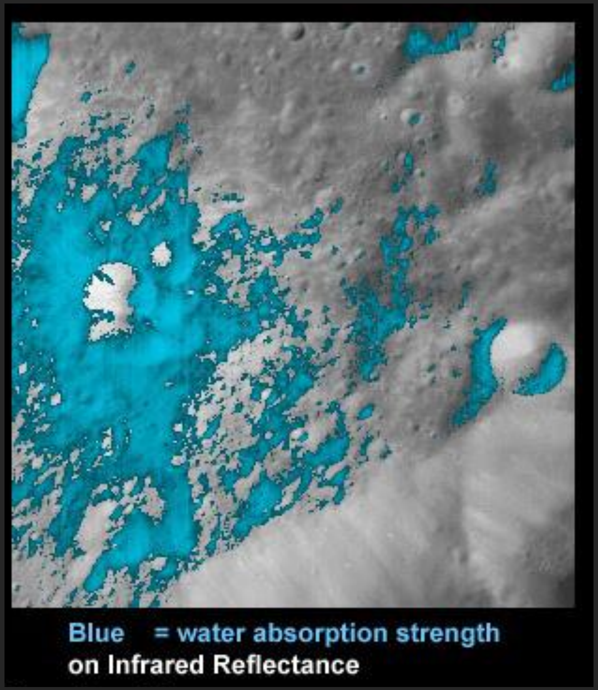


Kivelson et al., 2022

Ganymede's surface is weathered by energetic charged particles in Jupiter's magnetosphere



Xu et al., 2022

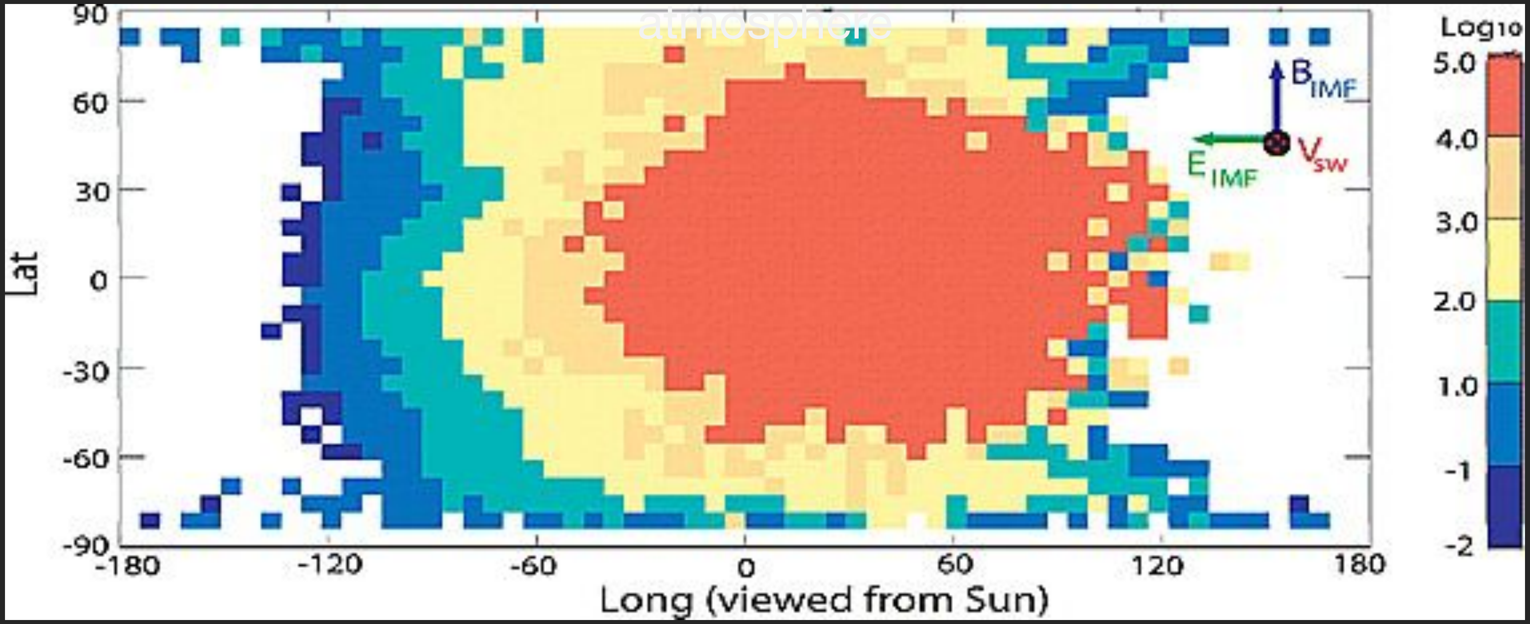


SRO/NASA/JPL-Caltech/USGS/Brow n Univ.

The Moon's outer ~100 nm contains hydrogen delivered by the solar wind

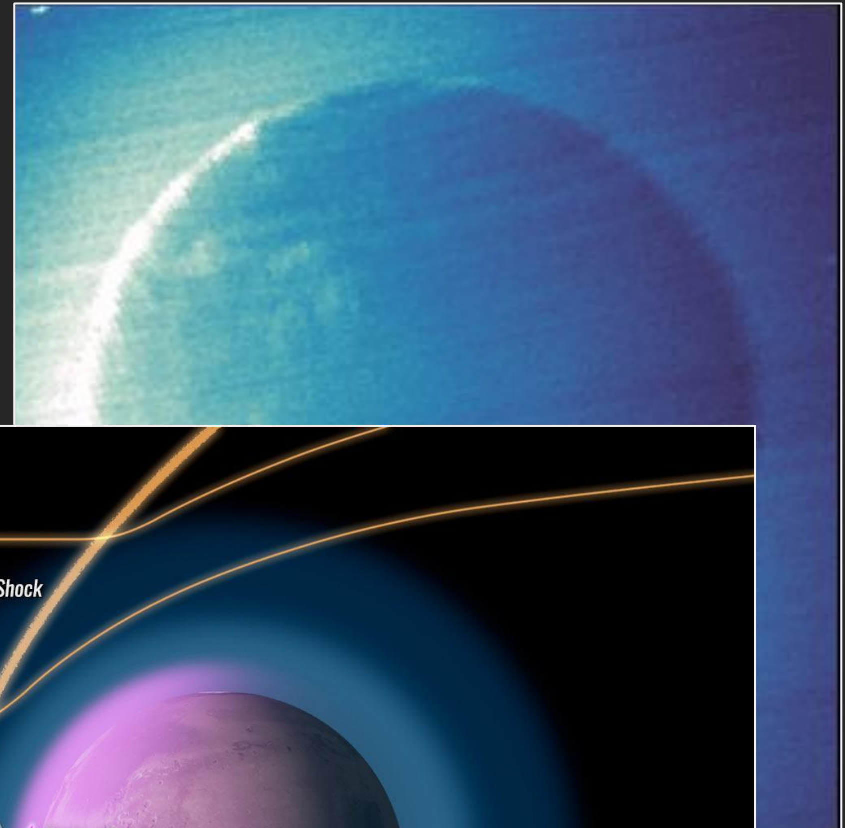
The curious helium budget at Mars can be partially explained by capture of solar wind alpha particles

Helium deposition at the top of the Mars atmosphere

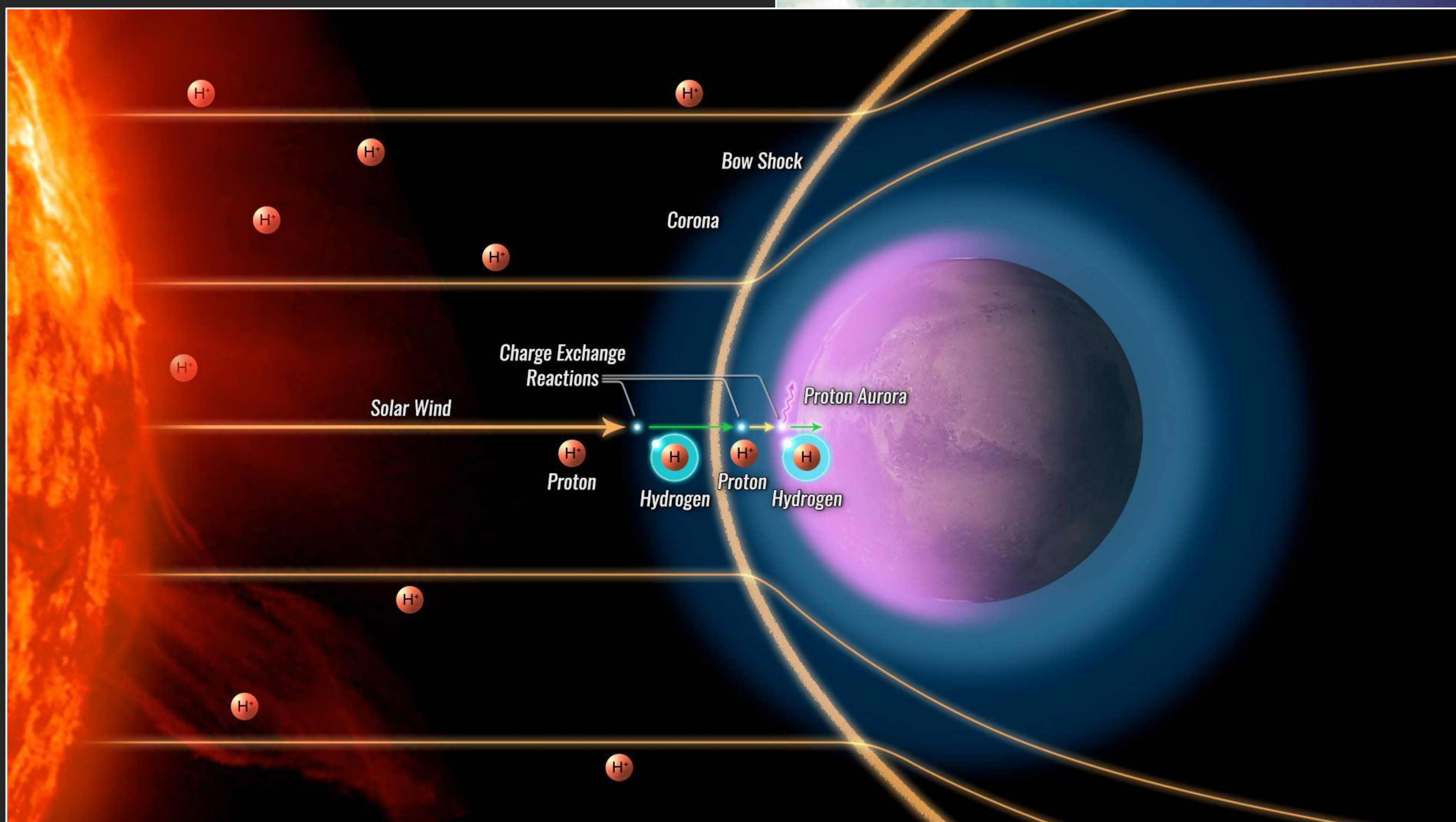


Chanteur et al., 2009

Solar wind protons burrow through the Martian magnetosphere, causing aurora before being captured by the atmosphere

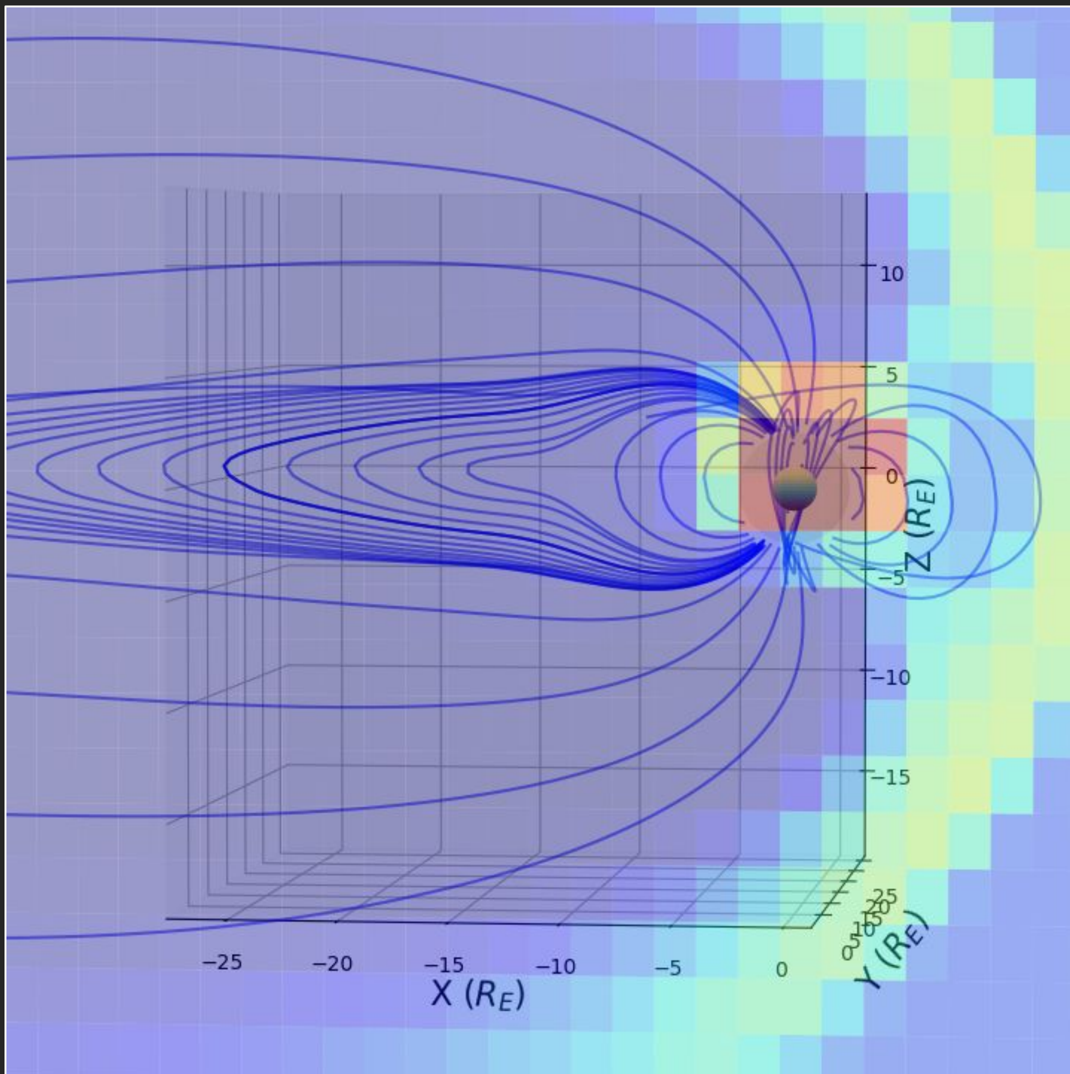


MUS



NASA GSFC / MAVEN

Speculative: Solar wind proton capture at Earth may offset hydrogen escape

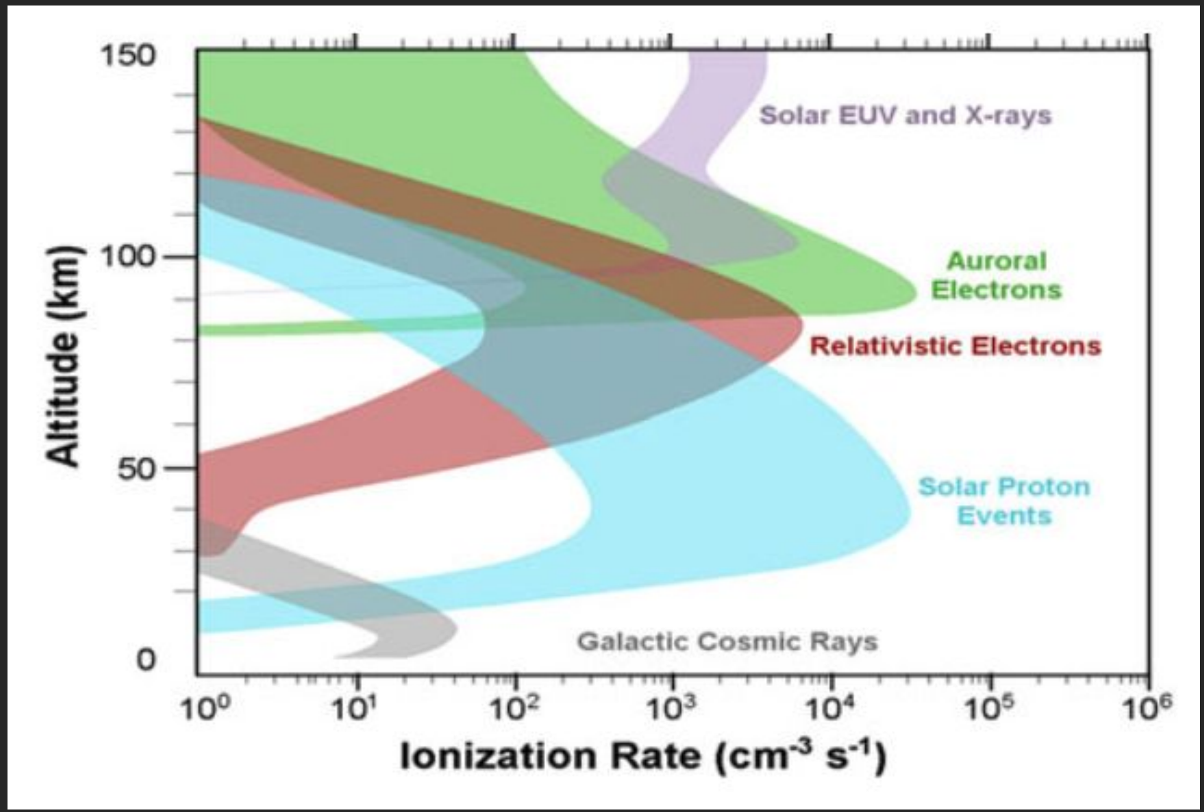


Courtesy P. Hinton

BOTE: Capture of ~1% of solar wind protons encountering Earth's bow shock would offset Earth's hydrogen loss

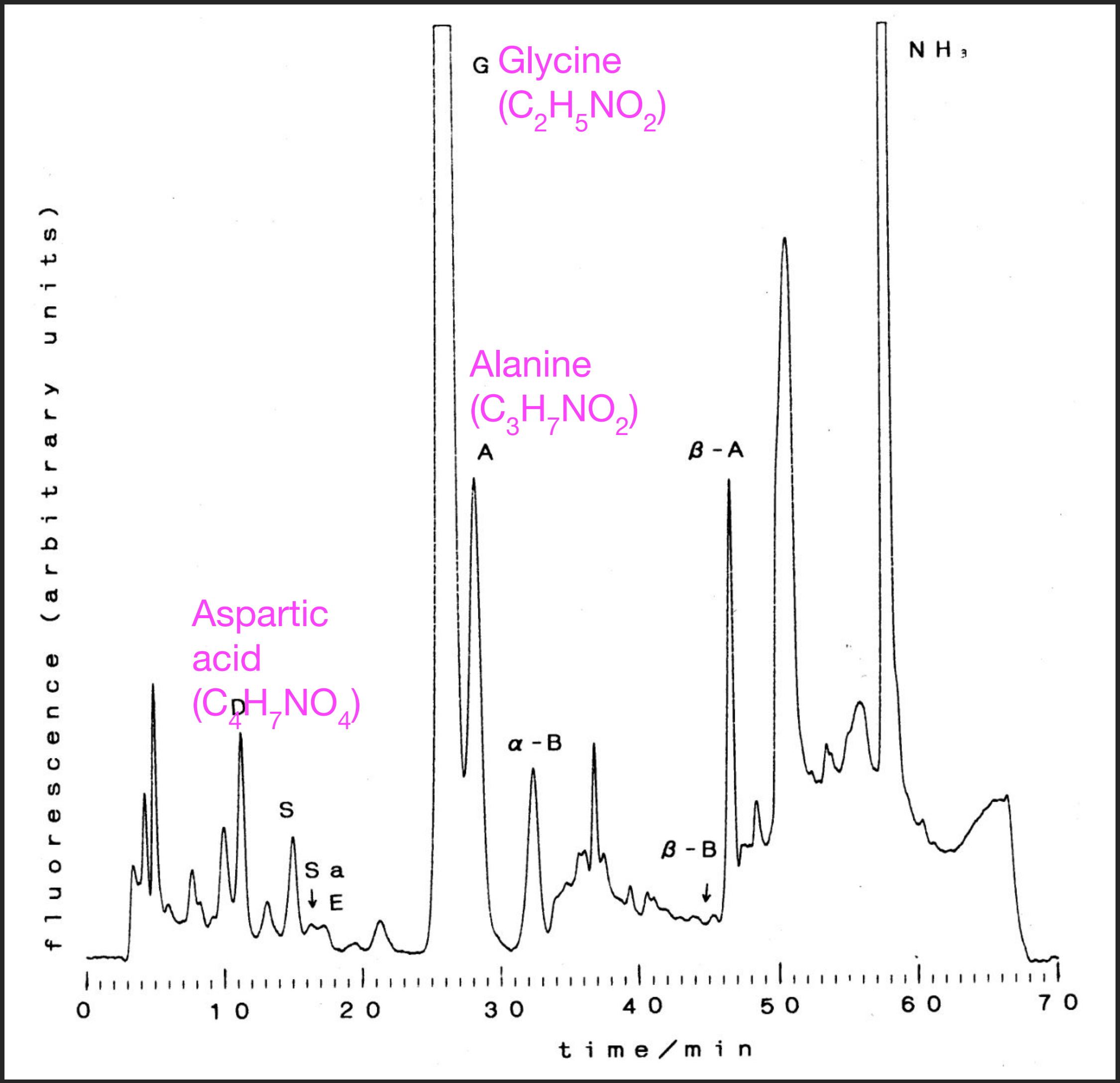
Stellar particles can drive atmospheric chemistry

SEPs penetrate deeper in atmospheres than EUV, so may initiate chemistry at low altitudes



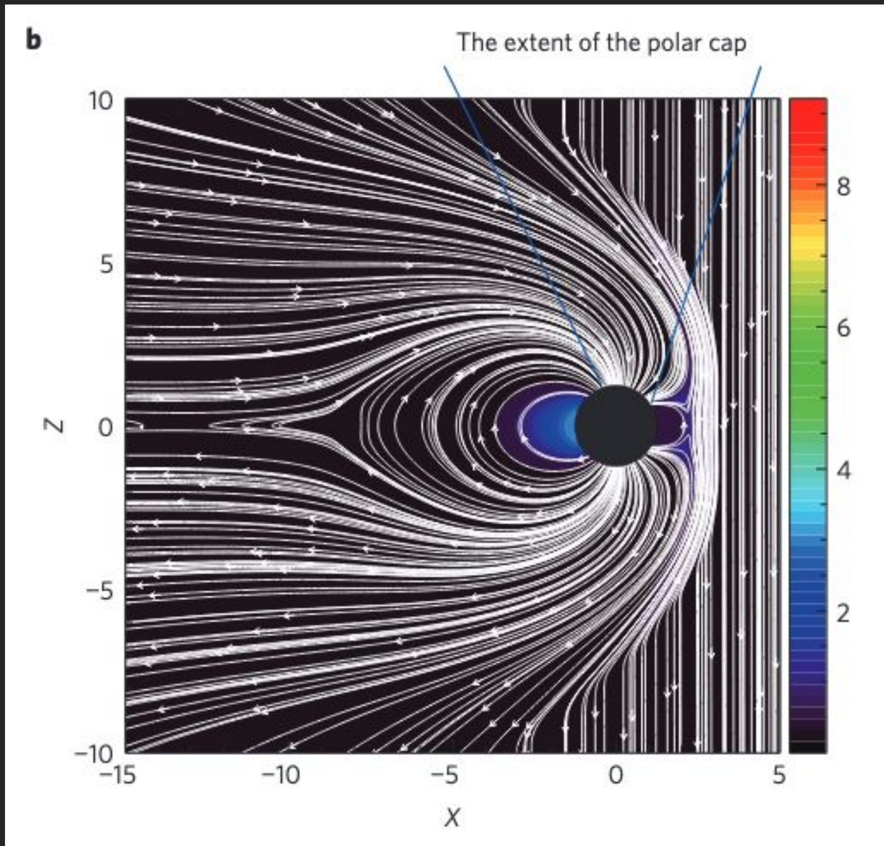
Airapetian et al., 2020

Energetic protons drive chemistry in atmospheric gas mixtures

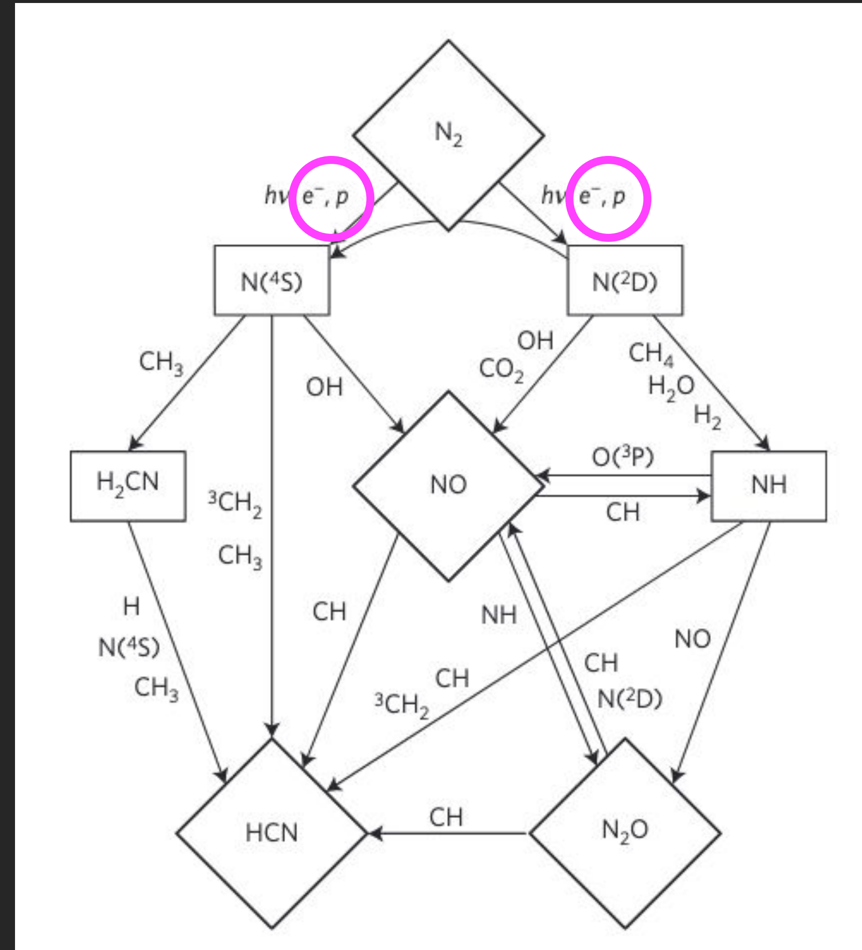


Kobayashi et al., 1998

Production of amino acids by irradiating mixture of CO, N, and H_2O with 3 MeV protons



Airapetian et al., 2016



Airapetian et al., 2016

Magnetosphere and atmospheric chemistry modeling suggests nitrogen could be fixed abiotically on early Earth by SEPs

Summary

- Photons dominate the energy input to solar system planets today
- Relative energy inputs should vary over time and from star to star
- Stellar particles play a role in the escape of planetary atmospheres
- Stellar particles can be absorbed by planets, with consequences for atmospheric composition, energetics, and ionization
- Stellar particles should drive chemistry in planetary atmospheres
- There are many open questions to discuss this week