Cosmic Showers: How Particle Space Weather Affects Planets

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Our Sun spits lots of stuff at planets.
What does this stellar output do to planets?

Courtesy Aurora Simonett
Particles carry much less energy to Mars than light

+ Solar irradiance \( \sim 6 \times 10^5 \text{ mW/m}^2 \)

What about Venus or Earth?
Particles carry much less energy to solar system planets than light

Jolitz et al., 2022
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.

Spectrum of Barnard’s Star relative to the Sun.

Smaller M Dwarfs are more likely to flare.

France et al., 2020

Martínez et al., 2020
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.
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... 

 Thermal escape or Jeans escape or photoevaporation? 

 \[ \lambda_{esc} = \frac{E_{escape}}{E_{thermal}} \]

 \( \lambda_{esc} < \sim 3 \) 

 Hydrodynamic escape or Blowoff / outflow or photoevaporation

...sometimes lots of escape
Atmosphere can escape via non-thermal processes, too

Photochemical escape

\[ \text{CO}_2 + \text{hv} \rightarrow \text{CO} + \text{O} \]

Dissociation

\[ ^{12}\text{C} \rightarrow ^{12}\text{C} + \text{O} \]

\[ ^{13}\text{C} \rightarrow ^{13}\text{C} + \text{O} \]

Ion escape

\[ \text{He}^+ \rightarrow \text{O}^+ + \text{O}^+ \]

Sputtering

Charge Exchange

Henderson et al., 2021
Stellar particles deposit energy, so can alter the thermal distribution. Under what conditions is this important?

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

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

Sufficiently energetic stellar particles can reach a planet’s exobase. When is this significant compared to other processes?
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
Ganymede’s surface is weathered by energetic charged particles in Jupiter’s magnetosphere
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

Chanteur et al., 2009
Solar wind protons burrow through the Martian magnetosphere, causing aurora before being captured by the atmosphere.
Speculative: Solar wind proton capture at Earth may offset hydrogen escape

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

Courtesy P. Hinton
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

Production of amino acids by irradiating mixture of CO, N, and H$_2$O with 3 MeV protons

Kobayashi et al., 1998
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