Attenuation of solar energetic particles by wave-particle interaction with an ion thruster plume

Robert D. Loper (robert.d.loper@nasa.gov)
Heliophysics and Planetary Science Branch, Marshall Space Flight Center, Huntsville, AL, United States

Abstract

Solar energetic particles (SEP) are a significant concern for interplanetary human spaceflight. This work investigates wave-particle interactions caused by the incidence of a beam of energetic protons, representing a notional SEP event, onto a cloud of xenon ions, representing a notional ion thruster plume. The resulting electromagnetic ion/ion instability is developed to investigate the degree to which energetic protons can be scattered out of the initial beam.

Motivation

Solar energetic particles (SEP) are a significant radiation hazard to both human and robotic spaceflight. Human lunar missions would spend most of the time outside the protection of Earth's magnetosphere, since the Moon is only within Earth's magnetotail for a few days per orbit. For human spaceflight to Mars (Figure 1), the amount of time—many months—spent outside the protection of a planetary magnetosphere makes it likely that the spacecraft and crew may be exposed to radiation from a SEP event at least once during the interplanetary mission. Current protection techniques include passive mitigation of incoming radiation by moving astronauts and critical hardware into more highly shielded areas of the spacecraft. The eventual objective of this investigation is to develop a technique for active mitigation of SEP radiation threats to spacecraft and crew, by exploring the interaction of a SEP event with the plasma plume expelled from an ion thruster.

This work considers a typical SEP event caused by the acceleration of solar wind particles by the passing shock of an interplanetary coronal mass ejection (ICME). Although the ICME propagates for the most part radially outward from the Sun, most accelerated particles tend to travel along the spiral interplanetary magnetic field (IMF) lines as they orbit those IMF lines (Figure 2). We approximate a notional SEP event as a wide, diffuse beam of energetic protons and electrons with an example time profile shown in Figure 3. Particles orbit the IMF line along which they travel, but their respective pitch angles (angle between the instantaneous velocity vector and the IMF line) are relatively small and we consider them to be approximately collimated.

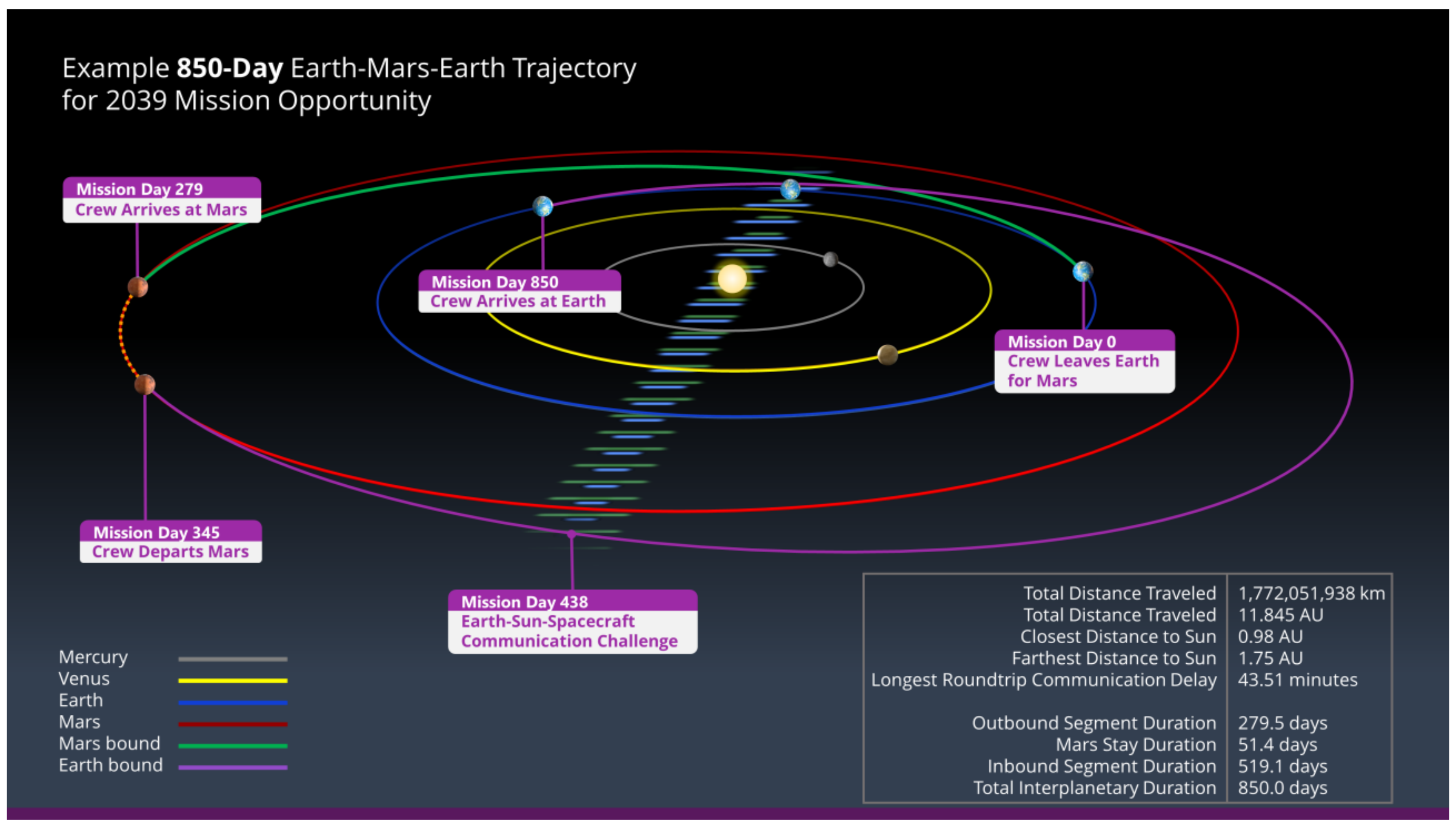

Figure 1: Concept for 2039 crewed Mars mission. Astronauts travel 9 months from Earth to Mars (green arc). Then astronauts spend 51 days on Mars, followed by about 17 months for the return flight (purple arc). In all, these astronauts will be in space for more than two years during their round trip, outside the protection of a planetary magnetic field. For such a lengthy mission, there is a significant risk of a SEP event occurring during the mission. (Source: NASA Moon to Mars Architecture Definition Document)

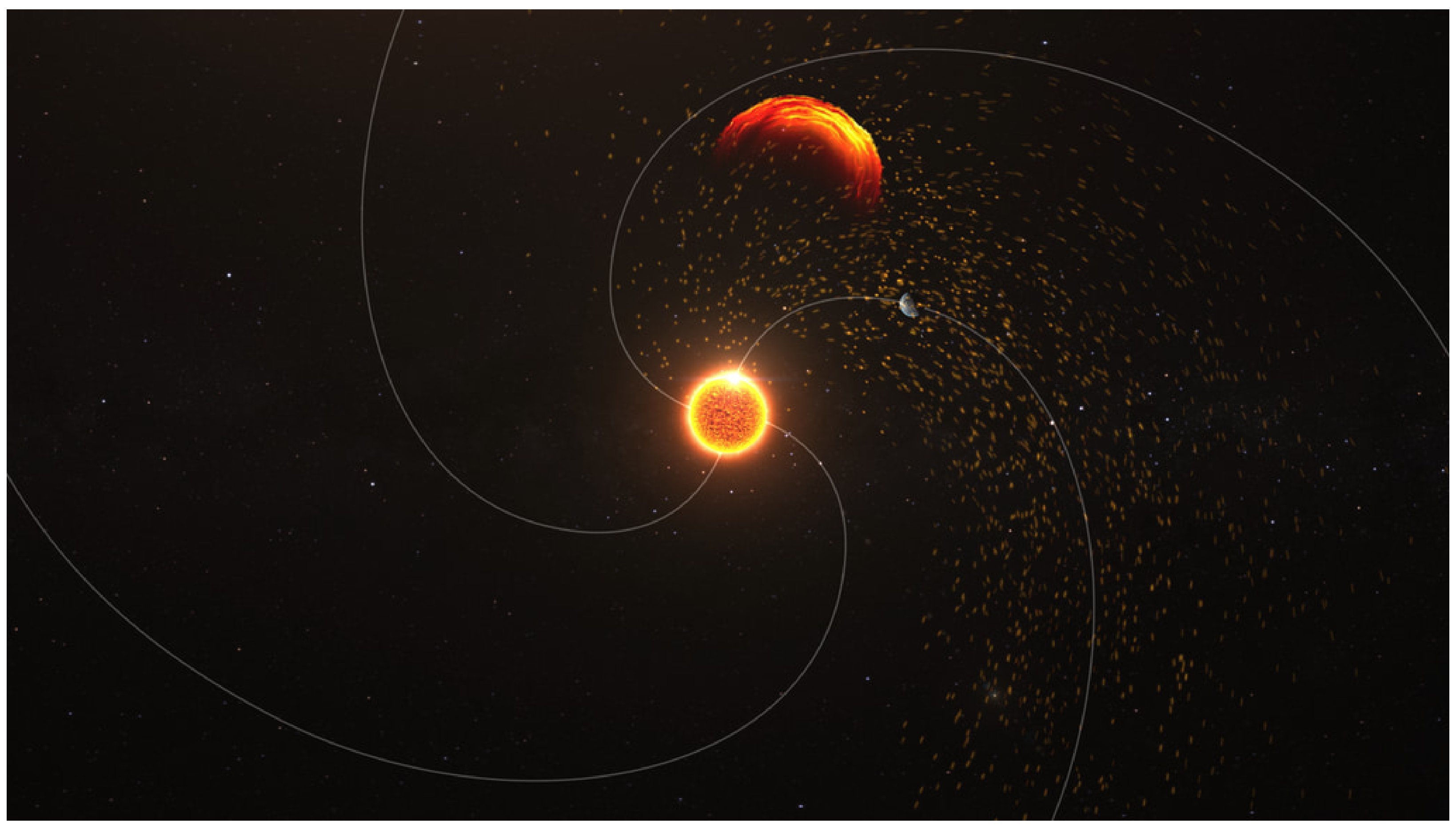

Figure 2: Coronal mass ejection (CME) propagating radially outward from the Sun. The associated shock can accelerate particles along the interplanetary magnetic field (IMF) lines (Source: NASA's Goddard Space Flight Center Conceptual Image Lab).

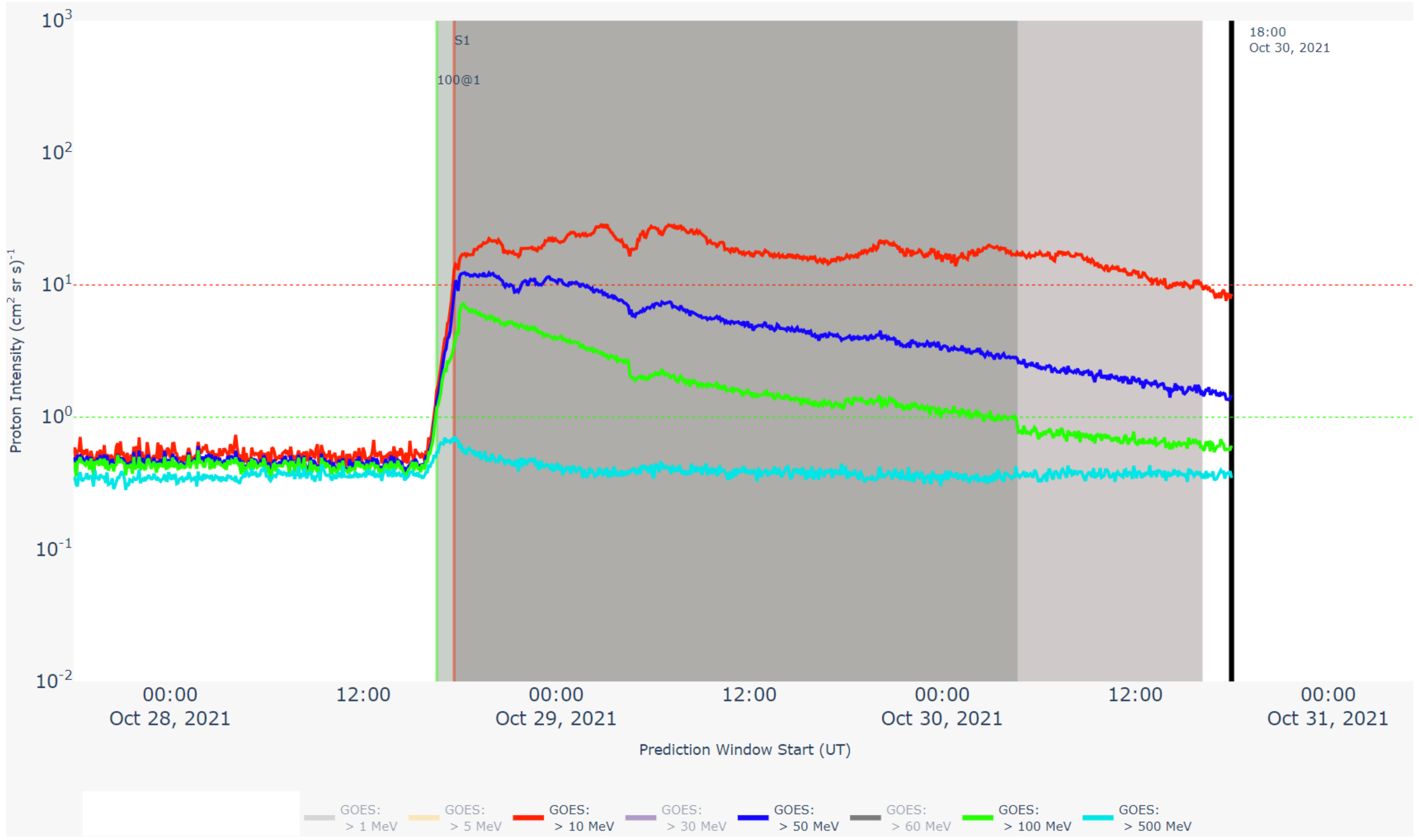

Figure 3: GOES >10 MeV (red), >50 MeV (blue), >100 MeV (green), and >500 MeV (cyan) proton fluxes during the 2021 October 28 SEP event. Notification thresholds are shown with horizontal dotted lines for >10 MeV at 10 pfu (red) and >100 MeV at 1 pfu (green) at geosynchronous orbit, where 1 pfu = 1 proton $(cm^2 \cdot sr \cdot s)^{-1}$) (Source: SEP Intensity Scoreboard, Community Coordinated Modeling Center, Goddard Space Flight Center).

Methodology

This work considers the electromagnetic ion/ion instability resulting from the interaction of a beam of energetic protons with a cloud of xenon ions representing a notional plasma plume (see Figure 4) from an ion thruster of the type currently being utilized for spacecraft applications.

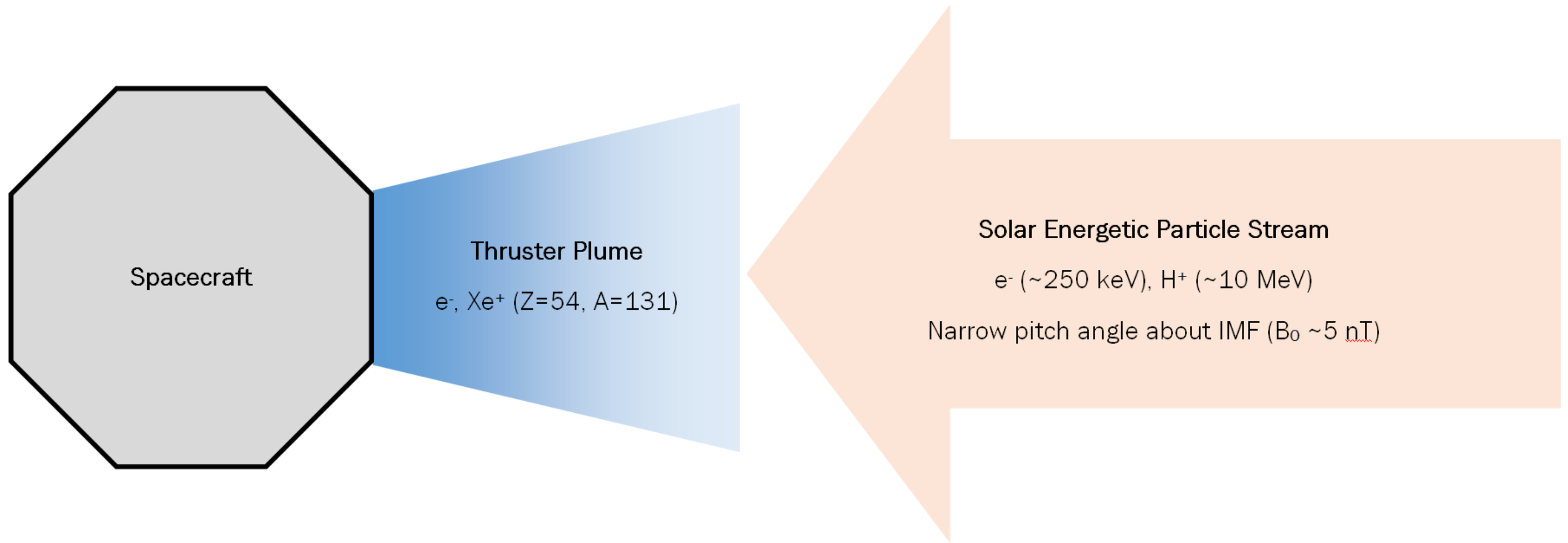

Figure 4: Notional arrangement of spacecraft (left) such that its ion thruster exhaust plume (center) is expelled antiparallel to the incoming solar energetic particles (right), representing reorientation of a spacecraft to fire its ion thruster antiparallel to an incoming SEP event. Such a technique would likely push the spacecraft off its course, so a course correction burn may be required once the SEP event subsides. This consideration would likely restrict use of this technique to interplanetary flights in which the required course correction is relatively minor and more easily achieved. This analysis is done in the rest frame of the exhaust plume, with the 10-MeV protons having speed ~0.14c (where c is the speed of light).

We begin from a hybrid-Vlasov system similar to that in Palmroth (2018), beginning with moments of the Vlasov equation for each ion species, coupled through the fields which are described by the Maxwell equations. We ignore the electron motions and concentrate on ion/ion interactions.

In our case, each ion species has a corresponding Vlasov equation:

$$\frac{\partial f_H}{\partial t} + \mathbf{u_H} \cdot \frac{\partial f_H}{\partial \mathbf{x}} + \frac{e}{m_H}(\mathbf{E} + \mathbf{u_H} \times \mathbf{B}) \cdot \frac{\partial f_H}{\partial \mathbf{u}} = 0$$

$$\frac{\partial f_{Xe}}{\partial t} + \mathbf{u_{Xe}} \cdot \frac{\partial f_{Xe}}{\partial \mathbf{x}} + \frac{e}{m_{Xe}}(\mathbf{E} + \mathbf{u_{Xe}} \times \mathbf{B}) \cdot \frac{\partial f_{Xe}}{\partial \mathbf{u}} = 0$$

We also have the Maxwell equations:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} \qquad \nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

The zeroth moment equations are (particle) continuity equations:

$$\frac{\partial n_H}{\partial t} + \nabla \cdot (n_H \mathbf{u}_H) = 0 \qquad \frac{\partial n_{Xe}}{\partial t} + \nabla \cdot (n_{Xe} \mathbf{u}_{Xe}) = 0$$

The first moment equations are the familiar Navier-Stokes equations (one per species), including Lorentz terms and pressure tensor $\mathbb{P}$:

$$n_H m_H(\frac{\partial \mathbf{u}_H}{\partial t} + (\mathbf{u_H} \cdot \nabla)\mathbf{u}_H) - n_H e(\mathbf{E} + \mathbf{u_H} \times \mathbf{B}) + \nabla \cdot \mathbb{P}_H = 0$$

$$n_H m_{Xe}(\frac{\partial \mathbf{u}_{Xe}}{\partial t} + (\mathbf{u_{Xe}} \cdot \nabla)\mathbf{u}_{Xe}) - n_{Xe} e(\mathbf{E} + \mathbf{u_{Xe}} \times \mathbf{B}) + \nabla \cdot \mathbb{P}_{Xe} = 0$$

From here, we need to close the system of equations. Usually, this is done either through assuming the $(n+1)^{th}$ moment of f to be zero or by use of some equation of state. We will assume, following Zhou and Bellan (2023), that our jet of SEP protons is approximately isothermal (with scalar pressure $P_H = n_H k_B T_H$) since departures from $\frac{T_\perp}{T_\parallel} \approx 1$ tend to be counteracted by other instabilities (Huang 2020, Opie 2022).

We sketch a calculation of the growth rate of oscillations along the IMF, with the thruster plume central axis aligned with the IMF, which we call the z axis. The linearized moment equations for the SEP protons become:

$$\frac{\partial n_H}{\partial t} + u_{H,z0}\frac{\partial n_{H,1}}{\partial z} + n_{H,0}\frac{\partial u_{H,z1}}{\partial z} = 0$$

$$m_H \frac{\partial u_{H,z1}}{\partial t} + m_H u_{H,z0}\frac{\partial u_{H,z1}}{\partial z} - e[\nabla \cdot \mathbf{E}_1 - \mathbf{u_{H,0}} \cdot (\nabla \times \mathbf{B}_1)] + k_B T_H \frac{\partial n_{H,1}}{\partial z} = 0$$

The xenon ions have similar equations, and the two linearized first moment equations (one for each ion species) are coupled by the field perturbations. Then we take certain steps to reduce the equations:

1. Take $\frac{\partial}{\partial z}$ of each momentum equation.
2. Plug each continuity equation into the corresponding momentum equation to eliminate $\frac{\partial v_{s,z1}}{\partial z}$.
3. Assume perturbations of the form $n_{s,1} = \eta_s \exp(ik_z z + \gamma t)$.
4. Divide through by $-(\frac{m_s \eta_s}{n_{s,0}})$.

Conclusions

- The growth rate for each species is $\gamma_s = -ik_z v_{s,z0} \pm \sqrt{\frac{n_{s,0} k_B T_H}{\eta_s m_s} k_z^2 + \text{Field Coupling}}$.
- The real component of this growth rate represents a portion of the population from each species being scattered out of the interaction region by wave-particle interaction.
- The imaginary component represents a velocity- and time-dependent modification of the mode k_z.
- Field coupling between the two species requires computational modeling to fully analyze the field behavior and impact on particle dynamics, but the existence of a growth rate with a nonzero real component merits deeper investigation of the technique.

Future Work

1. More modeling is needed to determine how the wave-particle interaction varies with the orientation of the thruster plume with respect to the IMF direction.
2. Particle in Cell (PIC) simulation of the interaction phase space to achieve kinetic modeling. The intent is to lay a foundation for future testing of the technique, either in the laboratory or in space.
3. Examination of the electromagnetic radiation generated by the wave-particle plasma interactions, including analysis of the expected radiated power spectrum as a function of the modeled SEP attenuation rate.
4. Relativistic calculations in order to model protons with energies >100 MeV.

References

- Bellan, P. M. 2006, Fundamentals of Plasma Physics (Cambridge, UK: Cambridge University Press)
- Huang, J. et al 2020 ApJS 246 70. https://doi.org/10.3847/1538-4365/ab74e0
- Opie, S. et al 2022 ApJ 941 176. https://doi.org/10.3847/1538-4357/ac982f
- Palmroth, M., Ganse, U., Pfau-Kempf, Y. et al. Vlasov methods in space physics and astrophysics. Living Rev Comput Astrophys 4, 1 (2018). https://doi.org/10.1007/s41115-018-0003-2
- Zhou, Yi, Paul M. Bellan; Two-stream instability with a growth rate insensitive to collisions in a dissipative plasma jet. Phys. Plasmas 1 May 2023; 30 (5): 052101. https://doi.org/10.1063/5.0146806