Radiation Effects for Relativistic Interstellar Spacecraft

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Introduction

Relativistic spacecraft will have to survive a radiation environment that is unique when compared to that experienced by the average spacecraft. In a relativistic interstellar spacecraft's reference frame, the interstellar medium (ISM) will look like a nearly mono-energetic beam of charged particles which impinges upon the leading edge of the spacecraft. Upon impact, ISM protons and electrons will slow via electronic and nuclear stopping mechanisms. Bremsstrahlung x-ray photons will also be produced within the spacecraft shield. We discuss the electronic and nuclear damage and production of x-rays for a number of incident ISM species, including protons, electrons, higher Z species and cosmic rays [1,2].

ISM Particle Fluxes

The ISM is made up of approximately 90% protons, 8% helium, and 2% heavier species. For a spacecraft with speed β_{sc} the kinetic energy of colliding ISM particles is given by $\mathrm{KE} = m_{0p}c^2(\gamma - 1) \sim \beta_{sc}^2 m_{0p}c^2$ for modest β_{sc} (typ. < 0.5), where $m_{0p}c^2$ is the rest mass of the colliding particle. For a spacecraft at β_{sc} = 0.2, a colliding ISM proton has kinetic energy of ~19 MeV and an electron has kinetic energy of ~10 keV. In the primed reference frame of the spacecraft, we have an ISM particle velocity of $\boldsymbol{v}' = (v_x', v_y', v_z') = c\boldsymbol{\beta} - \boldsymbol{v}$, where $c\boldsymbol{\beta}$ is the spacecraft velocity in the ISM frame and $\boldsymbol{v} = (v_x, v_y, v_z)$ is the ISM frame particle velocity. In the ISM frame, the particle velocity is then $\boldsymbol{v} = c\boldsymbol{\beta} - \boldsymbol{v}'$. We can therefore write the velocity vector distribution for particles in a thermalized ISM at temperature T hitting the spacecraft as

$$f(v) = 4\pi|\boldsymbol{v}|^2\left[\frac{m}{2\pi kT}\right]^{3/2}\exp[-m|\boldsymbol{v}|^2/2kT].$$

We can parameterize the particle distribution in spherical coordinates (θ,φ), where θ is measured from the z-axis and φ is in the x-y plane with $\theta = \cos^{-1}(v_z/v)$ and $\varphi = \tan^{-1}(v_y/v_x)$. As we show in our paper, for a spacecraft travelling along the z-axis we can write the particle flux as a function of the co-angle relative to the x-y plane as

$$\Gamma_n(\theta,\varphi) = \frac{n_p c}{\sqrt{2\pi}}\left[\left(\frac{kT}{mc^2}\right)^{1/2}\sin\theta + \sqrt{2\pi}\beta\cos\varphi\right].$$

Bremsstrahlung Photon Production

For electron impacts, an empirical fit to photon production per unit solid angle and electron current via electron impacts for various material is given approximately by

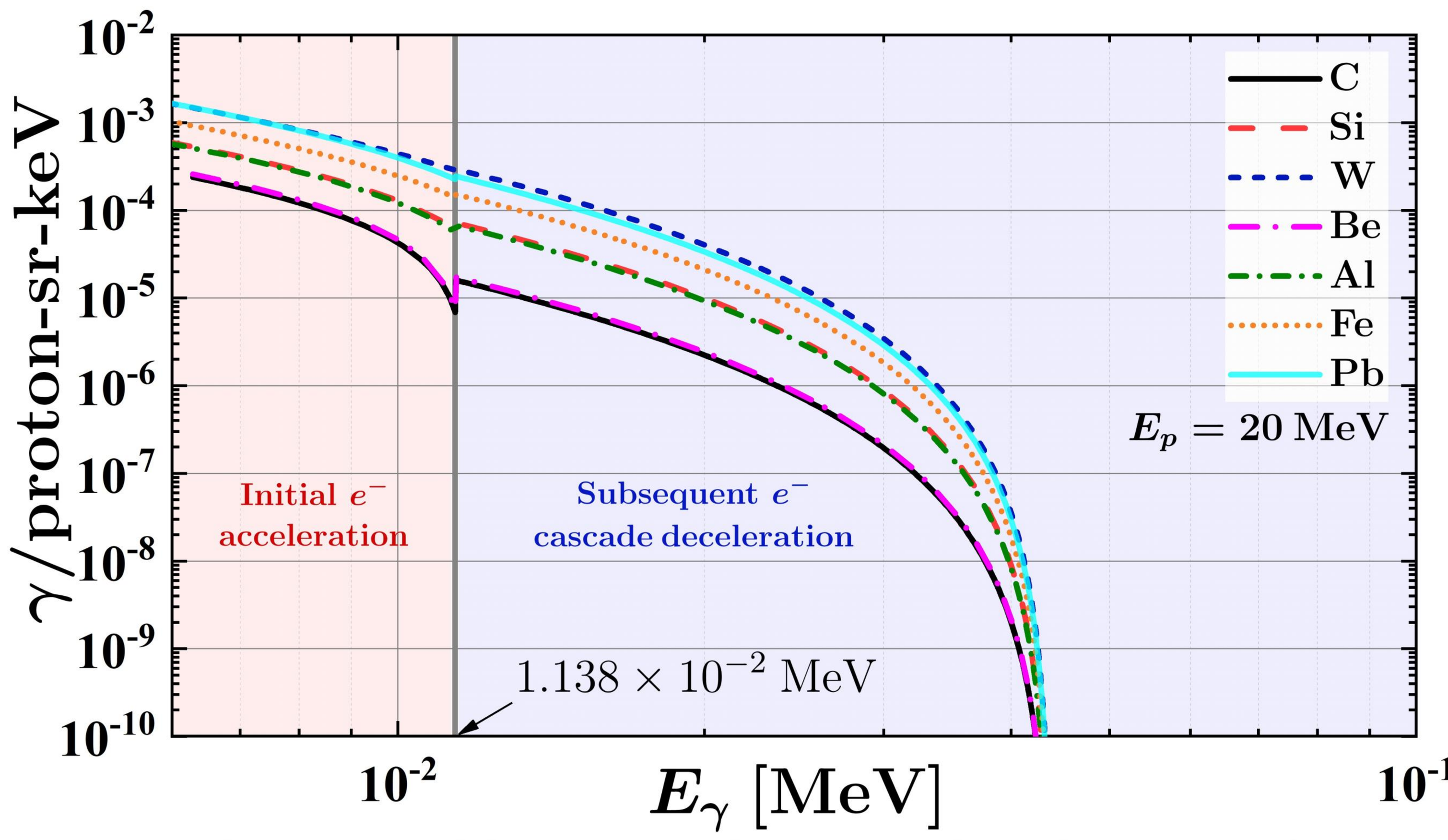
$$\frac{dN_\gamma}{dE_\gamma}dE_\gamma\, dI\, dt = \kappa Z^n\left(\frac{E_0}{E_\gamma} - 1\right)^x,$$

where I is the electron current, t is the irradiation time, n is the principle quantum number (n = 1), κ is an empirically determined constant with value 1.35×10^9 γ/s/sr/mA/keV, and $x = 1.109 - 0.00435\,Z + 0.00175\,E_0$, where Z is the target atomic number and E_0 is the incident electron energy [3]. We can therefore write the photon flux at any point inside the spacecraft as

$$\Gamma_i = \kappa Z^n\left(\frac{E_0}{E_\gamma} - 1\right)^x\int_{\Sigma_f}\boldsymbol{F}_s'\cdot\boldsymbol{n}\,dA,$$

where Σ_f is the spacecraft surface exposed to the ISM flux, $\boldsymbol{n}$ is the surface normal vector of Σ_f, and $\boldsymbol{F}_s'$ is the incident species flux, which is approximately given by $\sim n_s c\boldsymbol{\beta}$, where n_s is the number density of the incident species.

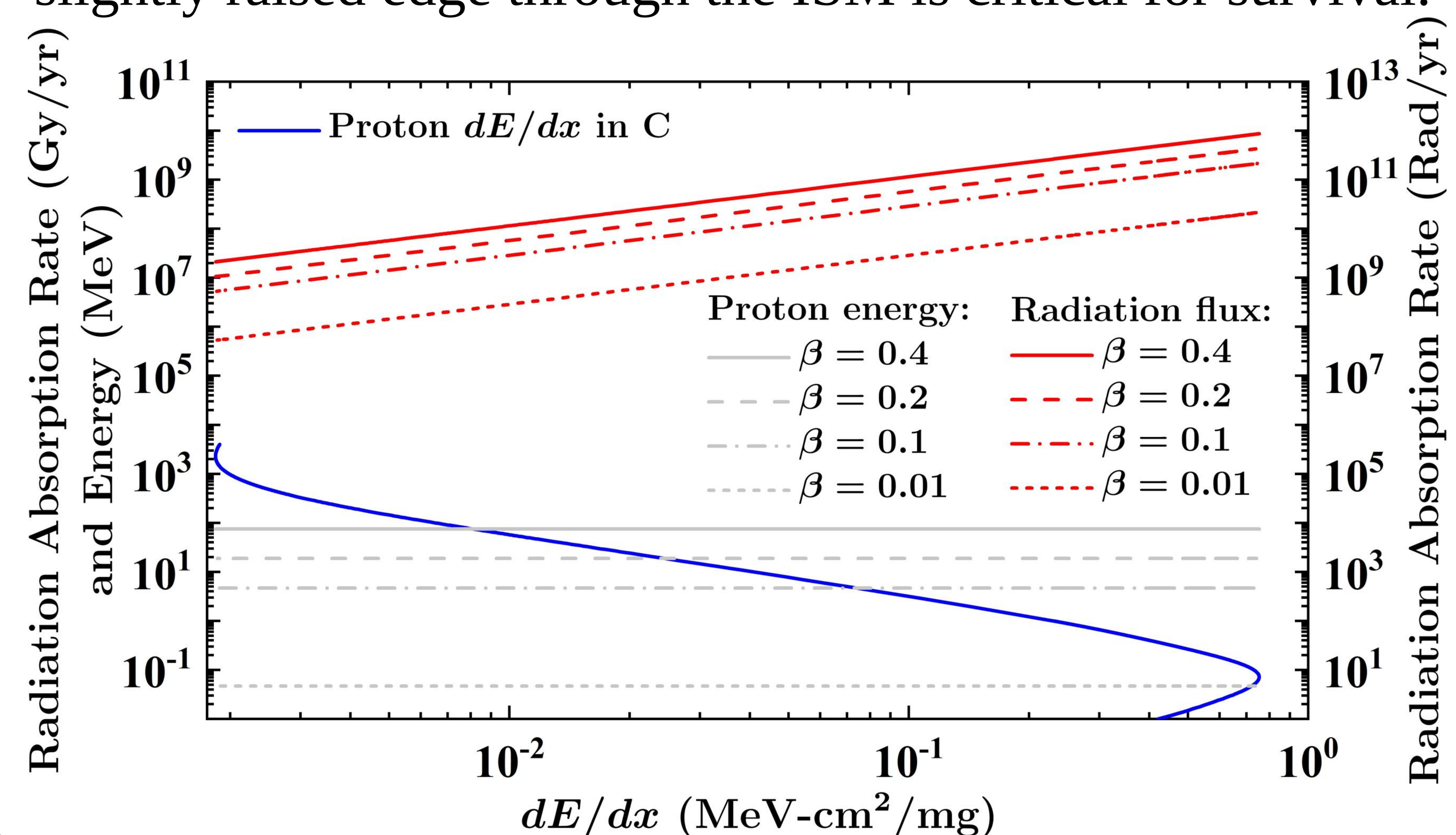
A complimentary expression for the production of photons due to proton impacts was developed by Ogier et al. [4], which describes a two-part production process wherein an initial wave of photons is produced as material electrons are accelerated by the incoming proton, and a second wave is produced by the consequent deceleration of the material electrons (the proton loses its kinetic energy by electron collisions and lattice phonon excitations).



Proton bremsstrahlung production distributions for 20 MeV protons incident on various target materials are shown above.

Radiation Doses

Normal radiation tolerance of commercial Si devices is typically about 10 kRad, while radiation hardened devices can withstand more than 1 Mrad per year. We calculate the radiation dose for a relativistic spacecraft assuming an ISM proton density of 0.2 cm^{-3}, which yields approximately 20×β proton hits per year per Angstrom areal cell. The atomic spacing is roughly an Angstrom yielding extremely large radiation damage (>100 GRad/yr), as illustrated in the plot below for various β. Flying "edge on" with a slightly raised edge through the ISM is critical for survival.



Conclusion

Relativistic spacecraft have to endure impacts with ISM particles while sustaining acceptable damage. A key component of the radiation environment is the radiation produced within the spacecraft upon impact and subsequent stopping of ISM particles. We compute direct atomic and nuclear damage as well as bremsstrahlung x-ray photons which need to be attenuated by the edge shield to protect critical components. X-ray production from incident electrons is small, but incident protons produce cascades of photons deeper below the surface. Flying "edge on" with a slightly raised edge with proper materials is critical. Further details can be found in our radiation effects papers [1,2,5].

References

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