DOSEFIELD: A Transparent 1-D Deep-Space Radiation Dose and Shielding Model with Source-Traceable Constants

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Abstract

DOSEFIELD is an open, deterministic one-dimensional model of the deep-space galactic cosmic ray (GCR) radiation environment: a parametric GCR spectrum is transported through a slab shield in the continuous-slowing-down approximation and converted to absorbed dose and ICRP-60 dose-equivalent in water. Every constant is taken from a cited primary source, and no parameter is fitted to any validation target. Against NIST PSTAR proton stopping-power tables the Bethe–Bloch engine agrees to a maximum deviation of 1.55% above 10 MeV across five low-Z materials (4.03% including the 1–10 MeV region, where shell corrections are omitted). Against the MSL/RAD cruise measurement — evaluated at a solar modulation and shield thickness chosen independently of the measurement — the model returns an absorbed dose of 0.308 mGy/day against a measured 0.458 ± 0.032 mGy/day (ratio 0.67×), a dose-equivalent of 1.473 mSv/day against a measured 1.75 ± 0.30 mSv/day (ratio 0.84×), and a mean quality factor ⟨Q⟩ of 4.78 against a measured 3.82 ± 0.25 (ratio 1.25×). The propagated 1σ-style input uncertainty on the dose-equivalent is 14.6%, which does not cover the absorbed-dose shortfall: that shortfall is model-form error from un-transported secondary production, and it is reported rather than corrected. Contemporaneous in-cruise neutron measurements (6 ± 2 μGy/day) account for only about 4% of the model's absorbed-dose deficit, so the deficit is attributed to secondary charged particles and target fragments, not neutrons. At equal areal density the model ranks five shield materials strictly by hydrogen content (H_2 < CH_4 < polyethylene < water < aluminium) at every thickness tested from 5 to 40 g/cm^2; liquid hydrogen reduces dose-equivalent by up to 44.2% relative to aluminium. This paper reports a methods and validation study, not a new physical result: the value of the work is a fully inspectable, source-traceable implementation and an honest, quantitative account of where and why it disagrees with flight data.

Keywords: space radiation; galactic cosmic rays; radiation shielding; Bethe–Bloch stopping power; MSL/RAD; dose equivalent; model validation; reproducible physics

1. Introduction

Crewed deep-space missions are limited as much by ionizing radiation as by propulsion. The Radiation Assessment Detector (RAD) aboard the Mars Science Laboratory measured the radiation field inside a real interplanetary spacecraft during its 253-day cruise, and reported a round-trip GCR dose-equivalent of 0.66 ± 0.12 Sv for the shortest transit achievable with current propulsion (Zeitlin et al., 2013). Numbers of that magnitude make shielding design a first-order engineering problem, and they make the credibility of shielding models a first-order scientific one.

The reference tools for this problem — HZETRN/OLTARIS, GEANT4/PLANETOCOSMICS, PHITS — are large, three-dimensional, and effectively closed to independent inspection by a reader without institutional access. This paper does not attempt to compete with them. It reports a small, fully inspectable model built under one governing constraint: no parameter is fitted to any validation target. Every constant is transcribed from a cited source, the comparison conditions against flight data were fixed from the mission literature before the comparison was run, and disagreements are reported at full size rather than absorbed into tuning. The contribution is methodological — a source-traceable, test-gated implementation — and diagnostic: a quantitative account of where a primaries-only model disagrees with a real measurement and why.

2. Methods

2.1 Electronic stopping power and CSDA range

Electronic mass stopping power follows the Bethe equation in the form given by the Particle Data Group (Navas et al., 2024, Eq. 34.5), with the density-effect term in Sternheimer's three-branch parameterisation (Sternheimer, Berger & Seltzer, 1984). Physical constants are CODATA 2018 values (Tiesinga et al., 2021); material parameters ($\langle Z/A \rangle$, mean excitation energy, Sternheimer coefficients) are PDG/ICRU-49 values. Shell, Barkas (z^3) and Bloch (z^4) corrections are omitted — the model's dominant stopping-power approximation — and this cost is quantified in Section 3.1. Continuous-slowing-down-approximation (CSDA) range is obtained by numerical integration of the reciprocal stopping power. Heavy ions scale the proton engine through the Barkas effective charge (Barkas, 1963).

2.2 GCR spectrum

The incident field uses the DLR-modified ISO-15390 parametric fit of Matthiä et al. (2013) for Z = 1–28, driven by a single solar-modulation parameter W (0 = solar minimum, 130 = strong solar maximum). The field is treated as isotropic and integrated by composite Simpson quadrature in log-energy from 10 MeV/n to 100 GeV/n. Absorbed dose and ICRP-60 dose-equivalent in water (ICRP, 1991) are computed from the resulting spectrum using the quality-factor relation Q(L): $Q = 1$ for $L < 10$ keV/µm; $Q = 0.32L - 2.2$ for $10 \le L \le 100$; $Q = 300/\sqrt{L}$ for $L > 100$ keV/µm.

2.3 Shielding transport and fragmentation

Slab transport is performed in residual-energy space: a particle entering a slab of areal density t exits with $E_{out} = R^{-1}(R(E_{in}) - t)$, and the integrand carries the Jacobian $dE_{in}/dE_{out} = S(E_{in})/S(E_{out})$. An optional fragmentation mode adds charge-changing nuclear interactions using the Bradt–Peters geometric cross-section (Bradt & Peters, 1950), giving a mean free path, primary survival $\exp(-t/\lambda)$, and a single-collision, charge- and mass-conserving fragment yield. Neutrons and target fragments are not produced — the deliberate scope boundary of the model, and the direct cause of the result in Section 3.2.

3. Results

All figures below were produced from the run of 29 July 2026 (repository commit e22ef18): the full test suite (111 tests, 6 files) passes, and every validation figure derives from a single shared code entry point that also drives the interactive application, so the two cannot diverge.

3.1 Stopping-power validation against NIST PSTAR

Model electronic stopping power was compared point-by-point against NIST PSTAR proton tables for five low-Z materials, ten tabulated energies each from 1 to 1000 MeV.

Material	Max deviation, ≥10 MeV	Max deviation, 1–1000 MeV
Aluminium	1.55%	4.03%
Water	0.67%	3.48%
Polyethylene	0.43%	3.45%
Methane	0.34%	2.66%
Liquid hydrogen	0.03%	0.14%

The residual is largest at 1 MeV and for the highest-Z material — the expected signature of the omitted shell correction. High-Z materials (lead, titanium) were tested during development and rejected: without shell corrections the engine deviates from PSTAR by tens of percent for them, so they are not offered in the model.

3.2 MSL/RAD cruise validation

Comparison conditions — solar modulation W = 30 (cruise Φ ≈ 550–800 MV) and 16 g/cm² aluminium-equivalent shielding, the average column density reported for RAD — were fixed from the mission literature (Guo et al., 2015) before the comparison was run.

Quantity	Model	Measured (MSL/RAD)	Ratio
Absorbed dose [mGy/day]	0.308	0.458 ± 0.032	0.67×
Dose-equivalent [mSv/day]	1.473	1.75 ± 0.30	0.84×
Mean quality factor ⟨Q⟩	4.78	3.82 ± 0.25	1.25×

Absorbed dose is under-predicted by 0.150 mGy/day (32.7% of the measured value) because RAD recorded the full field produced inside the spacecraft, including secondaries, while the model transports primaries only. The neutron component of the same cruise was measured directly (Köhler et al., 2015): 6 ± 2 µGy/day absorbed — only about 4% of the model's 0.150 mGy/day deficit. The bulk of the missing dose is therefore carried by secondary charged particles and target fragments, not by neutrons. ⟨Q⟩ is over-predicted (1.25×) because, without fragmentation, heavy ions are not broken into lower-LET fragments; since $H = \langle Q \rangle D$, the under-predicted D and over-predicted ⟨Q⟩ partially cancel, giving a dose-equivalent ratio (0.84×) closer to unity than either factor alone — a property of the physics, not a design goal.

Enabling the optional fragmentation mode at the same point moves the model as predicted and no further: ⟨Q⟩ falls from 4.78 to 4.41 (measured 3.82), while absorbed dose falls from 0.308 to 0.258 mGy/day — moving away from the measurement, because fragmentation removes primaries without producing the neutral and target-fragment secondaries that would replace their dose. A model tuned to match RAD would not behave this way.

3.3 Material ranking

At equal areal density and solar minimum, dose-equivalent increases strictly along H_2 < CH_4 < polyethylene < water < aluminium at every thickness tested (5, 10, 20, 30, 40 g/cm^2) — exactly the ordering by hydrogen content. Liquid hydrogen beats aluminium by up to 44.2% at 40 g/cm^2; polyethylene, the best solid, beats aluminium by 11.6% at 20 g/cm^2 in the primaries-only model. Enabling fragmentation widens the polyethylene-versus-aluminium advantage at 20 g/cm^2 to 33.3%, because iron's computed charge-changing mean free path is 6.8 g/cm^2 in polyethylene against 21.8 g/cm^2 in aluminium.

4. Propagated Uncertainty and Self-Validation

The 1σ-style relative uncertainty of the computed dose-equivalent is propagated in quadrature from three sources: GCR flux (14%, the DLR-model deviation from AMS-02 hydrogen data below 1.5 GeV/n — Norbury et al., 2018), stopping-power data (4%, the ICRU-49 compound bound), and this run's own computed PSTAR deviation (1.55%). The total, 14.6%, gives $H = 1.47 \pm 0.22$ mSv/day at the RAD comparison point. This band is explicitly an input uncertainty: it excludes the model-form error responsible for the 0.67× absorbed-dose ratio, and it excludes the ICRP-60 Q(L) relation, a regulatory convention rather than a measured quantity. It therefore does not, and is not offered to, cover the absorbed-dose gap.

Because there is no reference implementation to check against, correctness is enforced by internal invariants: 111 automated tests in continuous integration, including a data-driven suite that regenerates the PSTAR comparison for every material and energy point; convergence checks (doubling numerical node density changes results by under 0.5%); reduction identities (zero shield thickness reproduces the free-space result; a single-layer multi-layer stack reproduces the validated single-slab result); and live physics invariants checked in the running application, including a directional assertion that absorbed dose is under-predicted and ⟨Q⟩ is over-predicted at the RAD point — a test that would fail if the model were ever adjusted to close the gap.

5. Limitations

Every omission is labelled with its expected direction of effect and its magnitude where traceable; rows without a computed number say so rather than estimating one.

Omission / approximation	Direction	Magnitude	Source
Secondary charged particles & target fragments not transported	absorbed dose under-predicted	0.308 vs 0.458 mGy/day = 0.67×	this work vs Guo et al. 2015
Secondary neutrons not produced	dose under-predicted	small: ≈4% of the deficit	Köhler et al. 2015
No fragmentation softening of LET spectrum	⟨Q⟩ over-predicted	4.78 vs 3.82 = 1.25×	this work vs Zeitlin et al. 2013
Shell, Barkas, Bloch corrections omitted	error grows at low energy	≤1.55% ≥10 MeV; ≤4.03% overall	NIST PSTAR
High-Z shields excluded	not offered	rejected in development; not recomputed	this work vs NIST PSTAR
1-D slab, single thickness	RAD saw anisotropic shielding	H over 10–20 g/cm^2: 1.67–1.37 mSv/day	Guo et al. 2015
Multi-layer stacks beyond single-layer limit	unvalidated	reduces exactly to validated single slab at the limit	this work

6. Conclusion

A one-dimensional, primaries-only model built from cited constants and fitted to nothing reproduces NIST PSTAR proton stopping power to 1.55% above 10 MeV and lands at 0.67× the measured absorbed dose, 0.84× the measured dose-equivalent, and 1.25× the measured mean quality factor of the MSL/RAD Mars-cruise measurement. The value of the result is in the structure of its error: absorbed dose is under-predicted and $\langle Q \rangle$ is over-predicted in the directions the omitted physics demands, an independent neutron measurement localises the missing dose to secondary charged particles rather than neutrons, and enabling fragmentation moves the model exactly as a non-tuned model should. Closing the absorbed-dose gap requires full secondary-particle transport, deliberately outside this scope. This paper's claim is narrow: a fully labelled, source-traceable, test-gated implementation, published with its disagreements at full size.

Data Availability Statement

The complete source code, transcribed reference data tables (NIST PSTAR, MSL/RAD), the automated test suite, and the continuous-integration configuration are publicly available under the MIT Licence at https://github.com/izbanovj3-prog/DOSEFIELD (results in this paper correspond to commit e22ef18). The interactive application is live at https://izbanovj3-prog.github.io/DOSEFIELD/. No human or animal subjects were involved in this research.

Acknowledgements

The author declares no conflicts of interest and received no funding for this work.

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