Exoplanet Mission Concept Study

Space Environment

Insoo Jun

Jet Propulsion Laboratory, California Institute of Technology

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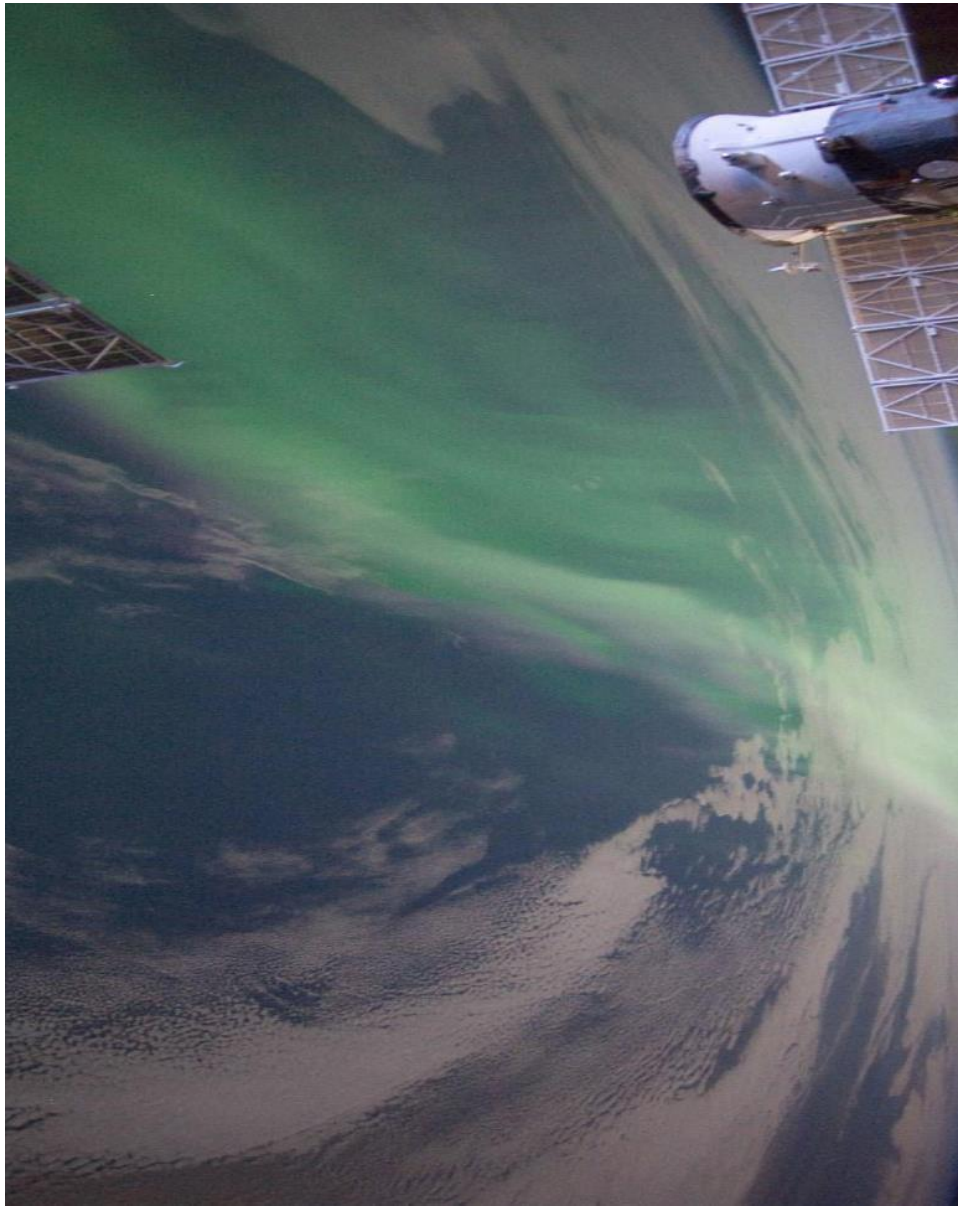
What constitutes the Space Environment?

Space environments and their effects that impact design, construction, and operation of NASA human and robotic space systems

Specific environments include:

- Ionizing radiation, neutral energetic particles
- Space plasma
- X-ray, UV/EUV, visible, IR photons
- Meteoroids and orbital debris
- Dust
- Vacuum, neutral atmosphere, atomic oxygen
- Electric and magnetic fields
- Microgravity
- Space climate and space weather



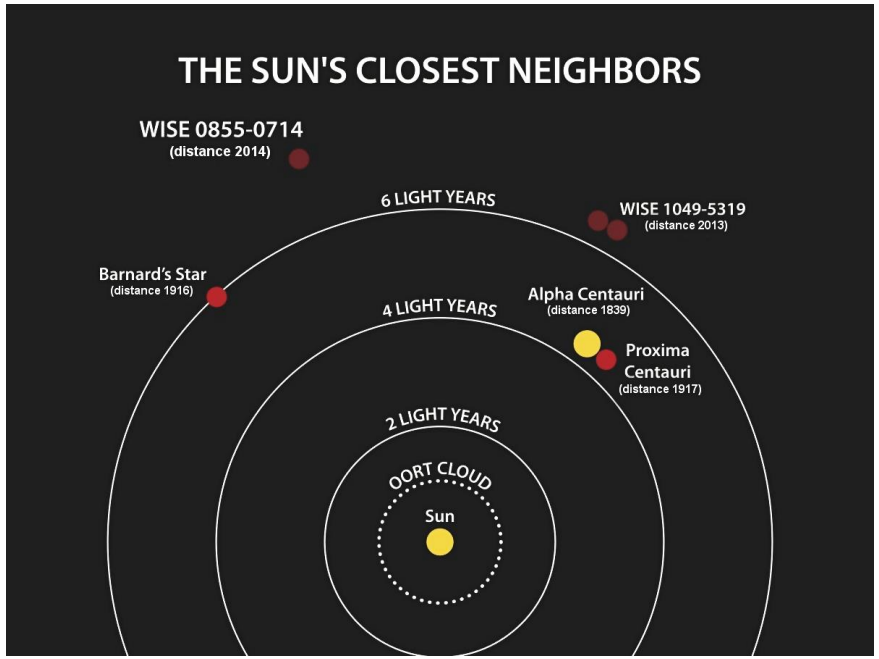
Why do we care?

Source Particles	Environment Effect
Trapped electrons; Trapped protons ; Solar protons	Total Ionizing Dose (TID) and Displacement Damage Dose (DDD)
Auroral electrons; Plasma electrons/ions	Surface Charging
High energy (> 1 MeV) trapped electrons	Internal Charging (IESD)
Trapped protons; Solar protons; Galactic cosmic ray	Single Event Effects (SEE)
MMOD; Dust	Structural Damage; ESD
Atomic oxygen; UV	Material Degradation

Preambles

- Assumptions:
  - Target: Alpha Centauri
  - Mission length: 40 years or less
  - Speed: 17 AU/day ~ 0.1c

- Mission Segment:
  - Within solar system
  - Interstellar transit
  - In the host solar system



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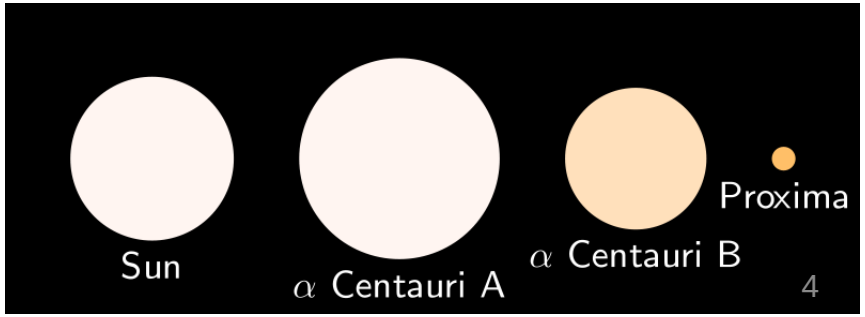

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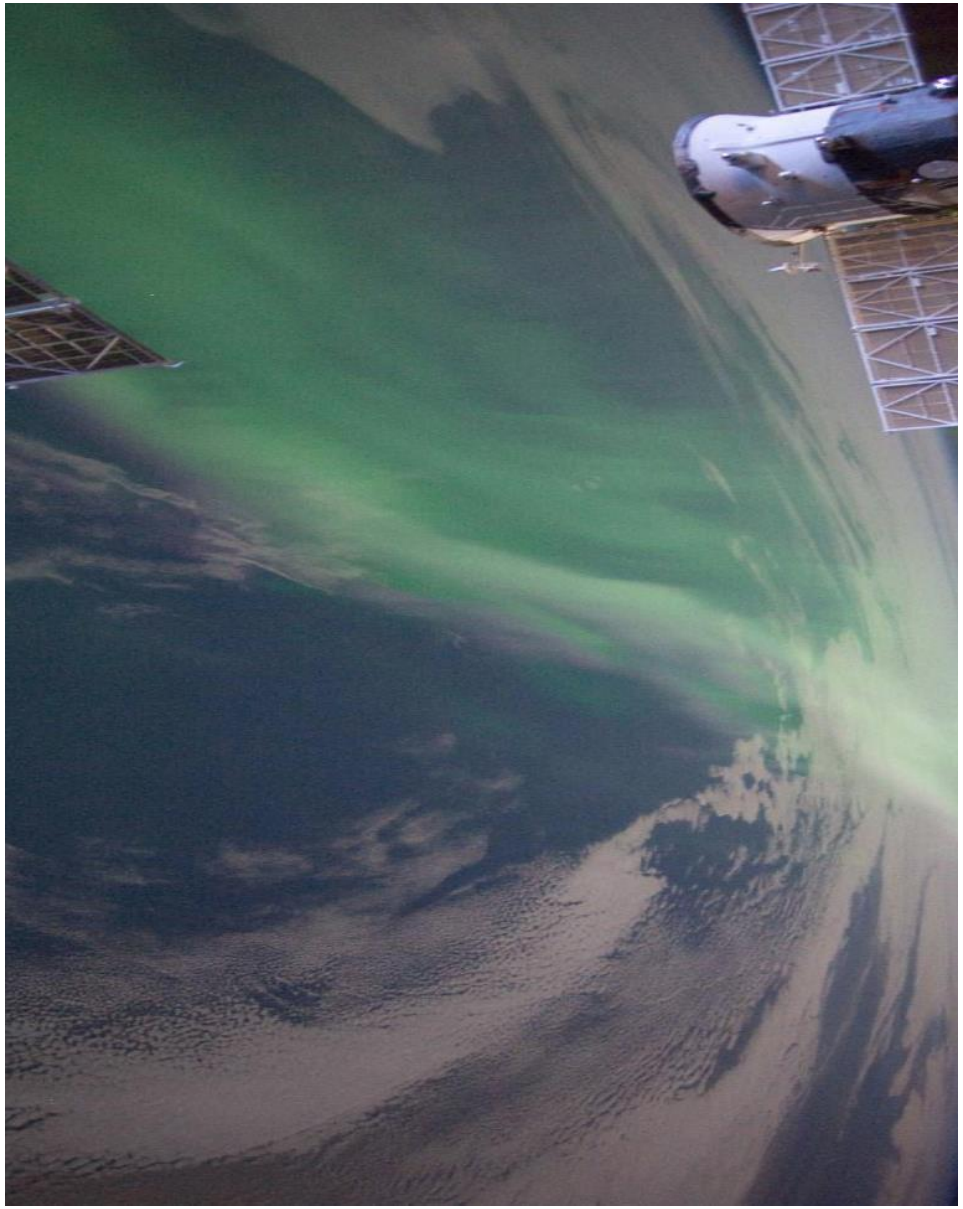


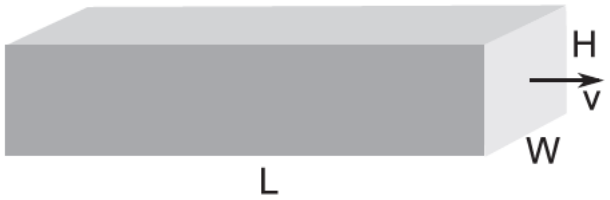


Figure 1. Schematic of the needle-like spacecraft of height H, width W, and length L, moving at relativistic speed v. The spacecraft surface area is $A = WH$.

Interstellar Gas and Dust

Hoang, ApJ, March, 2017 (For a Microchip-like spacecraft)

Gas

- The gas environment has not considered for any other mission in the past for impact to spacecraft.
  - Low relative velocity between spacecraft and gas molecules in the interplanetary space

- Gas column density (or fluence) ~ 2×10^{18} cm^{-2} along the path to α-Centauri.

- Main effect:
  - Formation of damage track:
    - Surface damage: ~0.1 mm for quartz, or much smaller for graphite

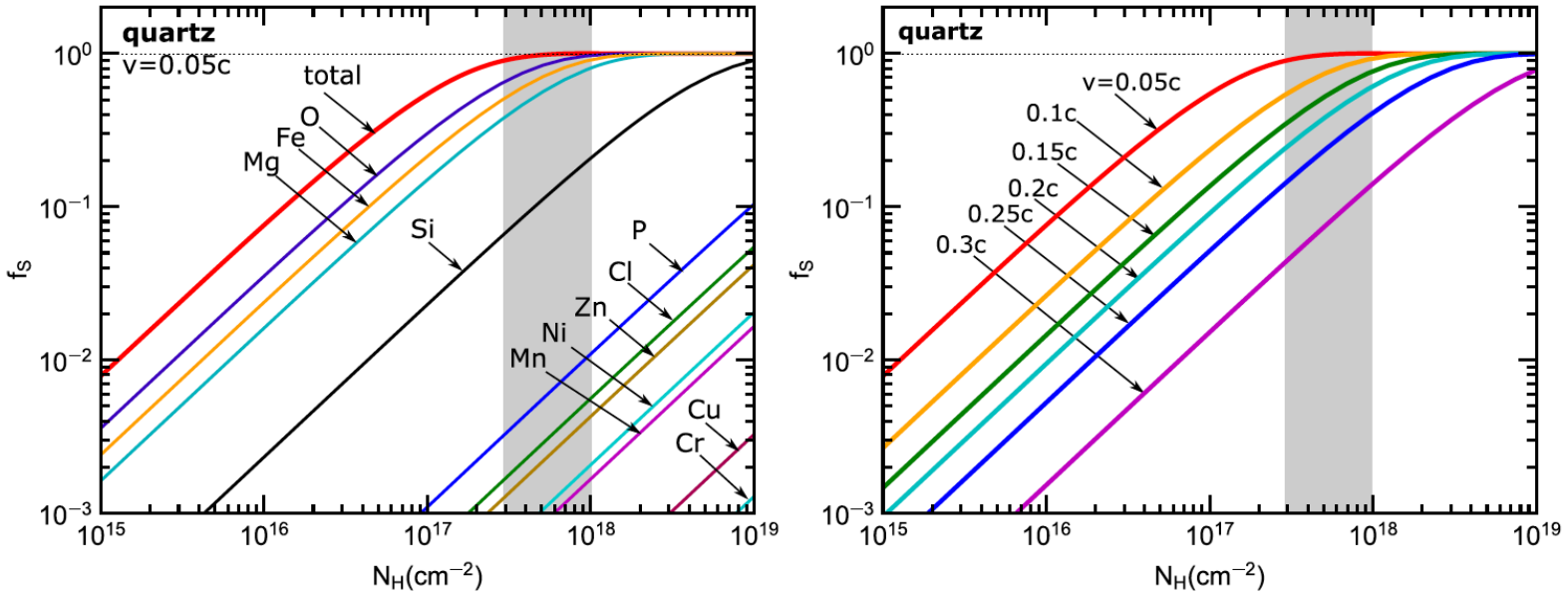


Figure 6. Left panel: fraction of spacecraft surface damaged by gas bombardment as a function of the column density of gas swept up by a spacecraft moving at $v = 0.05c$. The contribution by each element is shown, with the dominant damage arising from O and Fe. The shaded area shows the measured gas column density toward α Centauri of $\log N_{\mathrm{H,obs}} = 17.80 \pm 0.30$ (Linsky & Wood 1996). Right panel: total value f_S for different speeds from $v = 0.05c$–$0.3c$.

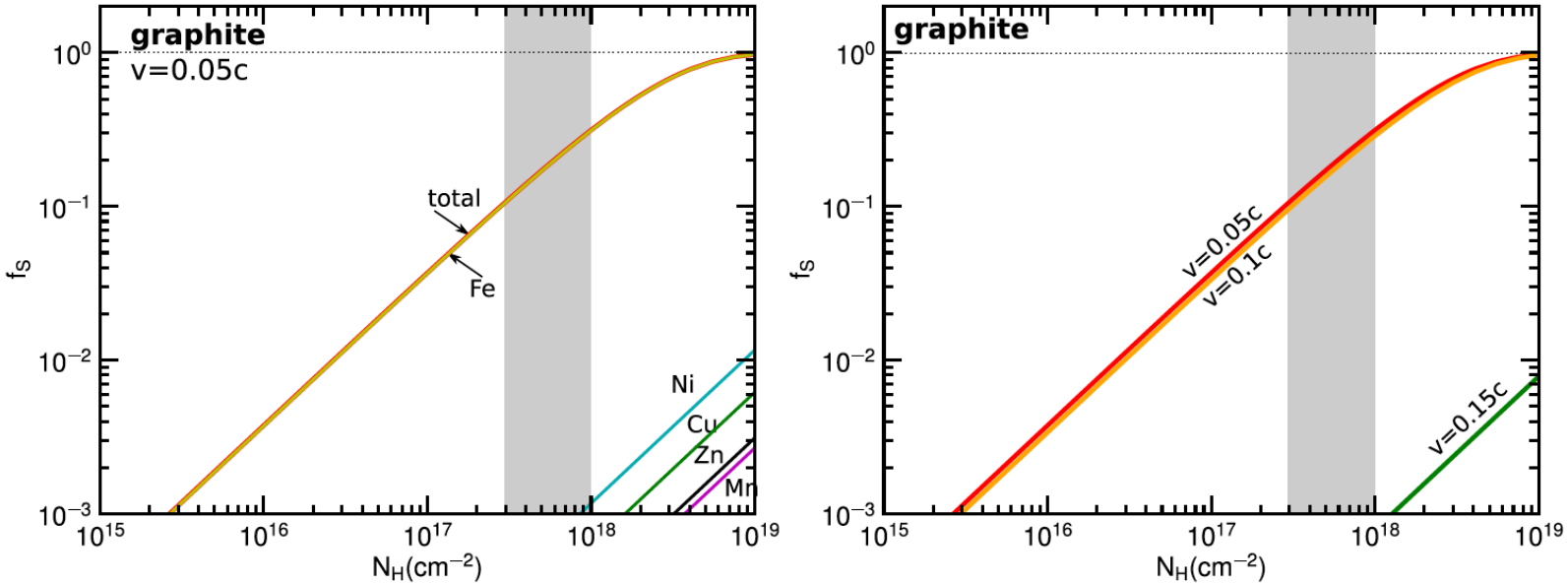


Figure 7. Same as Figure 6, but for graphite material. Damage is essentially determined by Fe atoms.

Dust

- Dust column density of 3 x 10^{17} cm^{-2}

- Weingartner & Draine model (2001)
  - Most dust grains < 0.25 μm
  - Hoang et al. adopted the upper limit of 1 μm and the lower limit of 0.001 μm

- These values are much smaller in size and mass than typical MMOD environment (e.g., Voyager), but the mission fluence and the particle speed are much higher – see later

- Main effect:
  - Erosion of the spacecraft surface
  - Production of micro-craters
  - 0.5 mm surface erosion at 0.2c

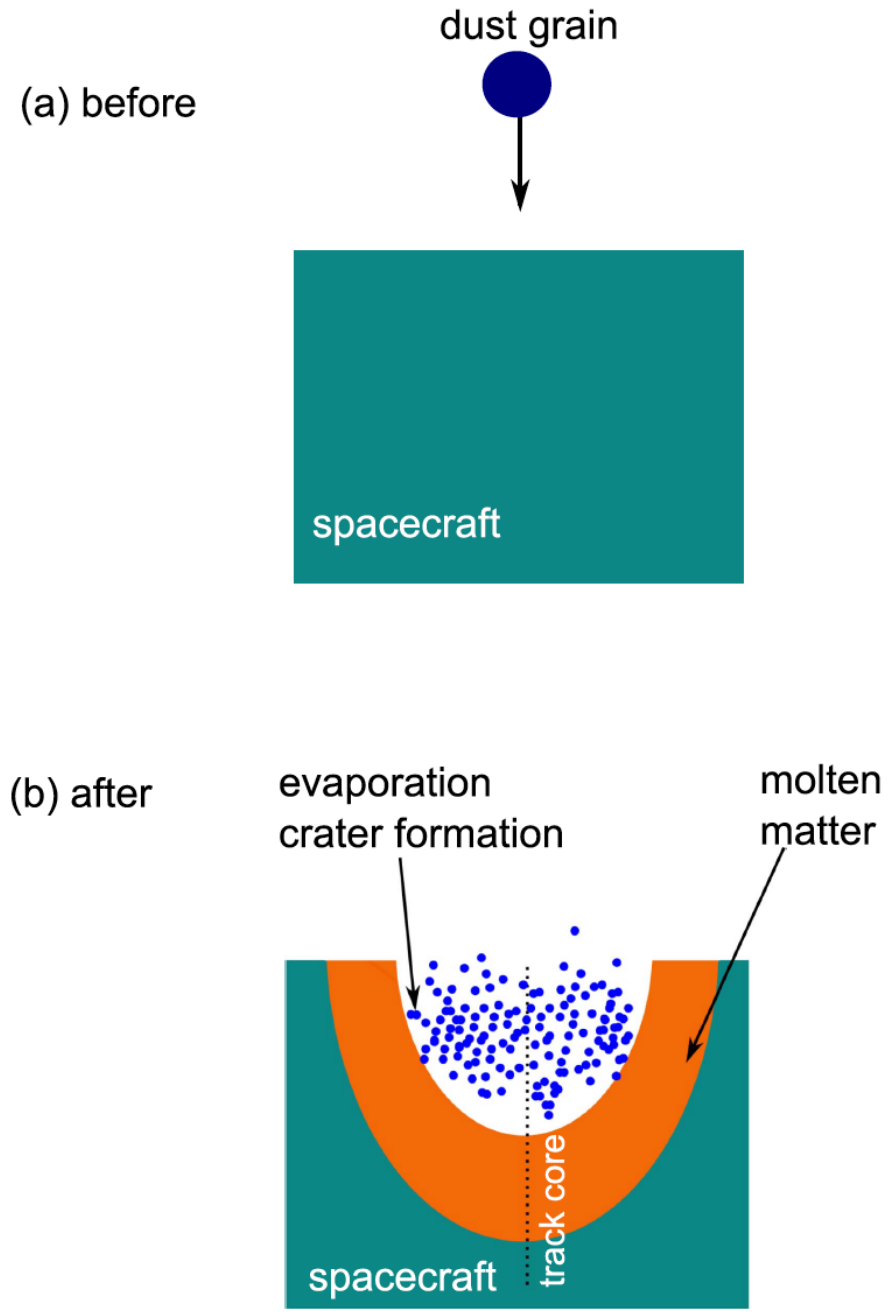
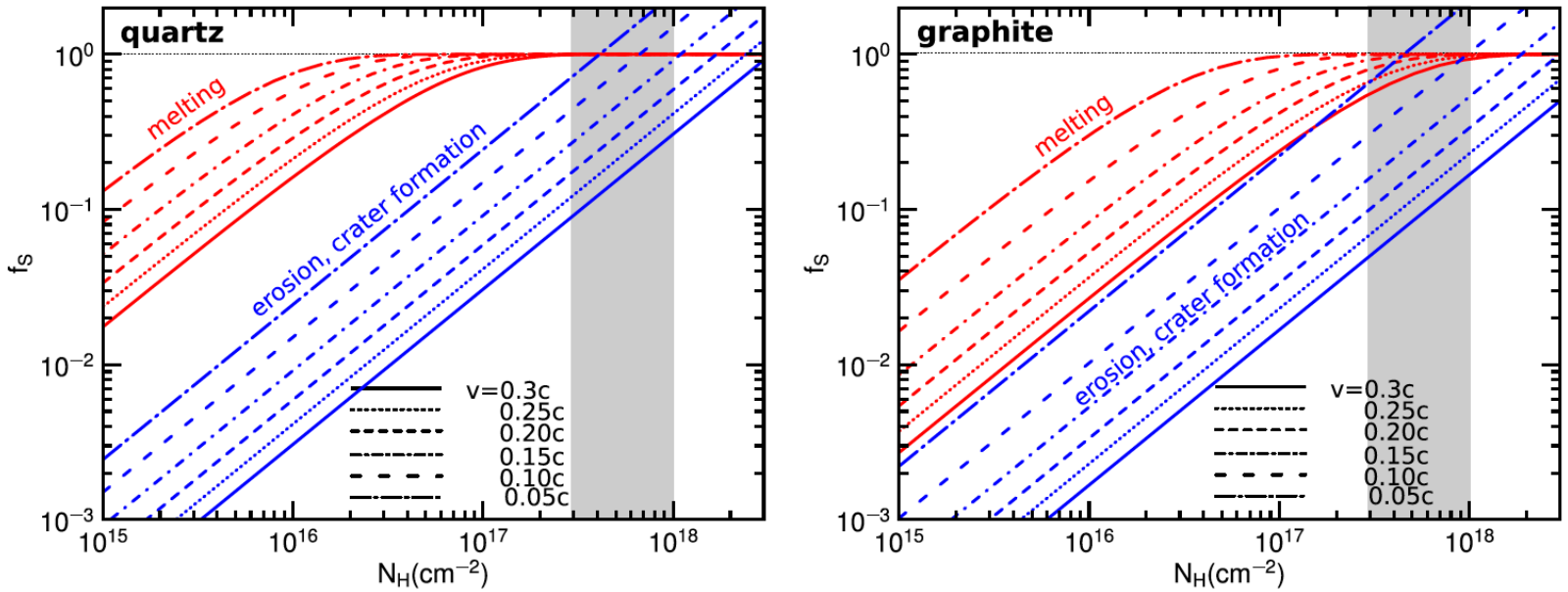


Figure 10. Schematic illustration of the collision impact from a dust grain on the spacecraft surface considered in the spacecraft's rest frame.



Fraction of surface erosion

Figure 11. Fraction of the spacecraft surface eroded (solid lines) and melted (dashed lines) due to dust bombardment, computed for quartz (left panel) and graphite (right panel) materials. The shaded areas show the measured gas column density toward α Centauri of $\log N_{\mathrm{H,obs}} = 17.80 \pm 0.30$ from Linsky & Wood (1996).

Fraction of volume erosion

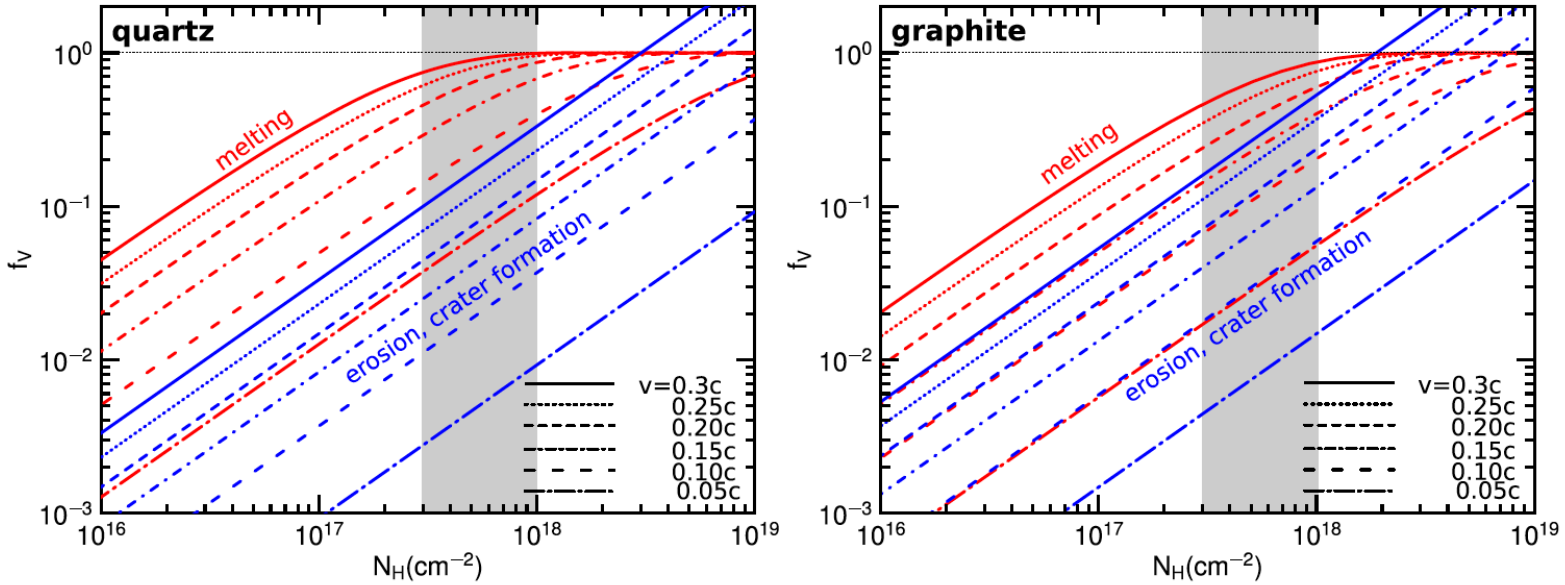


Figure 12. Fraction of the spacecraft volume eroded (red lines) and melted (blue lines) due to bombardment of interstellar dust grains computed for quartz (left panel) and graphite (right panel) materials. A thickness of the surface layer $L = 1$ cm is assumed.

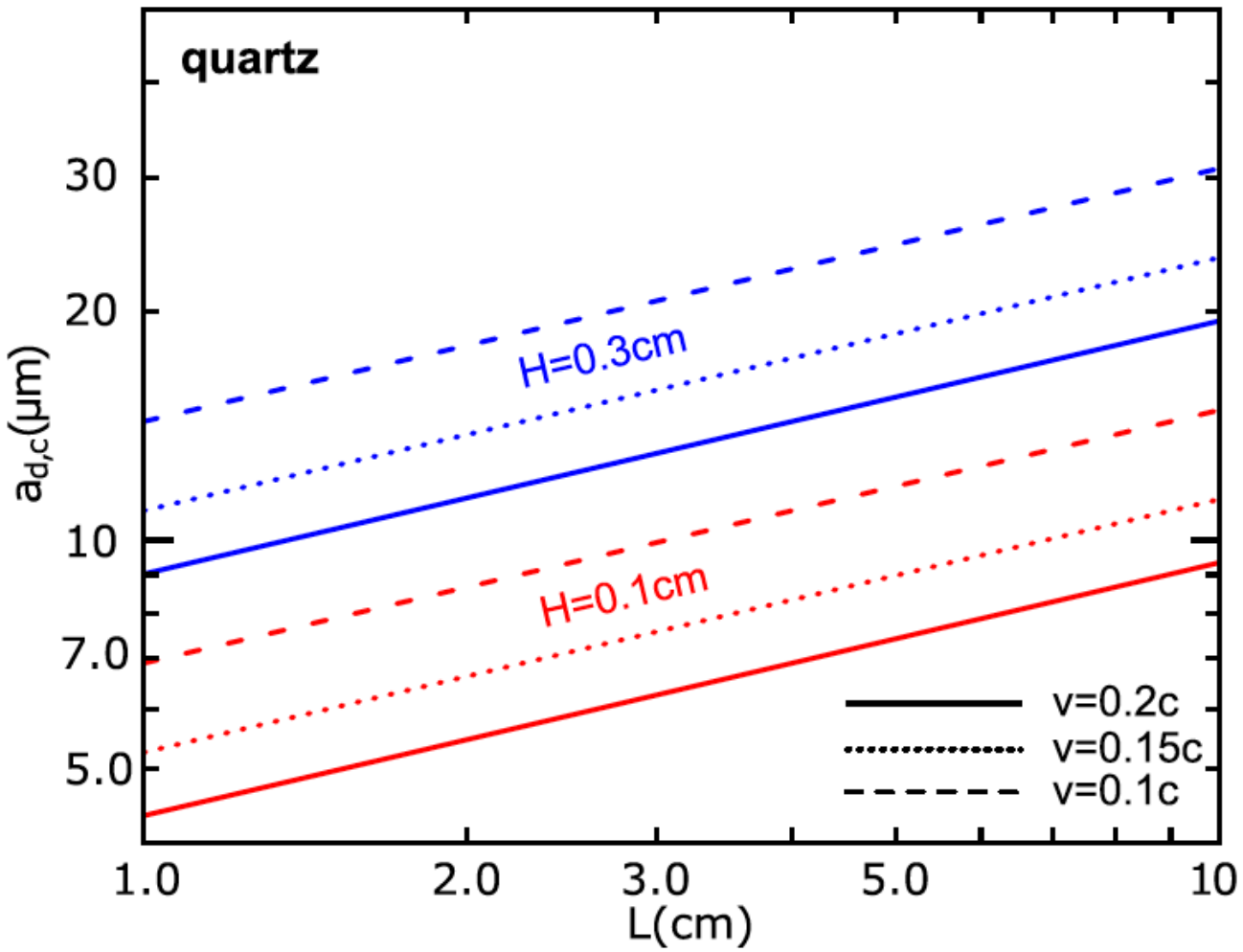


Figure 13. Critical size of the projectile grain that would result in the complete evaporation of the spacecraft vs. the spacecraft length L for $H = 0.1$ cm and 0.3 cm.

Voyager Solid Particle Environment

Meteoroids

Particle Mass (grams)	Integral Fluences (Particles m^{-2} of mass greater than M)
10^{-10}	2.0×10^{3}
10^{-9}	7.9×10^{2}
10^{-6}	8.8
10^{-5}	7.0×10^{-1}
10^{-4}	5.4×10^{-2}
10^{-3}	2.6×10^{-3}
10^{-2}	1.9×10^{-4}
10^{-1}	1.0×10^{-5}
10^{0}	8.0×10^{-7}
Mean relative speed (km/s)	14
Particle mass density (g/cm^3)	0.5

~3.6 µm

Saturn's E-ring Particle

Particle Mass, M (g)	Integral Fluence Particles $\geq$ M (m^{-2})
1.0×10^{-9}	1.9×10^{4}
1.0×10^{-8}	1.9×10^{4}
1.4×10^{-8}	1.9×10^{4}
3.4×10^{-8}	1.1×10^{4}
1.0×10^{-7}	5.2×10^{3}
2.7×10^{-7}	2.6×10^{3}
3.8×10^{-7}	2.1×10^{3}
3.9×10^{-7}	2.7×10^{-3}
1.0×10^{-7}	2.7×10^{-3}
1.0	2.7×10^{-3}
2.7×10^{2}	2.7×10^{-3}
1.0×10^{3}	1.1×10^{-3}
Particle Density	$1.0\ g/cm^3$
Mean Relative Velocity	19 km/s

~6.2 µm

Summary

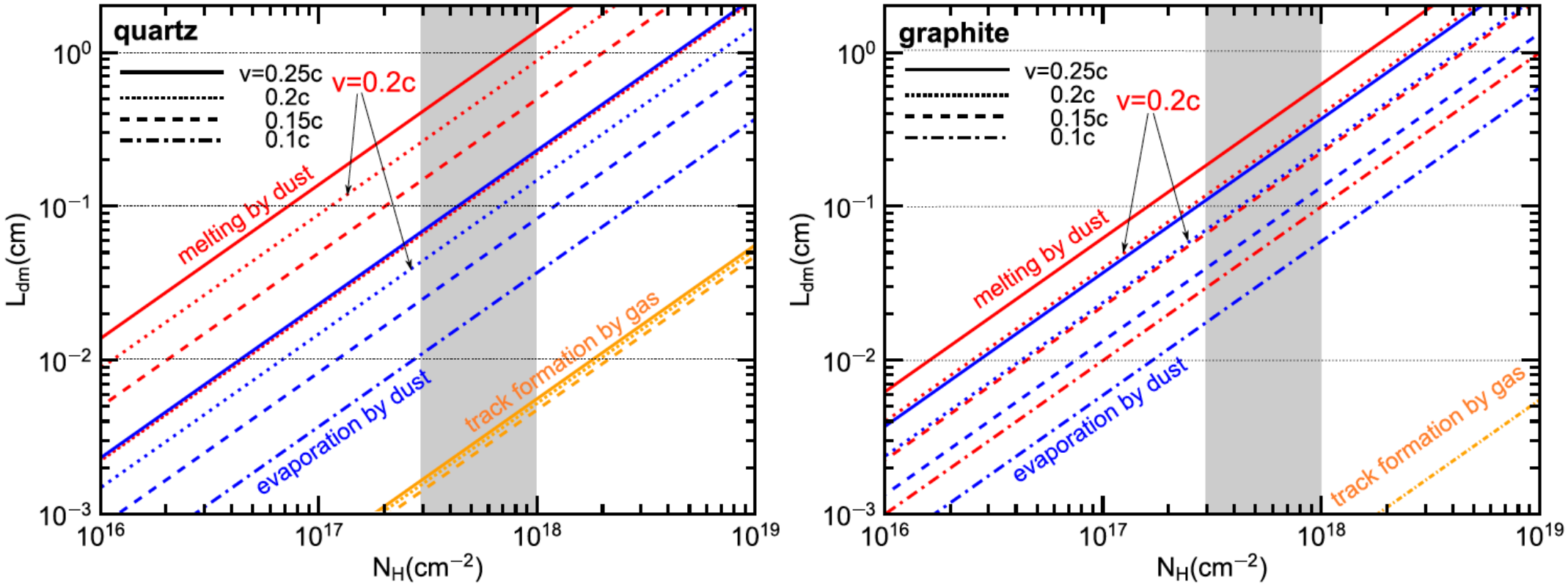
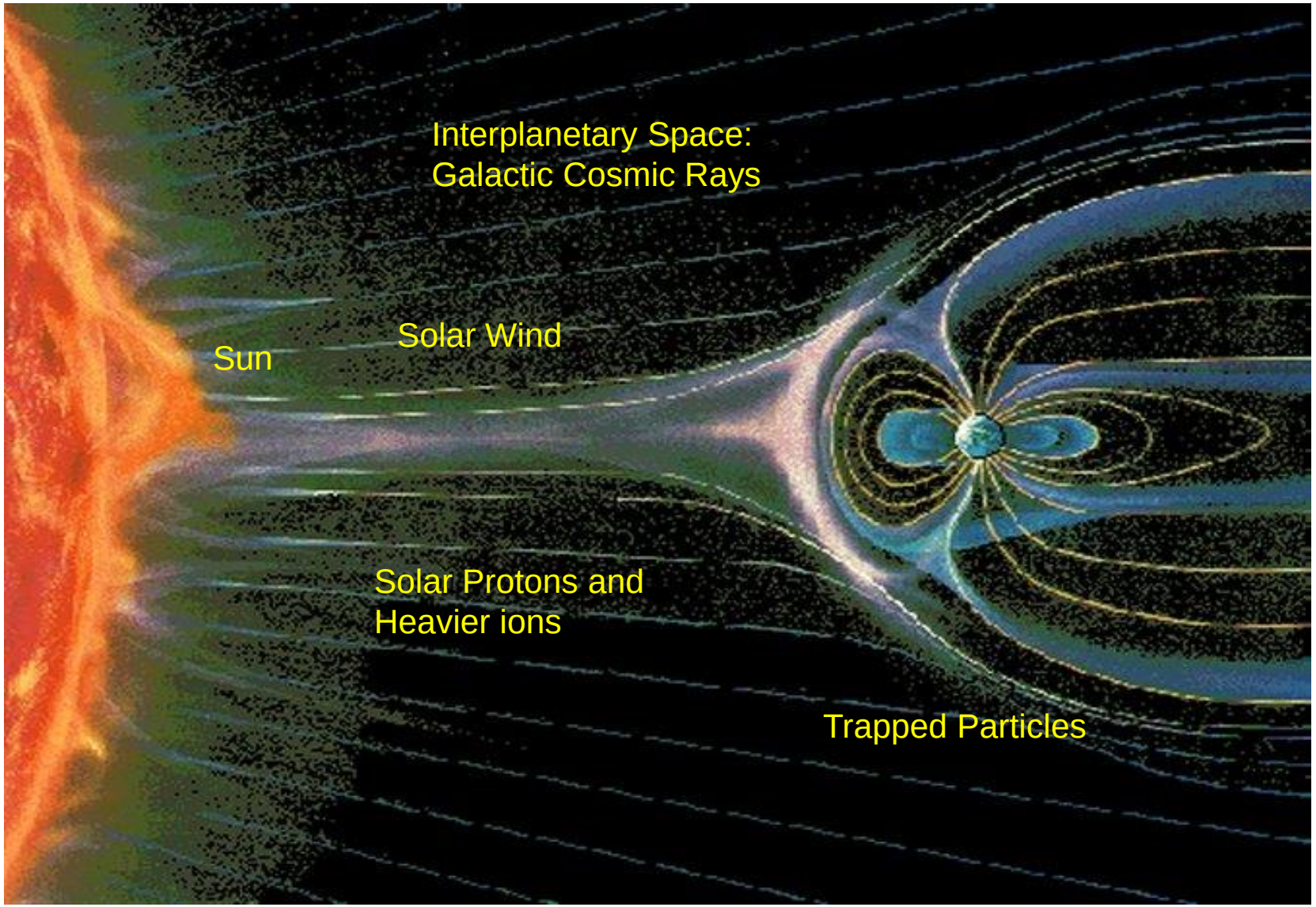


Figure 16. Thickness of surface damaged by dust bombardment and gas bombardment for quartz (left) and graphite (right). Melting for graphite is less efficient than for quartz because of its high melting temperature.

Interplanetary dust has much greater effect than gas

The Space Radiation

The Space Radiation Environment



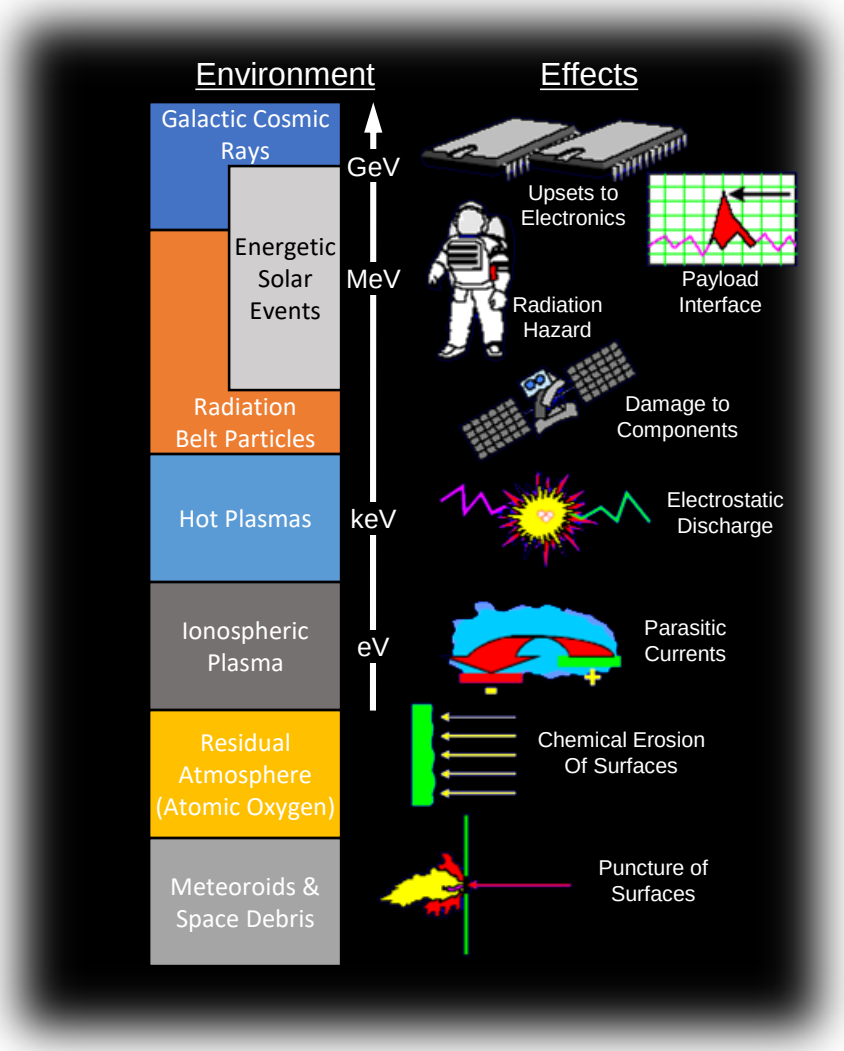
Radiation environment within our solar system?

Radiation environment during the interstellar transit?

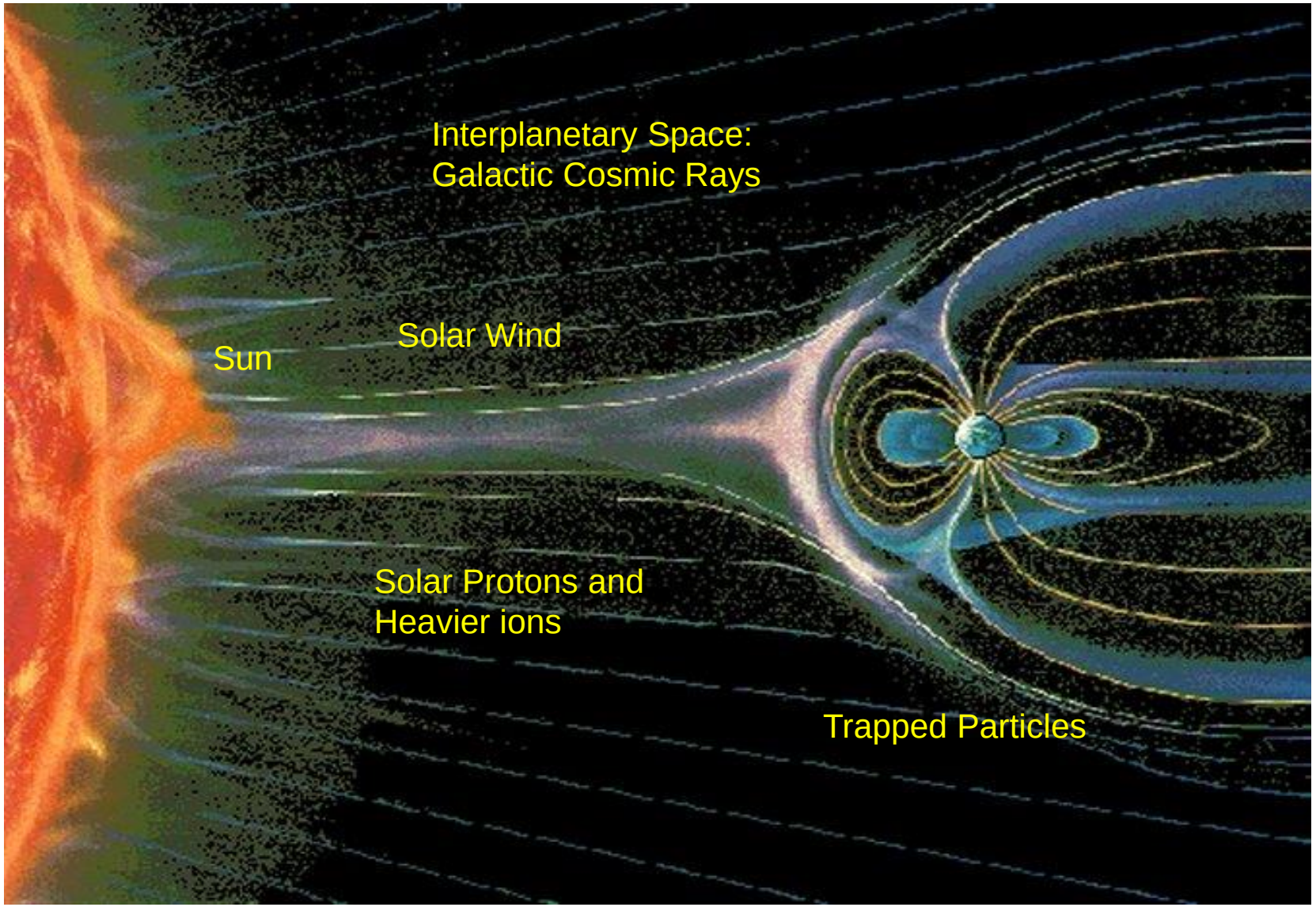
Radiation environment in the host solar system?

Overview of Radiation Effects

- Total Ionizing Dose
  - Cumulative long term ionizing damage mainly due to protons and electrons
- Displacement Damage Dose
  - Cumulative long term non-ionizing damage mainly due to protons, electrons, and neutrons
- Single Event Effects
  - Event caused by a single charged particle (heavy ions and/or protons) traversing the active volume of microelectronic devices
- Charging
  - Electrons deposit charges in material which induces electrostatic discharge



The Space Radiation Environment



Radiation environment within our solar system?
100 hours with 0.1c → negligible

Radiation environment during the interstellar transit? → Interstellar GCR dominates → SEE

Radiation environment in the host solar system during capture?
→ Big unknown. Will assume it will be similar to our solar system and it will take Voyager-like environment → TID/DDD

Interstellar GCR

Cummings, ApJ, Nov, 2016.

V1 ~ 15 times 1 AU

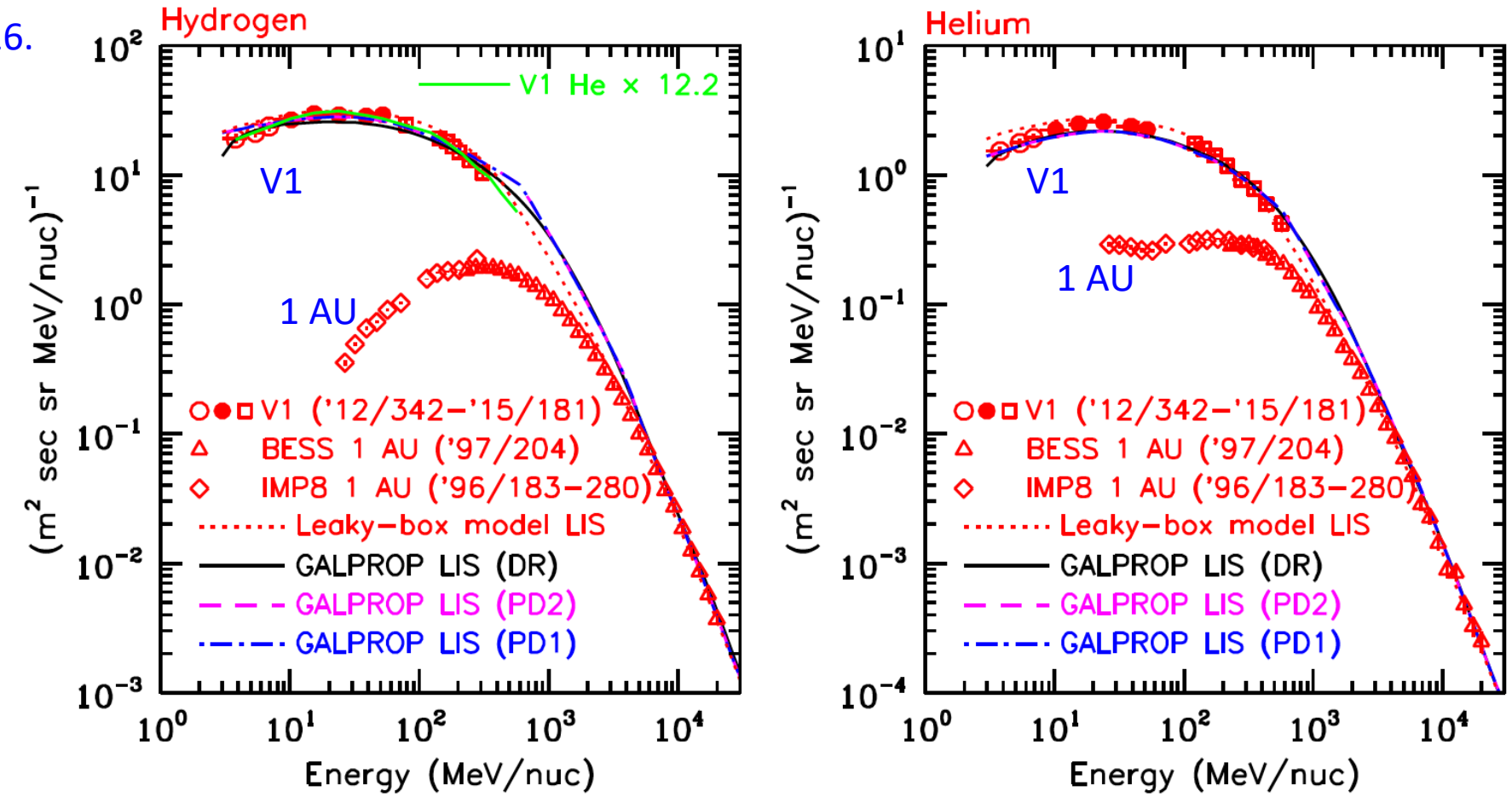


Figure 3. Differential energy spectra of H (left) and He (right) from V1 for the period 2012/342–2015/181, and solar-modulated spectra at 1 AU from a BESS balloon flight in 1997 (Shikaze et al. 2007) and from IMP8 in the latter part of 1996 (McDonald 1998). The three different symbols for the V1 data correspond to different telescope types described in the Appendix. All data are plotted with their statistical and systematic uncertainties added in quadrature. Also shown are estimated spectra in the LISM from a leaky-box model and three GALPROP models as described in the text.

Interstellar TID

From Oleg G. Semyonov
(https://arxiv.org/ftp/physics/papers/0610/0610030.pdf)

- For non-relativistic flight, the “unshielded” absorption dose is

  ~ 35 rad(H2O)/year

Voyager Specification

* Table 20. Charged Particle and Nuclear Radiation

NOTE: All Values Unshielded - Shielding will alter the local electronics environments significantly.

	Bus Mounted Electronics and Science Instruments		Non-Bus Mounted Science Instruments**	
Particles	Peak Flux (cm^{-2}-s-1) Unshielded	Fluence (cm^{-2}) Unshielded	Peak Flux (cm^{-2}-s-1) Unshielded	Fluence (cm^{-2}) Unshielded
Protons*	9×10^7 (E > 1 MeV)	5×10^{12} (20 MeV Eq)	9×10^7 (E > 1 MeV)	5×10^{12} (20 MeV Eq)
Electrons (Peak Values Selected)	2×10^8 [$11R_J$] (E > 0.4 MeV) 4×10^0Rad(Si)/s [$11R_J$]	4×10^{12} [$5R_J$] (3 MeV Eq) 2×10^5Rad(Si) [$9.5R_J$]	2×10^8 [$11R_J$] (E > 0.4 MeV) 4×10^0Rad(Si)/s [$11R_J$]	4×10^{12} [$5R_J$] (3 MeV Eq) 2×10^5Rad(Si) [$9.5R_J$]
RTG AND RHU Neutrons (1.0 ≤ E ≤ 3.0 MeV)	80	1×10^{10} 200 krad (Si)	10	1×10^9
RTG and RHU Gamma (0.3 ≤ E ≤ 3.0 MeV)	3200	1×10^3*** Rad (Si)	350***	100*** Rad (Si)

NOTE:
*Proton flux and fluence assume a 1 MeV cutoff. Proton levels for true external surface problems are higher than those above. The level is 3.1×10^8 Rad (Si).
**Value for Scan Platform Instrument Location; for all other locations contact Environmental Requirements Engineers.
***Unshielded ionization dose level is really controlled by electron and proton environments above.

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Summary

- Among radiation, dust, and gas, the interstellar dust environment appears to be most influential to spacecraft design
  - Evaporation and erosion

- A few mitigation schemes have been suggested (Hoang et al, 2017)
  - Electric deflection
  - Radiation pressure deflection

- It seems that these environments are not considered to be absolute show-stoppers for an interstellar mission although the current existing models need to be continuously updated and improved as new data become available:

- (From Semyonov)
  - "Despite increased flow and energy of particles of beamed cosmic rays at relativistic velocities of starships, these cosmic rays will be largely absorbed or deflected away from a ship by the combined windward *shielding system already in place to deal with relativistic interstellar gas/dust.*"
  - "Cosmic dust will also contribute to the radiation hazard, because the dust particles are actually lumps of high-energy nucleons at relativistic velocities. A serious problem will be the sputtering of a ship's bow or a radiation shield by the relativistic dust particles. Nevertheless, the shielding of relativistic starships from hard ionizing radiation produced by interstellar gas and cosmic rays *does not seem to be far beyond existing technology.*

Backup

Reliability Concerns Unique to Interstellar Missions

Will Need:

- Advanced attitude control system
- Ultra-high levels of autonomy (multi-year command turn around) for control, health, and in-system scientific exploration and data return
- Ability for self-repair, system redundancy, and fault tolerance
- Careful consideration of flight spare vs. functional redundancy.
- Robots capable of in-flight repairs—the ultimate integrated health management system!
- Development of common replacement parts strategy
- Means for actively regenerating key systems in-flight
- Advanced techniques for reconfiguring/reprogramming electronic systems in-flight
- New institutions for space research spanning ~50 years or more…

THE STARS ARE CALLING AND WE MUST GO