Material Interactions with Solar Wind Ion Environments

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Abstract

Spacecraft designs for a number of current and future missions include gossamer polymer structures with thin metallic reflection coatings to shield instruments from the Sun, solar sail propulsion systems for use in a variety of locations in the inner solar system from 0.5 to 1 AU. In addition, there is interest in designing spacecraft for solar physics missions requiring operations as close to the Sun as 0.16 to 0.2 AU. Integrity of the metallic coatings is critical in many of these applications since degradation due to removal of thin metallic coatings by ion sputtering and light ion blistering of thicker metallic coatings will result in modification of material optical and thermal properties or exposure of polymers to solar UV photons which can potentially compromise mission requirements. This study evaluates solar wind environments over a range of radial distances from the Sun to determine if ion fluences to spacecraft surfaces can reach levels sufficient to produce detrimental effects due to ion sputtering and blister formation.

Examples of Radiation Blisters, Exfoliation

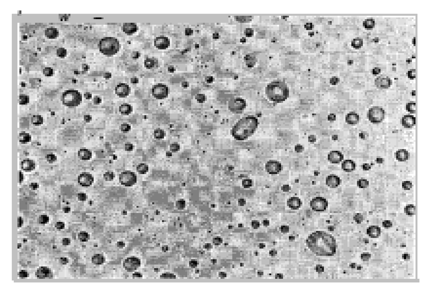


Fig. 1 Photomicrograph of blisters in an 800Å gold film over a pure aluminum substrate, after bombardment by 3.2×10^{17} ions/cm² (600×) (strong bond).

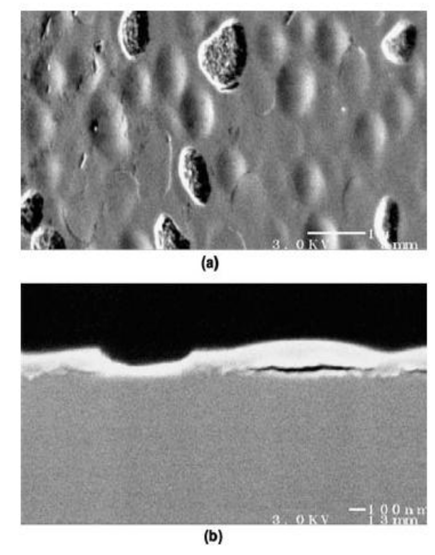
Anderson and Dahms, 1967

--0.5 to 2 keV H⁺ at 3.2×10^{17} ions/cm²

--Blisters 1-30 μm in diameter on

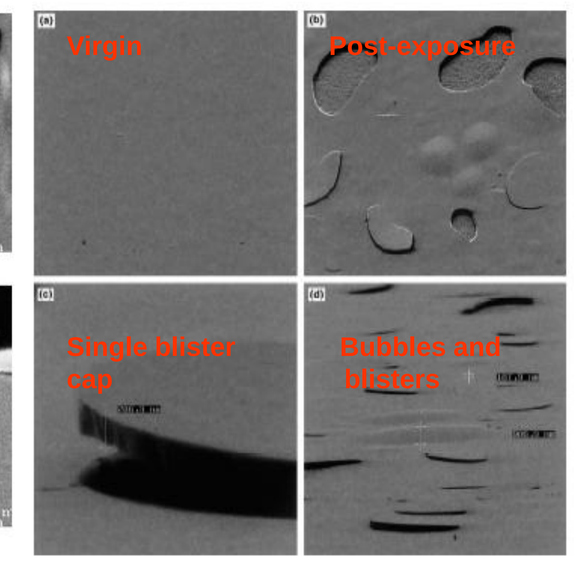
60 nm to 100 nm Au, Cu, Al coatings

--Blister sufficient to change Au coating absorbance by 17%



Giguere et al., 2005

4×10^{16} H+/cm² at 10 keV on GaAs (400°C; 30 sec) showing (a) surface and (b) cross section

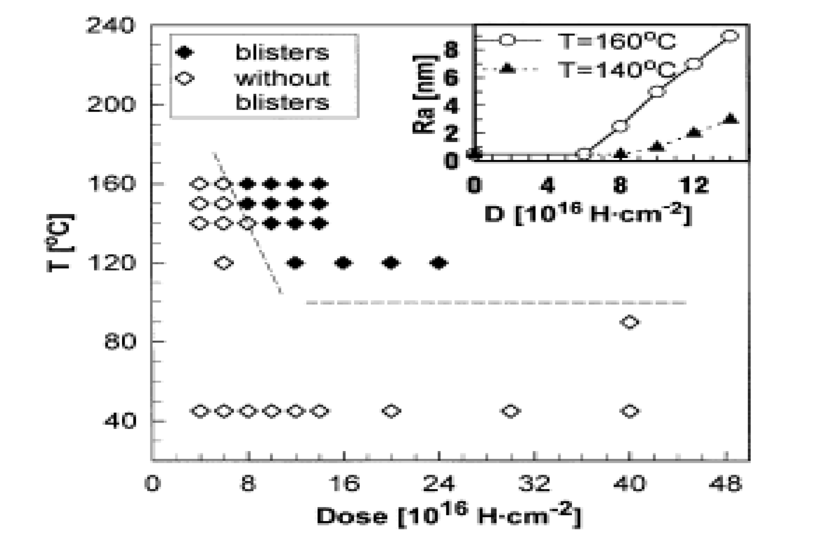


(from Shutthanandan et al., 2001)

40 keV H+ ions on $Y\text{-}ZrO_2$

1×10^{17} H⁺/cm² · annealed at 770 K

Blister Formation Threshold



Blistering in metals is frequently observed when the light ion fluence exceeds ~10^{16} to 10^{17} ions/cm2

Ion Damage and Surface Modification

• Numerous studies were conducted in the 1960's and 1970's to assess the potential impact of solar wind ions on spacecraft surfaces demonstrating that ions of solar wind energies can alter surface properties of materials although the effects are often small at 1 AU

• *McKeown et al.* [1965] adopted a mean 1 AU solar wind flux of ~2×10^{8} particles/cm²-sec from Mariner II observations [*Neugebauer and Snyder*, 1962] and assumed the ion flux was composed of:
  ~2 keV hydrogen ions at 1×10^{8} H⁺/cm²-sec (3.2×10^{15} H+/cm²-year)
  ~8 keV helium ions at 0.7×10^{8} He⁺⁺/cm²-sec (2.2×10^{15} He⁺⁺/cm²-year)
to estimate an aluminum erosion rate of 0.1 nm/year due to sputtering by solar wind H⁺ and He⁺⁺

• *Gillette* [1968] estimate 0.6 nm of Si_2O_3 mirror coatings may be lost by sputtering when exposure to fluences of 1.0×10^{17} protons/cm²
  --Surface is not degraded and in fact may become smoother and more reflective due to the ion interaction with the mirror coating

Optical Properties

Kan et al., 1972		
--ZrO_2-pigmented coating	$\Delta\alpha_S$=0.015	3 keV H⁺, H_2^+ (1.2×10^{16} ions/cm²)
Breuch, 1967		
--TiO_2-pigmented silicone (Thermatrol)	$\Delta\alpha_S$=0.003	2 keV H⁺, H_2^+ (7×10^{15} H⁺/cm²)
--ZnO-pigmented silicate (Z-93)	$\Delta\alpha_S$=0.002	2 keV H⁺, H_2^+ (8×10^{15} H⁺/cm²)
--Z-93	$\Delta\alpha_S$=0.016	2 keV H⁺, H_2^+ (5×10^{15} H⁺/cm²)
	$\Delta\alpha_S$=0.029	2 keV H⁺, H_2^+ (8×10^{15} H⁺/cm)
Gillette and Brown [1965]		
--Z-93	$\Delta\alpha_S$=0.02	8 keV H⁺ (1×10^{15} H⁺/cm²)
	$\Delta\alpha_S$=0.10	8 keV H⁺ (1×10^{16} H⁺/cm²)
Jorgenson [1966]		
--Z-93	$\Delta\alpha_S$=0.02 to $\Delta\alpha_S$=0.10	0.5 keV H_2^+ (1×10^{16} H⁺/cm²)
--S-13	$\Delta\alpha_S$=0.02	0.5 keV H_2^+ (1×10^{15} H⁺/cm²)
	$\Delta\alpha_S$=0.07	0.5 keV H_2^+ (1×10^{16} H⁺/cm²)

Solar Wind as a Radiation Environment

Solar wind is typically considered a benign radiation environment for structural materials but can damage surfaces where optical properties are important

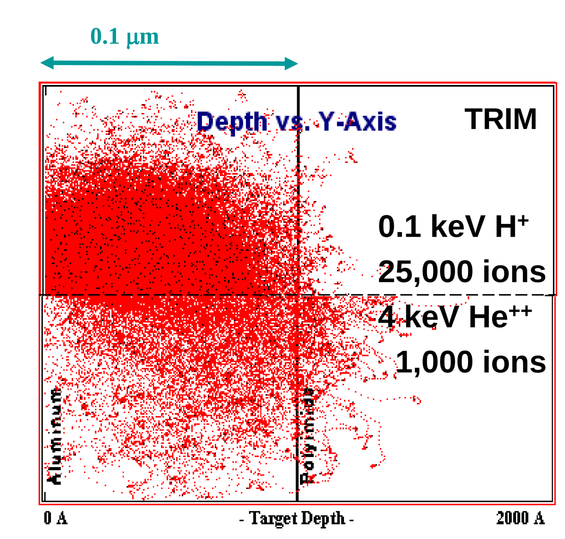
Solar wind velocity ~400 km/sec to 800 km/sec, mean ~450 km/sec
• Kinetic energy of H⁺ ~ 0.21 keV to 3.3 keV, mean 1.1 keV
• Kinetic energy of He⁺⁺ ~ 0.84 keV to 13 keV, mean 4.2 keV

H⁺ flux ~ NV ~ (7 H⁺/cm³)(450 x10³ m/s) ~ 3.2×10^{8} H⁺/cm²-sec

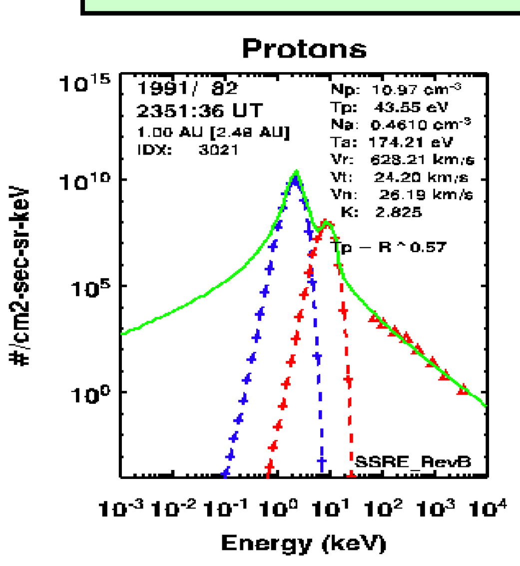
He⁺⁺/H⁺ ~ 0.038 He⁺⁺ flux ~ 0.12×10^{8} H⁺/cm²-sec

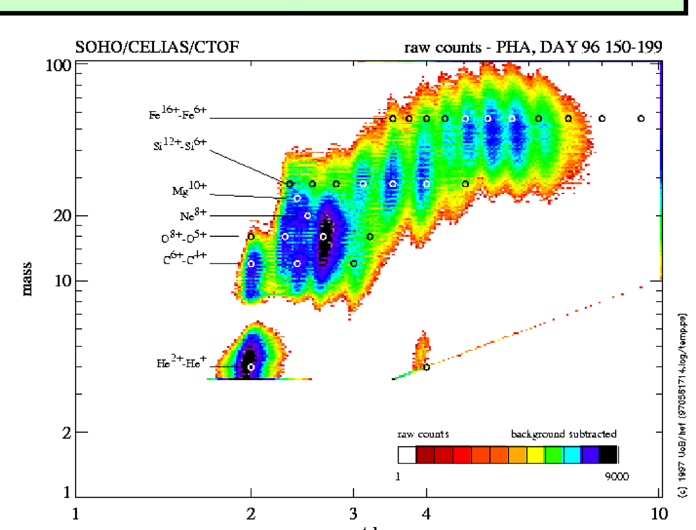
Solar wind light ion fluence
• H⁺ ~ 9.9×10^{15} H⁺/cm²-year
• He⁺⁺ ~ 3.8×10^{14} H⁺/cm²-year

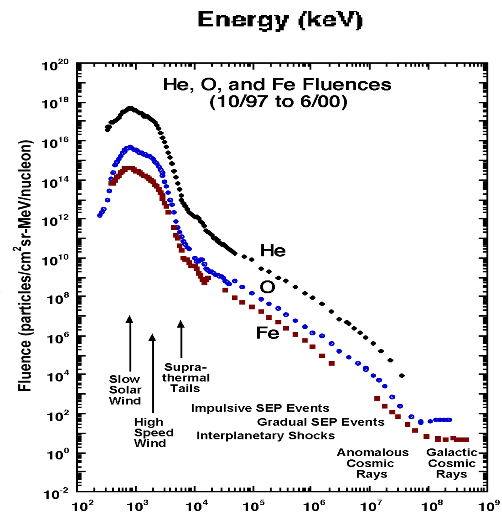
Solar wind penetration depths are only fractions of a micron
• Surface interactions with bulk materials
• Thin coatings ≤0.2 μm impacted throughout material



Solar Wind Ion Composition







(from R. Mewaldt, G. Gloeckler, and G. Mason)

Solar Wind Major, Minor Ions

Solar wind is dominated by hydrogen ions (~96%) with helium the dominant minor species (~3%). Other minor heavy ions make up the remainder (~1%) of the ion composition observed in interplanetary space.

Ion flux, fluence in interplanetary space is dominated by the ~1 keV/nucleon solar wind. The complete ion spectrum includes solar energetic particles and cosmic rays at energies extending from 10's MeV to 10's GeV although the flux is significantly reduced compared to the solar wind ions.

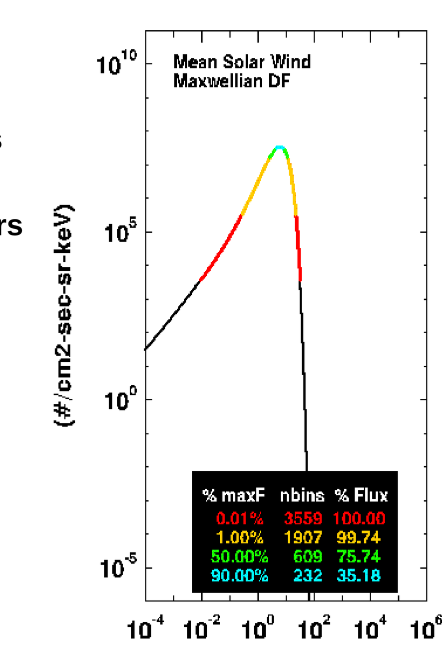
Ion Flux Model

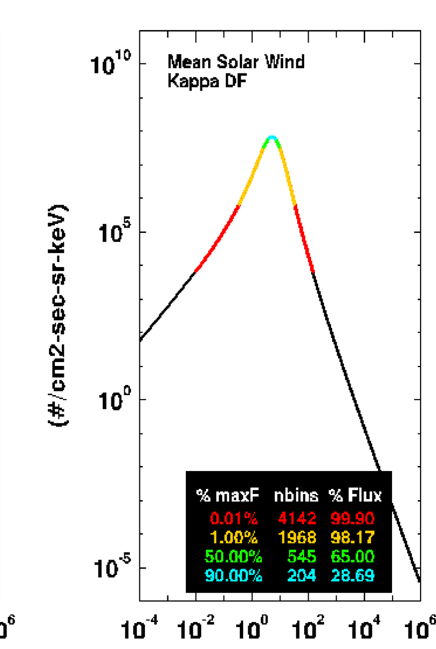
Ion flux models constructed from moments (N,T,V, N_α/N_p) for this study

Solar Wind Data Sources

--Ulysses	~2 x 5 AU, 12.5 yrs
--IMP-8	~35 R_E, 30+ yrs
--Helios 1,2	~0.3 - 1.0 AU, ~6 yrs
--Genesis	~3 years, L1
--ACE	~9+ years, L1

Directional flux model
• Directional flux to surface is integrated from Maxwellian distribution functions
• Moments (N,T,V, etc.) used to evaluate flux
• Technique for conservatively estimating solar wind sputtering and blistering is to assume the integrated directional flux all has the energy of peak flux in the analysis



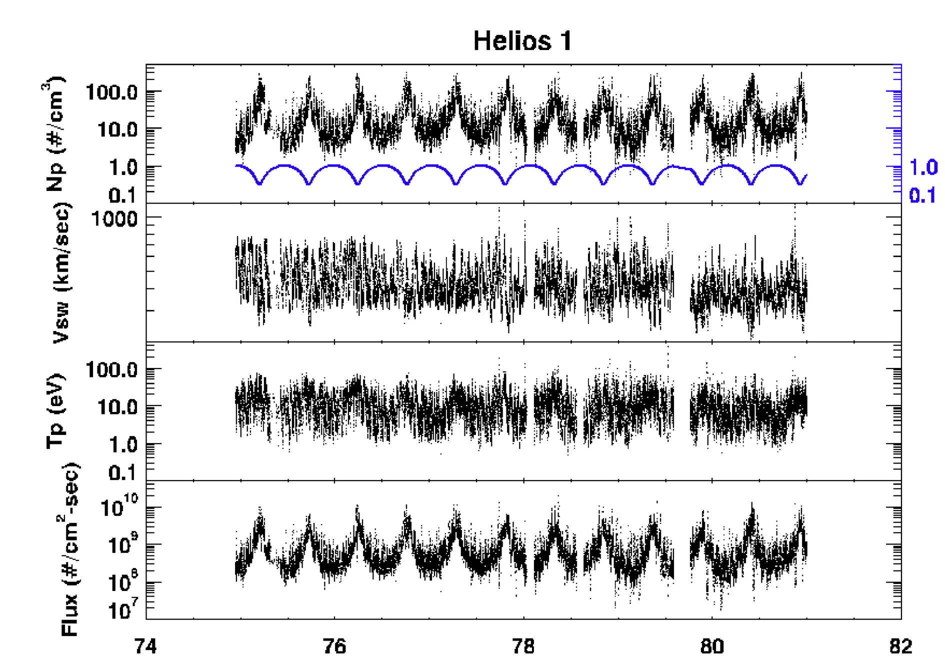


$$\Gamma=\left(N_o\frac{V_{mean}}{4}\right)\left[\exp(-S^2\cos^2\theta)+\pi^{1/2}S\cos\theta\{1+\mathrm{erf}(S\cos\theta)\}\right]$$

$$S=\frac{2}{\sqrt{\pi}}\frac{V_{bulk}}{V}\qquad V_{mean}=\left[\frac{8kT}{M\pi}\right]^{1/2}$$

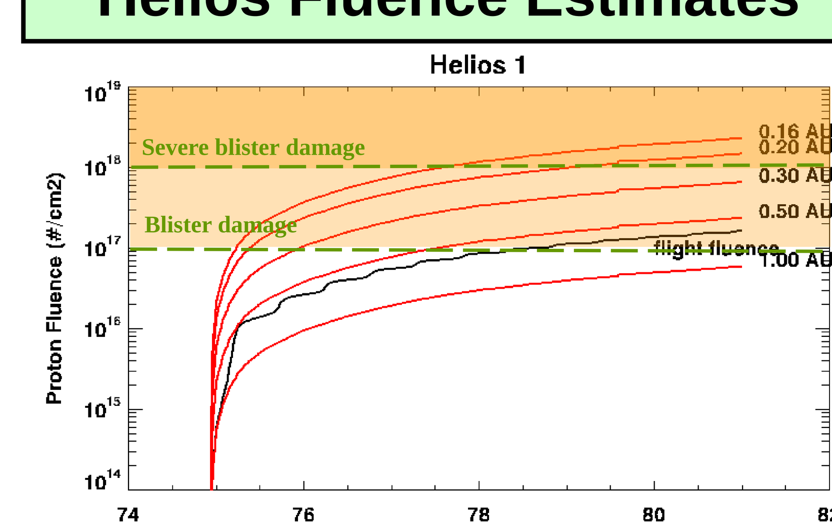
[Johnson, 1990]

Helios 1



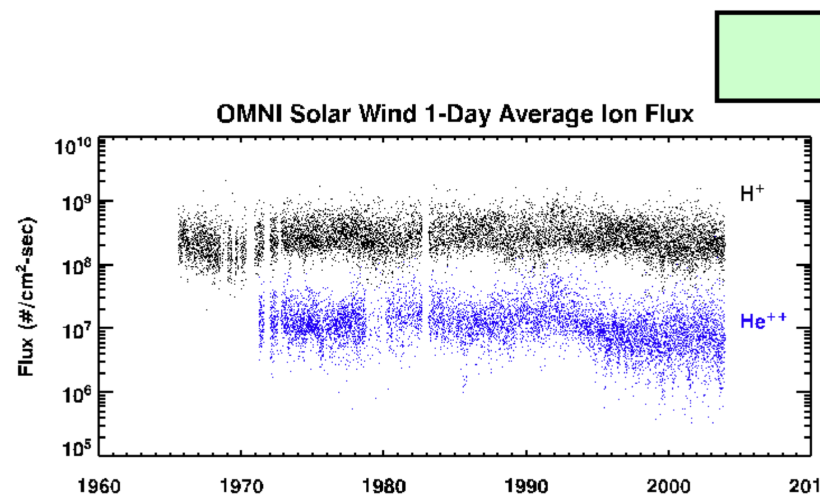
The Helios 1 data set is particularly useful for studies of the inner heliosphere due to range of distances (~0.3 to 1 AU) sampled by the spacecraft

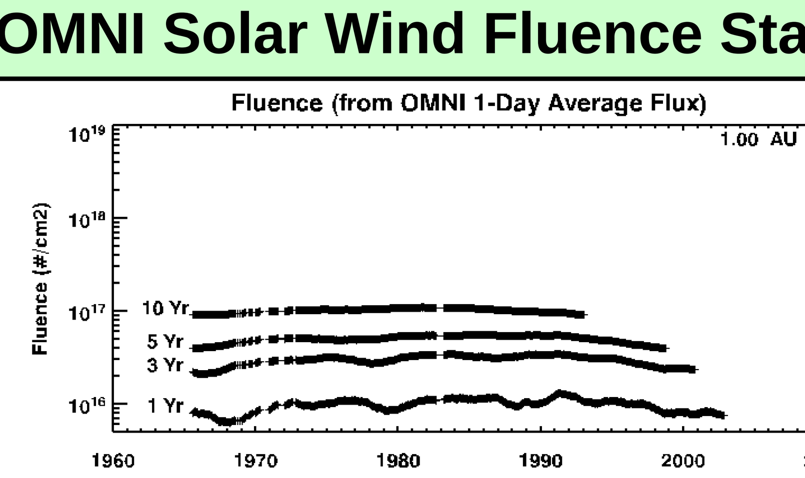
Helios Fluence Estimates

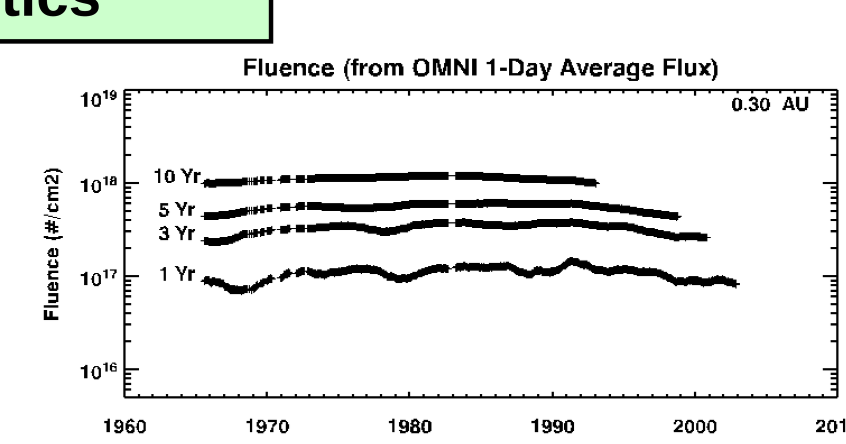


• Proton fluence integrated along Helios 1 trajectory (black line) exceeds fluence threshold where blister damage has been reported in ~4 years
• Scaled Helios 1 environments (red lines) for circular orbits about the Sun at the indicated radial distances demonstrate fluence variations in inner heliosphere

OMNI Solar Wind Fluence Statistics





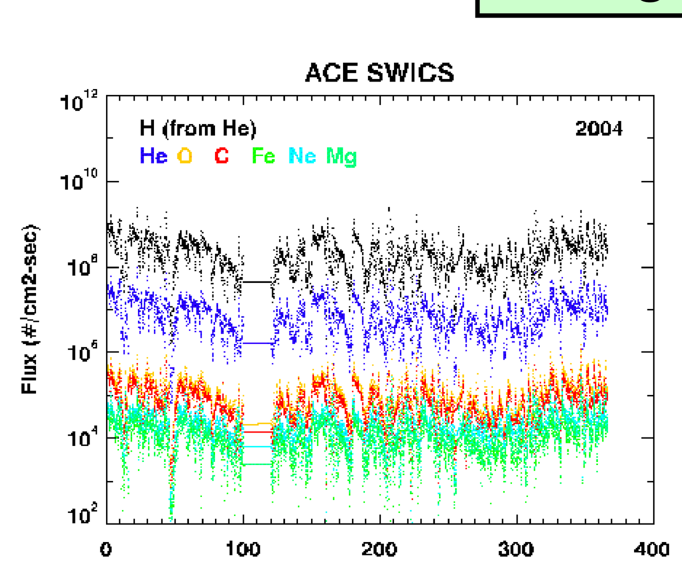


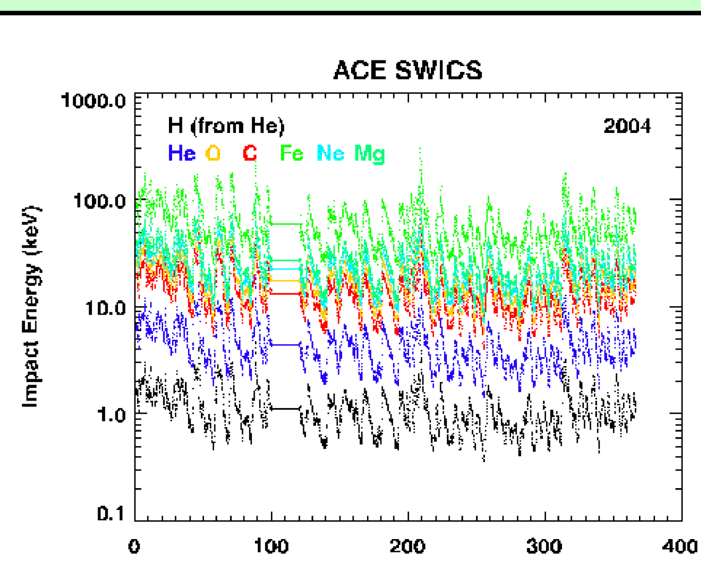
OMNI hourly average solar wind moments are excellent source of data to examine variations in solar wind ion fluence for extended periods of time to determine mean, worst case environments for radiation damage studies.

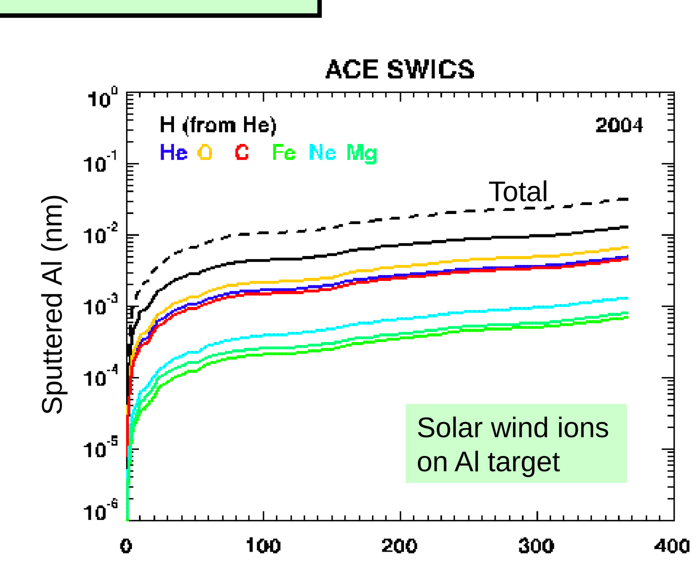
• Flux integrated for periods of N years (N=1, 3, 5, 10)
• Shift start time and integrate for new fluence
• Fluence estimates are based on real time history of observed solar wind environments
• ~10 years required to reach fluence ~10^{17} H⁺/cm²

• H⁺ fluence reaches 10^{17} H⁺/cm² levels required for blister damage within 1 to 3 years
• Fluence environments in inner heliosphere provide sufficient fluence to produce blister damage

Light, Heavy Ion Sputtering Assessment







In addition to the work on proton fluence, we have completed an analysis of sputter yields of aluminum due to the combined effects of the light H, He ions and heavy O, C, Ne, Mg, and Fe ions. Protons dominate the sputtering process even though sputter yields due to H impact are low because H fluences are orders of magnitude greater than all other ions in the solar wind. O is the next most important ion followed by nearly equal contributions by He and C. Including heavy ions nearly triples the sputter loss of aluminum for the data used here.

Summary

• Interplanetary H+ ion fluence can reach values where blister damage has been reported for materials in laboratory measurements (especially metals)
  --Requires long exposures at solar wind flux for distances ~1 AU from Sun
  --High ion fluences in inner heliosphere (particularly at locations ≤0.5 AU) can reach thresholds for blister damage in a few years

• Sputter erosion due to solar wind is only fractions of nanometer a year even if heavy ions are included (increasing sputter yields by ~3x at 1 AU)

• Future work:
  --Evaluation of dose rate effects to determine potential for damage to materials
  --More detailed analysis of heavy ion contributions including solar flare effects
  --Statistical analysis of heavy ions for extended periods of time