



Solar Wind as an Ionizing Radiation Environment in Interplanetary Space

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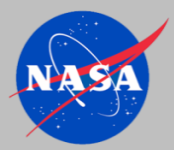
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Solar Corona

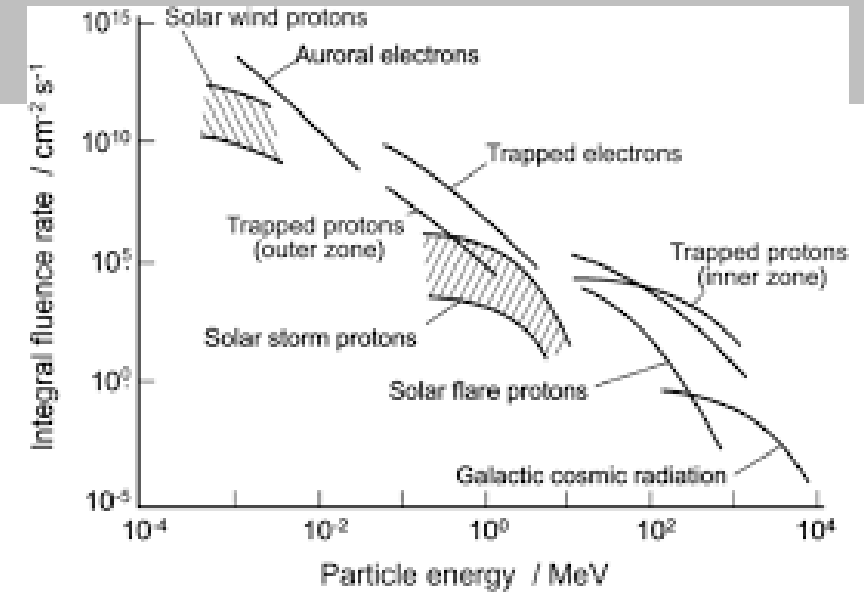
21 August 2017 solar eclipse, white light image, Oregon, USA

Source: P. Aniol/M. Druckmüller/S. Habbal/Courtesy NASA



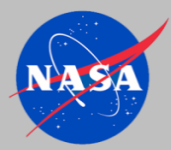
Introduction

- High energy radiation environments responsible for radiation damage to materials, electronics, and crew are well characterized and modeled:
 - Galactic cosmic rays Badhwar-O'Neil 2020, CREME96, Nymmik
 - Solar particle events Emission of Solar Protons, SAPHIRE, JPL, King 1972
 - Trapped radiation belts AE8/AP8, AE9/AP9/IRENE
- Low energy radiation environments in interplanetary space can produce radiation damage to thin materials and material surfaces:
 - Solar wind
 - Magnetosheath
 - Magnetotail
- Concern to spacecraft design and operations is radiation damage to surfaces and thin materials with mission critical applications on exterior of spacecraft
 - Applications: thermal control coatings, sunshields, multilayer insulation, optical thin film coatings, solar sails, thermo-optical properties of space exposed materials



Outline

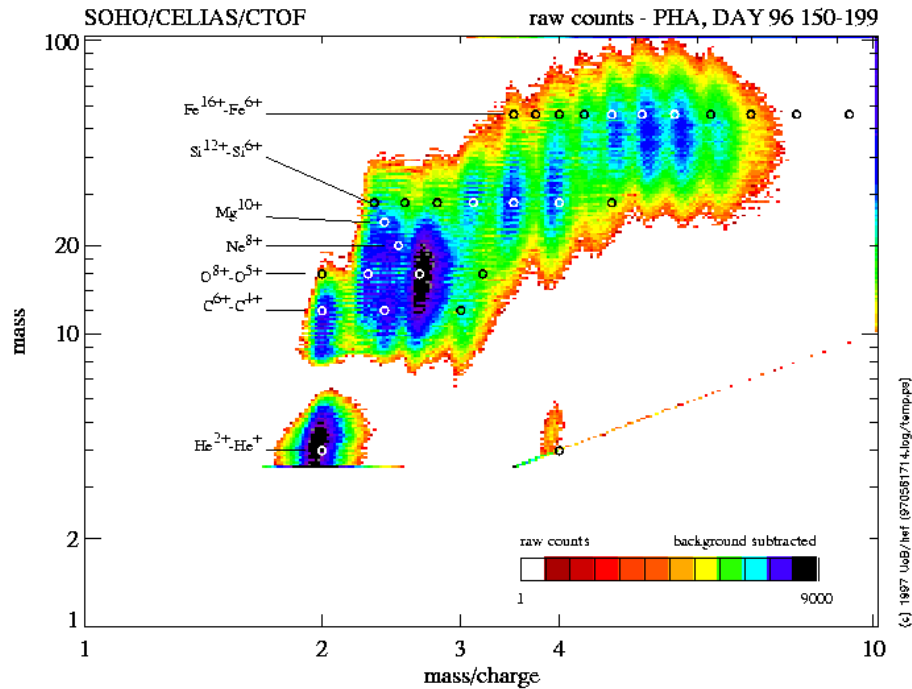
Properties of solar wind ions, flux and fluence
Solar wind as a radiation environment
Total ionizing dose
Proton blistering
Sputtering



Solar Wind Properties

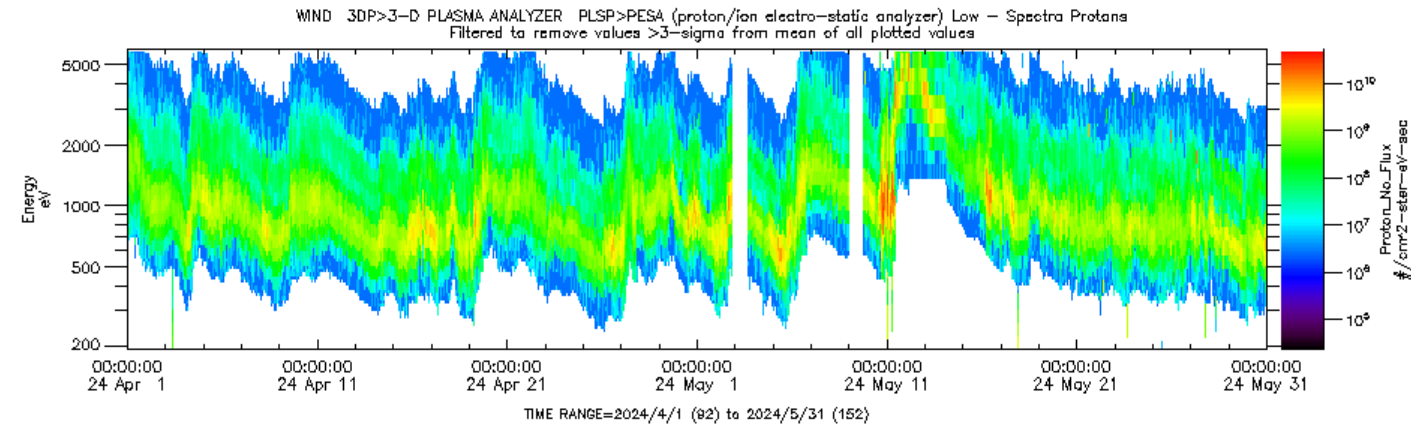
- Solar wind ion composition

- Hydrogen ions (~96%) are the dominant ions in the solar wind
- Helium is the dominant minor species (~3%)
- Other minor heavy ions make up the remainder (~1%) of the ion composition including C, O, Ne, Mg, Si, Fe



WIND/3DP
UC Berkeley

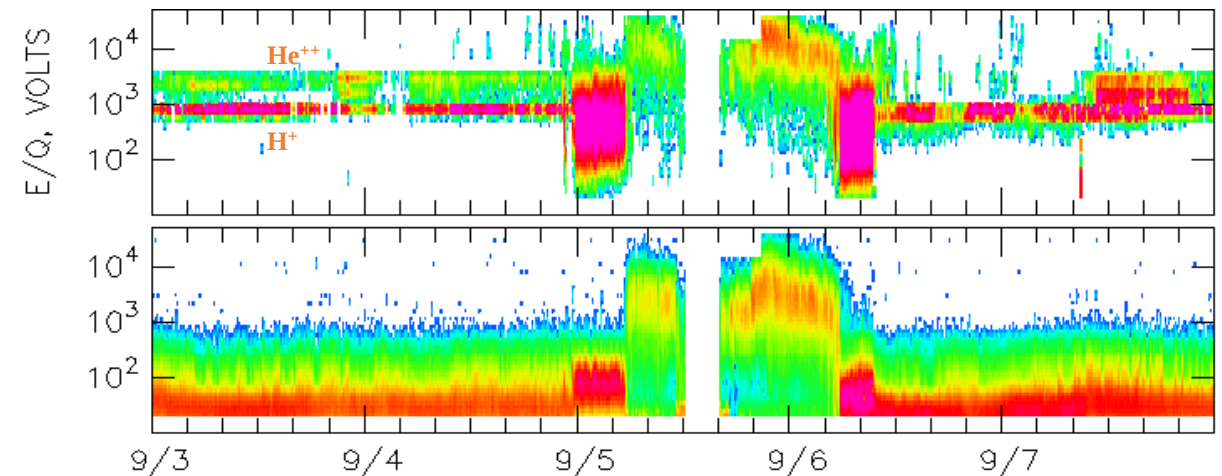
1 Apr 2024 – 31 May 2024



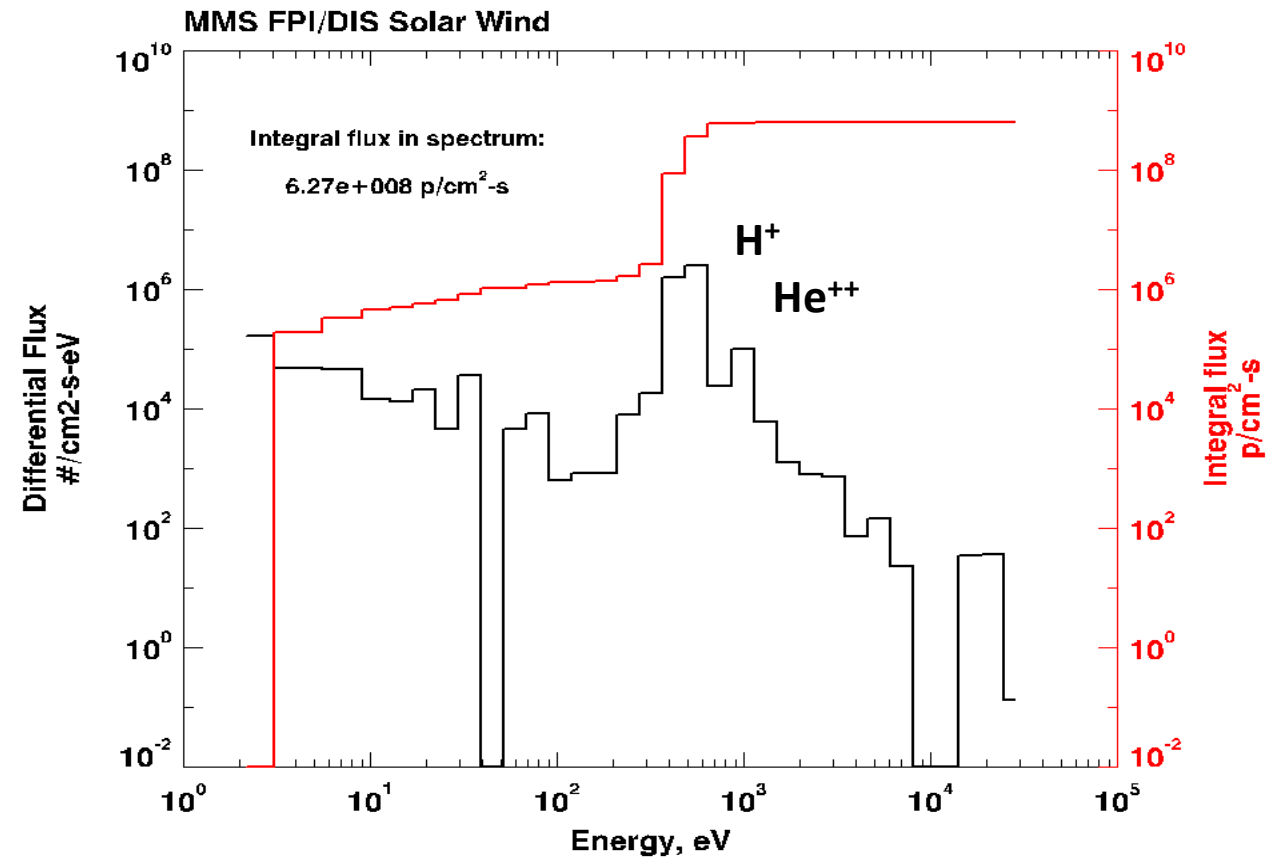
Please acknowledge PI, R. Lin/S. Bale at UC Berkeley and CDAWeb when using these data.
Key Parameter and Survey data (labels K0,K1,K2) are preliminary browse data.
Generated by CDAWeb on Mon Oct 21 02:17:57 2024

Geotail CPI/HPA
Univ. of Iowa

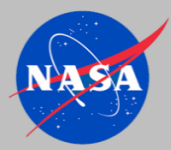
3 - 9 Sep 1999



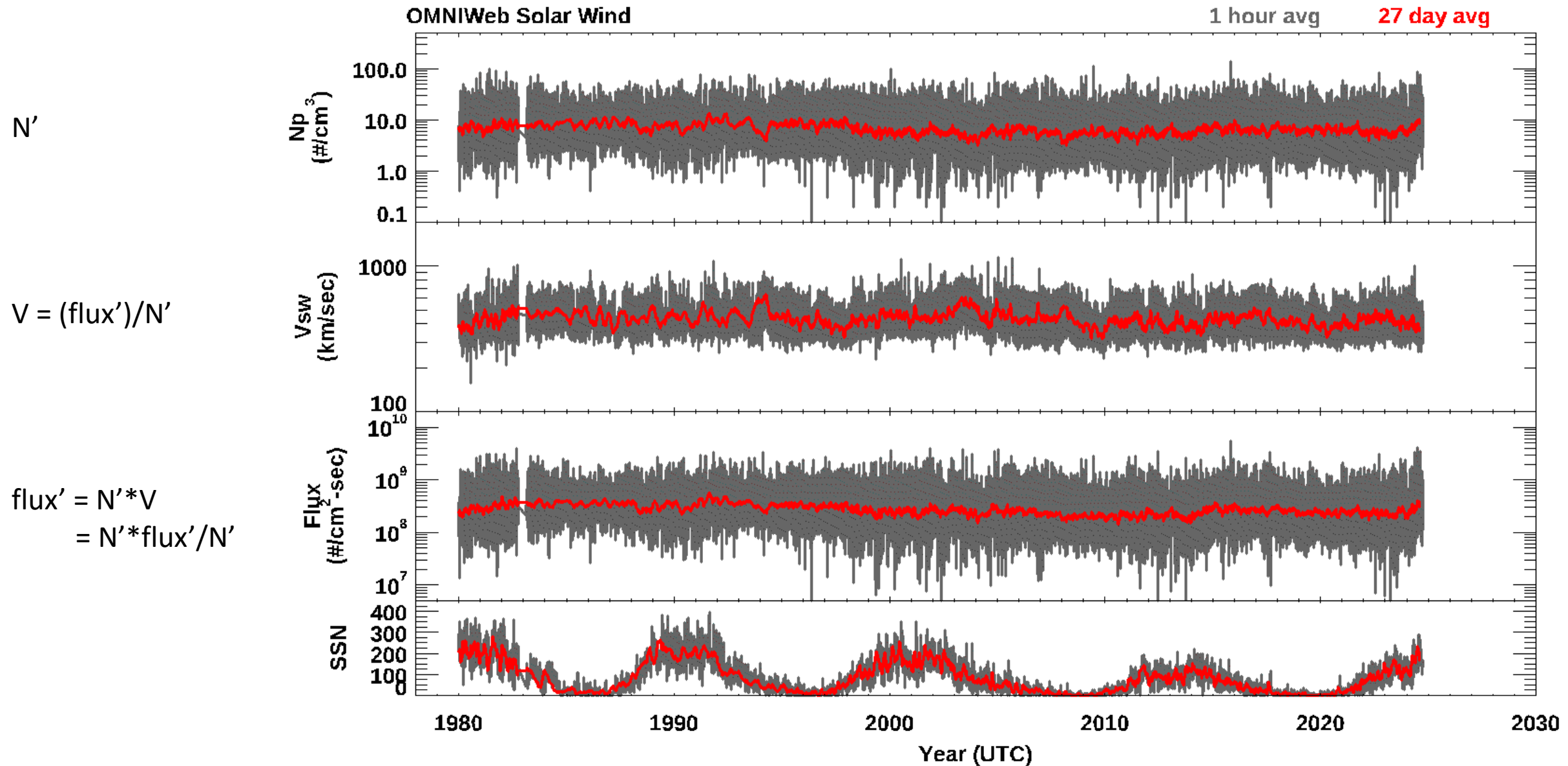
- NASA's Magnetospheric Multiscale (MMS) spacecraft samples solar wind upstream of Earth's magnetosphere using the Fast Plasma Investigation Dual Ion Spectrometers
- Differential ion energy spectrum shows peaks for H^+ and He^{++} ions
- Differential ion energy spectrum integrated over energy from ~ 2 eV to 28 keV to obtain the cumulative ion flux in the spectrum
- Total flux in spectrum: $6.3 \times 10^8 \text{ p/cm}^2\text{-s}$



(MMS FPI/DIS data courtesy of M. Chandler, NASA MSFC)



Solar Wind Velocity, Density, and Flux (from GSFC's OMNIWeb Moments)



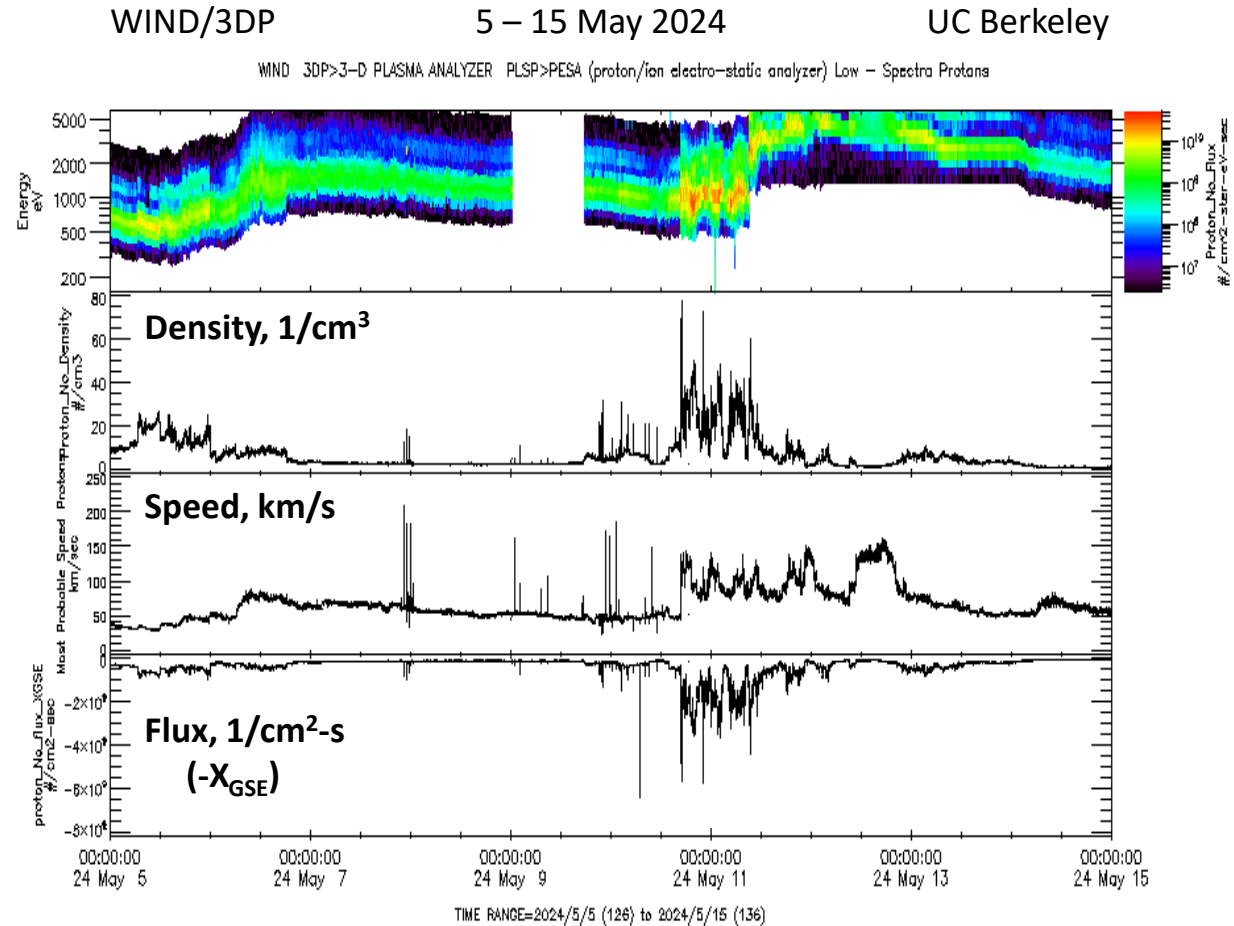
OMNI data: <https://omniweb.gsfc.nasa.gov/>

- Density and velocity are anti-correlated in slow and fast solar wind flows, respectively, resulting in about 2x variation in flux ($\sim N \cdot V$)
- CME shocks where both N and V are high result in proton flux enhancements on the order of 10x to 100x

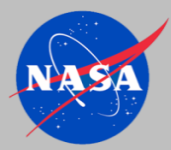
Parameter	Slow SW	Fast SW	CME (shock)
$\langle N \rangle_p$, #/cm ³	4.7 (a)	1.4 (a)	~ 40 to 100 (b)
$\langle V \rangle_p$, km/s	400 (a)	750 (a)	~ 800 to 1000 (b)
$\langle H^+ \text{ energy} \rangle_p$, keV	0.8 (a)	3.34 (a)	~ 3.34 to 5.22 (b)
$\langle He^{++} \text{ energy} \rangle_p$, keV	3.2 (a)	13.36 (a)	13.36 to 20.88 (b)
$\langle H^+ \text{ flux} \rangle_p$, #/cm ² -s	1.88×10^8 (a)	1.05×10^8 (a)	32.0×10^8 to 100×10^8 (b,c)
$\langle He^{++} \text{ flux} \rangle_p$	7.14×10^6 (c)	3.99×10^6 (c)	

Source:

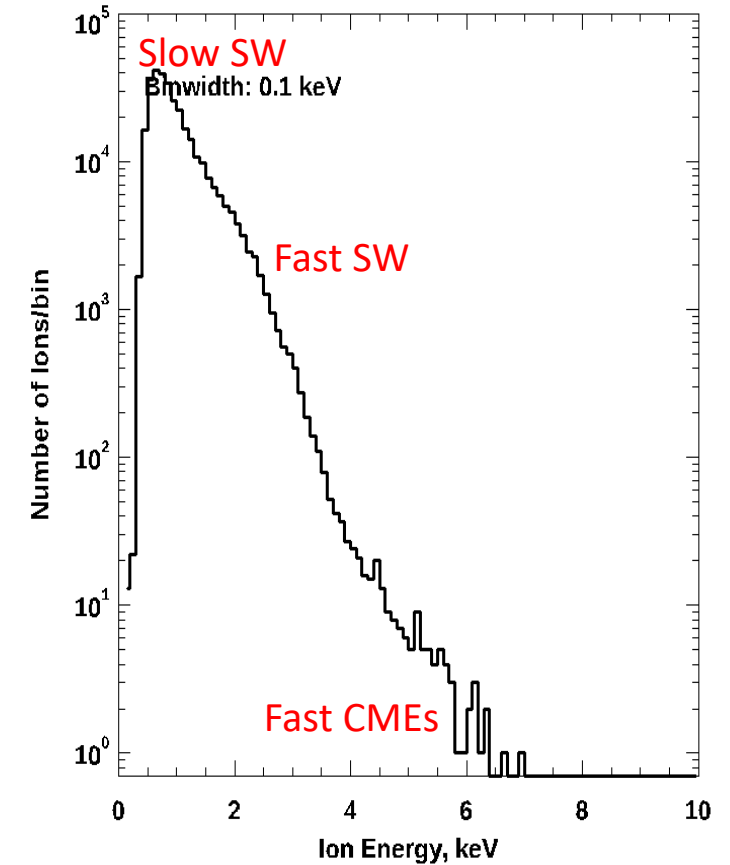
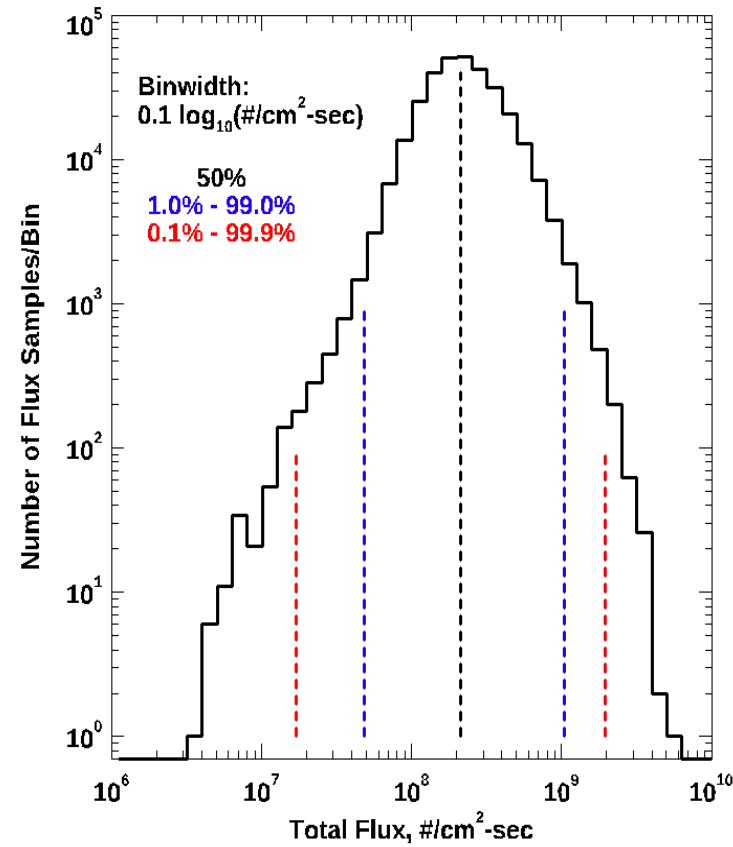
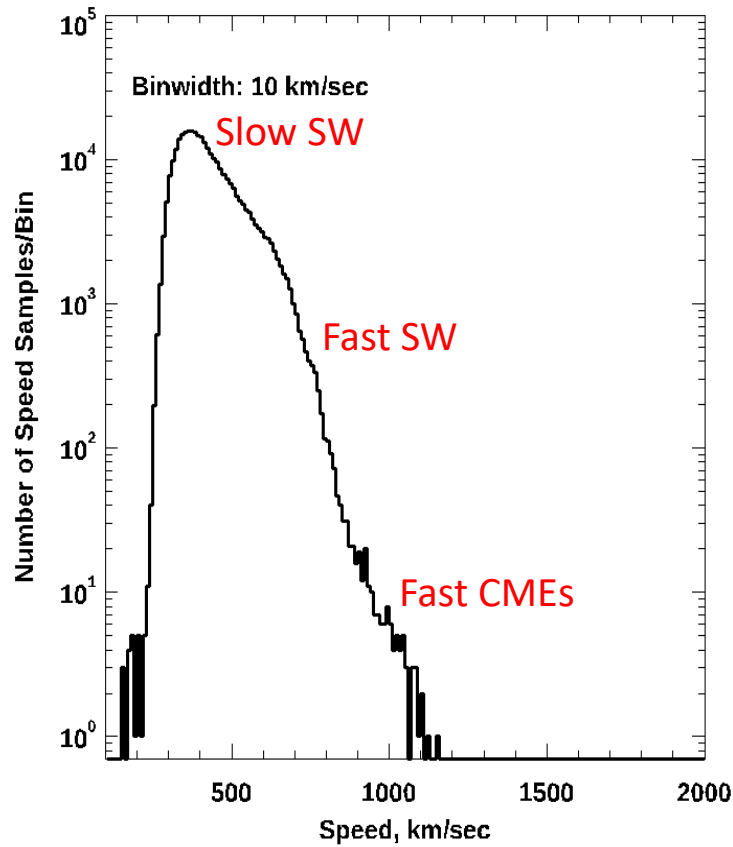
- $\langle \dots \rangle_p$: from WIND most probable values, Dec 1994 – Sep 2011 (from Le Chat et al., 2012)
- Estimated from OMNIWeb data set
- He^{++} values estimated from $0.038 \cdot H^{++}$ flux, fluence



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Generated by CDAWeb on Mon Oct 21 03:35:22 2024



Fast, Slow Solar Wind and CME Contribution to Proton Flux



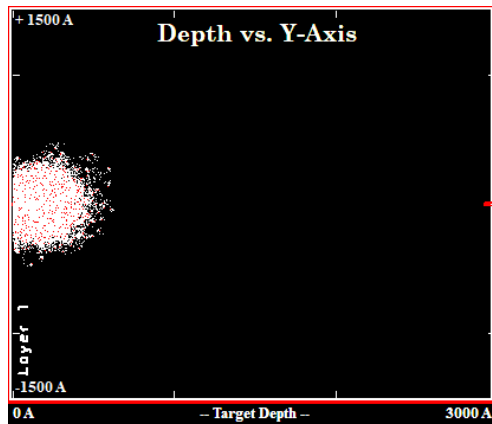
$\sim 0.1 \text{ keV} \leq \text{energy} \leq 7 \text{ keV}$

Proton, Helium Penetration Depth in Materials

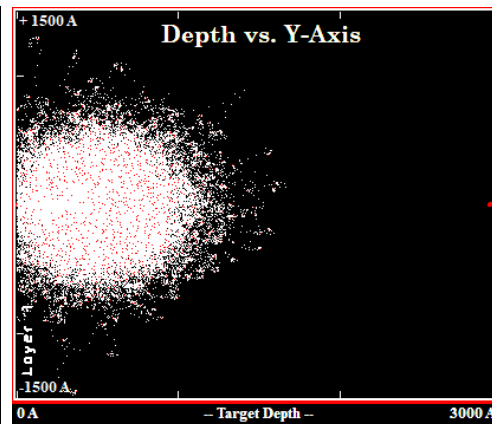
- Solar wind is generally considered a benign radiation environment
- Low energy ions (0.1 keV to 7 keV) only penetrate to shallow depths in materials
 - Slow and fast solar wind ions penetrate 50 nm to 150 nm in aluminum, respectively
 - Fast ions in CMEs may penetrate to 150 nm to 300 nm in aluminum

TRIM* simulations: 10,000 ions, XY plane

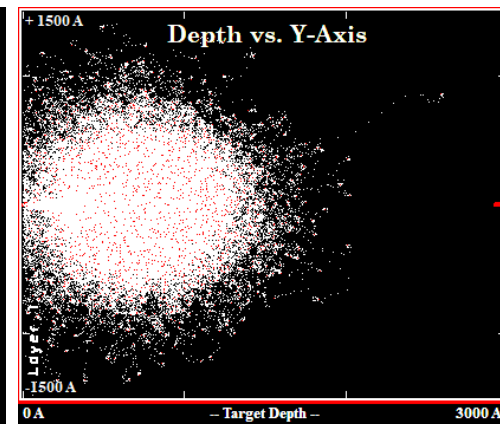
density = 2.7 g/cm³



0.8 keV H⁺ on 3000Å AL
Slow SW



3.34 keV H⁺ on 3000Å AL
Fast SW



5.22 keV H⁺ on 3000Å AL
CME

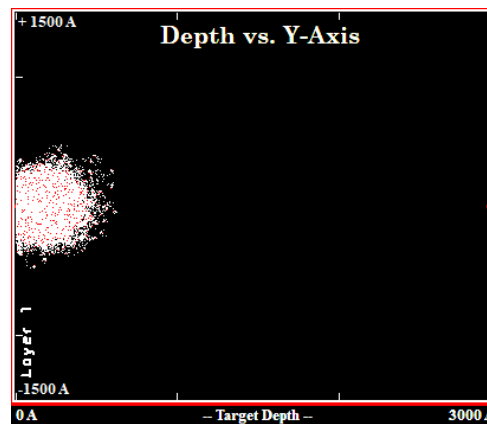
*TRIM: Transport of Ions in Matter

Proton, Helium Penetration Depth in Materials

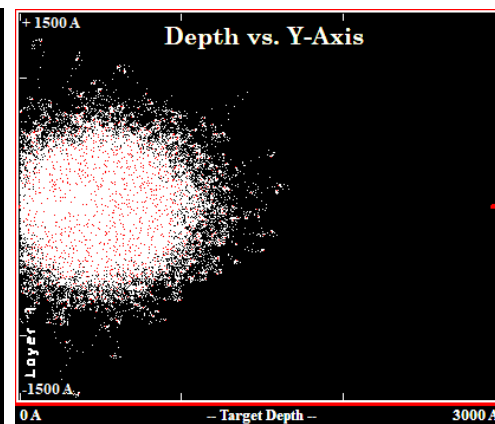
- Solar wind is generally considered a benign radiation environment
- Low energy ions (0.1 keV to 7 keV) only penetrate to shallow depths in materials
 - Slow and fast solar wind ions penetrate 50 nm to 150 nm in aluminum, respectively
 - Fast ions in CMEs may penetrate to 150 nm to 300 nm in aluminum
- H and He velocity in the solar wind is about equal, so He energies are typically 4x H energies
- Solar wind penetration depths in metals are only fractions of a micron (<500 nm)
 - Bulk materials impacted only on “surfaces”
 - 1000 Å (0.1 μm) Al coating on polymer can be damaged throughout the metal layer

TRIM* simulations: 10,000 ions, XY plane

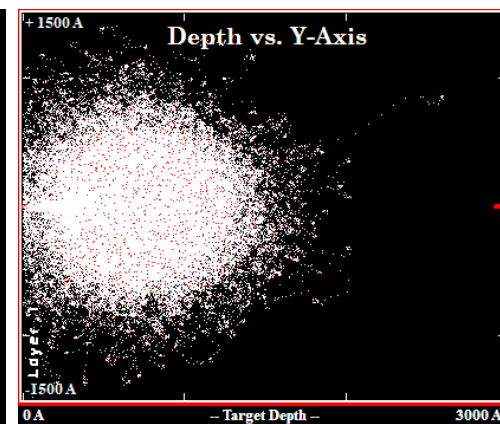
density = 2.7 g/cm³



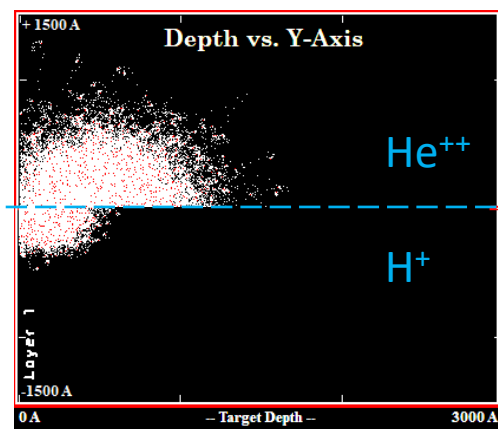
0.8 keV H⁺ on 3000Å AL
Slow SW



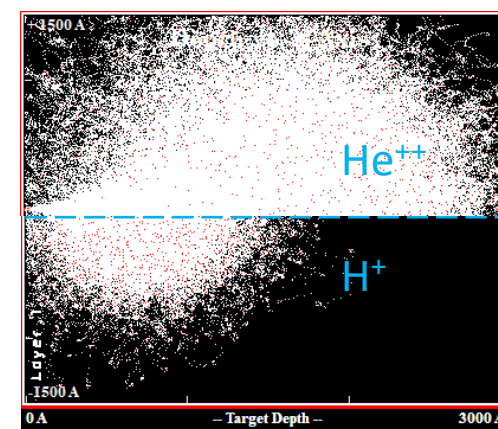
3.34 keV H⁺ on 3000Å AL
Fast SW



5.22 keV H⁺ on 3000Å AL
CME



3.2 keV He⁺⁺ and 0.8 keV H⁺
on 3000Å AL (Slow SW)



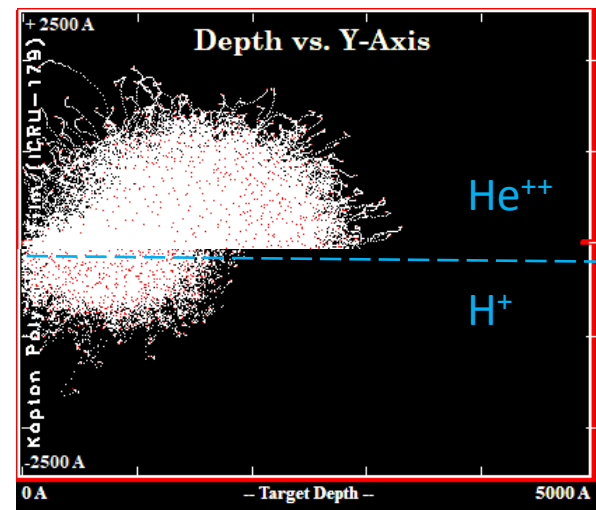
20.88 keV He⁺⁺ and 5.22 keV H⁺
on 3000Å AL (CME)

*TRIM: Transport of Ions in Matter

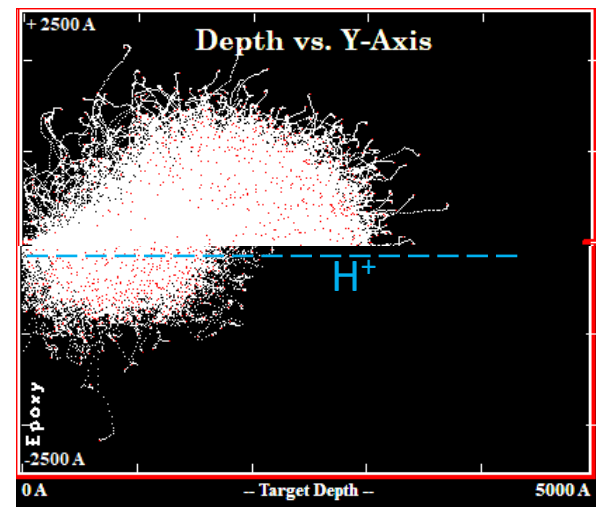
TRIM* simulations: 10,000 ions, XY plane

- H, He ions penetrate deeper into polymers due to their lower density

13.3 keV He^{++} and 3.34 keV H^+
on 5000Å Kapton (Fast SW)
density = 1.42 g/cm³



13.3 keV He^{++} and 3.34 keV H^+
on 5000Å epoxy (Fast SW)
density = 1.18 g/cm³



*TRIM: Transport of Ions in Matter

- Solar wind light ions and electrons can damage or degrade the surface of materials through multiple processes including:
 - Radiation degradation (total dose)
 - Proton blistering of soft metals
 - Ion sputtering
- These processes can result in changes to
 - Optical properties including the absorption, emittance, and reflectivity of light
 - Modification of charging properties (SEY, surface conductivity)
- While the damage is restricted to the surface of the materials, it is a possible concern to space system design where thermo-optical properties of the metal surfaces are important and particularly in cases where thin metallic layers are used in mission critical applications such as
 - Solar sail propulsion systems
 - Thermal control coatings
 - First surface reflectors in space exposed multilayer insulation
 - Reflective sunshields

Anderson and Dahms, JSR, 1967

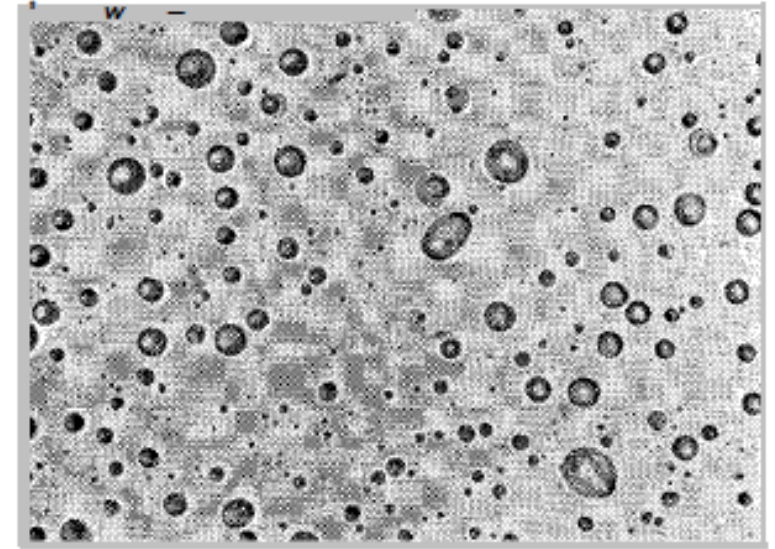
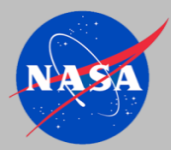


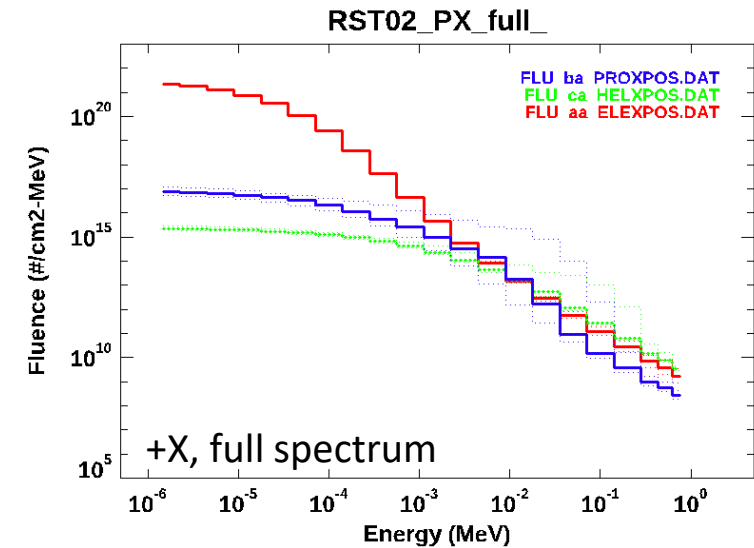
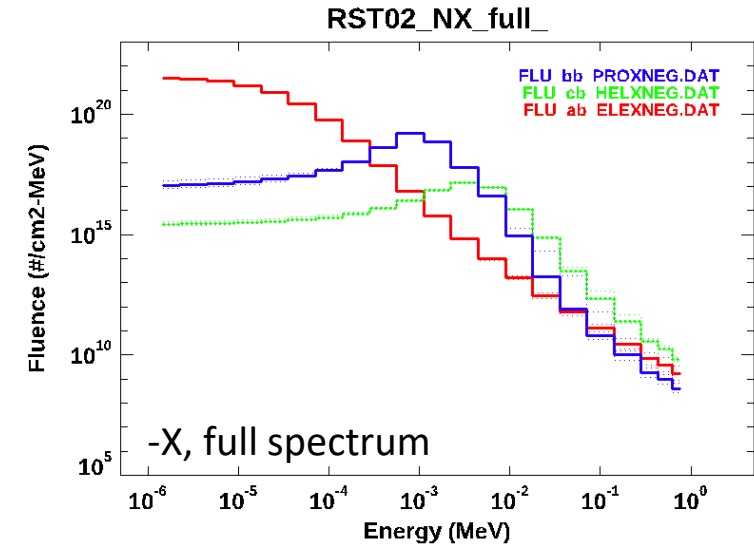
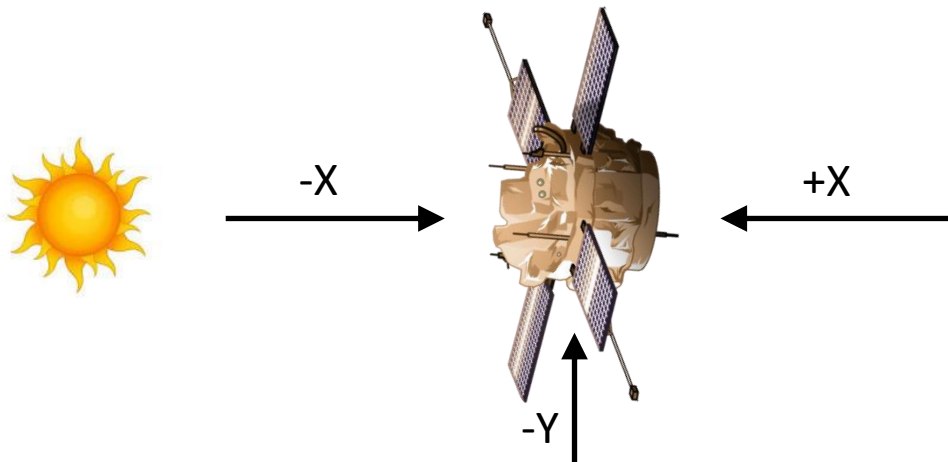
Fig. 1 Photomicrograph of blisters in an 800Å gold film over a pure aluminum substrate, after bombardment by 3.2×10^{17} ions/cm² (600X) (strong bond).

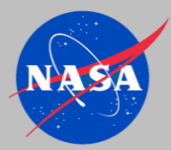
- 0.5 to 2 keV H⁺ at fluence of 3.2×10^{17} ions/cm²
- Blisters 1-30 μm in diameter on 60 nm to 100 nm thick Au, Cu, Al coatings
- Blisters sufficient to change absorbance of Au coating by 17%



Total Ionizing Dose (TID)

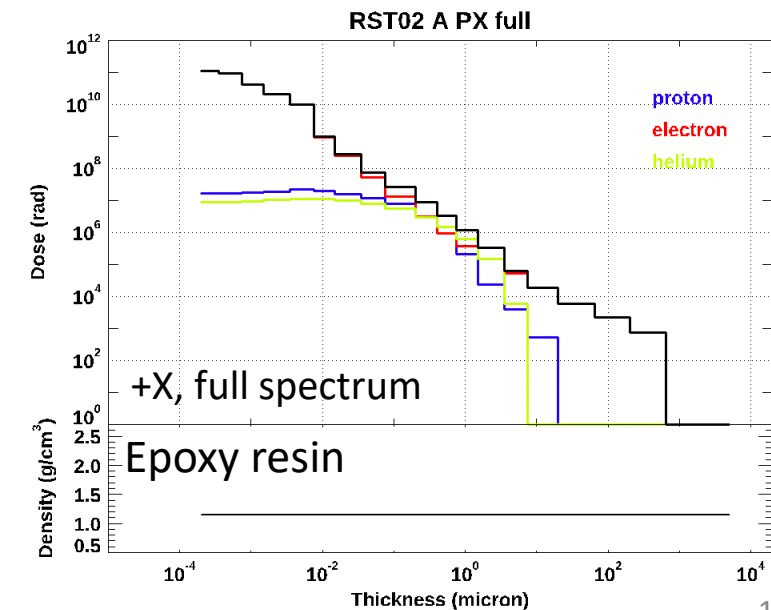
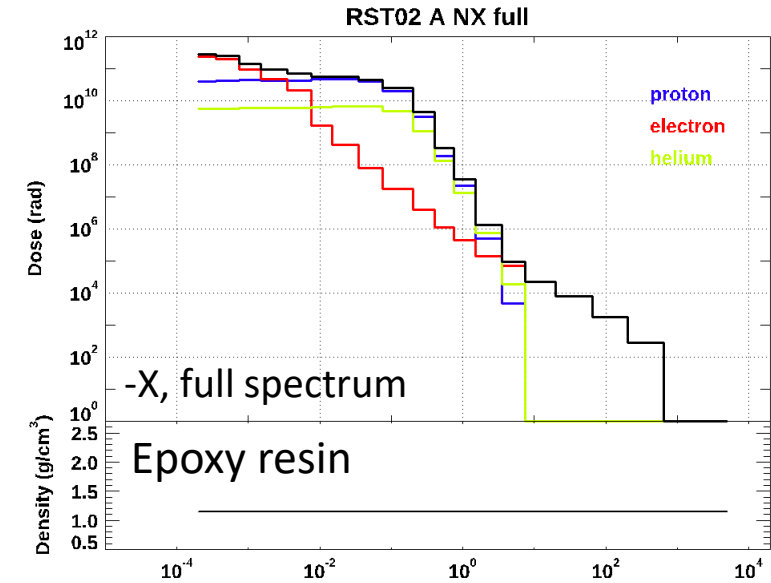
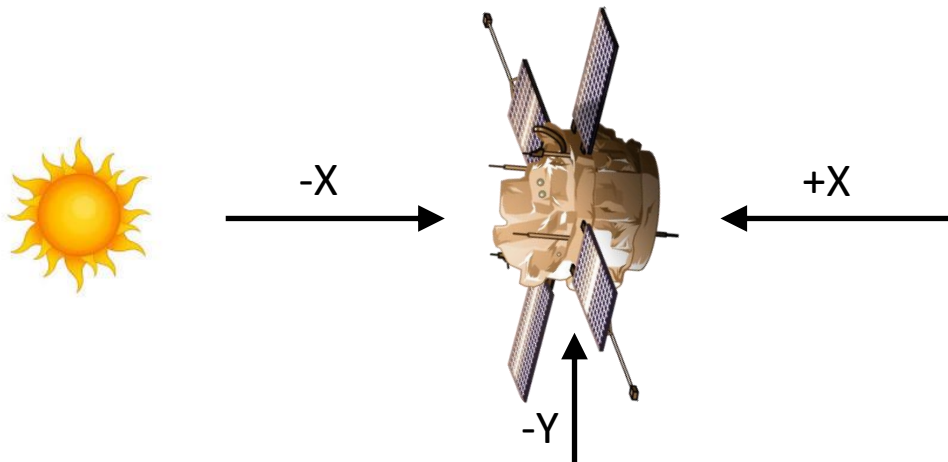
- Solar wind electrons and ions can generate very large TID near the surface of materials due to the large annual fluence of the charge particles
- Proton flux is highly anisotropic with a strong peak on surfaces exposed to the solar wind flow from the Sun
- Electrons are nearly isotropic and impact all surfaces

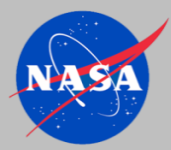




Total Ionizing Dose (TID)

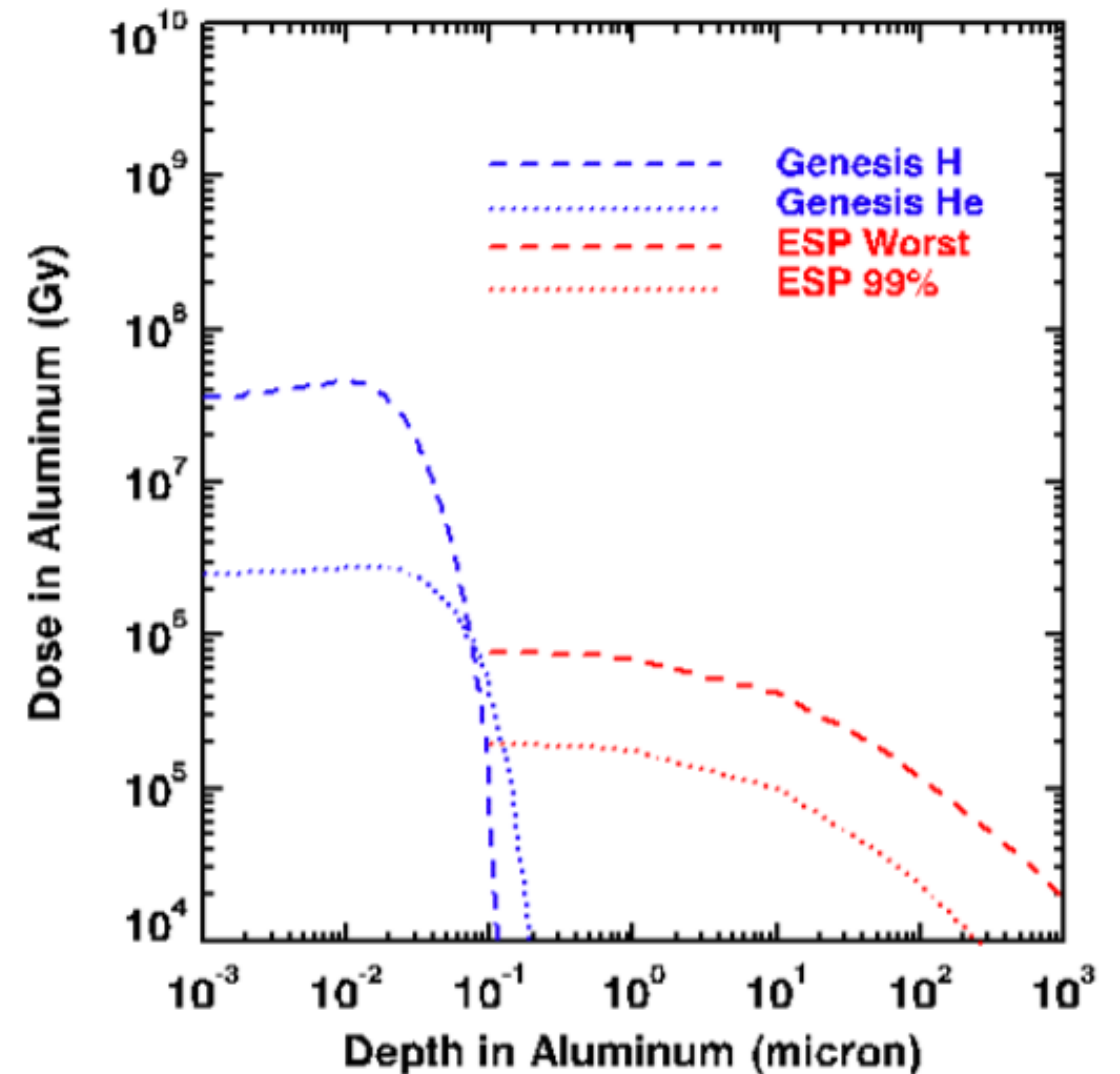
- Solar wind electrons and ions can generate very large TID near the surface of materials due to the large annual fluence of the charge particles
- Proton flux is highly anisotropic with a strong peak on surfaces exposed to the solar wind flow from the Sun
- Electrons are nearly isotropic and impact all surfaces
- Radiation dose is very large near material surface!
 - Both environments give 10^9 to 10^{11} rad (1 Grad to 100 Grad) doses in the first 0.01 micron
 - Sun facing surfaces (-X environment) has >0.1 Grad dose to depth of nearly 1 micron
 - Electrons dominate surface dose for -Y, +X environments
 - Protons dominate surface dose for -X environment





Solar Wind vs Solar Particle Event Dose

- Genesis L1 solar wind environment, 24 August 2001 to 1 April 2004 (the time the Genesis capsule was open to the solar wind)
- Ion dose computed using TRIM code and converting ionization events into total ionizing dose
- Emission of Solar Proton (ESP) Model



(Minow et al. 2007)

Questions?



Solar Corona

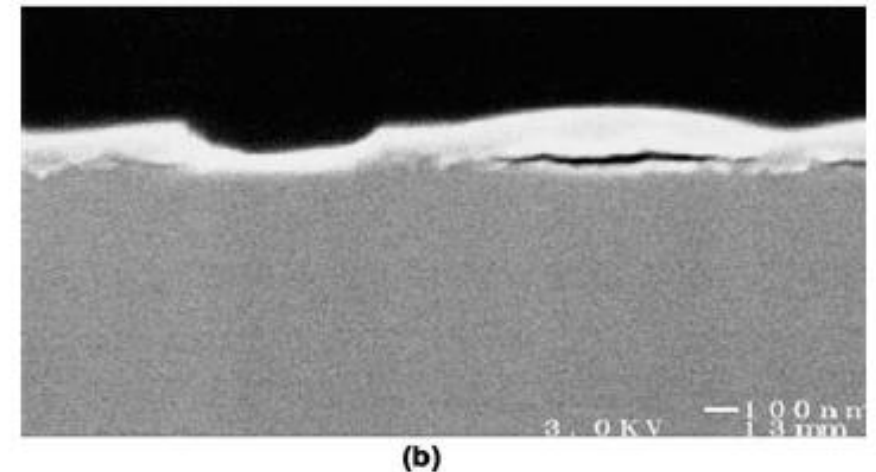
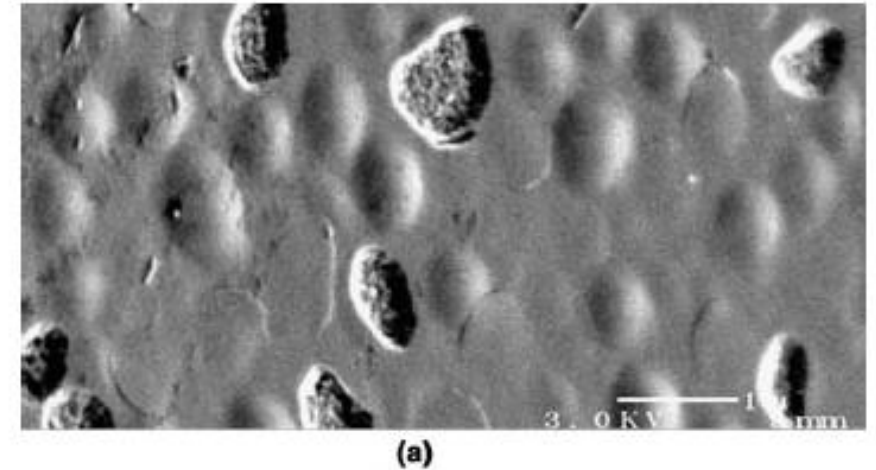
21 August 2017 solar eclipse, white light image, Oregon, USA

Source: P. Aniol/M. Druckmüller/S. Habbal/Courtesy NASA

Blister Damage

- Blistering and embrittlement are established damage mechanisms for metallic materials used in industries where metals are exposed to H_2 (e.g., nuclear fusion reactors, chemical plants, and refineries). The damage mechanism is blistering of soft metal surfaces due to accumulation of hydrogen gas (H_2) within the metal.
- Concern to spacecraft is the potential for short-term changes in metal surface properties, and thin metallic coatings in particular, when they are exposed to solar wind (which is composed of ~96% H^+ ions) with impact to thermal and optical properties of mission critical materials.
- Particular concern is for thin metal coatings where the thermal and optical properties are mission critical including:
 - Solar sails
 - Sun shields
 - Multi-layer insulation, thermal control coatings

Giguere et al., 2005

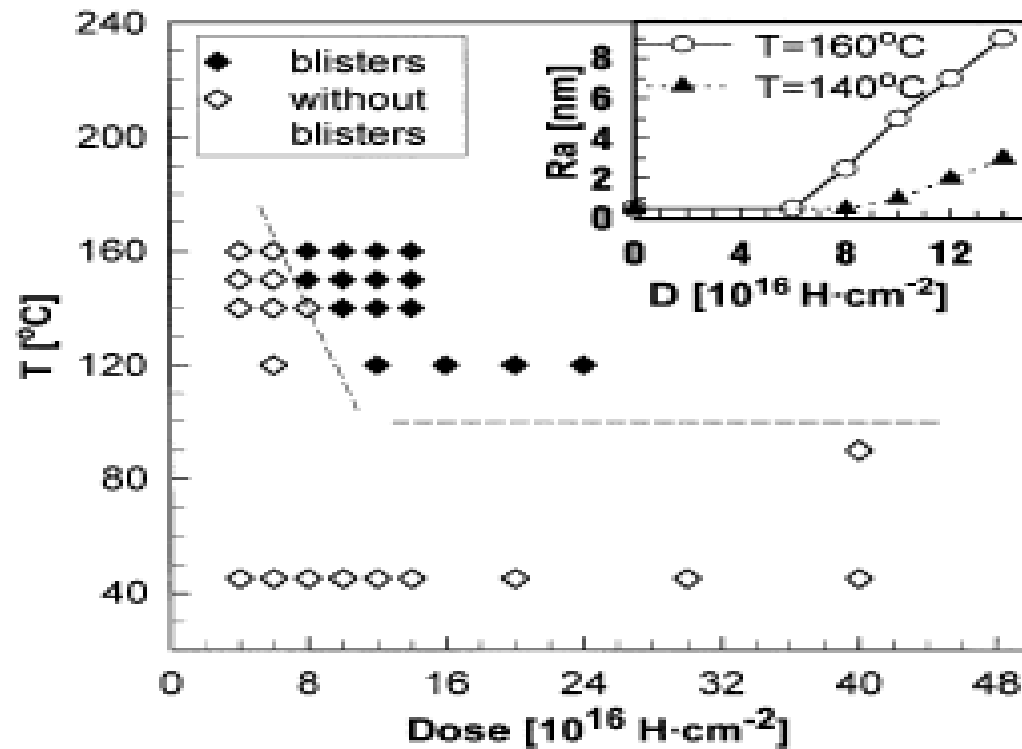


(a) Surface and (b) cross section view

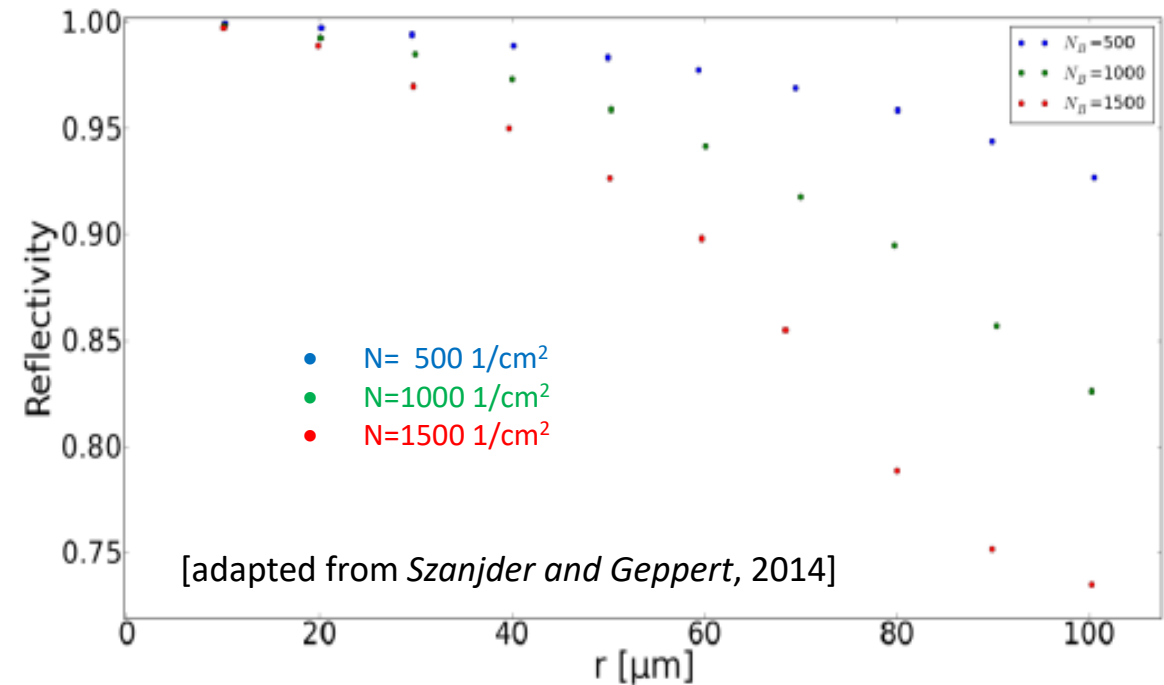
$4 \times 10^{16} H^+ / cm^2$ at 10 keV on GaAs (400°C; 30 sec)

Blister Formation Threshold

- Left: Blister size and fluence threshold depends on temperature
- Right: Optical properties will degrade as blisters accumulate and grow in size



50 keV H^+ on GaAs (*Gawlik et al., 2001*)



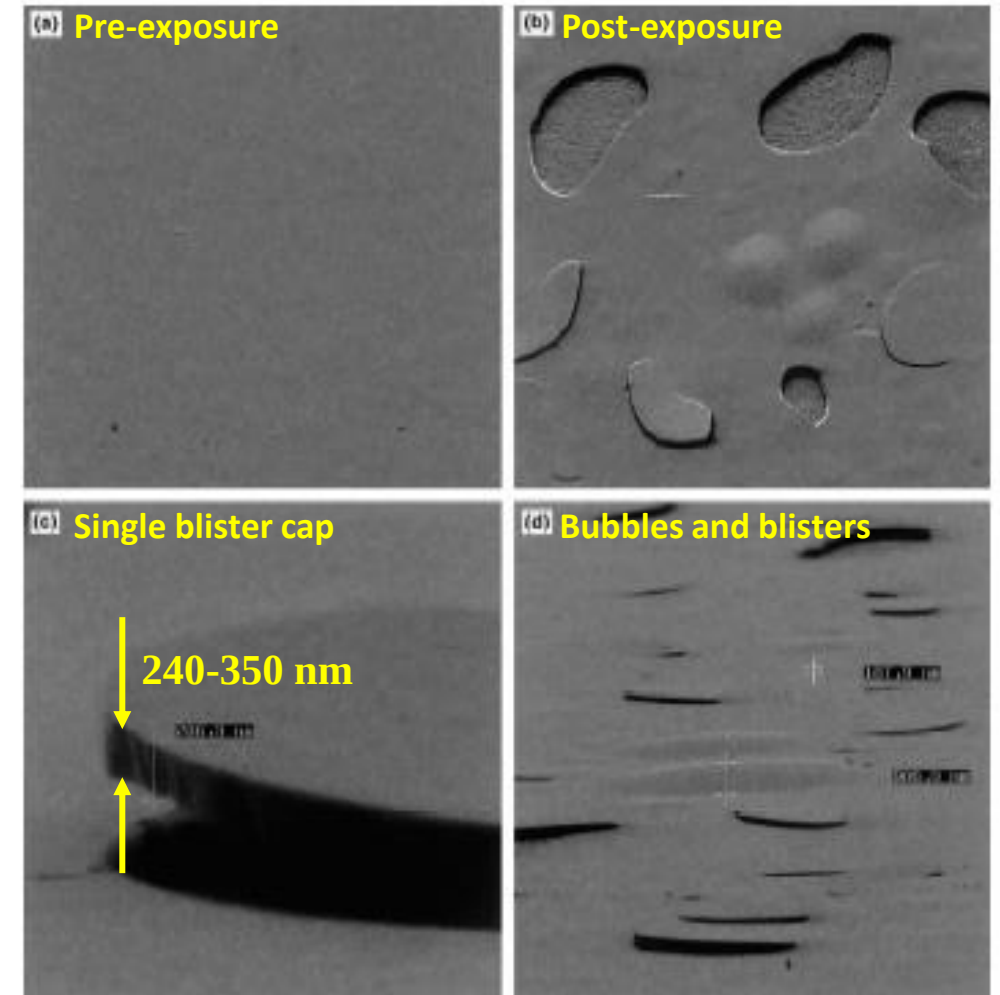
[adapted from *Szanjder and Geppert, 2014*]

Reflectivity of metal foil covered with H_2 bubbles as function of average bubble radius for three bubble surface densities N

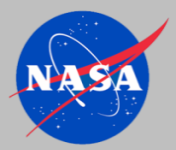
Blister Damage

- NASA evaluated hydrogen blistering in the past and found little concern for damage to exposed surfaces unless spacecraft were flown close to the Sun or exposed to solar wind near Earth for long periods of time (c.f., *Minow et al.*, 2006 and references therein; *Minow and McWilliams*, 2006).
- Information from the literature when this work was done in 2006 suggested the threshold for blister formation was an ion fluence of $\sim 10^{17}$ p/cm²
 - 10-year exposures at 1.0 AU required to reach threshold
- Recent work indicates the fluence threshold for blister formation is on the order of 10^{16} p/cm², an order of magnitude less than reported in earlier work [*Szanjder et al.*, 2014, 2015, 2018, 2019]
- New information on fluence threshold suggests blister damage may form after about a year exposure to solar wind at 1 AU or even quicker at distances closer to the Sun

Shutthanandan et al., 2001

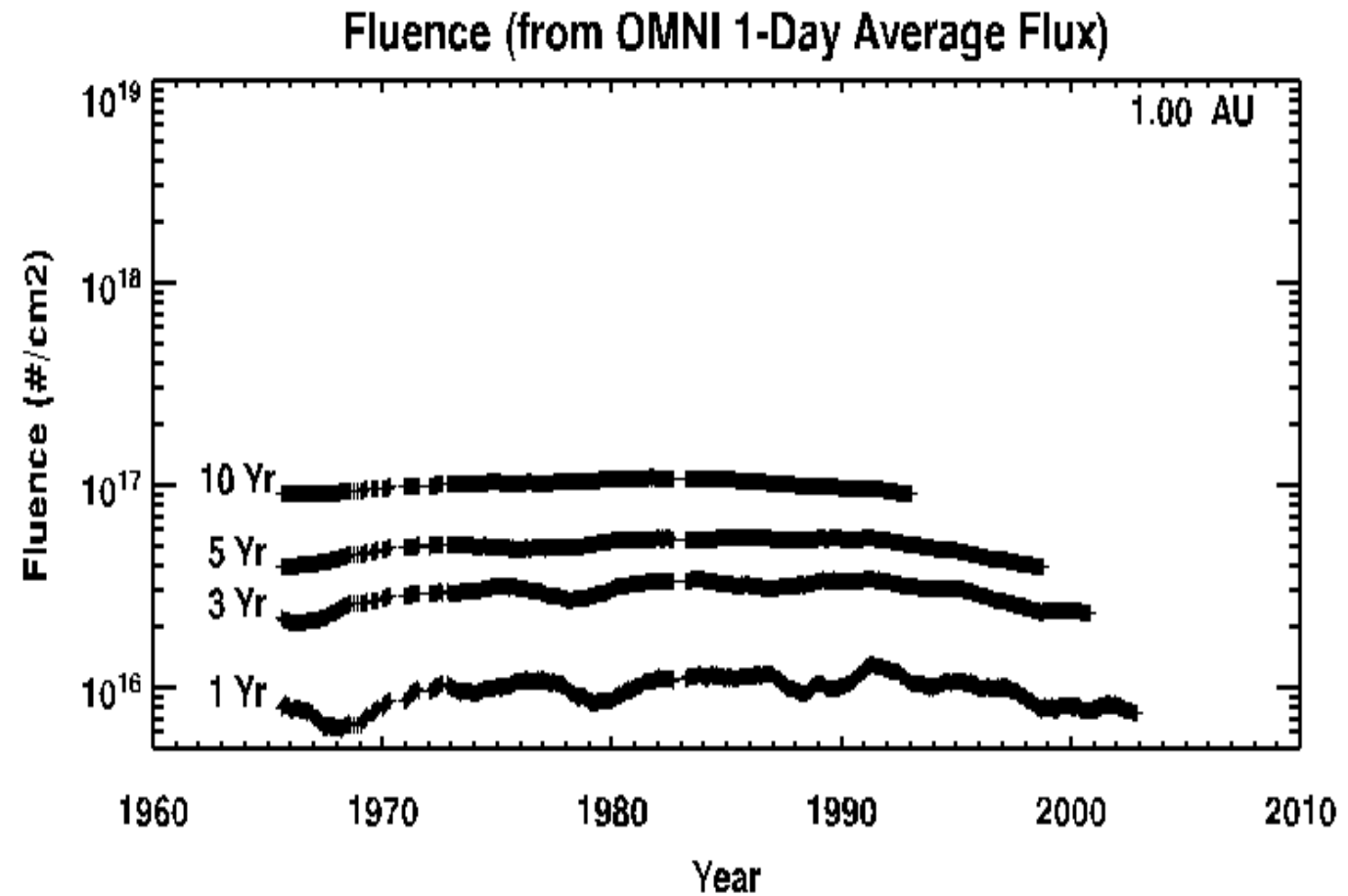


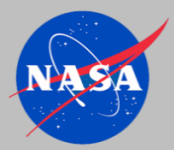
**40 keV H⁺ ions on Y-ZrO₂
 1×10^{17} H⁺/cm² annealed at 770 K**



OMNI Solar Wind Fluence – 1 AU

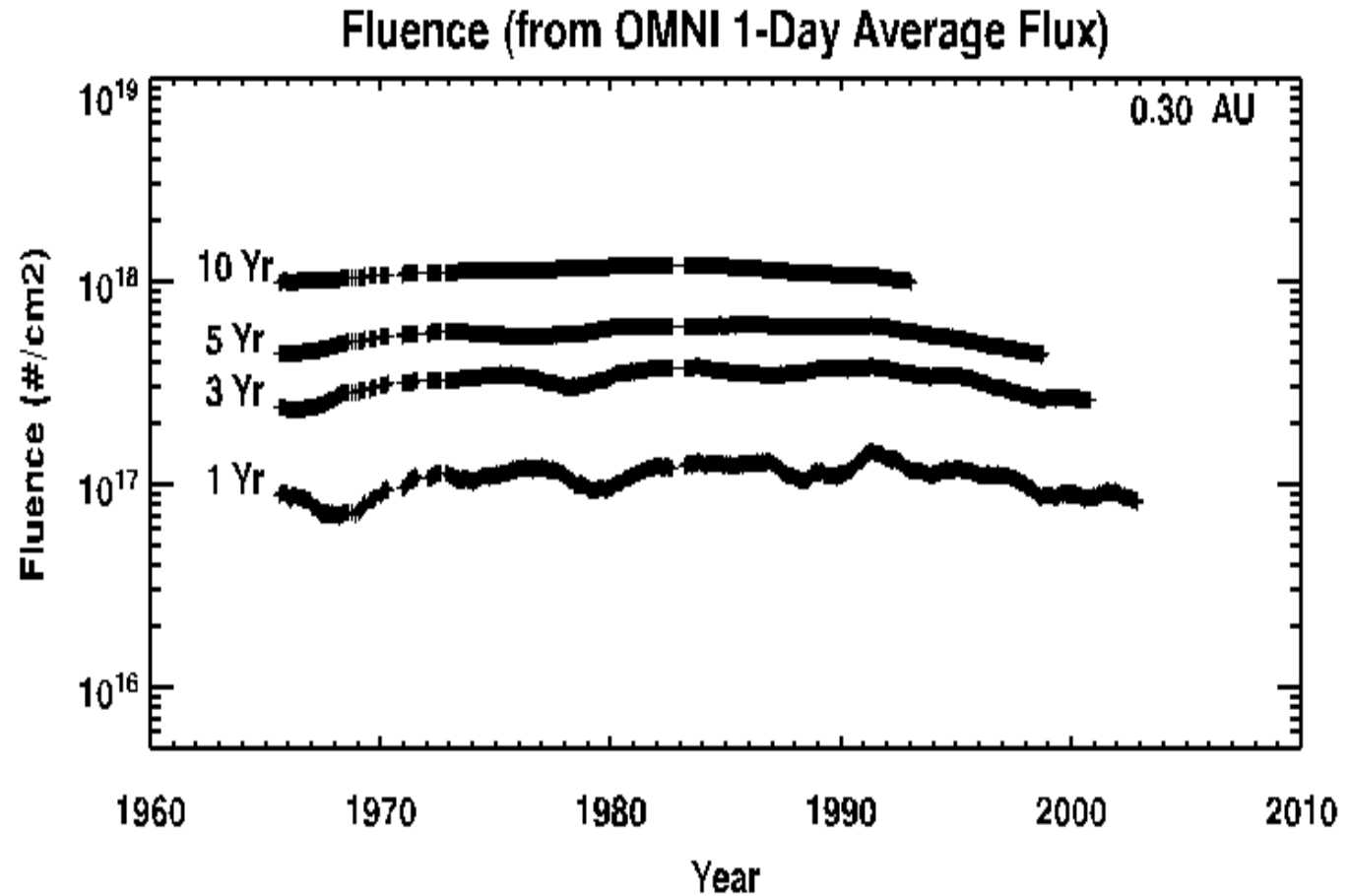
- Running fluence estimate
 - Integrate flux over time to obtain fluence for periods of N years where N = 1, 3, 5, and 10 years
 - Shift start time and integrate again for a new fluence for different time period
 - Repeat for complete data record
- Fluence estimates are based on real time history of measured solar wind N, T, and V values
- Periods of
 - ~10 years required for fluence of $\sim 10^{17}$ H⁺/cm²
 - ~Only 0.6 to ~ 1 year for $\sim 10^{16}$ H⁺/cm²





OMNI Solar Wind Fluence – 0.30 AU

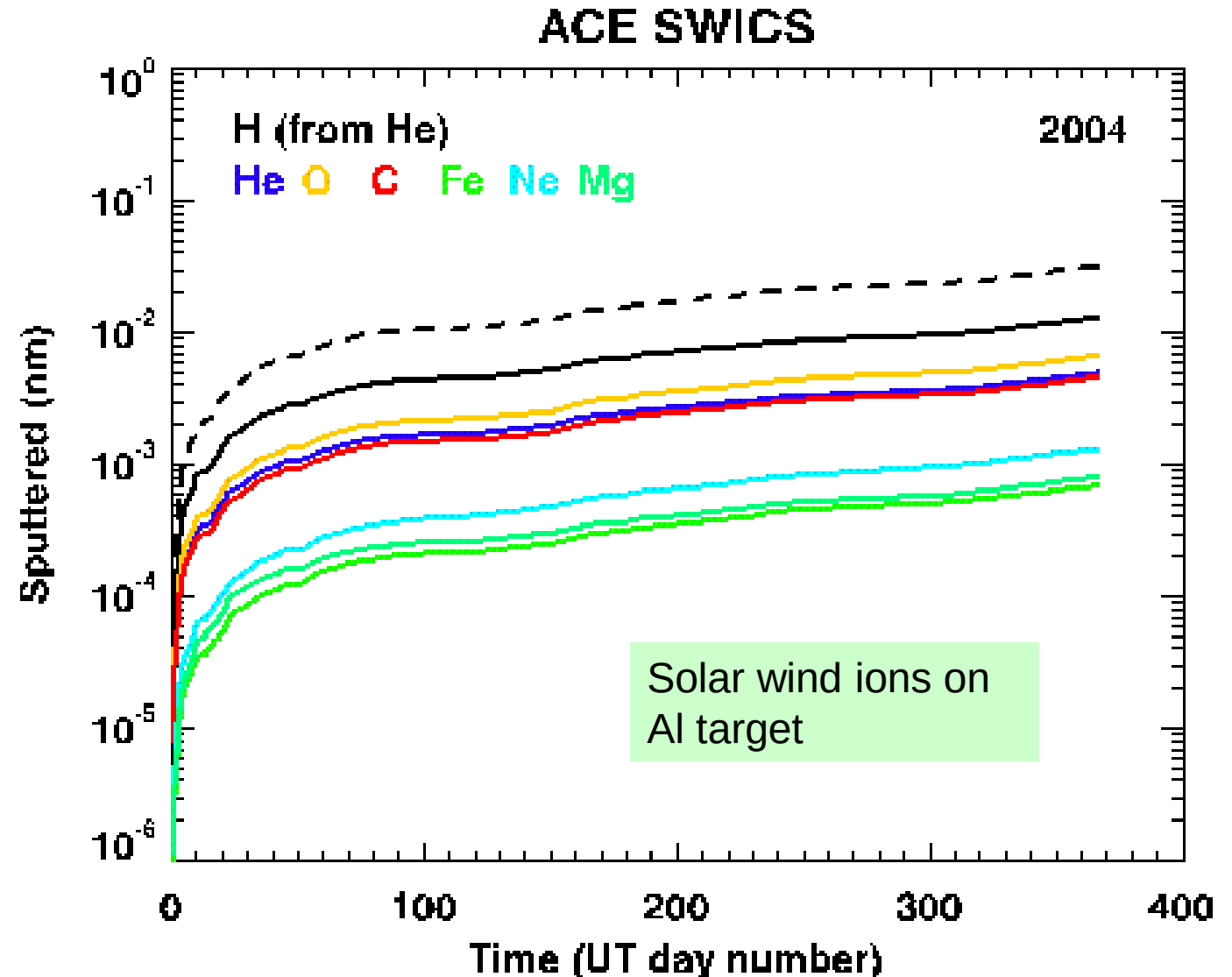
- Running fluence estimate
 - Integrate flux over time to obtain fluence for periods of N years where N = 1, 3, 5, and 10 years
 - Shift start time and integrate again for a new fluence for different time period
 - Repeat for complete data record
- Fluence estimates are based on real time history of measured solar wind N, T, and V values
- Periods of
 - ~10 years required for fluence of $\sim 10^{17} \text{ H}^+/\text{cm}^2$
 - ~Only 0.6 to ~ 1 year for $\sim 10^{16} \text{ H}^+/\text{cm}^2$
- Much higher fluences can be achieved over the same time periods for locations closer to the Sun

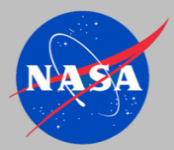


Radial scaling of solar wind parameters

Density	$N \sim 1/R^2$
Velocity	$V \sim \text{constant}$
Temperature	$T \sim 1/R^{0.57}$

- In addition to the work on proton fluence, we have completed a preliminary 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 using data from the ACE SWICS instrument
- 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 but the loss remains only a fraction of a nanometer over a year





Changes in Optical Properties

- *Kan et al., 1972*
 - ZrO₂-pigmented coating $\Delta\alpha_s=0.015$ 3 keV H⁺, H₂⁺ ions at 1.2×10^{16} ions/cm²
- *Breuch, 1967*
 - TiO₂-pigmented silicone (Thermatrol) $\Delta\alpha_s=0.003$ 2 keV H⁺, H₂⁺ ions at 7×10^{15} H⁺/cm²
 - ZnO-pigmented silicate (Z-93) $\Delta\alpha_s=0.002$ 2 keV H⁺, H₂⁺ ions at 8×10^{15} H⁺/cm²
 - Z-93 $\Delta\alpha_s=0.016$ 2 keV H⁺, H₂⁺ ions at 5×10^{15} H⁺/cm²
 - $\Delta\alpha_s=0.029$ 2 keV H⁺, H₂⁺ ions at 8×10^{15} H⁺/cm²
- *Gillette and Brown, 1965*
 - Z-93 $\Delta\alpha_s=0.02$ 8 keV H⁺ at 1×10^{15} H⁺/cm²
 - $\Delta\alpha_s=0.10$ 8 keV H⁺ at 1×10^{16} H⁺/cm²
- *Jorgenson, 1966*
 - Z-93 $\Delta\alpha_s=0.02$ to $\Delta\alpha_s=0.10$ 0.5 keV H₂⁺ at 1×10^{16} H⁺/cm²
 - S-13 $\Delta\alpha_s=0.02$ 0.5 keV H₂⁺ at 1×10^{15} H⁺/cm²
 - $\Delta\alpha_s=0.07$ 0.5 keV H₂⁺ at 1×10^{16} H⁺/cm²