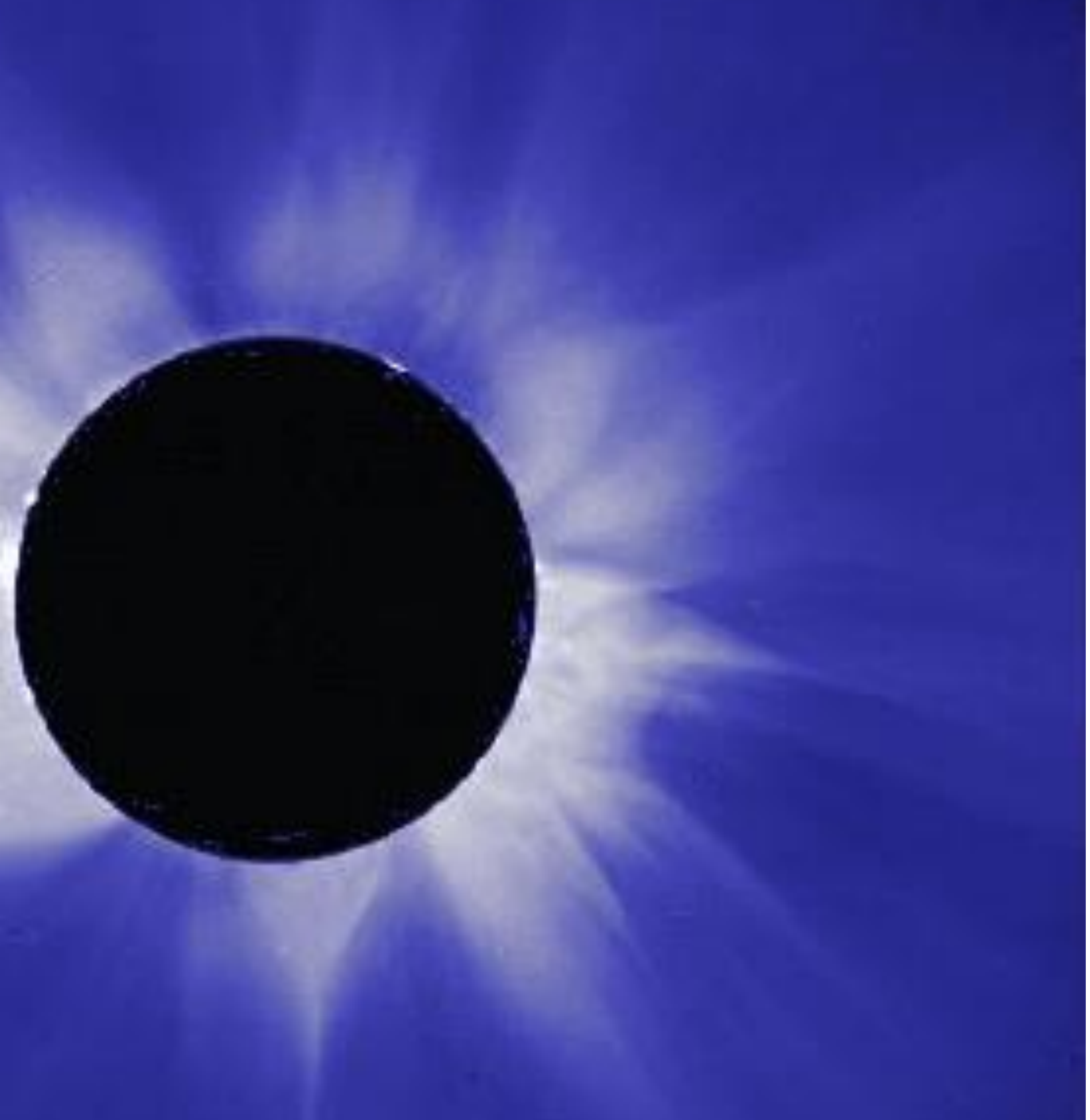

White light image, solar eclipse, India, 16 Feb 1980
Source: High Altitude Observatory/NCAR

Solar Wind as a Space Radiation Environment

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Introduction

- Solar wind, the expansion of the ionized gas in the solar corona into the heliosphere, is a low energy charged particle radiation environment with potential for impact to surfaces of space exposed materials in interplanetary space

- The light ion component is of particular interest since protons with mean energies of about 1 keV are known to damage or degrade the surface of soft metals (e.g., Al, Cu, Au) through a number of processes including sputtering, blistering, and exfoliation of the metal surface

- While the damage is restricted to the surface of the materials, it is a possible concern to space system design where the 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, first surface multilayer insulation, and reflective sunshields

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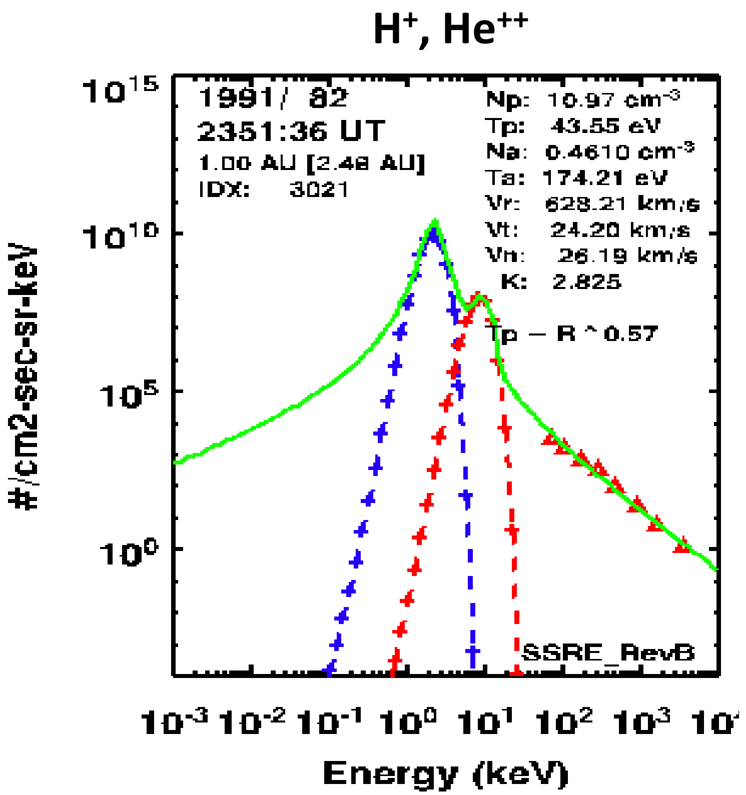
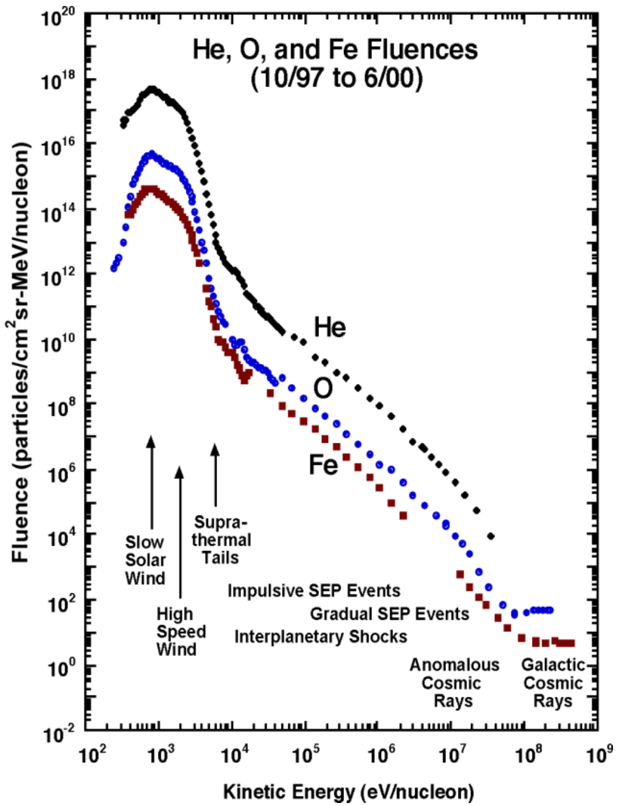
Outline

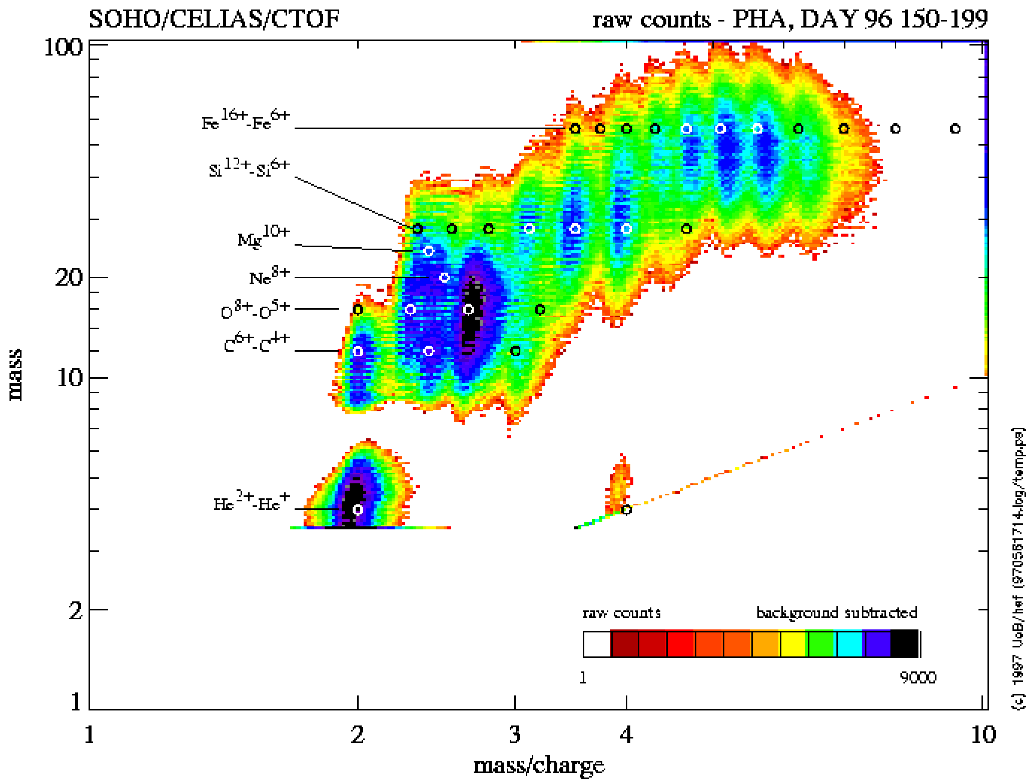
Properties of solar wind ions, flux and fluence
Solar wind as a radiation environment
Proton blistering
Sputtering
Ion flux models and fluence statistics
Blistering onset and sputtering assessment
Summary

Solar Wind Properties

- Solar wind is dominated by hydrogen ions (~96%) with helium the dominant minor species (~3%) and 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.





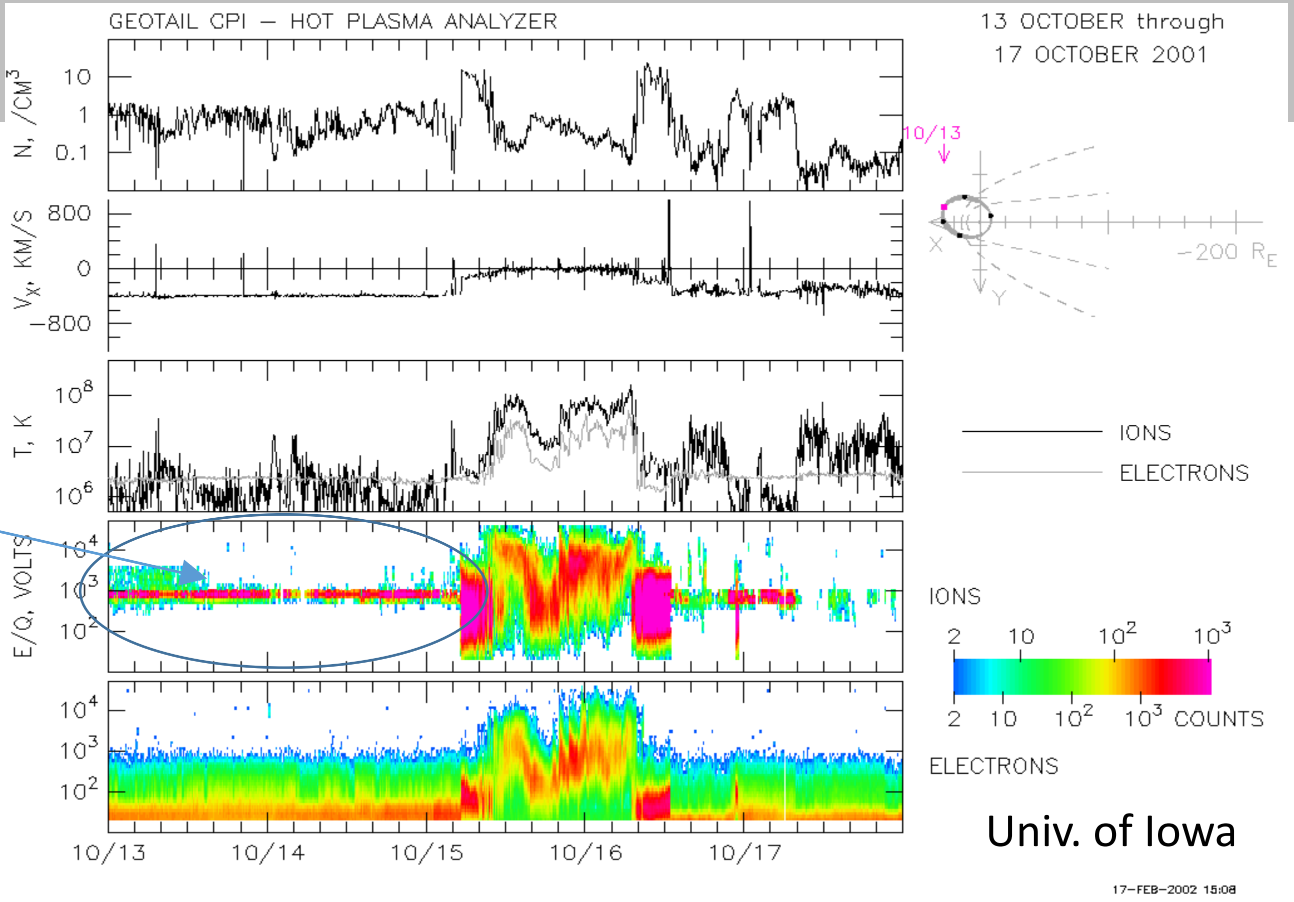


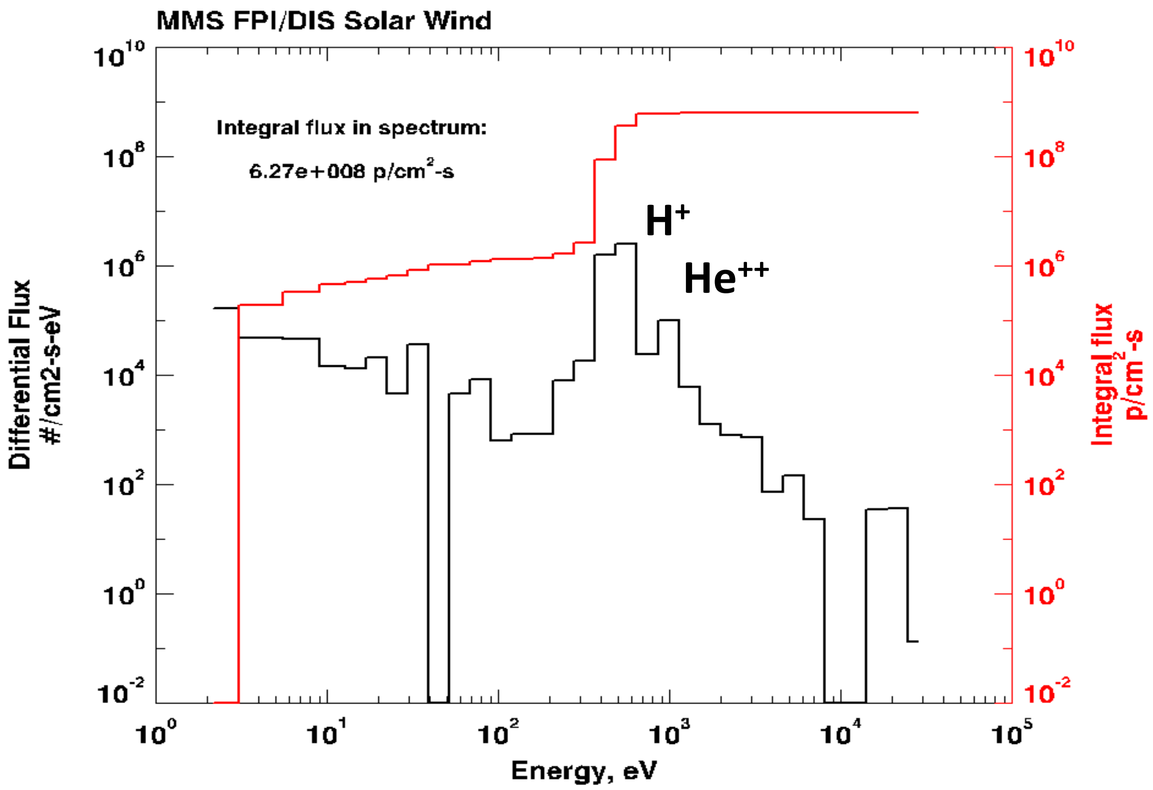
(from R. Mewaldt, G. Gloeckler, and G. Mason)

Example Solar Wind Ion Spectra

Right:

- Geotail ion and electron data for 5 day period (University of Iowa)
- Solar wind is a very narrow beam of ~1 keV ions





Left:

- Differential ion energy spectrum from NASA's MMS spacecraft upstream of Earth in solar wind (data courtesy of M. Chandler, NASA MSFC)
- Differential energy spectrum integrated over energy from ~2 eV to 28 keV
- Total flux in spectrum: 6.3×10^8 p/cm^2-s

Solar Wind Plasma Moments

- The distribution function f(**x**,**v**) describes the position and velocity of all particles in a distribution. Integrating f(**x**,**v**) over space removes the spatial dependence for the velocity distribution f(**v**).

- Moments of the velocity distribution are given by

$$M_n \equiv \int f(\boldsymbol{v})\boldsymbol{v}^n d^3v$$

where the limits of integration are over all velocities.

- The zeroth-order moment gives the number density of all particles in the distribution

$$N = \int f(\boldsymbol{v}) d^3v \text{ particles/cm3}$$

- First-order moment gives the number flux density (or "number flux")

$$N\boldsymbol{V} = \int f(\boldsymbol{v})\boldsymbol{v}\, d^3v \text{ particles/cm2-sec}$$

- The average (or bulk) velocity can be obtained from the number flux as

$$V = N\boldsymbol{V}/\, N \text{ cm/sec}$$

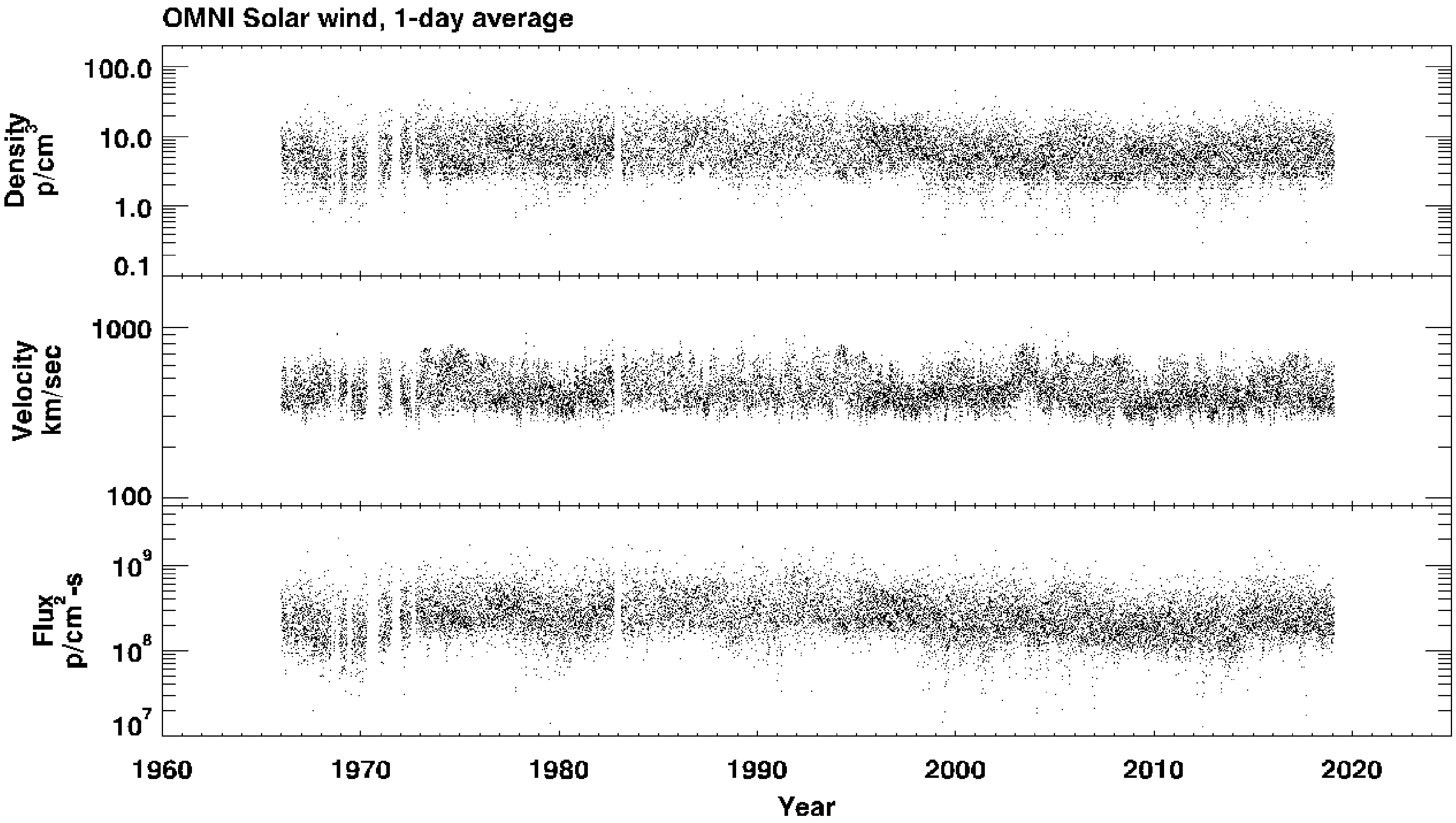
[*Fazakerley et al.*, 1998; *Paschman et al.*, 1998]

GSFC OMNI Solar Wind Velocity, Density Moments and Flux

N’

V = (flux’)/N’

Flux = N’*V
= N’*flux’/N’
= flux’



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

Flux from Maxwellian Distribution Functions

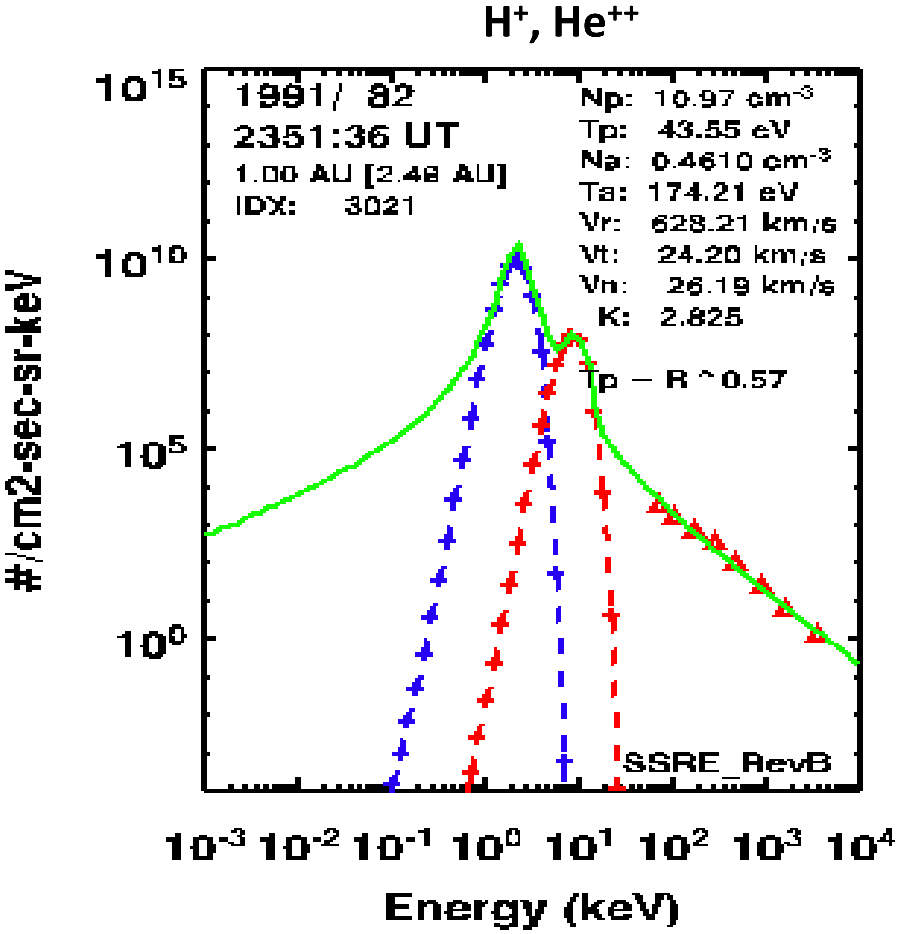
- Directional flux to surface integrated from Maxwellian distribution functions (a good approximations for solar wind ions) is given by

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

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

[*Johnson*, 1990]

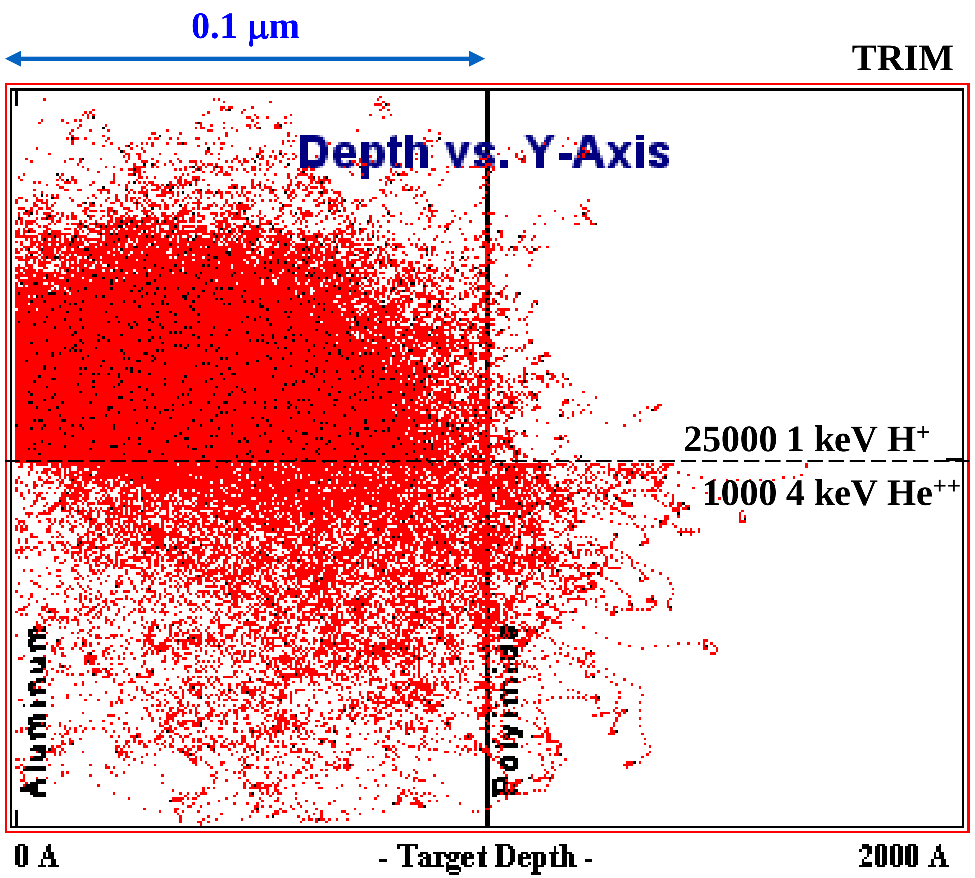
- The moments (N, V) or (N, V, T) obtained from space science data archives are a convenient method for estimating the ion flux and fluer to surfaces in space



Solar Wind as Radiation Environment

- Solar wind is generally considered a benign radiation environment
  - 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^+/cm^3)(450 x10^3 m/s) ~ 3.2x10^8 H^+/cm^2-sec
  - He^{++}/H^+ ~ 0.038 He^{++} flux ~ 0.12x10^8 He^{++}/cm^2-sec
  - Fluence
    - H^+ ~ 9.9x10^{15} H^+/cm^2-year
    - He^{++} ~ 3.8x10^{14} He^{++}/cm^2-year

- Solar wind penetration depths in metals are only fractions of a micron
  - Bulk materials impacted only on "surfaces"
  - 1000 Å (0.1 µm) coating is impacted throughout the material



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

Anderson and Dahms, JSR, 1967

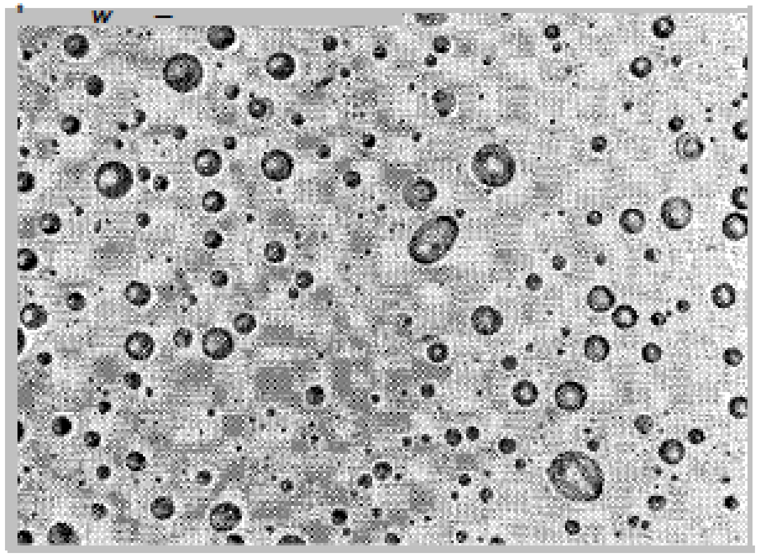
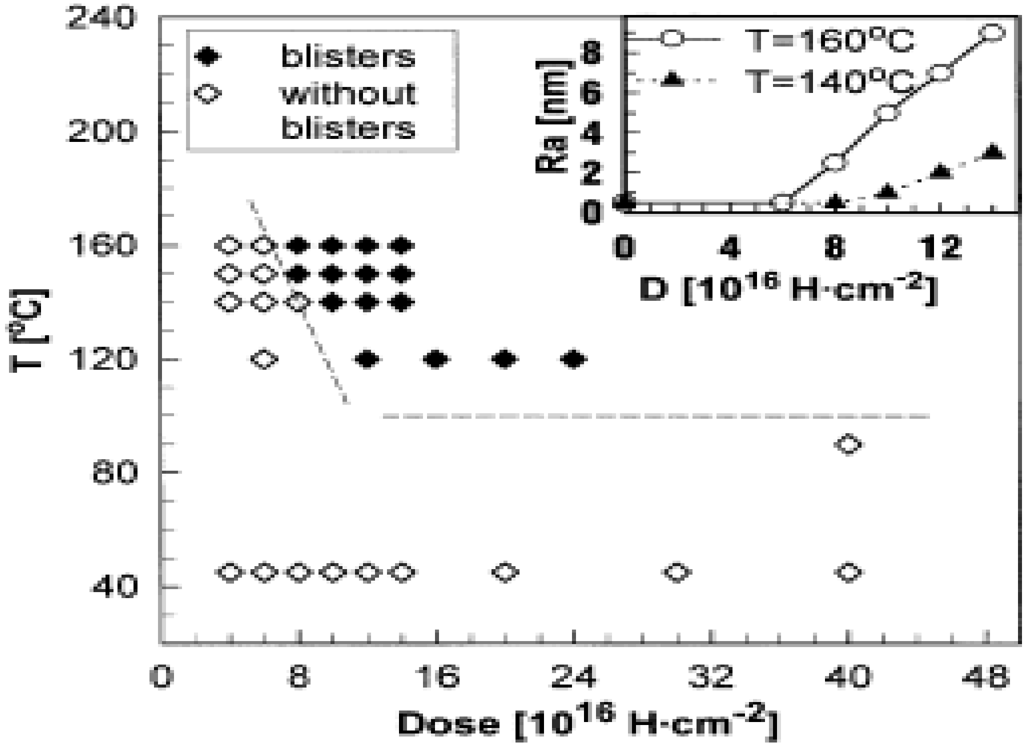


Fig. 1 Photomicrograph of blisters in an 800A gold film over a pure aluminum substrate, after bombardment by 3.2 X 10^{17} ions/cm² (600×) (strong bond).

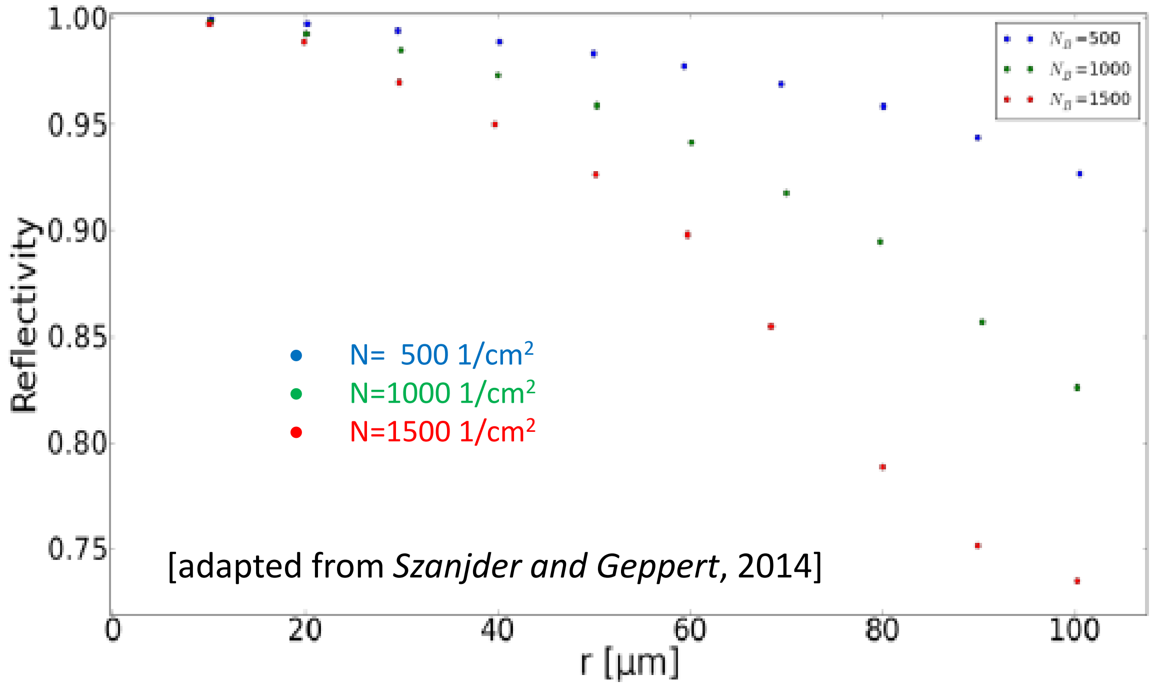
--0.5 to 2 keV H^+ at fluence of 3.2×10^{17} ions/cm^2
--Blisters 1-30 μm in diameter on 60 nm to 100 nm thick Au, Cu, Al coatings
--Blisters sufficient to change absorbance of Au coating by 17%

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)



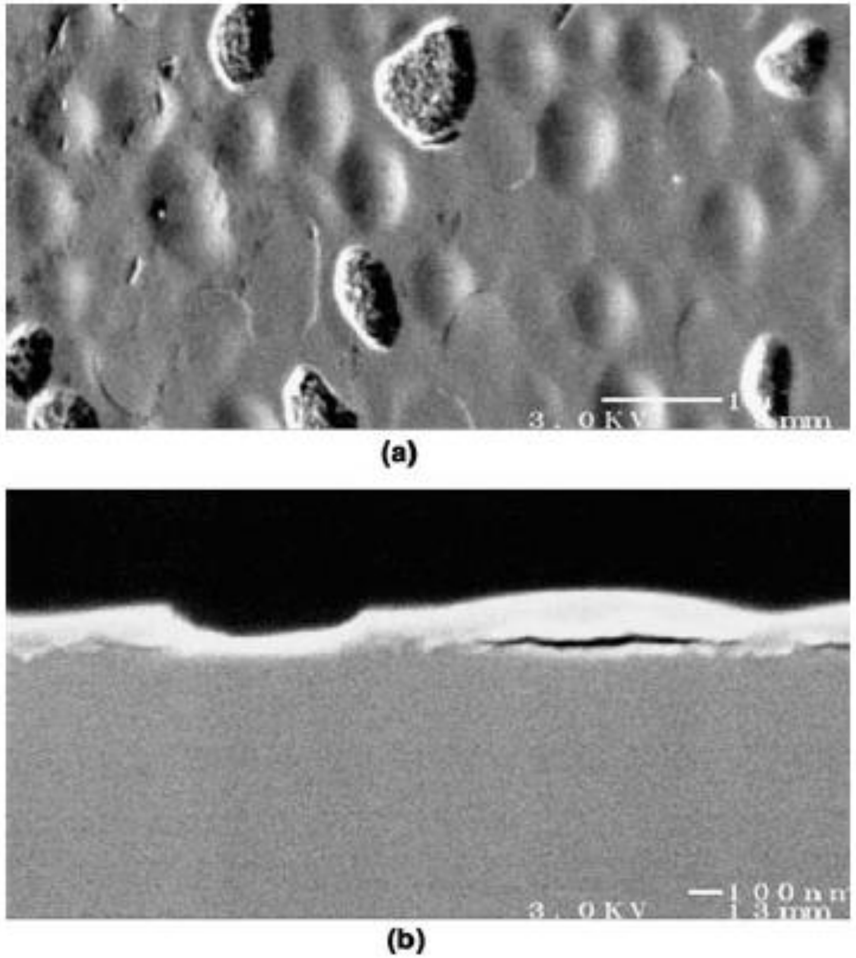
Reflectivity of metal foil covered with H2 bubbles as function of average bubble radius for three bubble surface densities N

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 ~10^{17} p/cm^2
  - 10-year exposures at 1.0 AU required to reach threshold

Giguere et al., 2005



(a) Surface and (b) cross section view

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

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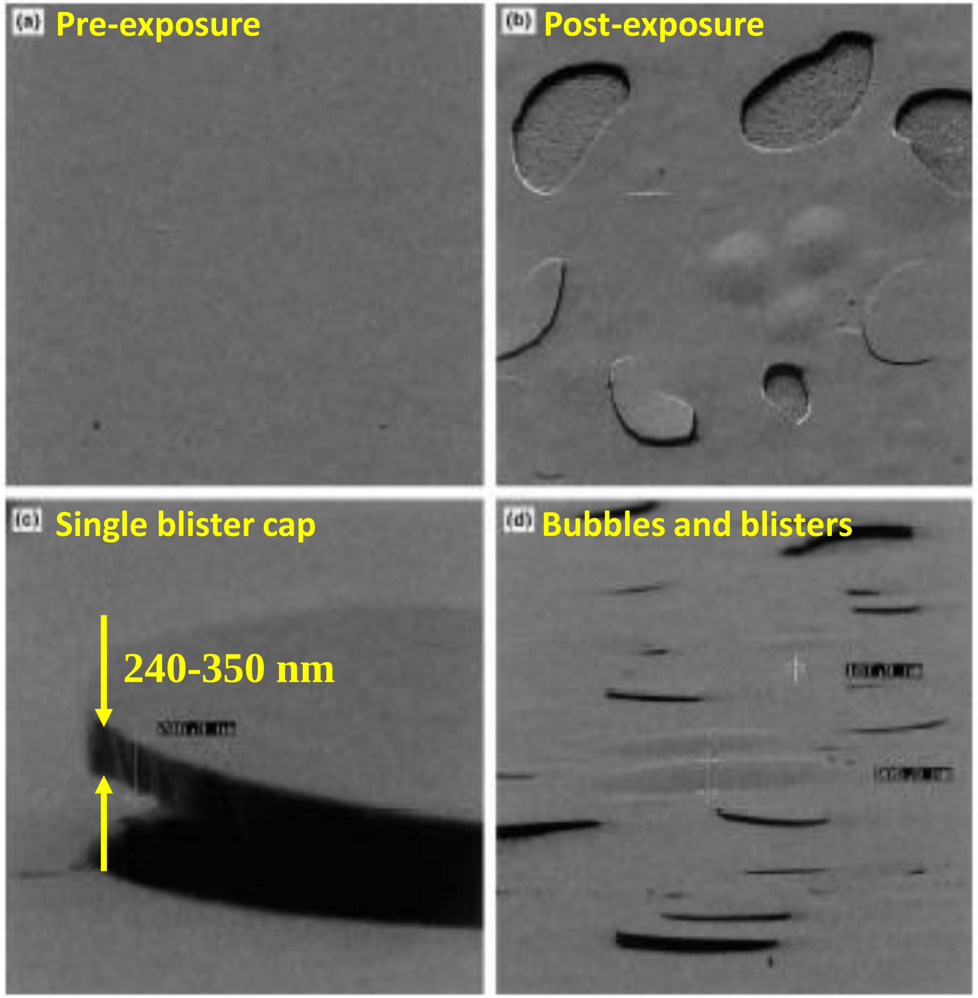
- Recent work indicates the fluence threshold for blister formation is on the order of 10^{16} p/cm^2, an order of magnitude less than reported in earlier work [*Szanjder et al*., 2014, 2015, 2018, 2019]

- New information on fluence threshold suggests blister damage many 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-ZrO_2
1x10^{17} H^+/cm^2 annealed at 770 K

Solar Wind Sputtering Damage

- Numerous studies conducted in the 1960's and 1970's to assess the potential impact of solar wind ions on spacecraft surfaces demonstrated that ions of solar wind energies can alter the 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 ~$2x10^8$ particles/cm^2-sec from Mariner II observations [*Neugebauer and Snyder*, 1962] and assumed the ion flux was composed of
  - ~2 keV hydrogen ions at $1x10^8$ protons/cm^2-sec (fluence of $3.2x10^{15}$ protons/cm^2-year)
  - ~8 keV helium ions at 0.7x108 alphas/cm2-sec (a fluence of $2.2x10^{15}$ alphas/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 $1.0x10^{17}$ protons/cm^2
  - Surface is not degraded and in fact may become smoother and more reflective due to the ion interaction with the mirror coating.

Changes in Optical Properties

- *Kan et al.*, 1972
  - ZrO_2-pigmented coating — $\Delta\alpha_S$=0.015 3 keV H^+, H_2^+ ions at 1.2x10^{16} ions/cm^2

- *Breuch*,1967
  - TiO_2-pigmented silicone (Thermatrol) — $\Delta\alpha_S$=0.003 2 keV H^+, H_2^+ ions at 7x10^{15} H^+/cm^2
  - ZnO-pigmented silicate (Z-93) — $\Delta\alpha_S$=0.002 2 keV H^+, H_2^+ ions at 8x10^{15} H^+/cm^2
  - Z-93 — $\Delta\alpha_S$=0.016 2 keV H^+, H_2^+ ions at 5x10^{15} H^+/cm^2

  $\Delta\alpha_S$=0.029 2 keV H^+, H_2^+ ions at 8x10^{15} H^+/cm^2

- *Gillette and Brown*, 1965
  - Z-93 — $\Delta\alpha_S$=0.02 8 keV H^+ at 1x10^{15} H^+/cm^2

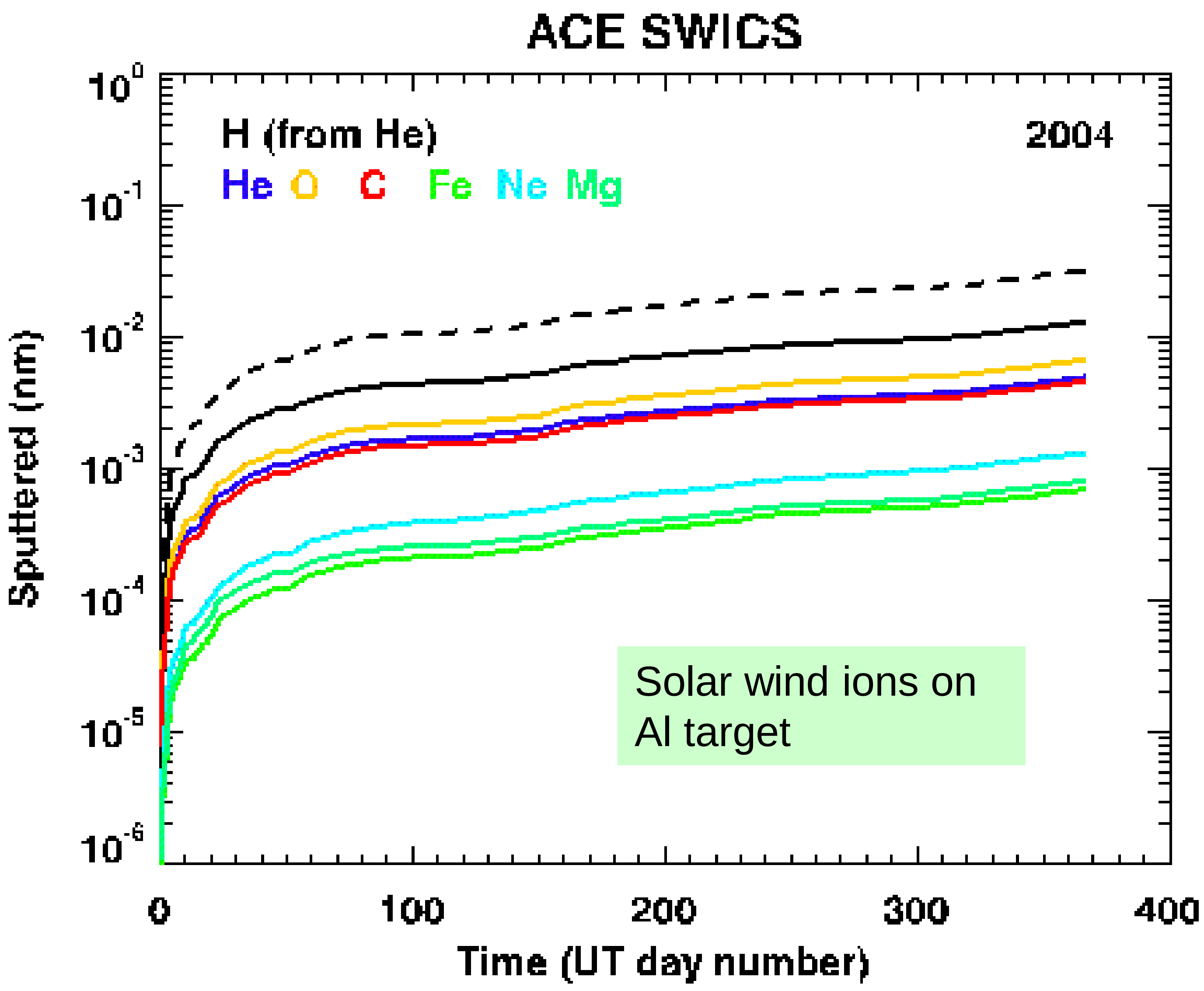
  $\Delta\alpha_S$=0.10 8 keV H^+ at 1x10^{16} H^+/cm^2

- *Jorgenson,* 1966
  - Z-93 — $\Delta\alpha_S$=0.02 to $\Delta\alpha_S$=0.10 0.5 keV H_2^+ at 1x10^{16} H^+/cm^2
  - S-13 — $\Delta\alpha_S$=0.02 0.5 keV H_2^+ at 1x10^{15} H^+/cm^2

  $\Delta\alpha_S$=0.07 0.5 keV H_2^+ at 1x10^{16} H^+/cm^2

Light, Heavy Ion Sputtering

- 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



Solar Wind Flux and Fluence Statistics

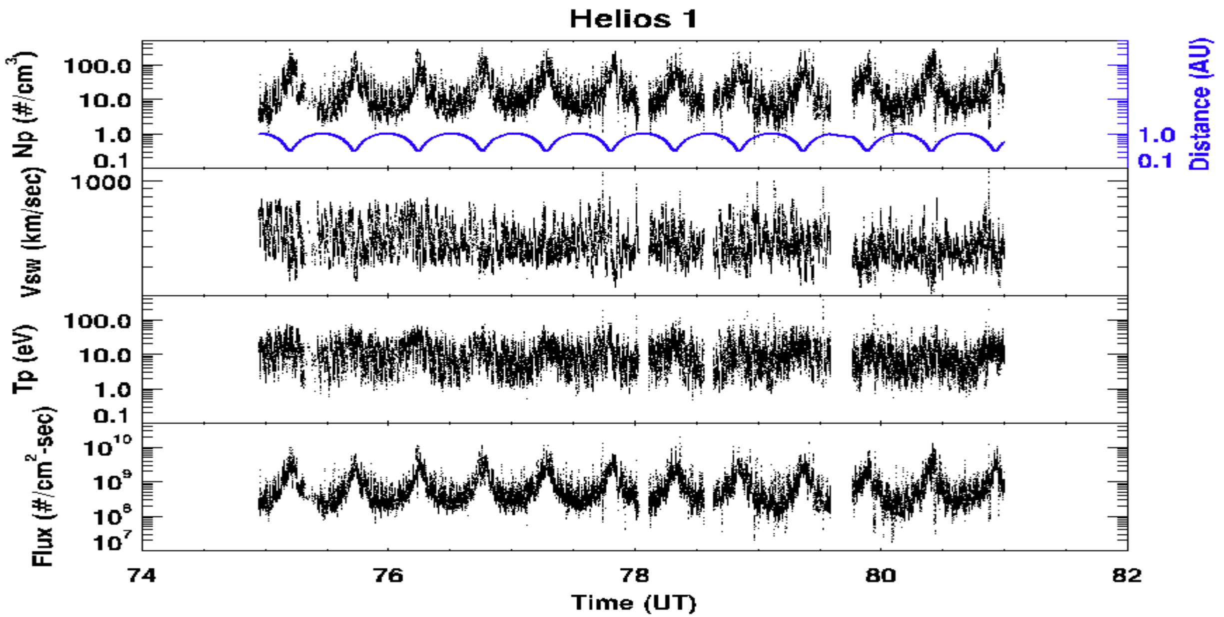
- Now let's examine the question of how long an exposure to the solar wind is require to reach a proton fluence in the 10^{16} H^+/cm^2 to 10^{17} H^+/cm^2 range required to generate blister damage or produce moderate changes in optical properties

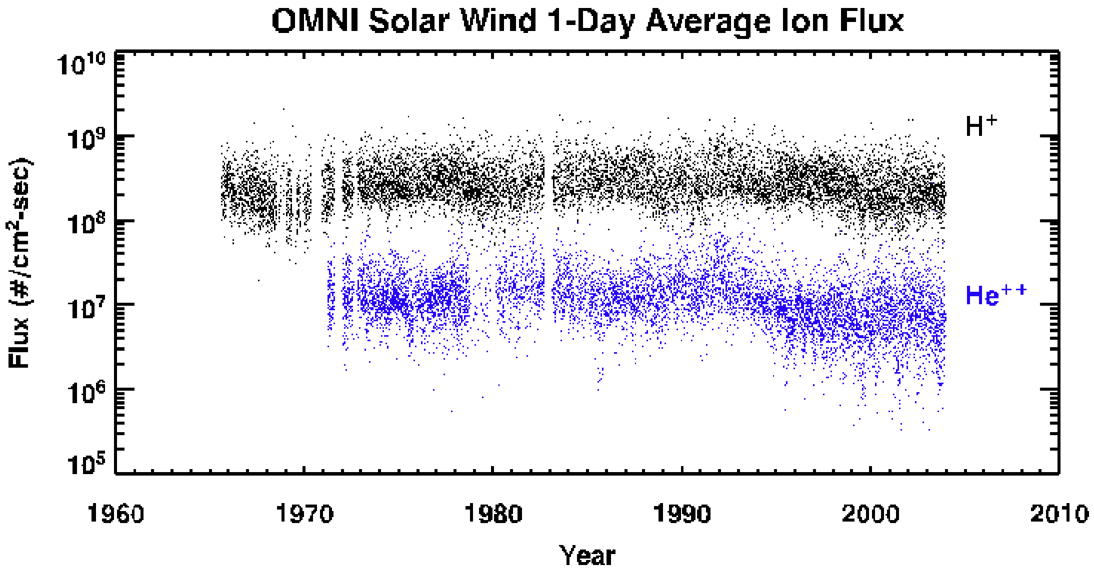
- Solar wind flux decreases as a function of radial distance from the Sun so exposures can be shorter at distances less than 1 AU
  - Density $N \sim 1/R^2$
  - Velocity $V \sim$ constant
  - Temperature $T \sim 1/R^{0.57}$

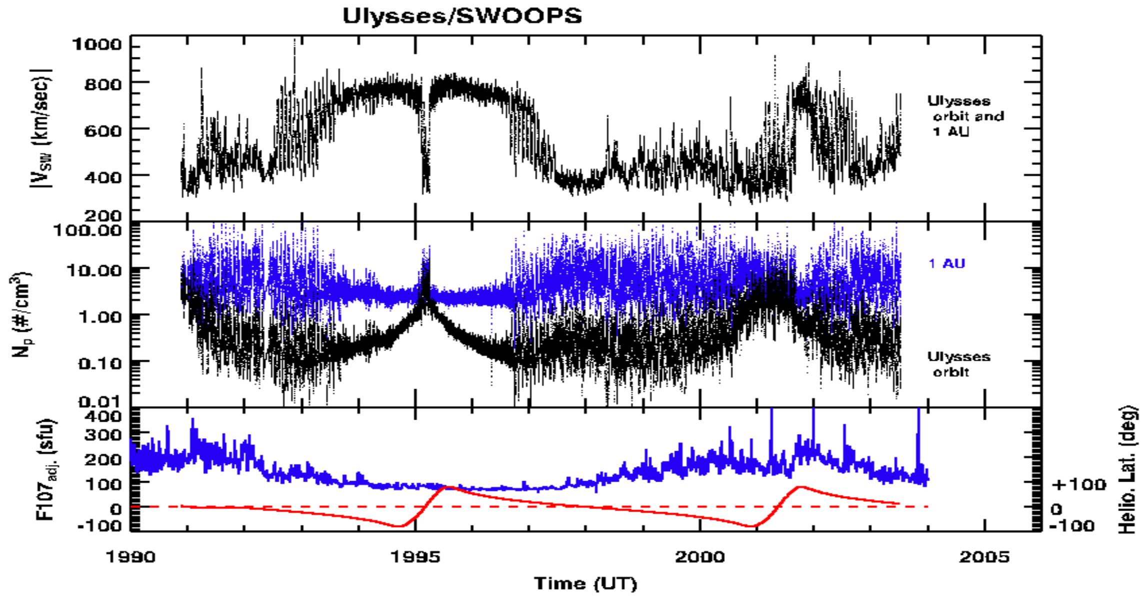
- Archives of solar wind plasma moments provide the long term data sets to estimate the quantities we seek…..

Solar Wind Data Sources

- Sources
  - Ulysses ~2 x 5 AU, ~19 years
  - IMP-8 ~35 R_E, 30+ years
  - Helios 1,2 ~0.31 to 1.0 AU, ~6 years
  - Genesis L1, ~3 years
  - ACE L1, ~23 years
  - WIND L1 (and to L2), ~26 years
  - DSCOVR L1, ~4+ years







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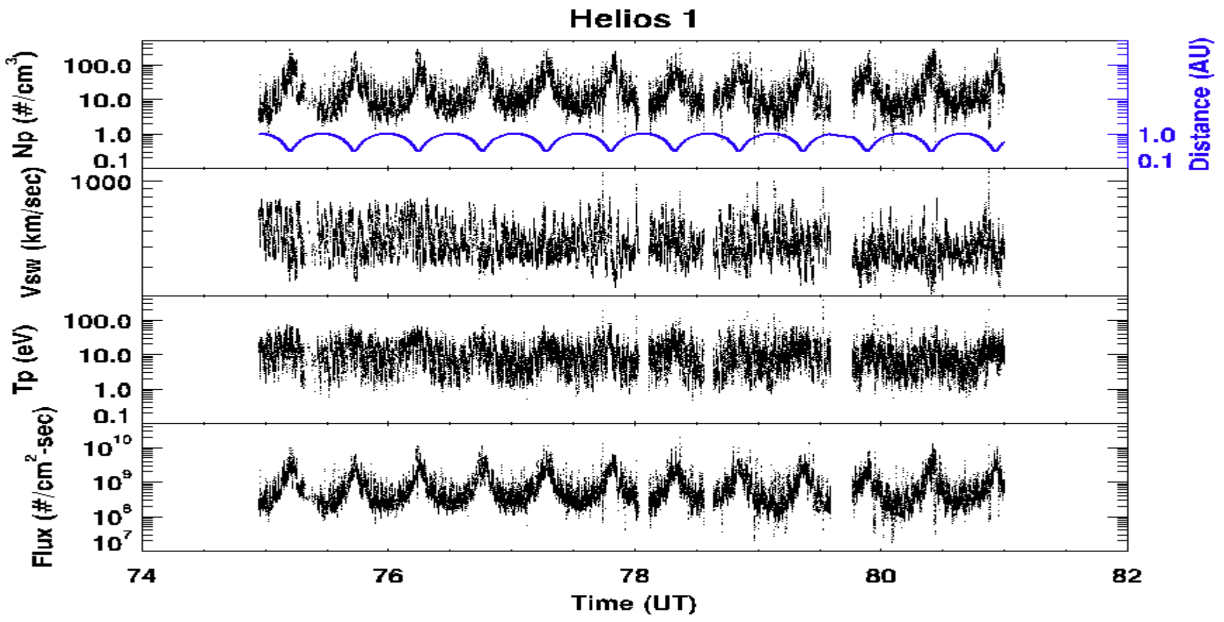
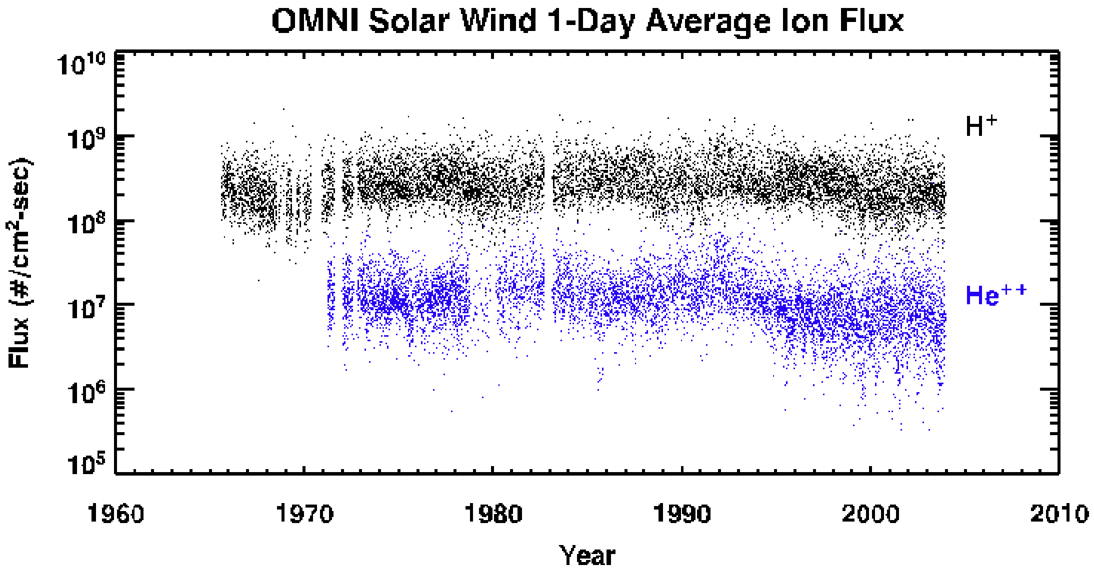
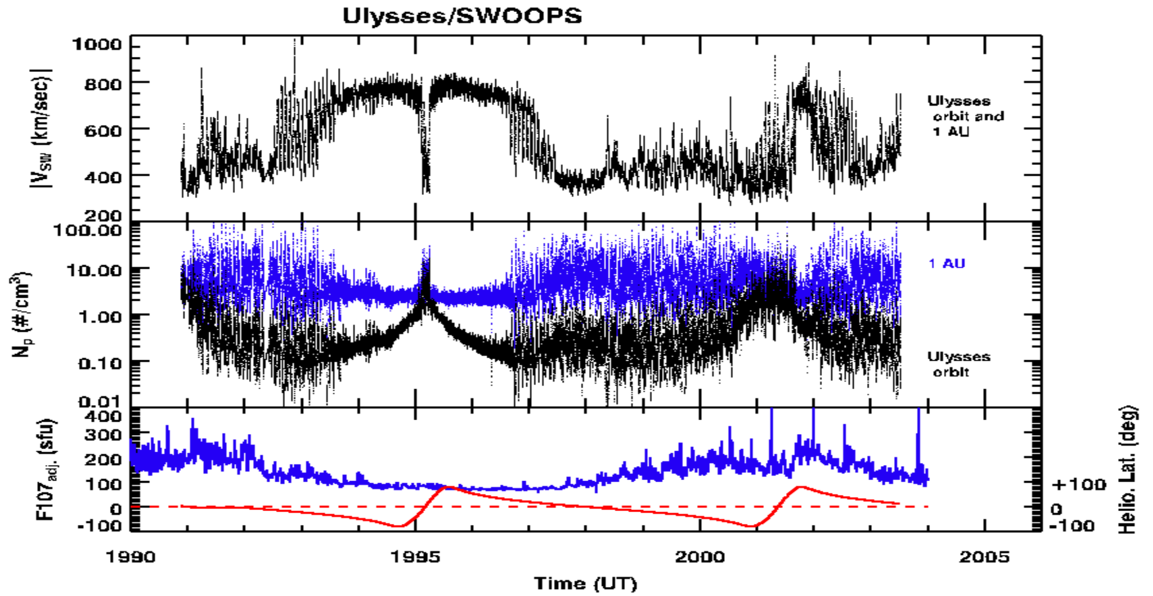
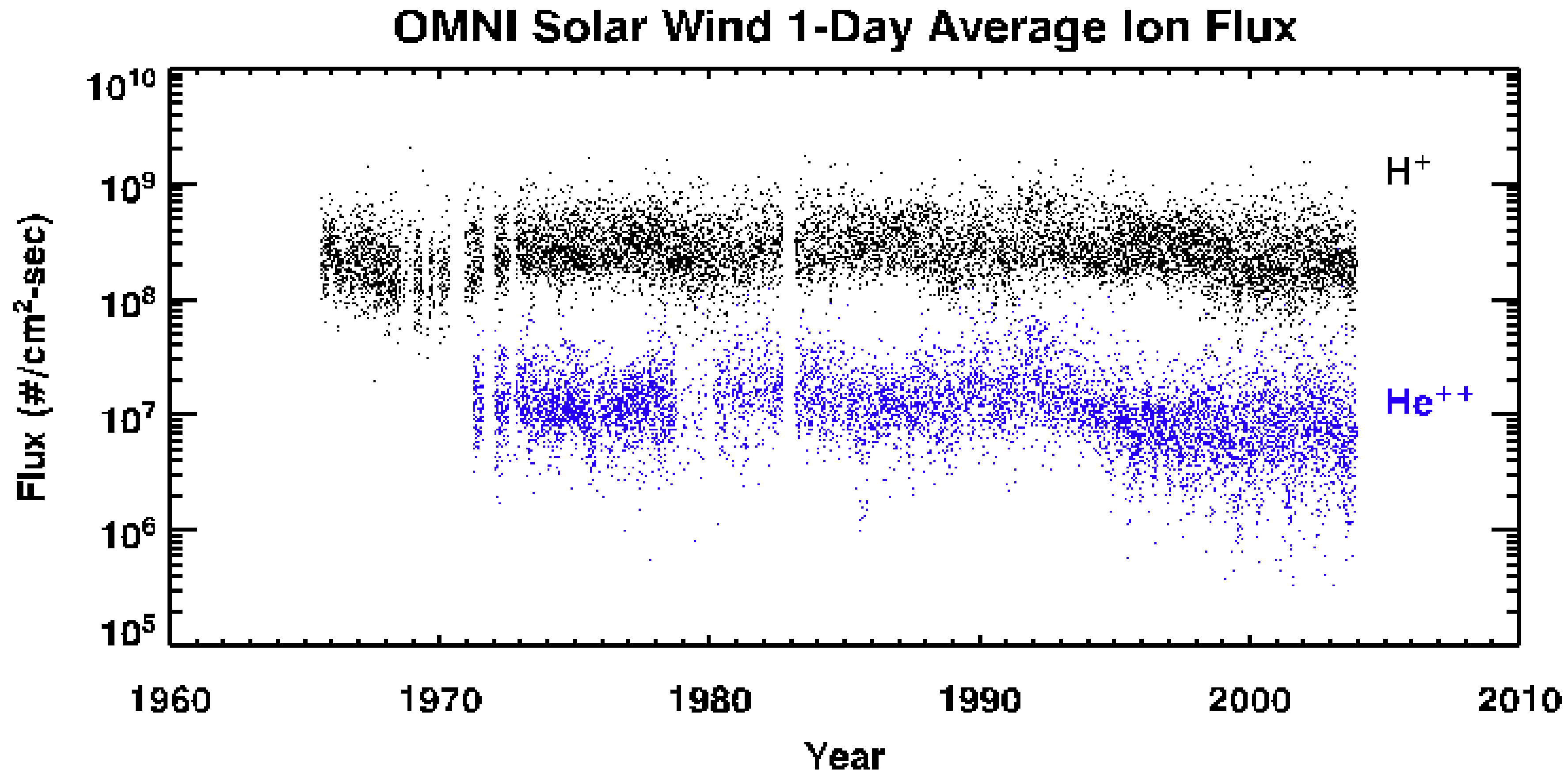






OMNI Solar Wind Flux

- OMNI hourly average solar wind moments are excellent source of data to examine variations in solar wind ion fluence at 1 AU for extended periods of time to determine mean, extreme environments for radiation damage studies (Source: https://omniweb.gsfc.nasa.gov/)



OMNI Solar Wind Fluence – 1 AU

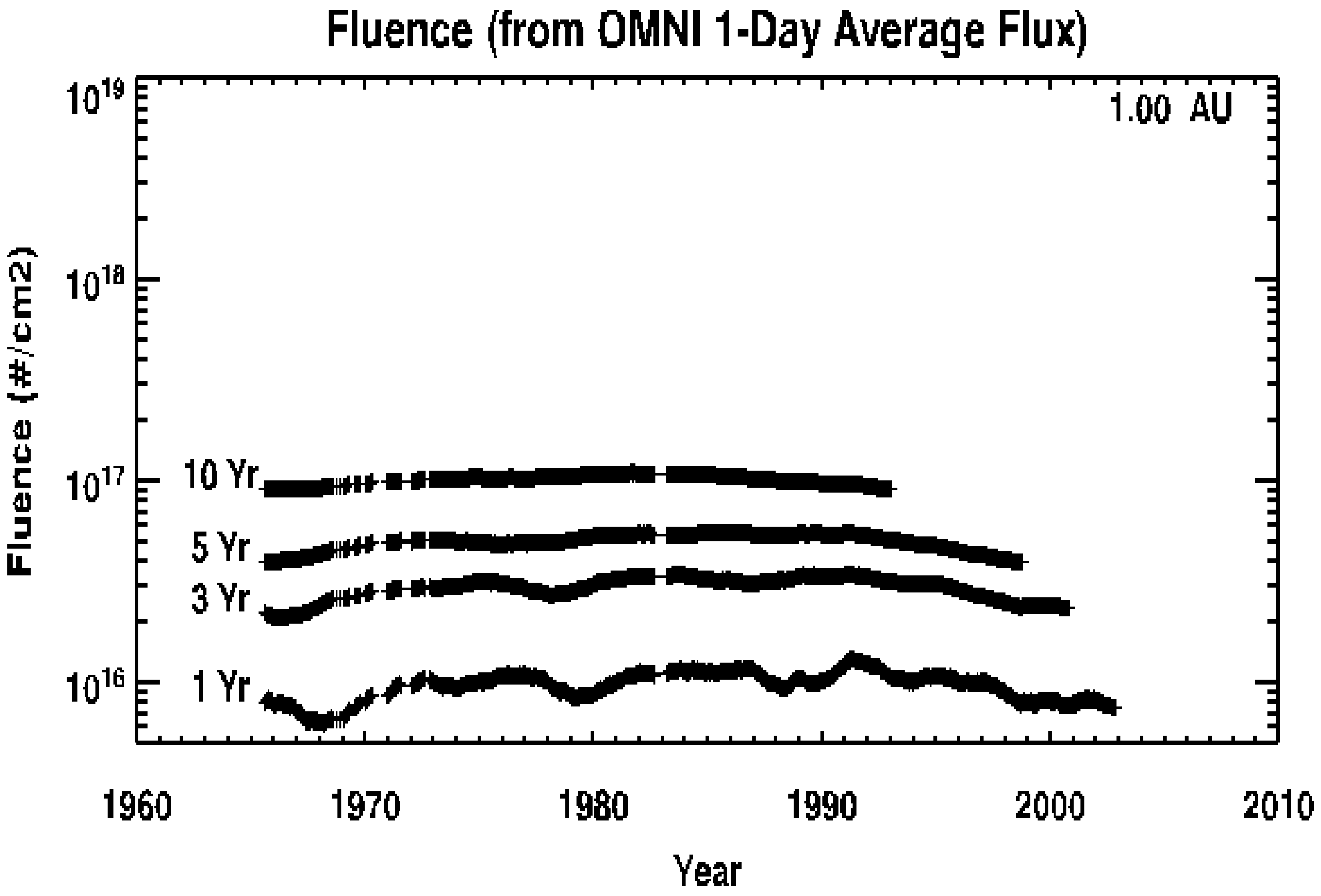
- Running fluence estimate
  - Integrate flux over time to obtain fluence for periods of N years where N = 1, 3, 5, and 10 years
  - Shift start time and integrate again for a new fluence for different time period
  - Repeat for complete data record

- 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 ~10^{17} H^+/cm^2

  ~Only 0.6 to ~ 1 year for ~10^{16} H^+/cm^2



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

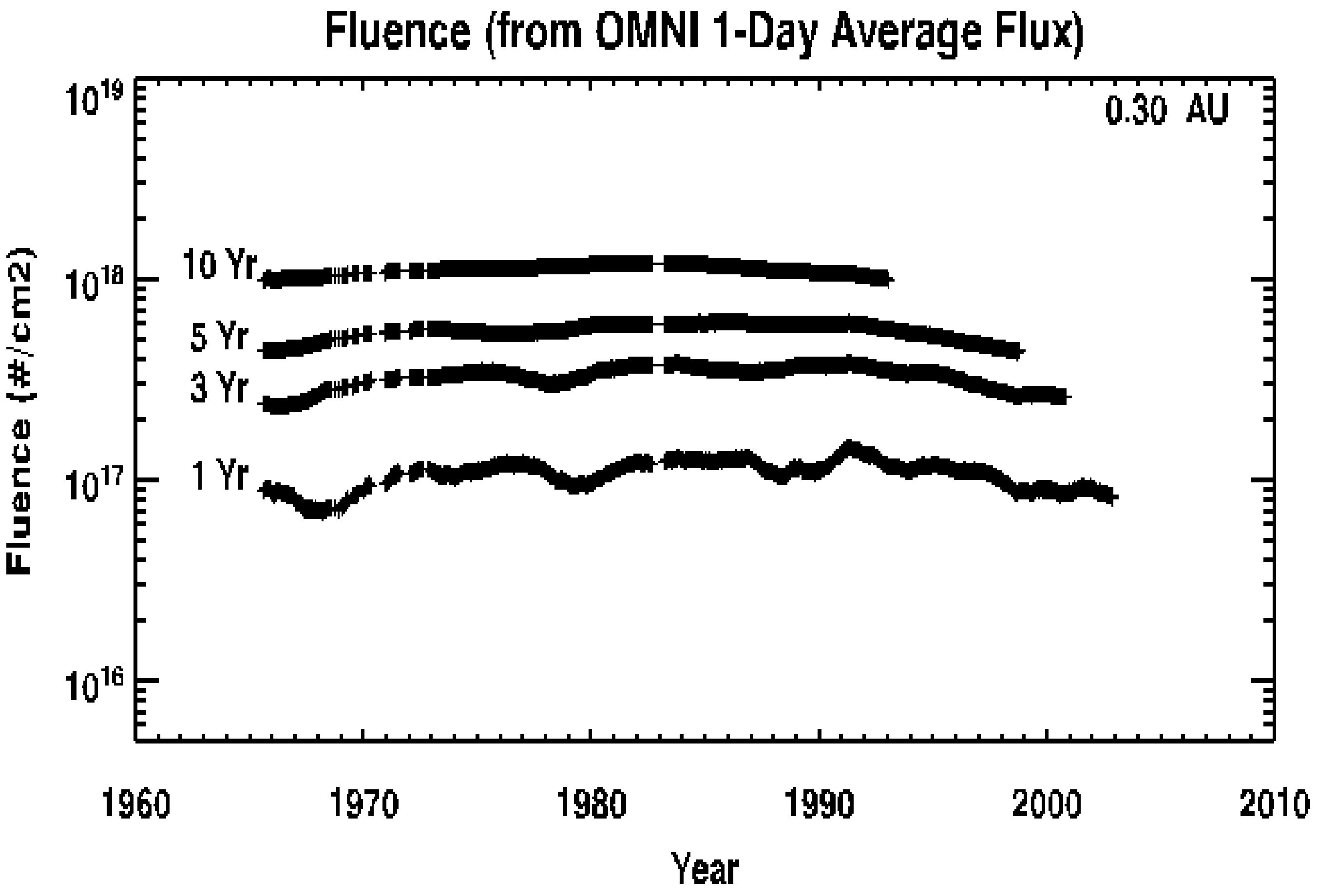
- Fluence estimates are based on real time history of measured solar wind N, T, and V values

- Periods of

  ~10 years required for fluence of ~10^{17} H^+/cm^2

  ~Only 0.6 to ~ 1 year for ~10^{16} H^+/cm^2

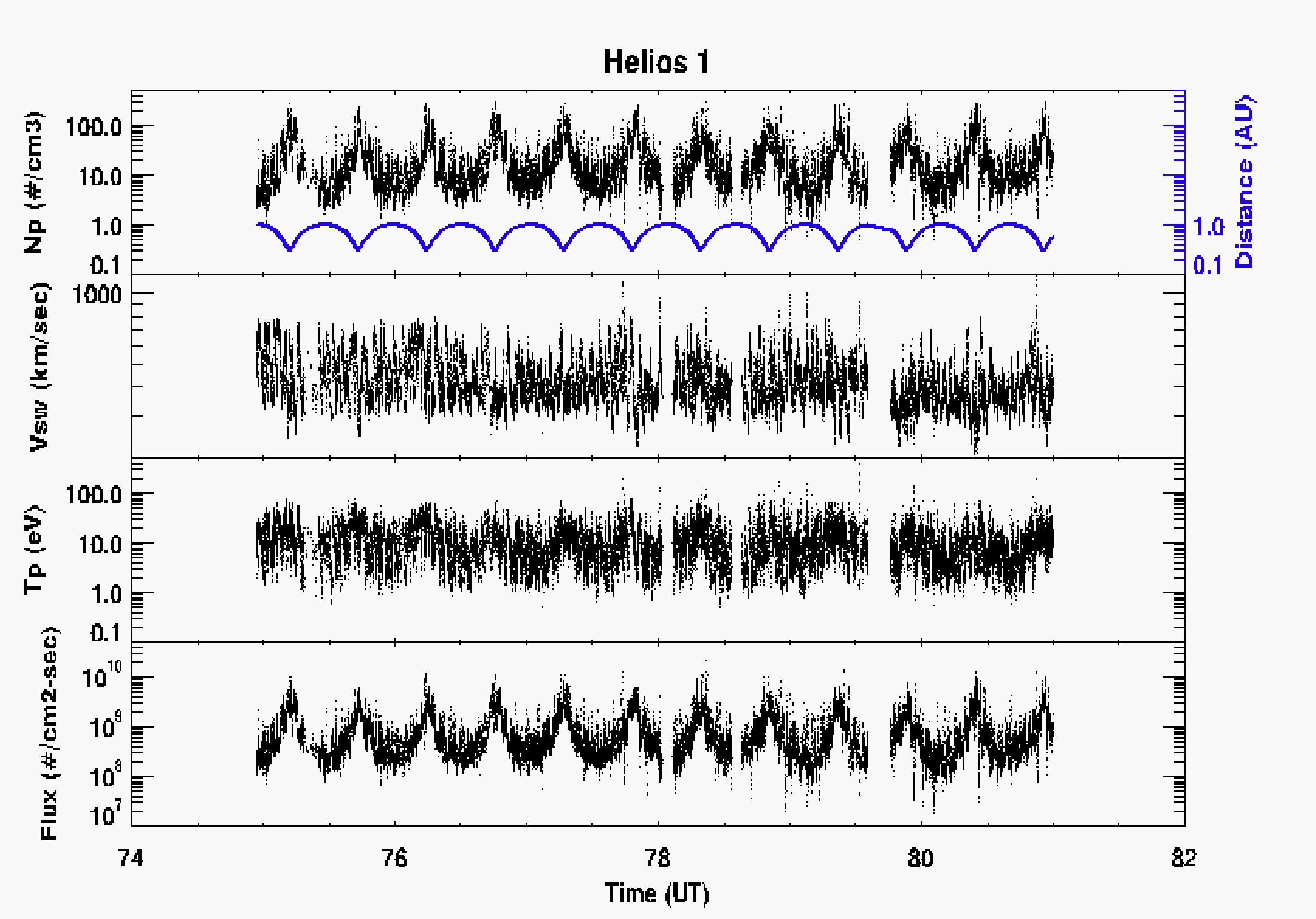
- Much higher fluences can be achieved over the same time periods for locations closer to the Sun



Example: Verify Increased Fluence with Helios 1 Data

- Helios 1 spacecraft provides a good example of proton fluences accumulated on spacecraft surfaces for missions to the inner heliosphere

- Helios 1 spacecraft
  - — One of two spacecraft launched into inner solar system to study solar processes
  - — Helios 1 launched 10 December 1974 and operational until 1985
  - — Orbit: 0.31 AU x 0.99 AU x 0.02° inclination
  - — Plasma Instrument Investigation instrument developed by Max Planck Institute measured low energy solar wind ion and electron plasma parameters
  - — H^{+}, He^{++} ions over range of energies from 231 eV to 16 keV



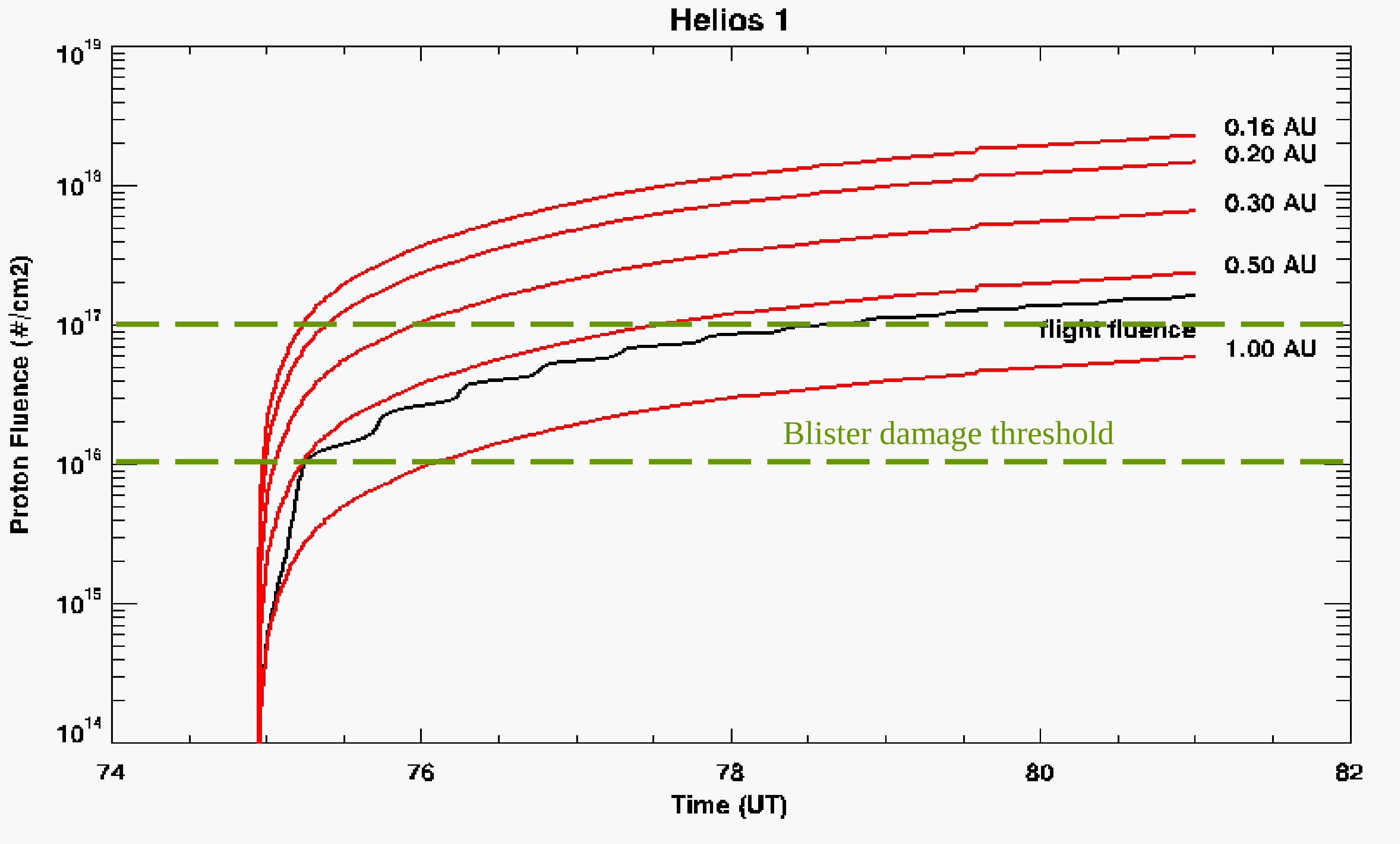
Helios 1 Mission Fluence

- Helios N, V, T ion moments used to generate flux: $\Gamma = \left(\frac{N_o}{2\beta\pi^{\frac{1}{2}}}\right)\left[\exp(-S^2\cos^2\theta) + \pi^{\frac{1}{2}} S\cos\theta\{1 + \mathrm{erf}(S\cos\theta)\}\right]$ [*Johnson*, 1990]

- (Black) Integrate flux over mission elapsed time to obtain mission fluence

- (Red) Flux scaled to fixed radial distance from Sun demonstrates time to reach the fluence threshold derived from Helios 1 records

- Time to ~10^{16} H^+/cm^2 fluence is ~1 year at 1 AU but much less than a year for locations closer to the Sun



Summary

- Interplanetary H^+ ion fluence can reach values where blister damage has been reported for materials in laboratory measurements (especially metals)

- Long exposures at distances of 1 AU from the Sun
  - ~10 years to fluence of ~10^{17} H^+/cm^2
  - ~ 1 year to fluence of ~10^{16} H^+/cm^2, potential issue for some missions, needs to be evaluated on case basis

- Threshold fluence for blister damage can be reached within a year for missions in the inner heliosphere, particularly for distances ≤0.5 AU from the Sun

- Solar wind sputtering not expected to be important