What does Mars' Upper Atmosphere have to do with its Climate History?

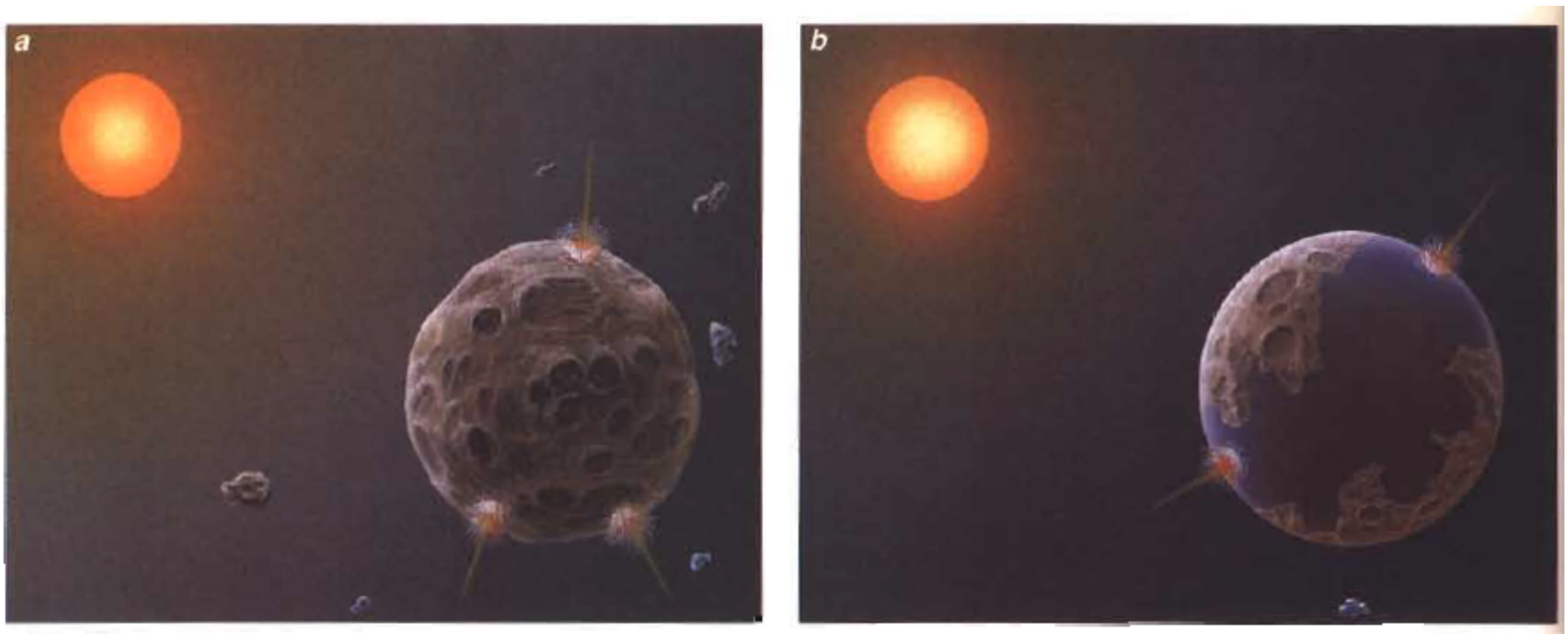
Janet Luhmann
Space Sciences Lab, University of California, Berkeley

MAVEN Media Event, August 2013

Remember the solar system is about 4.5 Billion years old.
Modern humans are about a few 100,000 years old.
The space age is about 5 decades old.

Thus investigations of the early history of our own Earth and its closest neighboring planets are the stuff (like much of astro-physics) of relatively unconstrained speculations.

MAVEN's job is to obtain key constraints for Mars.



Much evidence points to an earlier, more hospitable Mars climate, with significant amounts of liquid water on the surface suggesting a thicker, wetter atmosphere once existed.

Neither much atmosphere nor much water are present today. There are two possibilities:

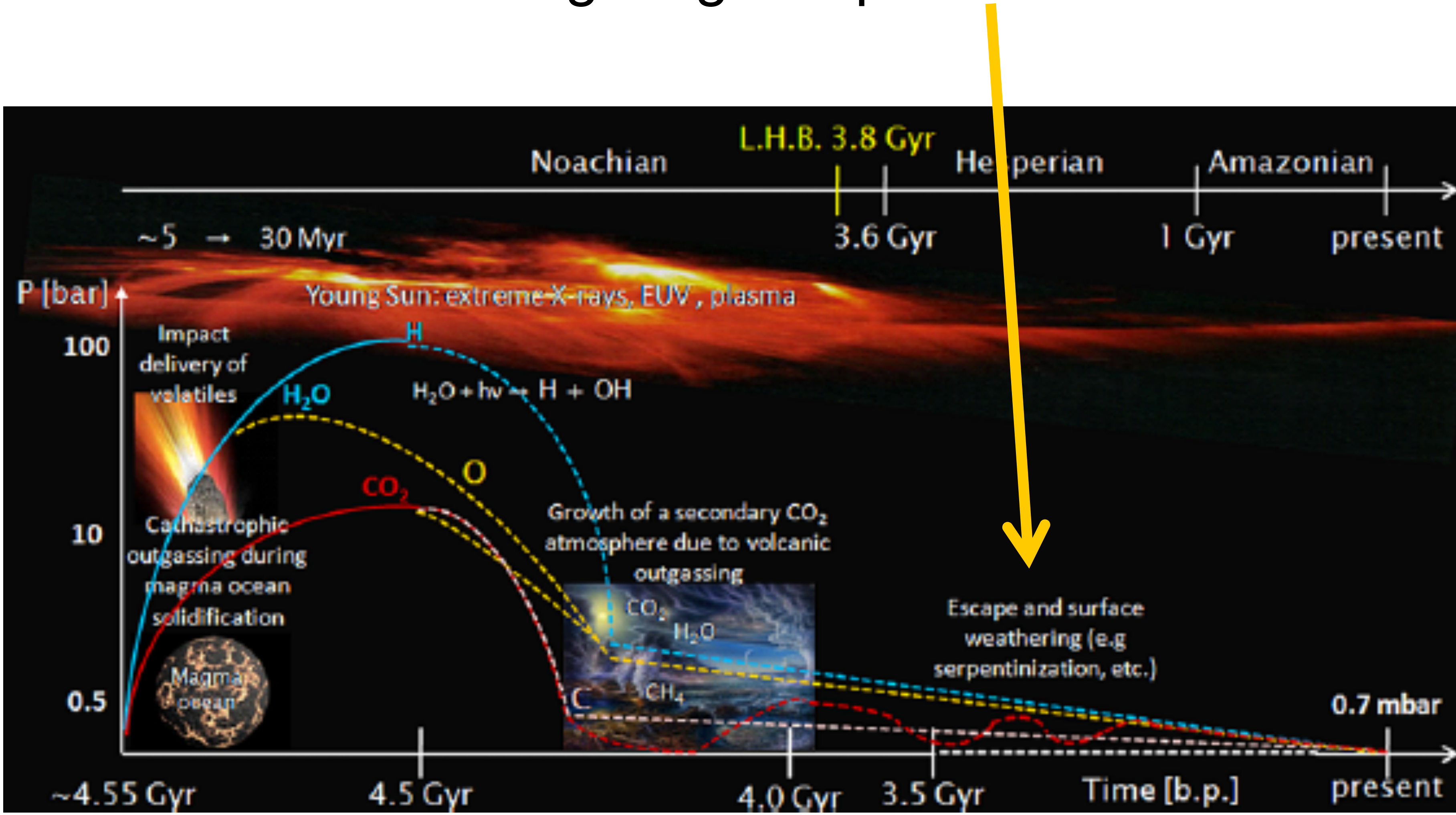
1. The atmosphere is **buried and/or frozen** in the polar ice caps
2. The atmosphere was lost because it **escaped to space**

Which is the answer?

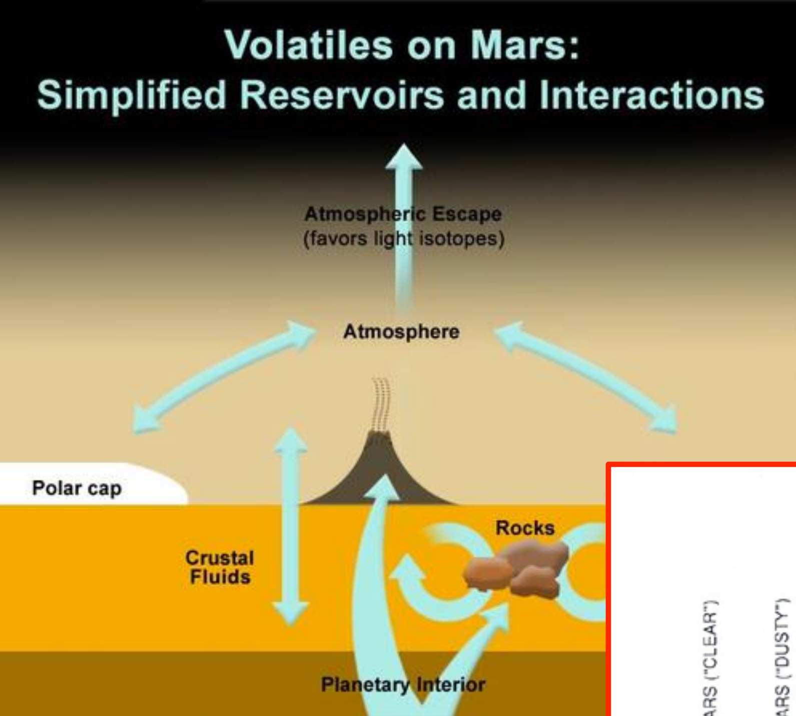
Isotopes-that you will hear more about later, plus measurements of the present abundance of water and ice in the polar caps and beneath the surface, plus surface composition- all point to #2- **Escape to Space.**

The question is HOW ??? (and of course how much?)

MAVEN is targeting this period

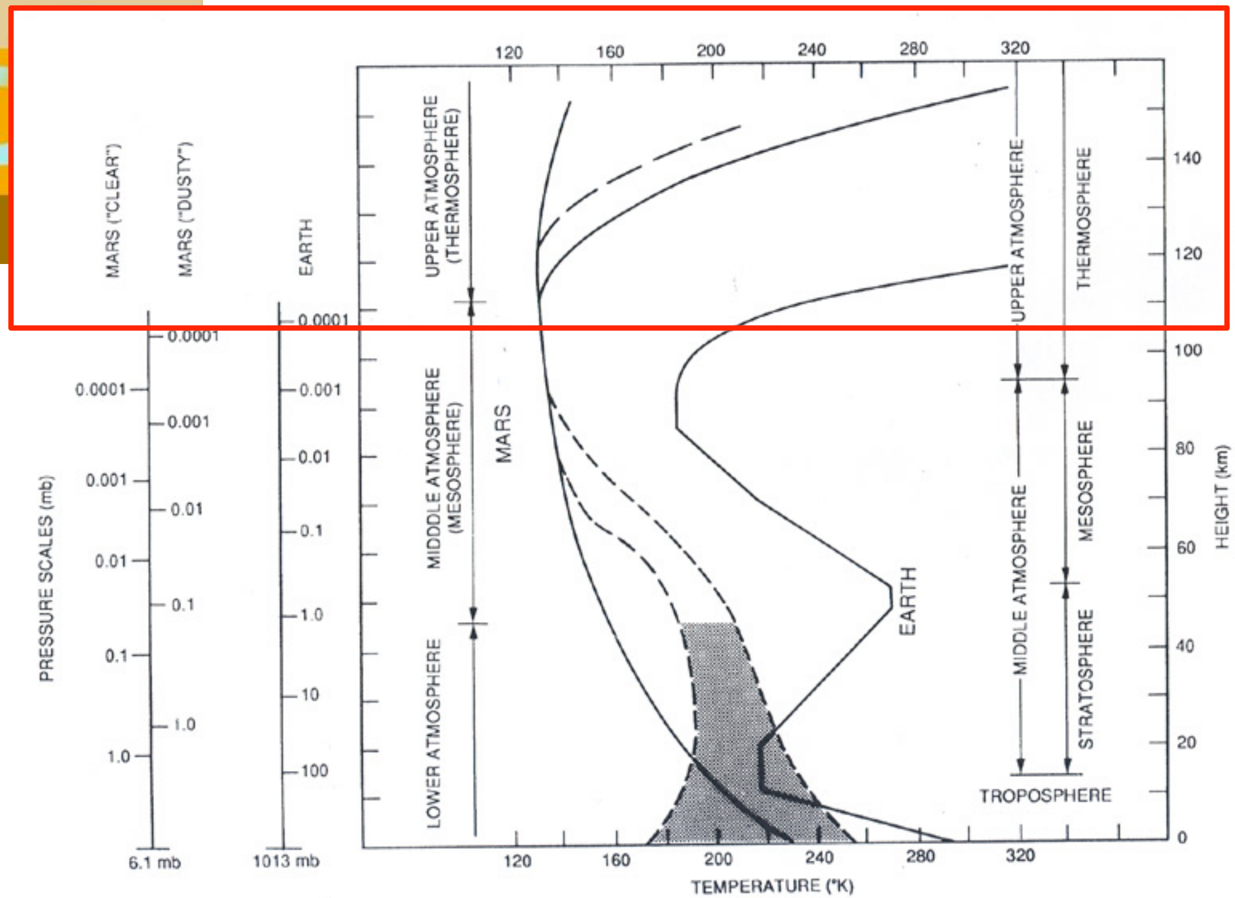


Lammer (2013 SSR) Mars atmosphere evolution diagram



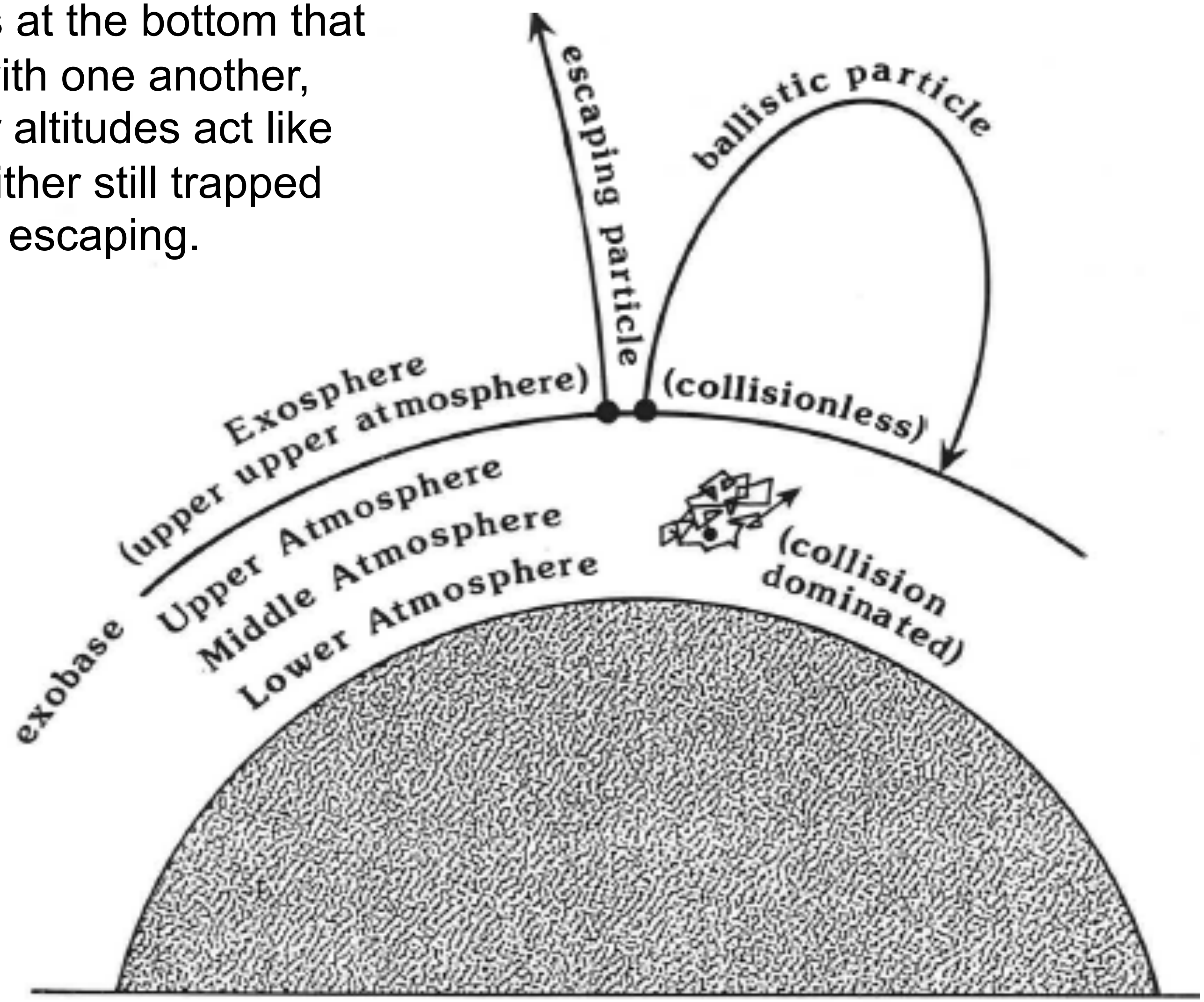
Escape occurs from the top of an atmosphere.

Mars current atmosphere at the surface has only as much pressure as the Earth's at stratospheric altitudes



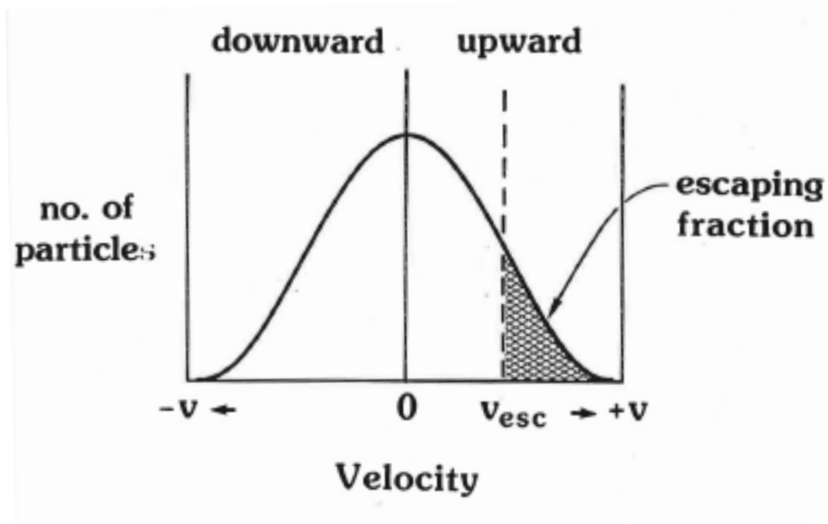
(Figures from MSL ChemCam Website and LASP website)

Upper atmospheres include gas particles at the bottom that still collide with one another, but at higher altitudes act like projectiles-either still trapped by gravity or escaping.



Concepts of "escape velocity" and of velocity distributions of atmospheric gases

The gas particles have a thermal or Maxwell-Boltzmann distribution in Velocity.



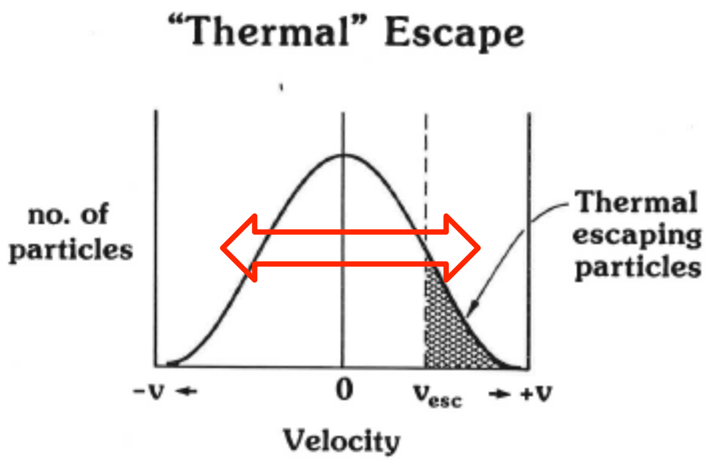
To escape planet's gravitational field, particle must have a velocity greater than the "escape velocity":

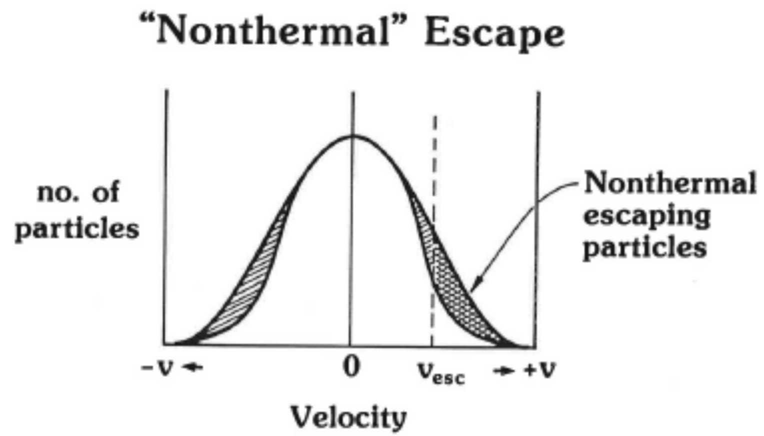
$$\frac{1}{2} mv^2 > \frac{m\,MG}{r}$$

or

$$v > v_{esc} = \left(\frac{2\,MG}{r}\right)^{1/2}$$

How can it get there? By both ‘thermal’ (heating), and ‘nonthermal’ processes

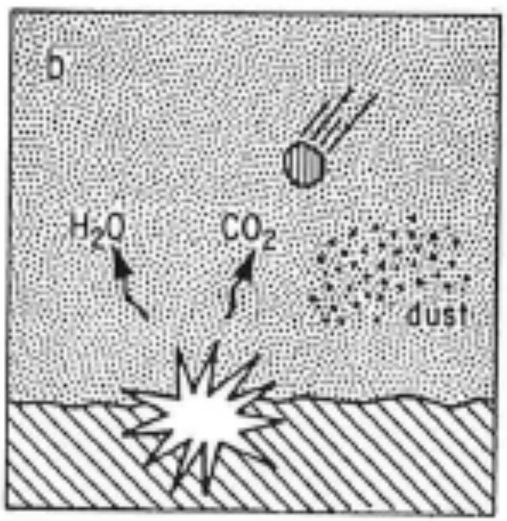




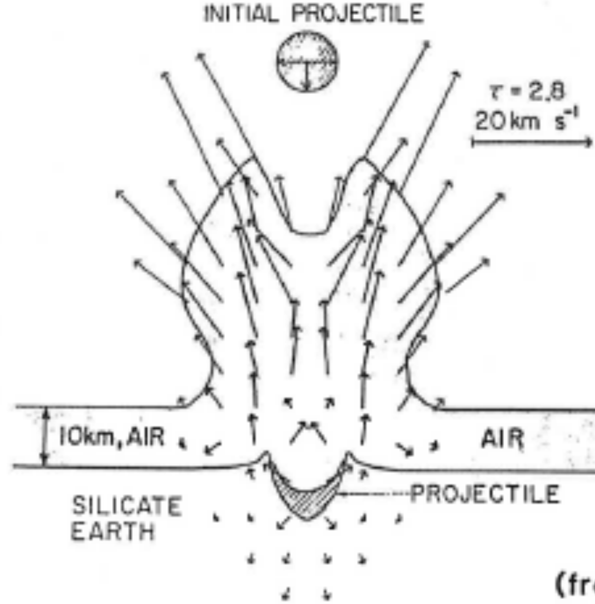
Heating widens this velocity distribution so more particles make it into the >V_{esc} area

Other processes like chemical reactions or particle collisions can also move some above the V_{esc} threshold by adding energy

Impacts-mentioned earlier, were a special ‘nonthermal’ process..
but not so important after the first billion years of Mars history.

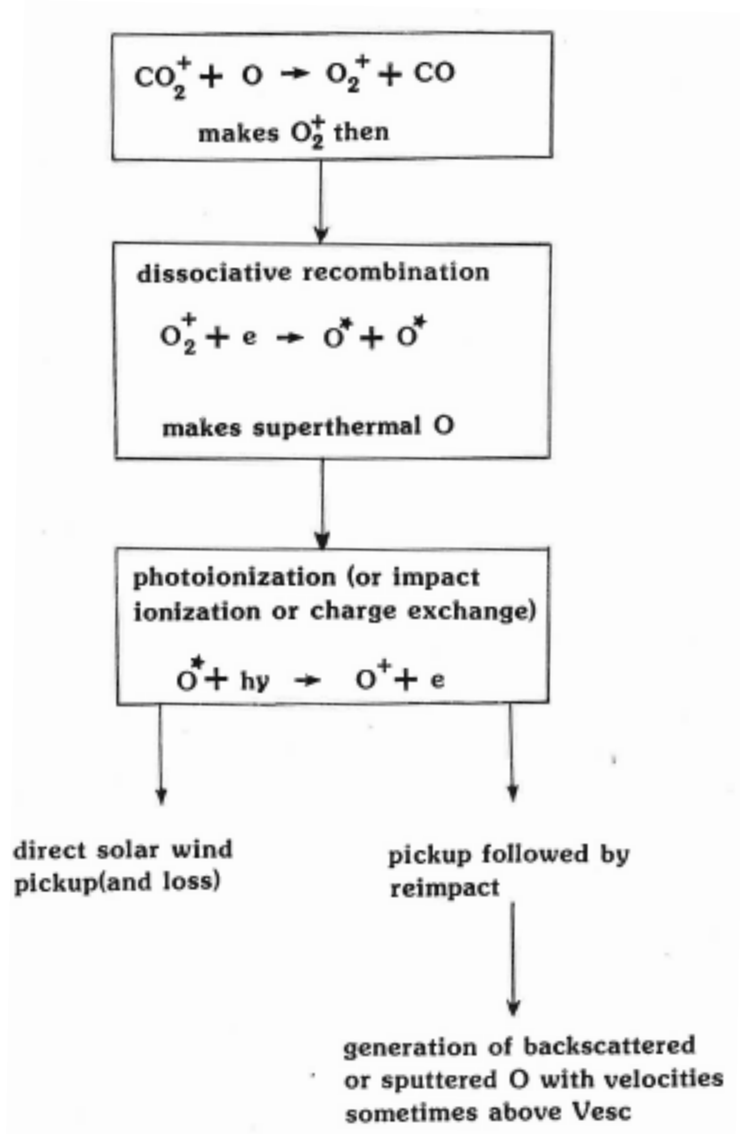


(from Abe and Matsui, 1985)



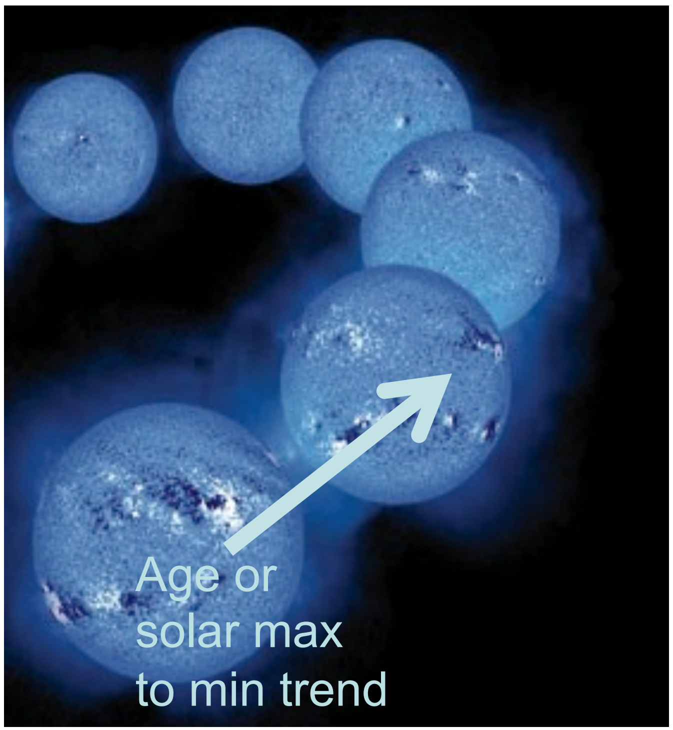
(from Ahrens, 1989)

Nonthermal sources related to photochemistry (here, for Oxygen, which is particularly important for planets, including Mars)

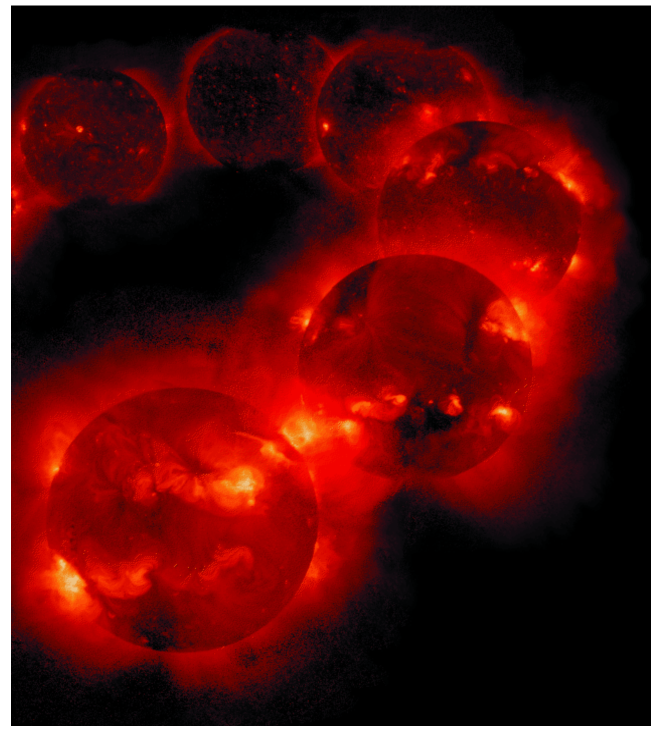


The photochemistry source is related to solar activity (also solar age). The short wavelengths heat and ionize.

Solar magnetic field

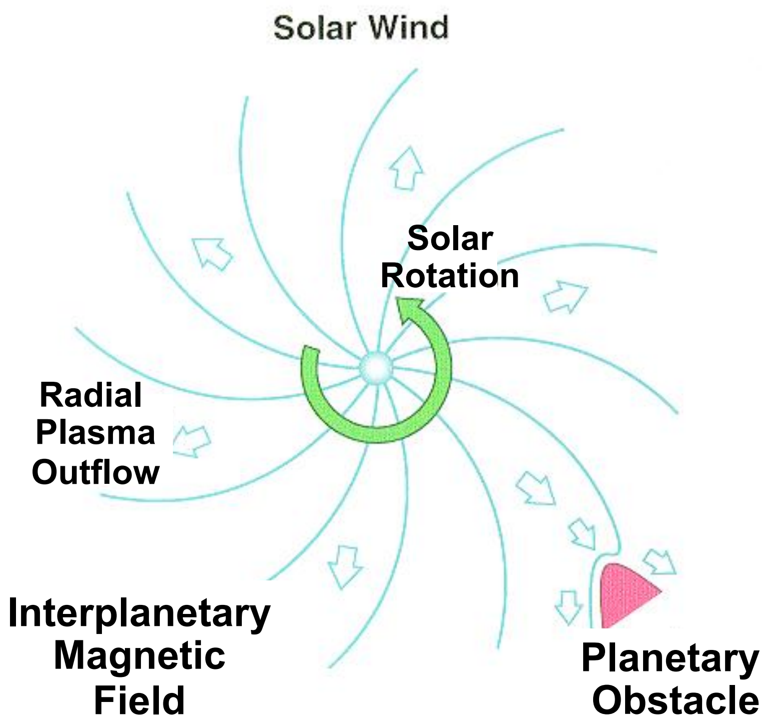


Solar Soft X-ray images



Images from Kitt Peak Observatory magnetograph (left) and the Yohkoh Soft X-ray Telescope, SXT (right) showing x-ray bright arcades over active regions, both evolving over the course of a solar cycle-a ‘model’ for solar evolution.

Other sources of nonthermal escape are related to the solar wind interaction



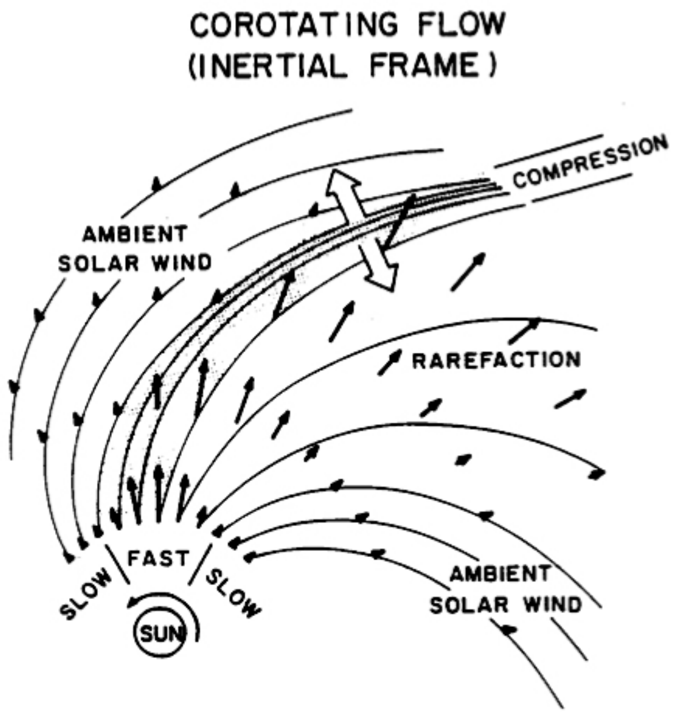
Some typical 'quiet time' properties at Mars:

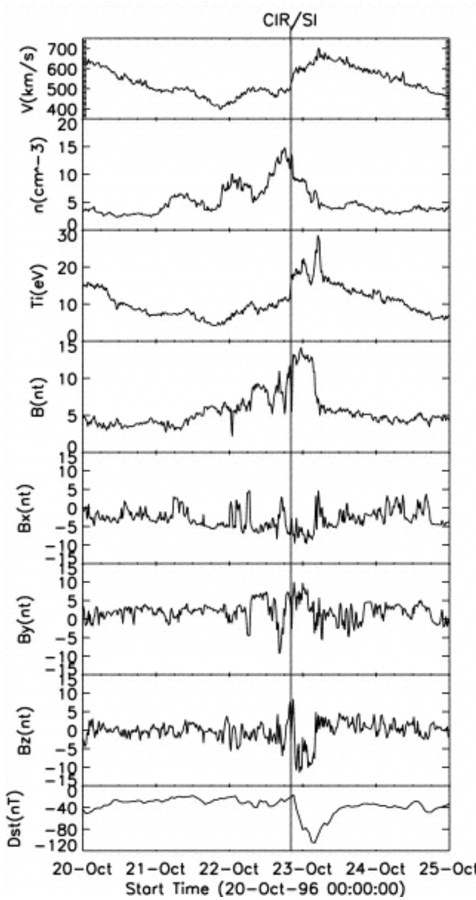
- density $\approx$ 1-3 cm^{-3}
- Magnetic field $\approx$ 1-3 nT
- speed$\approx$ 300-600 km/s
- Spiral Field angle ~50°

1.5 AU

Note even quiet conditions are not uniform or constant.

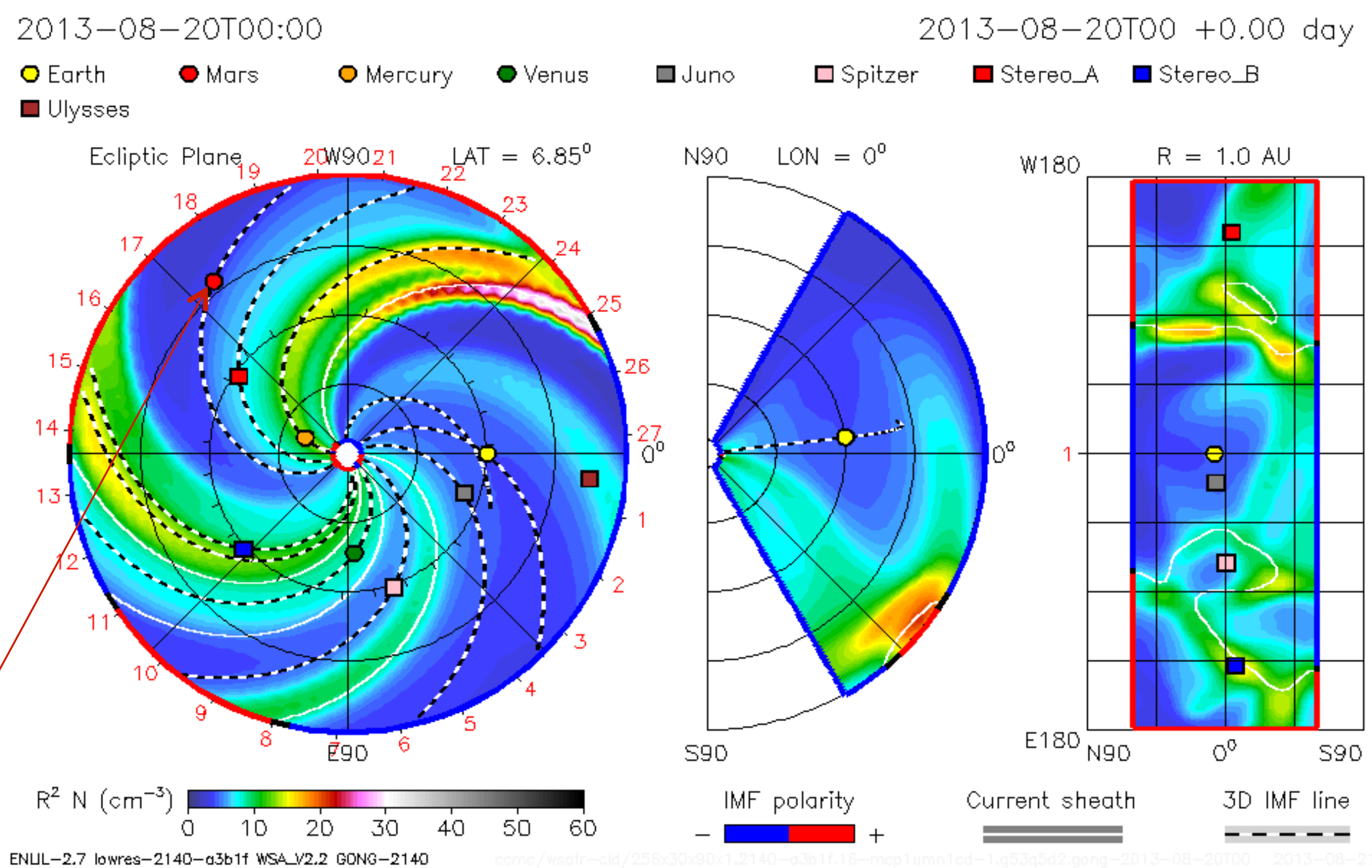
Solar Wind stream interaction regions (SIRs-or CIRs if corotating) cause interplanetary field and flow deflections, and field and density enhancements





(figures from V. Pizzo, JGR 1991 (left), and J. Zhang, ApJ, 2006 (right))

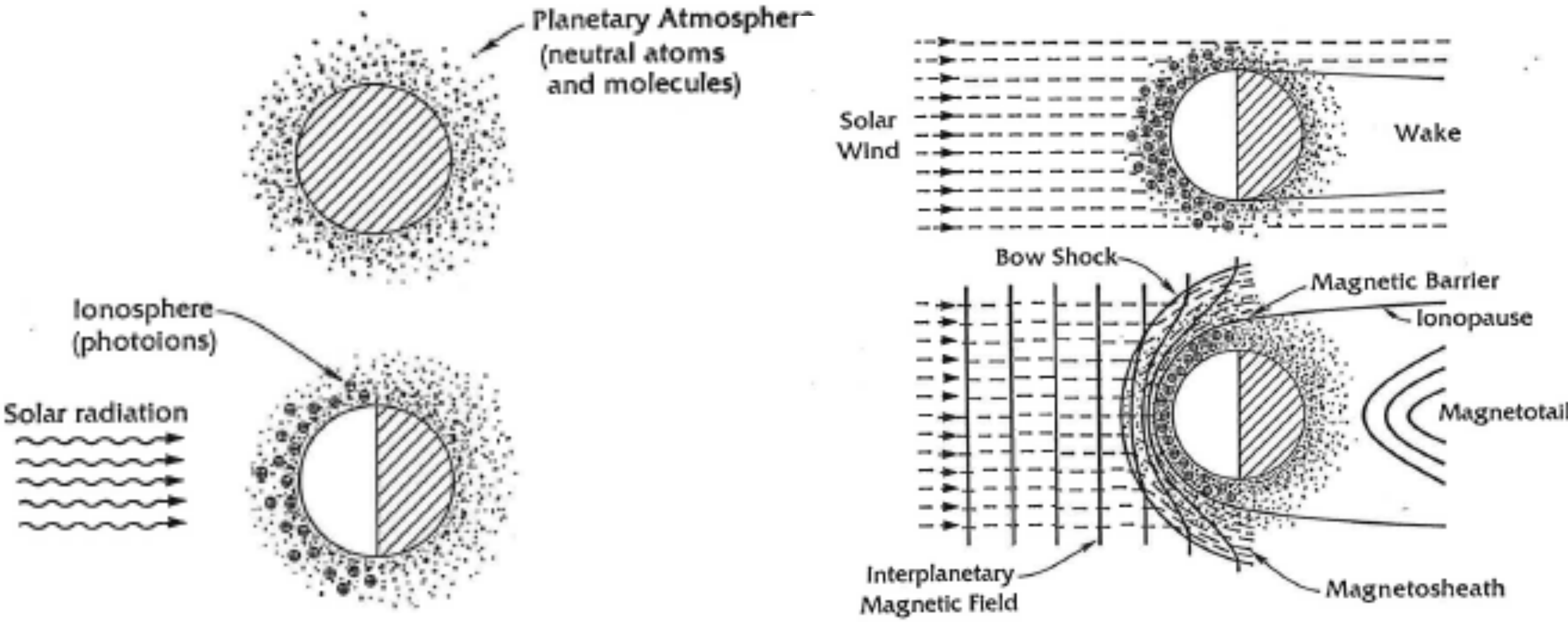
We’ve known about the existence of the solar wind since the late 50s-early 60s-now realistic models exist



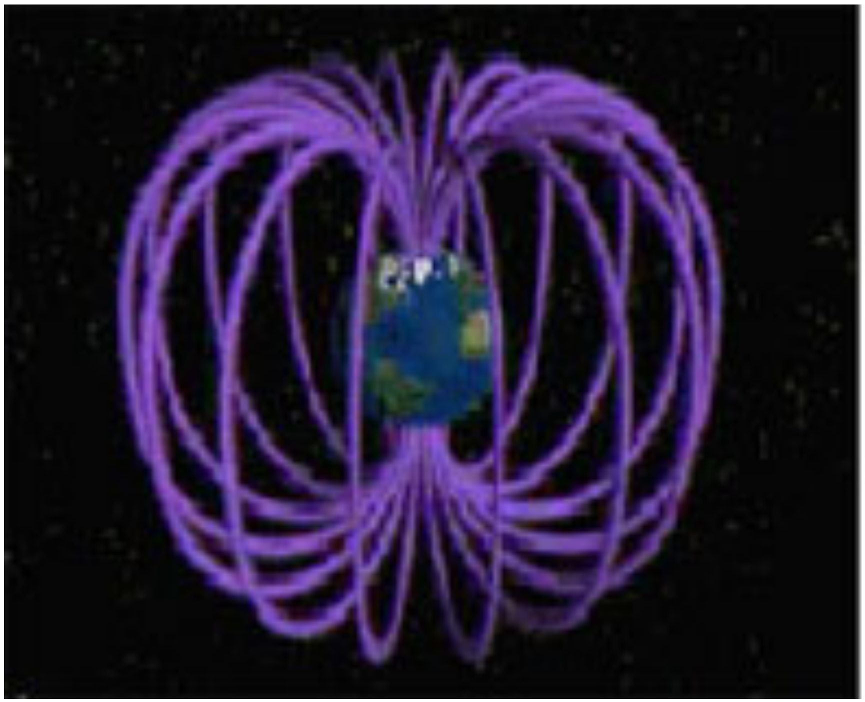
Mars

(A model from D. Odstrcil run at GSFC)

Because Mars has no strong planetary magnetic field, this solar wind interacts directly with its upper atmosphere

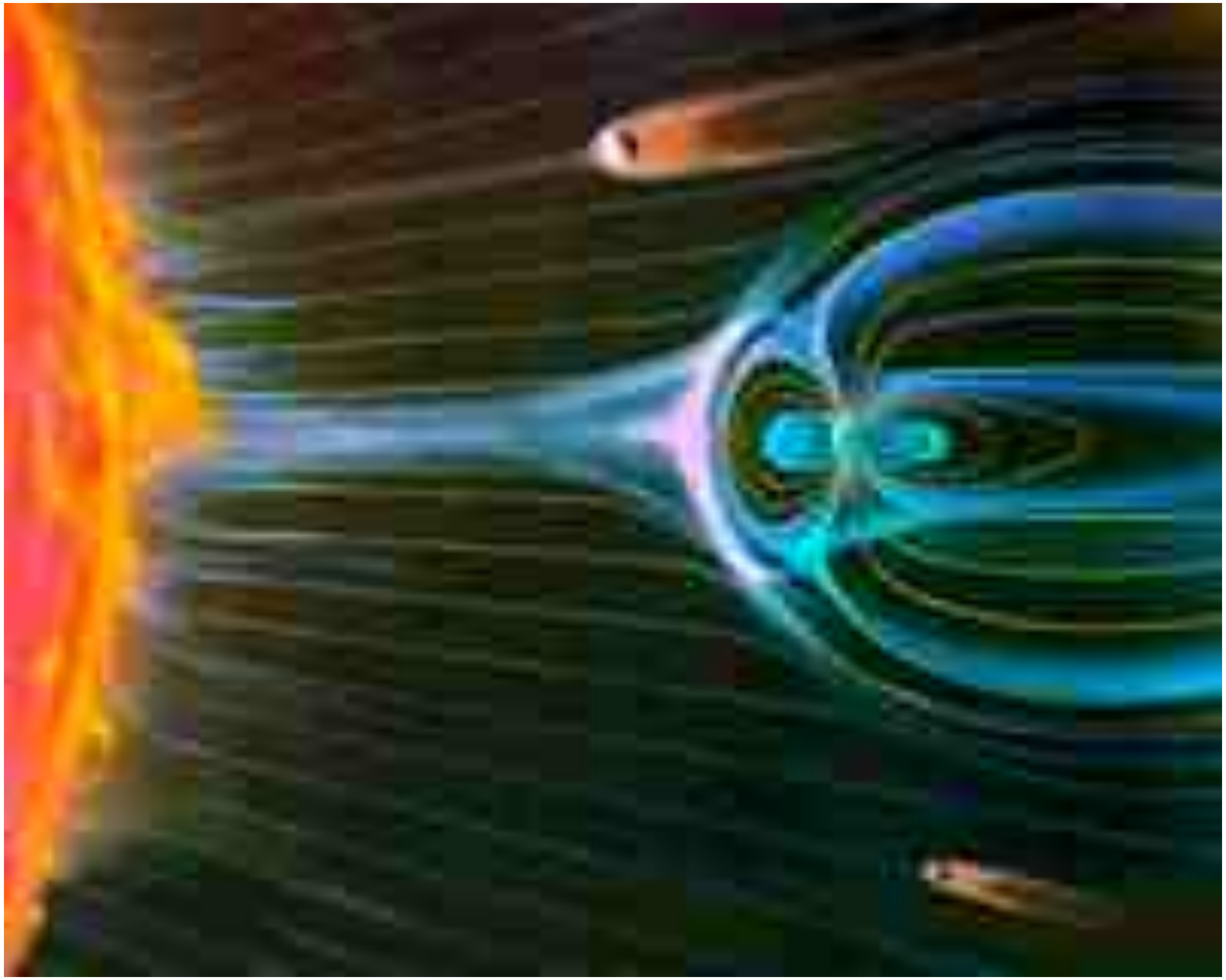


Can the much different planetary magnetic fields on Earth and Mars explain their climate differences?



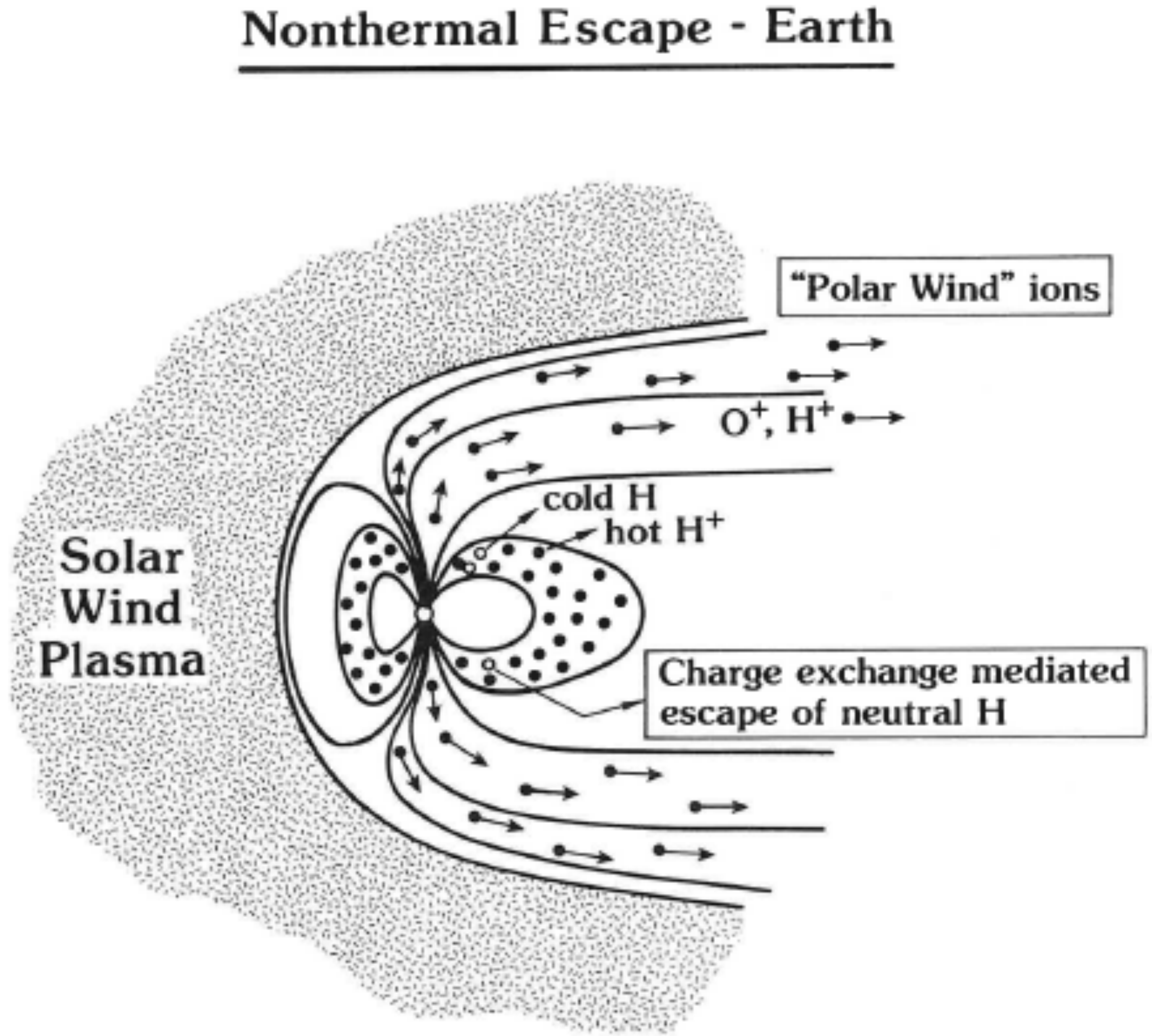
Other contributing factors:
Mars is further from the Sun (~1.5 AU vs 1 AU)
Mars is smaller/less massive

In particular, do planetary magnetospheres “shield” planetary atmospheres from possibly important loss processes?



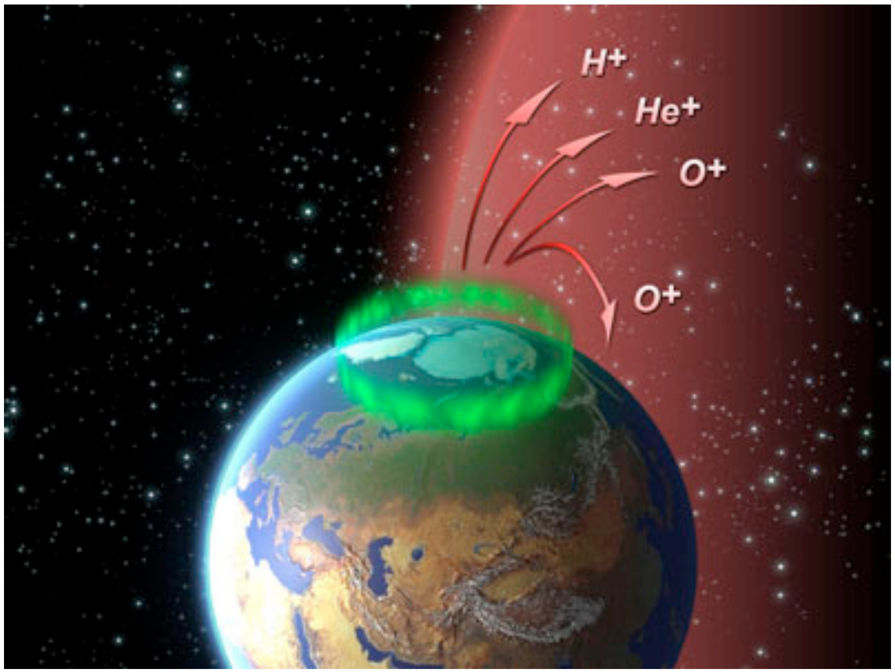
ESA web image

We know relatively much about Earth's response to 'space weather'



Earth atmosphere escape is however quite different in its details due to its strong planetary magnetic field

Earth's Polar Atmospheric Ion Outflows



(from ESA Cluster News)

Include:

* Classic light ion 'polar wind' (H+ and He+)
*Cusp 'ion fountain'
*Highly variable but most intense 'Auroral wind'

-each outflow has a distinct physical cause. The latter two include heavy ion species like O+. Not all outflowing ions escape to space directly, but most are believed to eventually do so.

Mars' More Direct Solar Wind Interaction-Related Loss Processes:

Atmospheric Ion 'pickup'-Observed on earlier missions but still many uncertain details on related escape

"Sputtering"-Related to ion pickup. Potentially Important but so far unobserved at Mars

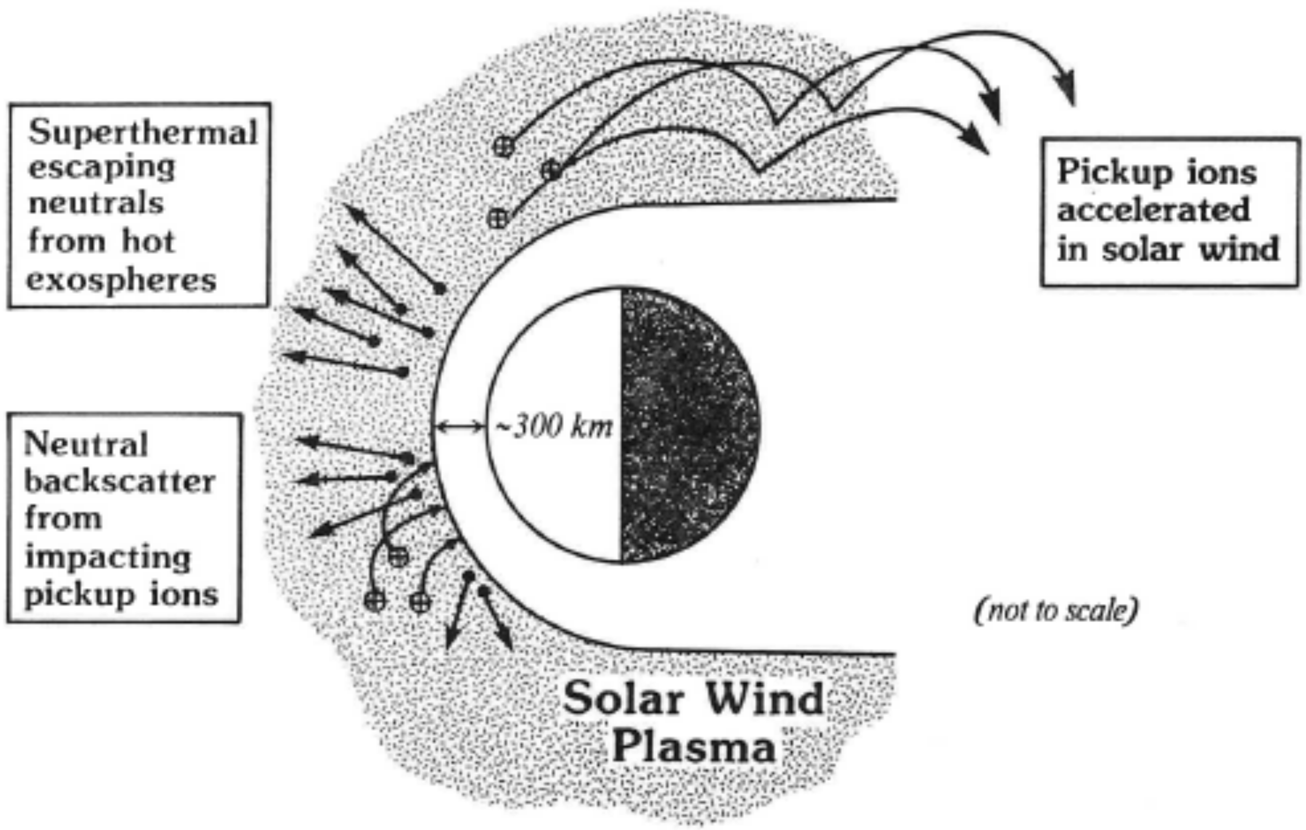
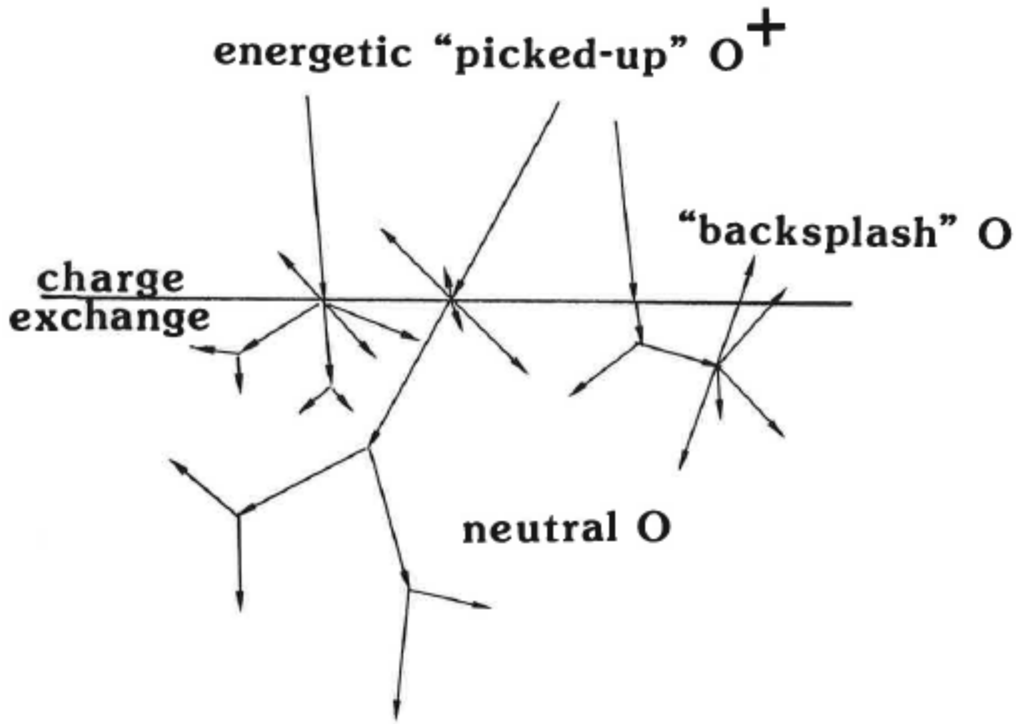


Illustration of the **sputtering process** near the upper boundary of the collision-dominated atmosphere

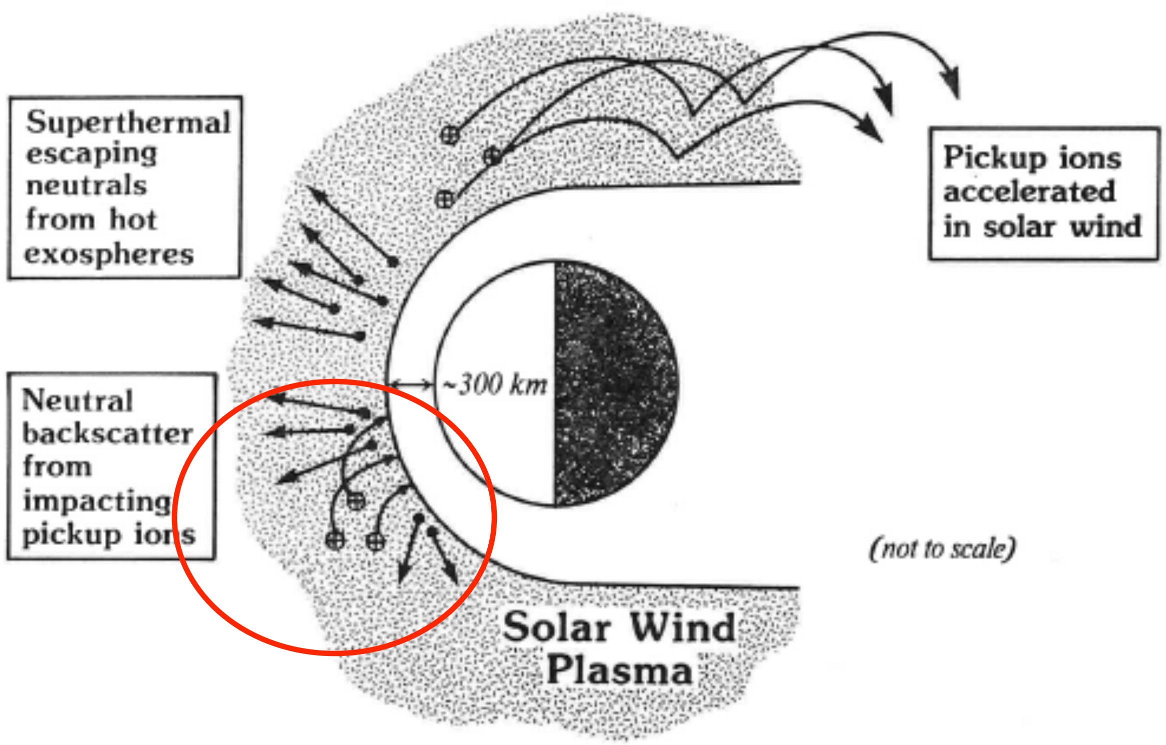


Here- incident picked up O+ ions interact with the upper atmosphere oxygen gas and other constituents including CO_2. Anything present here may be ejected.

Mars' More Direct Solar Wind Interaction-Related Processes:

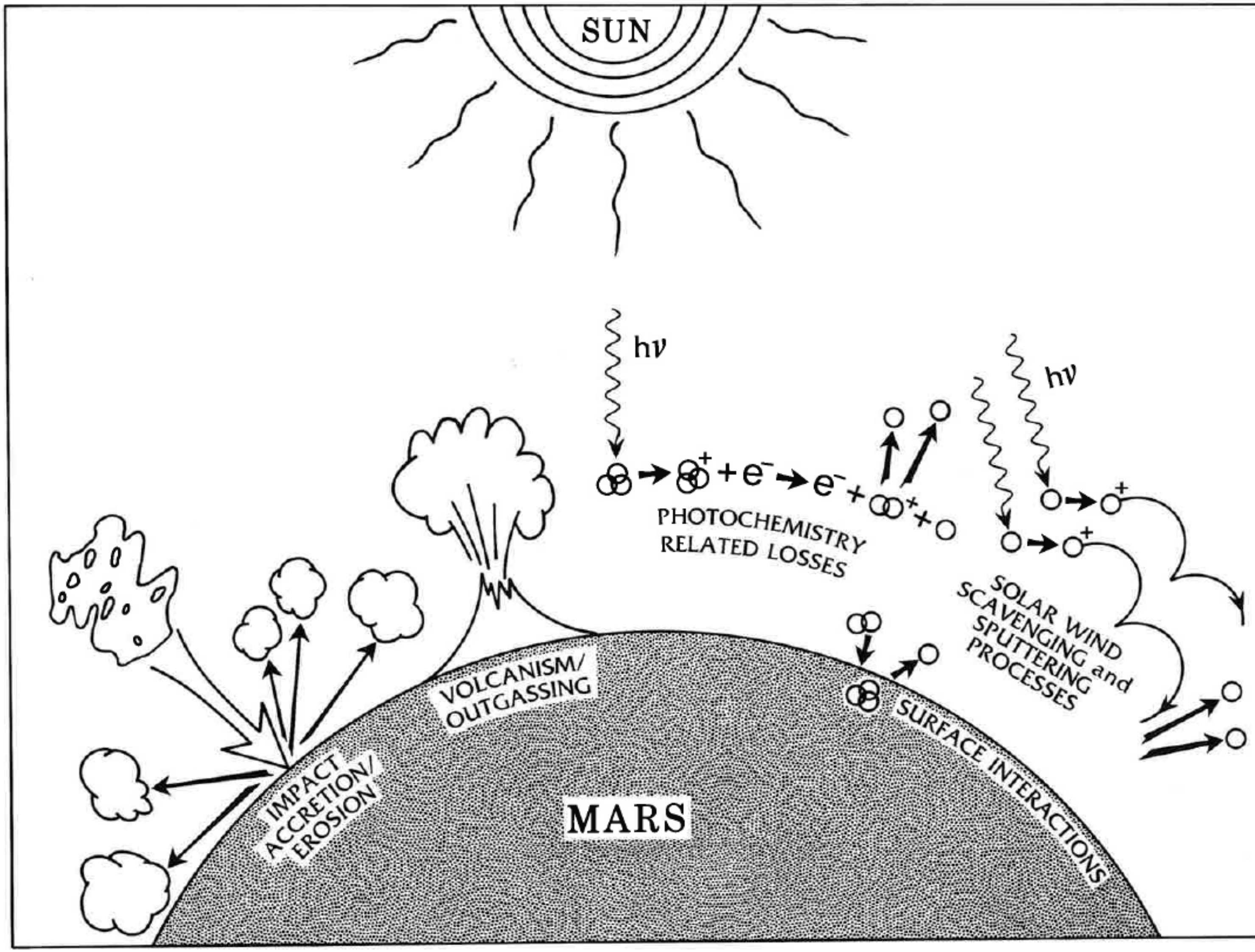
Atmospheric Ion 'pickup'-Observed on earlier missions but still many uncertain details on related escape

"Sputtering"-Related to ion pickup. Potentially Important but So Far Unobserved

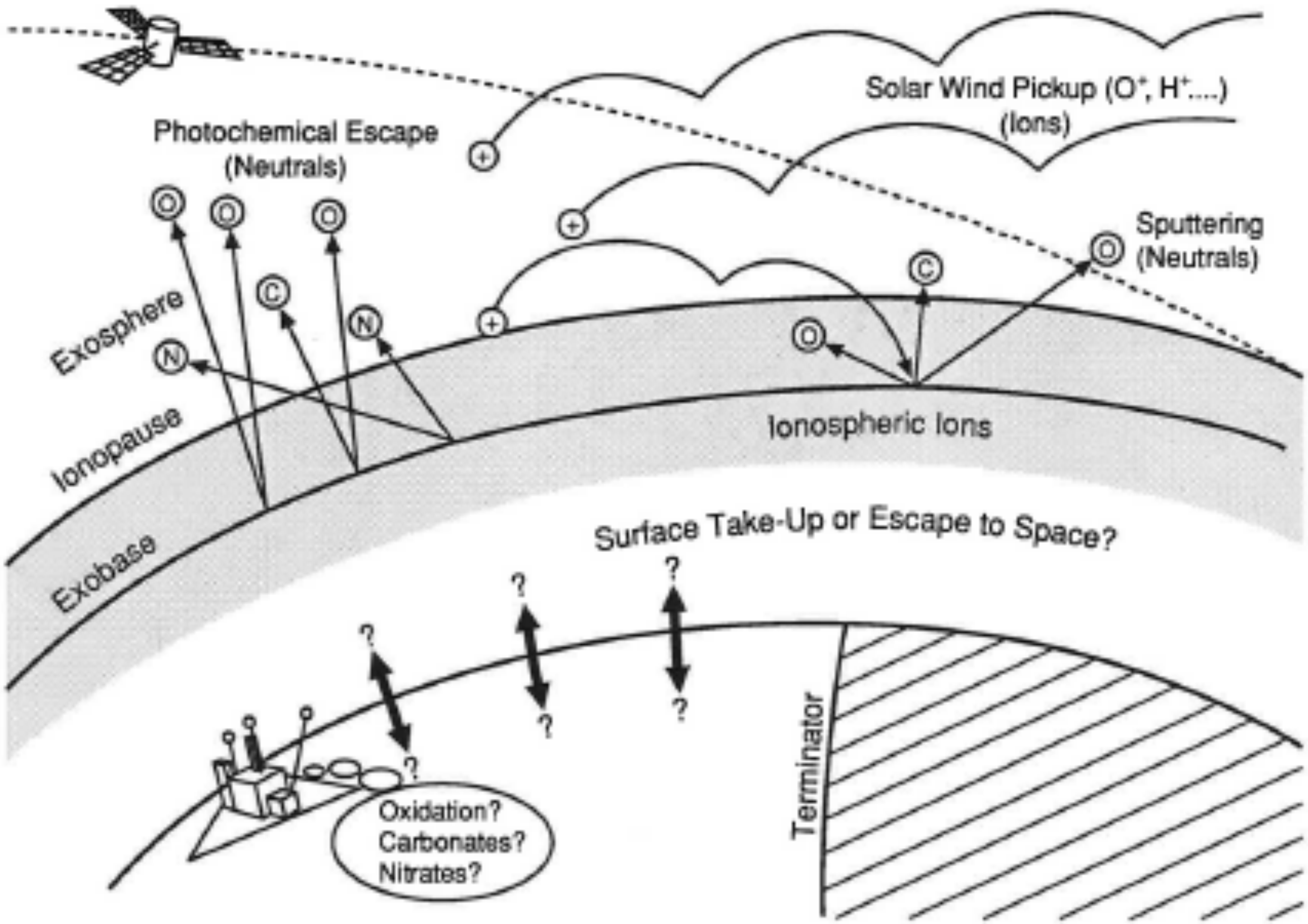


Notice that sputtering uses pickup ions that don't escape to make escaping neutrals

Early Mars was a complicated scene



But today it is still affected by the same escape processes- though altered by its current state



Current (Estimated) Escape Rates

H (thermal)	$\sim 1.7 \times 10^{26}\ s^{-1}$
O (nonthermal)	$\sim 8.6 \times 10^{25}\ s^{-1}$ *
CO_2 (sputtering)	$\sim 3 \times 10^{23}\ s^{-1}$

Loss over 3.5 Gyr at present rates:

H_2O equivalent	~3 m
CO_2 equivalent	~1 mb

To get rid of the atmosphere and water that is estimated to have been there, loss rates would have had to be much greater in the past

*includes $\sim 6 \times 10^{24}$ ions s^{-1} picked up by solar wind. Phobos-2 measured $\sim 10^{24}$ - $10^{25}\ s^{-1}$

If the current processes are the answer, could these have been high enough?

Example:

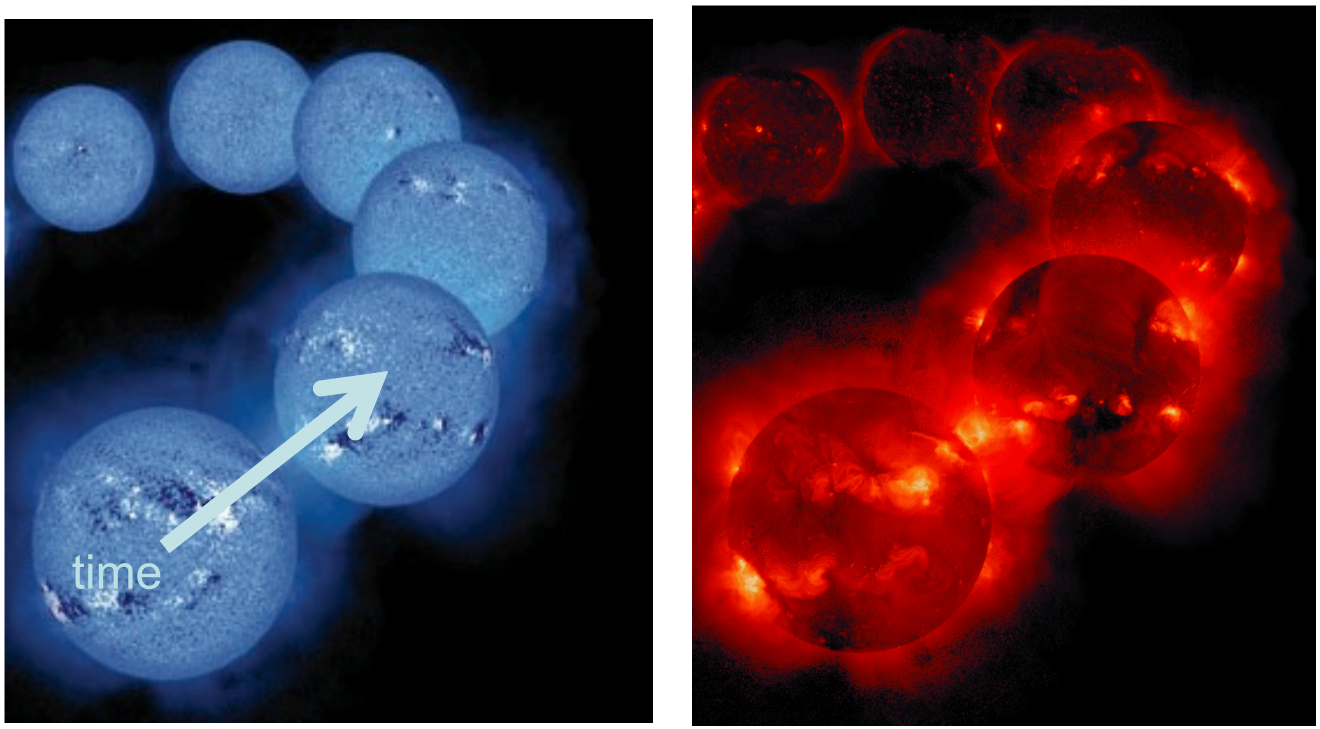
Estimated volume of an early ocean of Mars
is ~6×10^7 km^3 H_2O (from surface features)

This amount contains about 2×10^{45} H_2O molecules

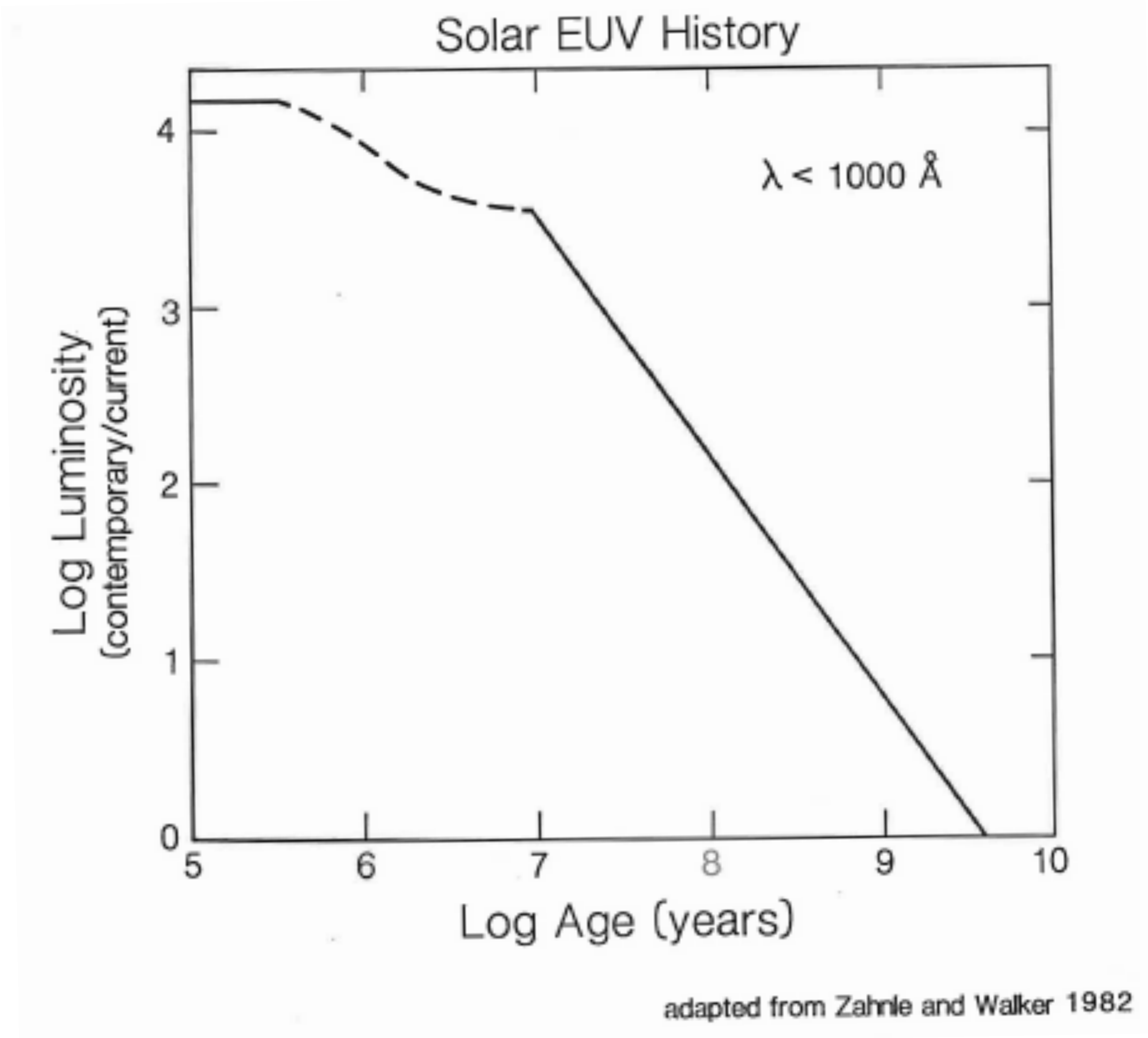
It is relatively easy to get rid of light hydrogen by heating.

To get rid of *the oxygen* in this ocean over 3.5 Byr, need an average loss rate of 1.8×10^{28} O atoms/sec (over 100 times greater than present)

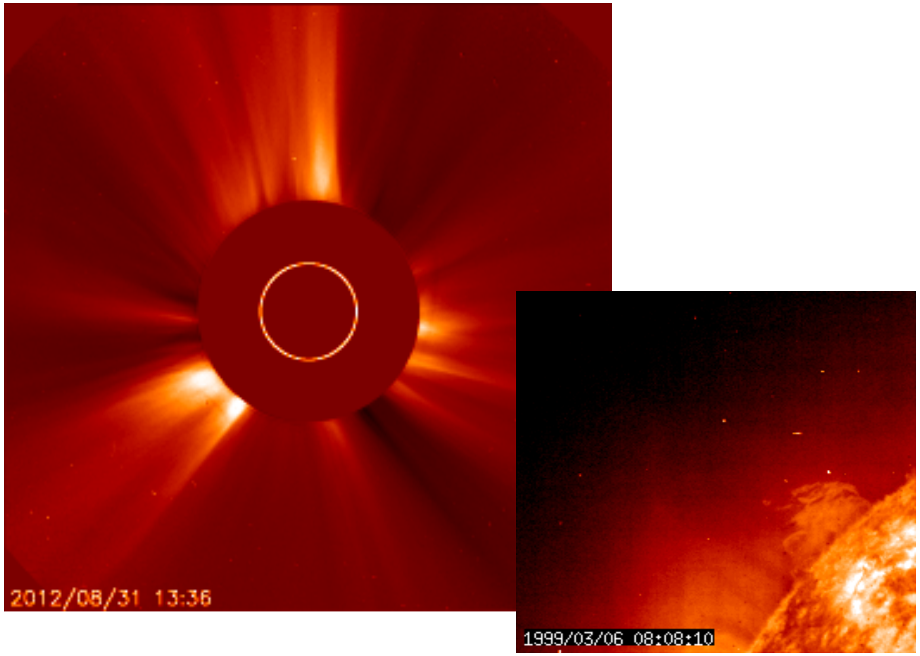
Sun-like stars tell us that in the past, the Sun may have been more magnetically active



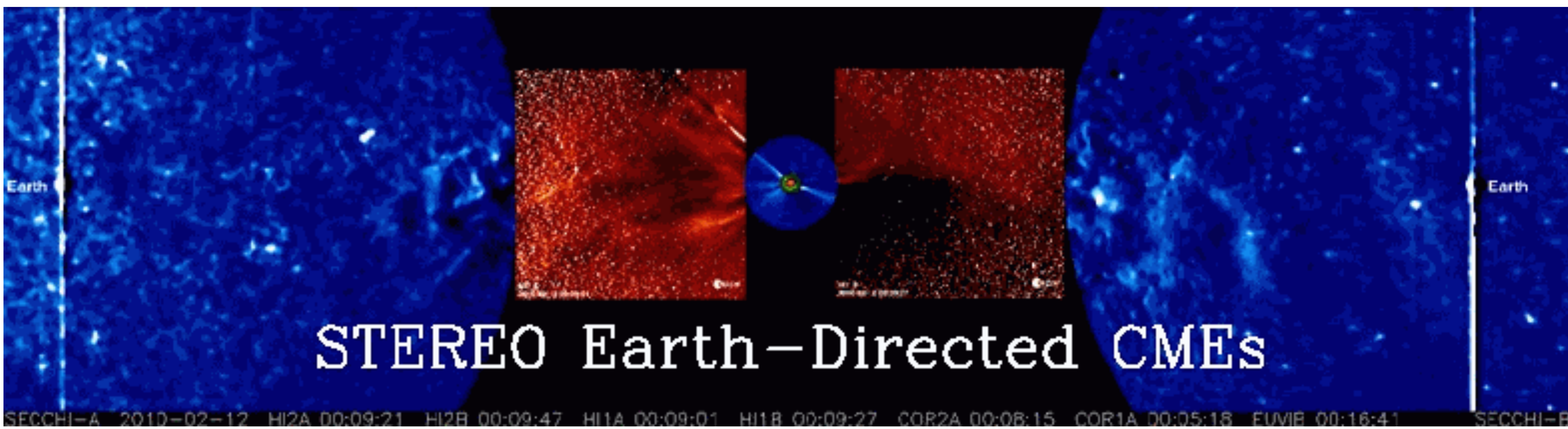
Images from Kitt Peak Observatory magnetograph (left) and the Yohkoh Soft X-ray Telescope, SXT (right) showing x-ray bright arcades over active regions, both evolving over the course of a solar cycle-a ‘model’ for solar evolution.



Part of the result is a trend of decreasing solar EUV emission with time

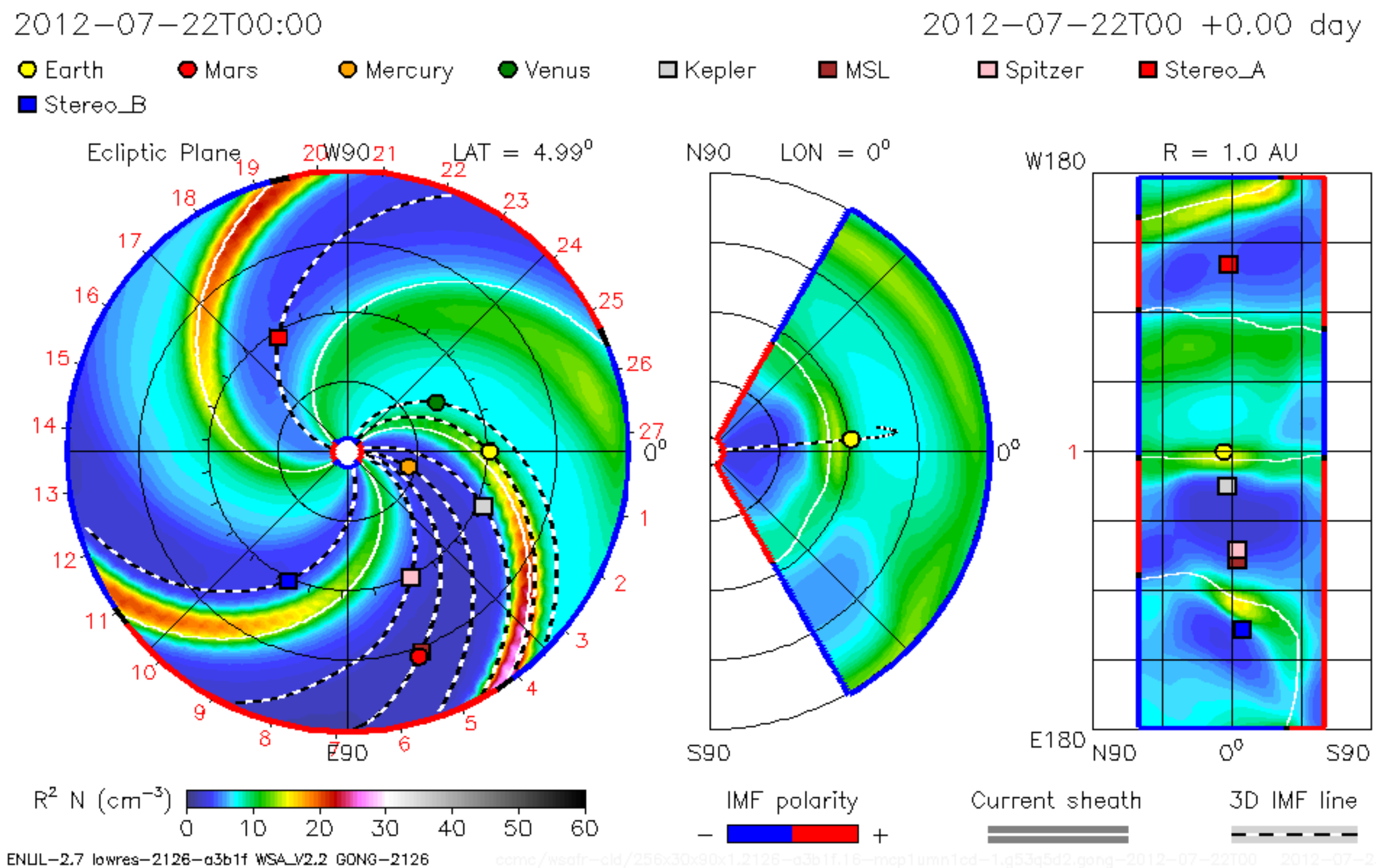


The early Sun was also likely to have been much more active- producing much more flares and Coronal Mass Ejections (CMEs)



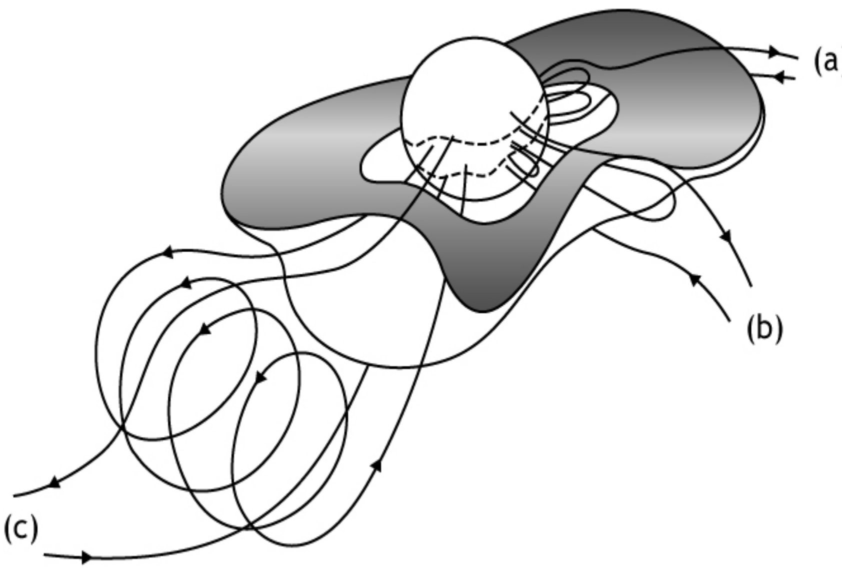
SOHO LASCO images and STEREO SECCHI images
(from SOHO website and Ying Liu, SSL (panorama))

Big CME events in particular have many parts: Including shocks

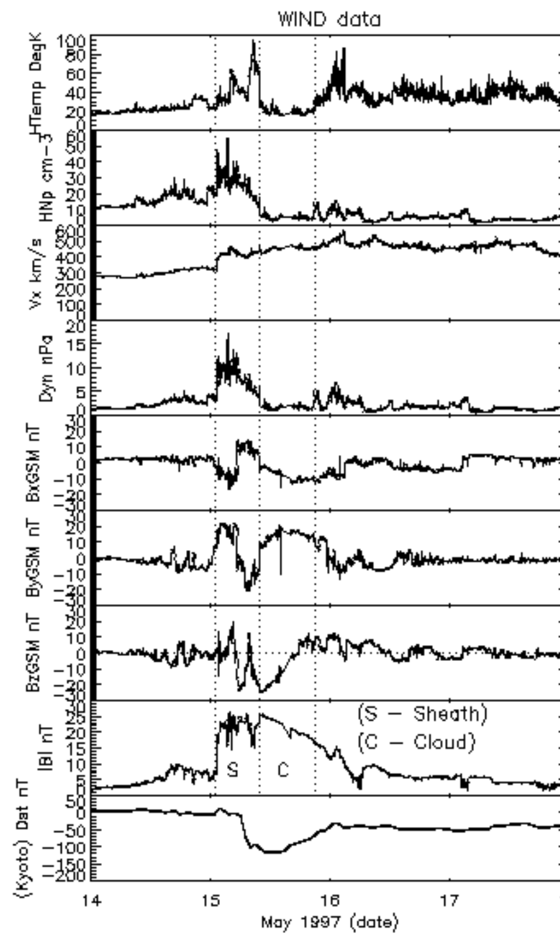


GSFC fast-turnaround 'ENLIL/cone CME' modeling indicated the direct STA hit for the major July 23, 2012 super-fast CME

..which are produced by magnetic ejecta that move much faster than the solar wind, plowing through and compressing the ambient flow as they travel

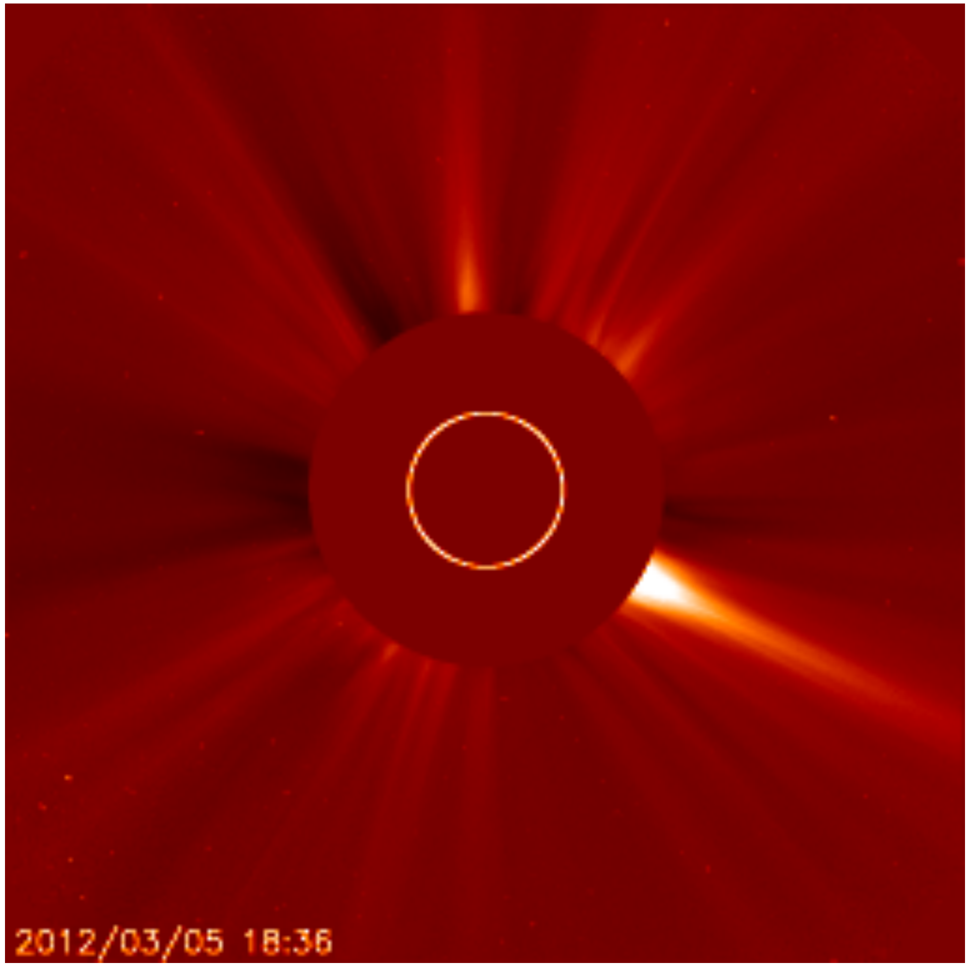


(from Crooker, 1993)

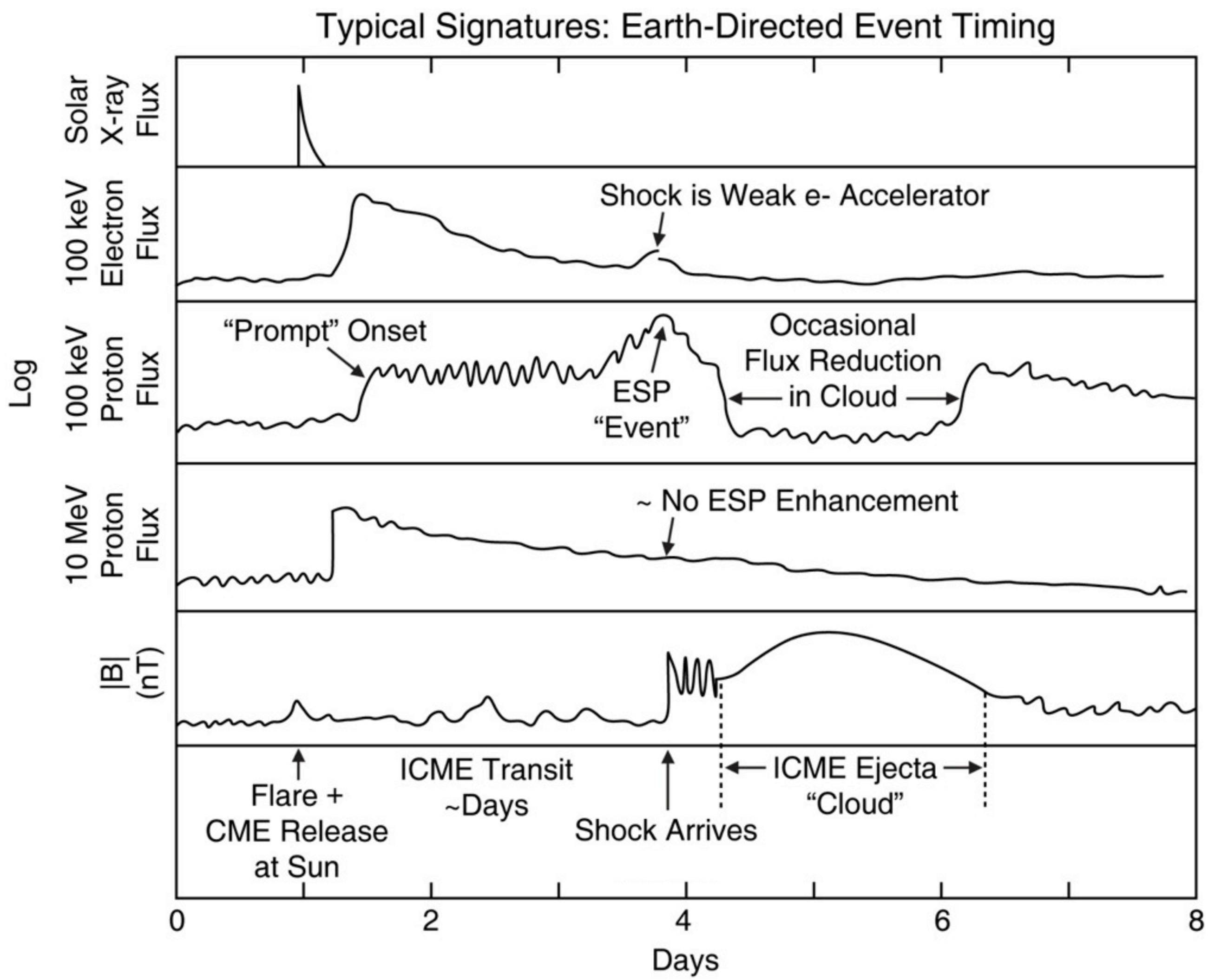


CMEs produce the largest solar wind disturbances

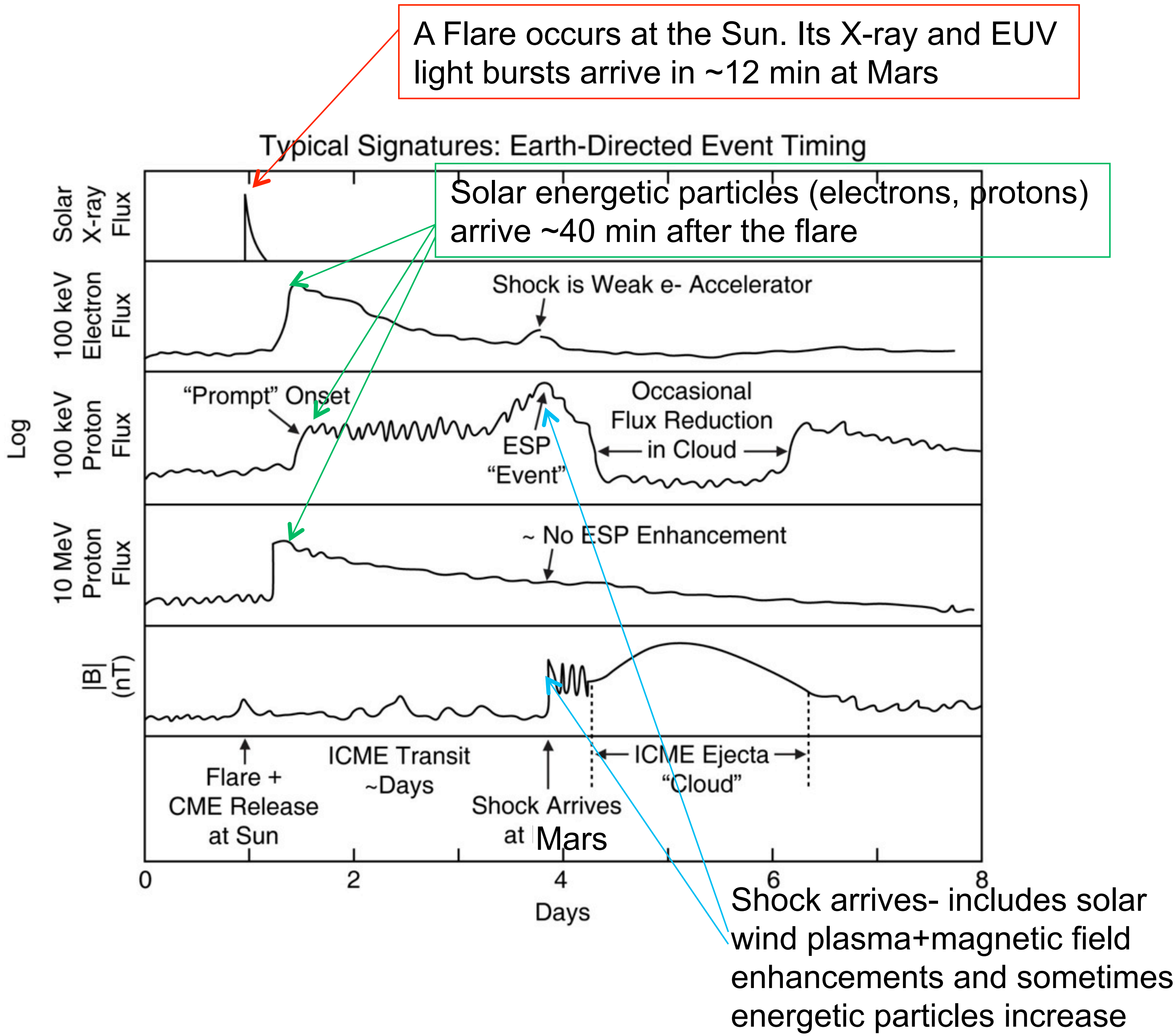
Solar energetic particles (SEPs) with protons of up to ~100 MeV or more are also part of these events



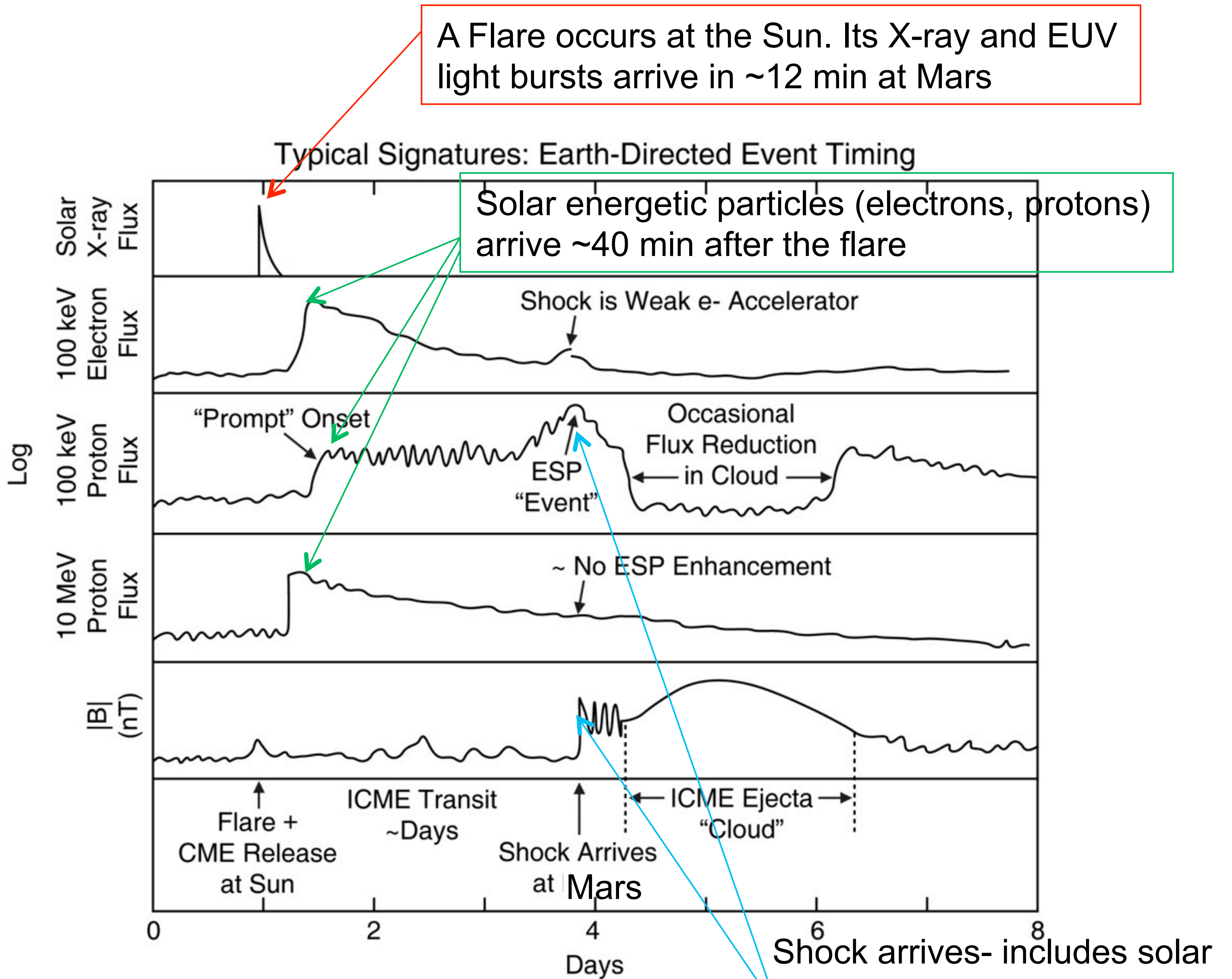
Here the SOHO coronagraph CCD is ‘snowed’ by SEPs in March 2012



Typical Signatures: Earth-Directed Event Timing
Log
Solar X-ray Flux
100 keV Electron Flux
Shock is Weak e- Accelerator
100 keV Proton Flux
"Prompt" Onset
ESP "Event"
Occasional Flux Reduction in Cloud
10 MeV Proton Flux
~ No ESP Enhancement
|B| (nT)
Flare + CME Release at Sun
ICME Transit ~Days
Shock Arrives
ICME Ejecta "Cloud"
0
2
4
6
8
Days

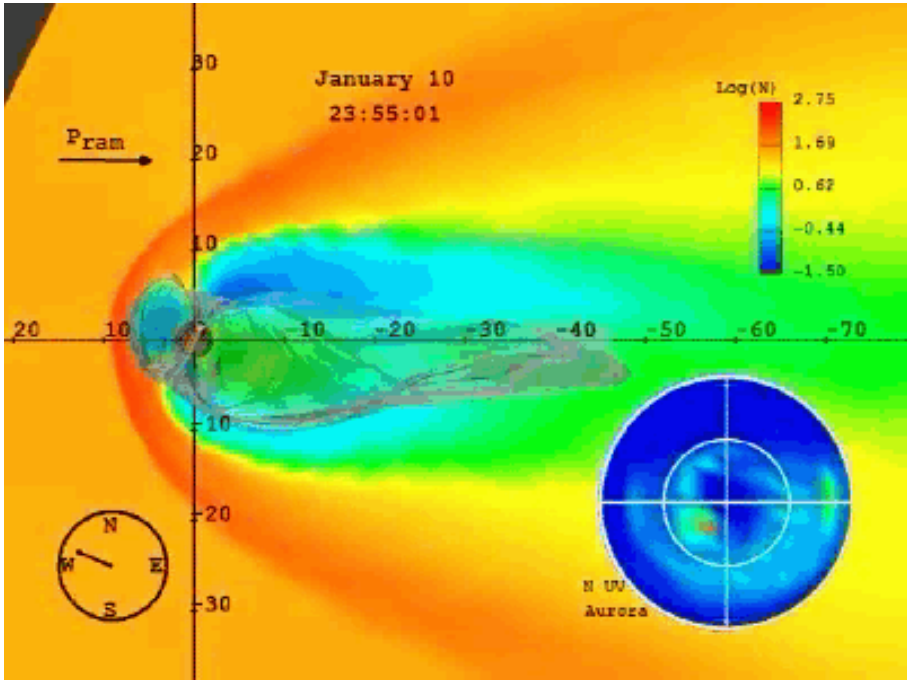


A Flare occurs at the Sun. Its X-ray and EUV light bursts arrive in ~12 min at Mars
Typical Signatures: Earth-Directed Event Timing
Solar energetic particles (electrons, protons) arrive ~40 min after the flare
Log
Solar X-ray Flux
100 keV Electron Flux
100 keV Proton Flux
10 MeV Proton Flux
|B| (nT)
Shock is Weak e- Accelerator
"Prompt" Onset
ESP "Event"
Occasional Flux Reduction in Cloud
~ No ESP Enhancement
Flare + CME Release at Sun
ICME Transit ~Days
Shock Arrives at Mars
ICME Ejecta "Cloud"
0
2
4
6
8
Days
Shock arrives- includes solar wind plasma+magnetic field enhancements and sometimes energetic particles increase



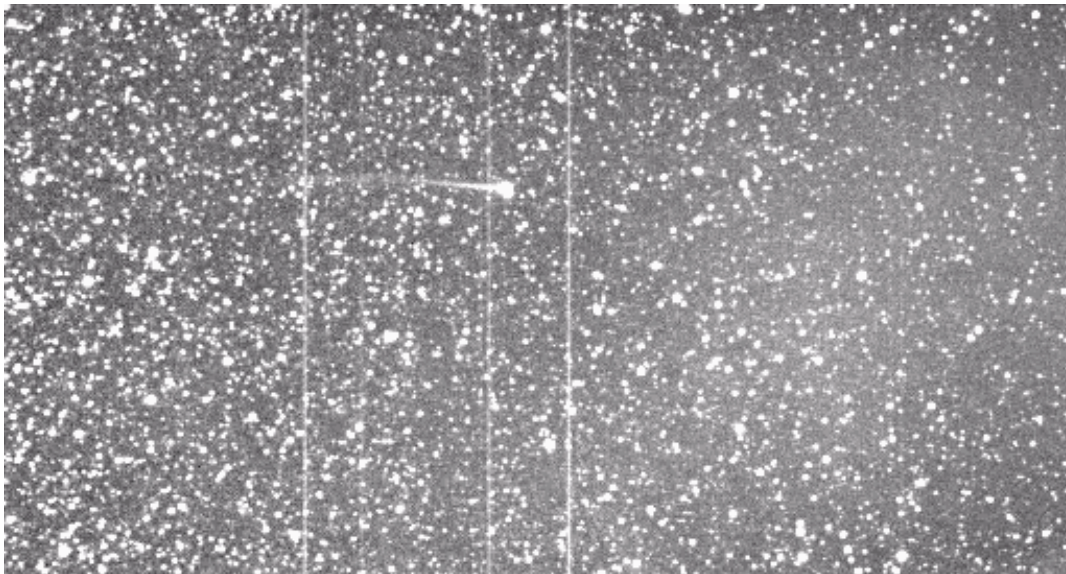
Note whole event with its different phases can last ~a week

These disturbances energize Earth's polar ionosphere, enhancing upper atmosphere heating, auroras, and related ion escape

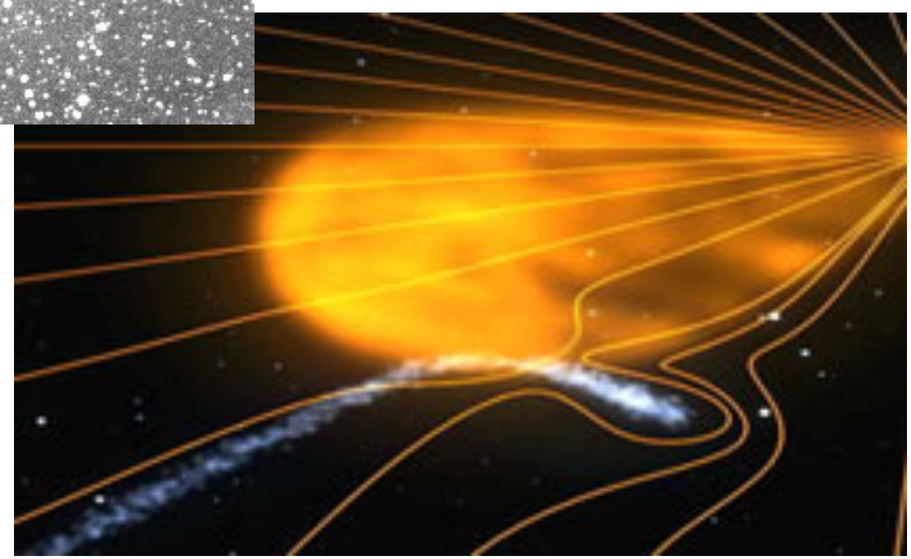


LFM MHD simulation from Goodrich et al. Inset shows the resulting enhancement of energy going into Earth's polar region when a coronal mass ejection (CME) disturbance goes by

Cometary tail ‘disconnection’ following a CME encounter is in some ways a counterpart to what must happen at Mars

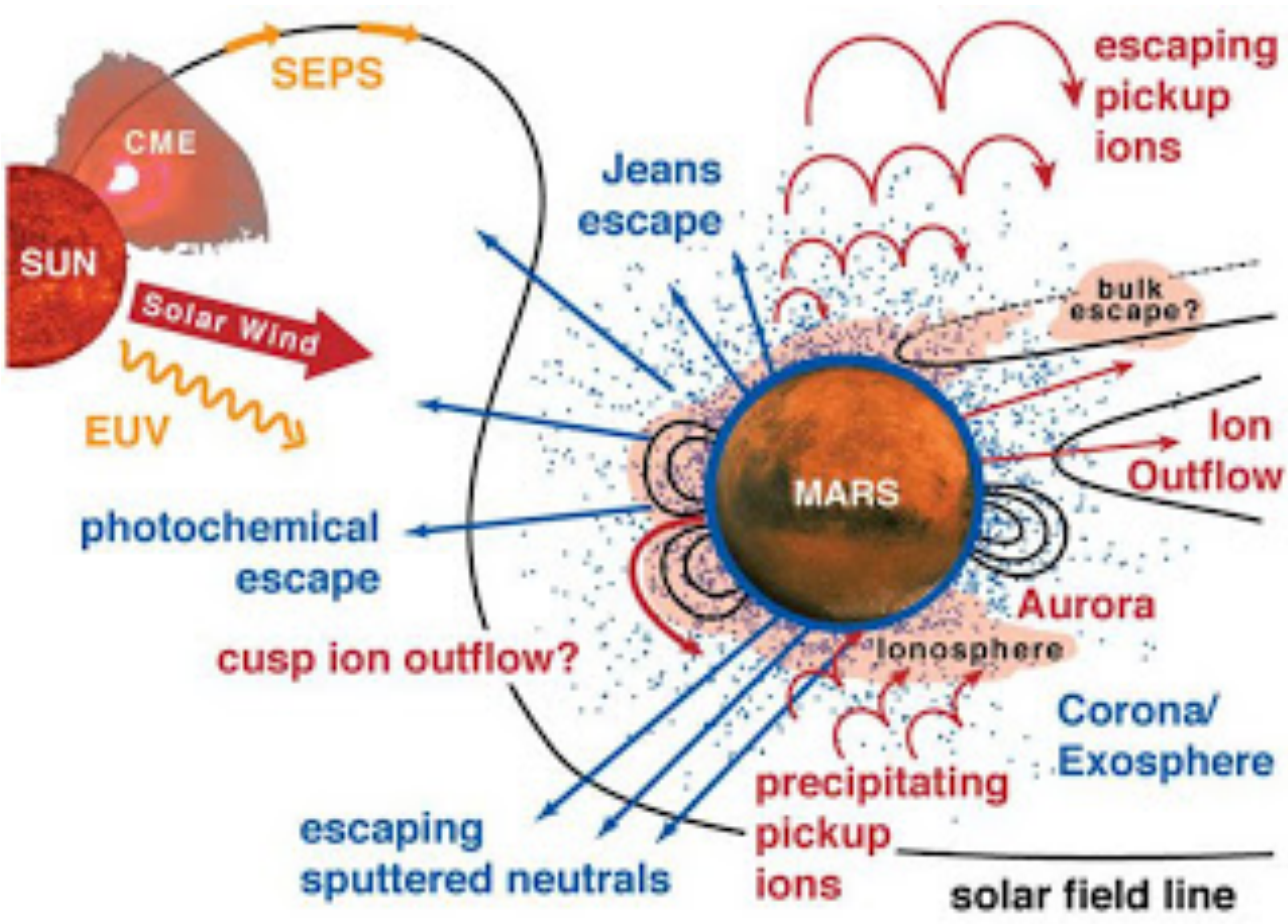


Question is whether this is just interruption of escape or actual enhancement?

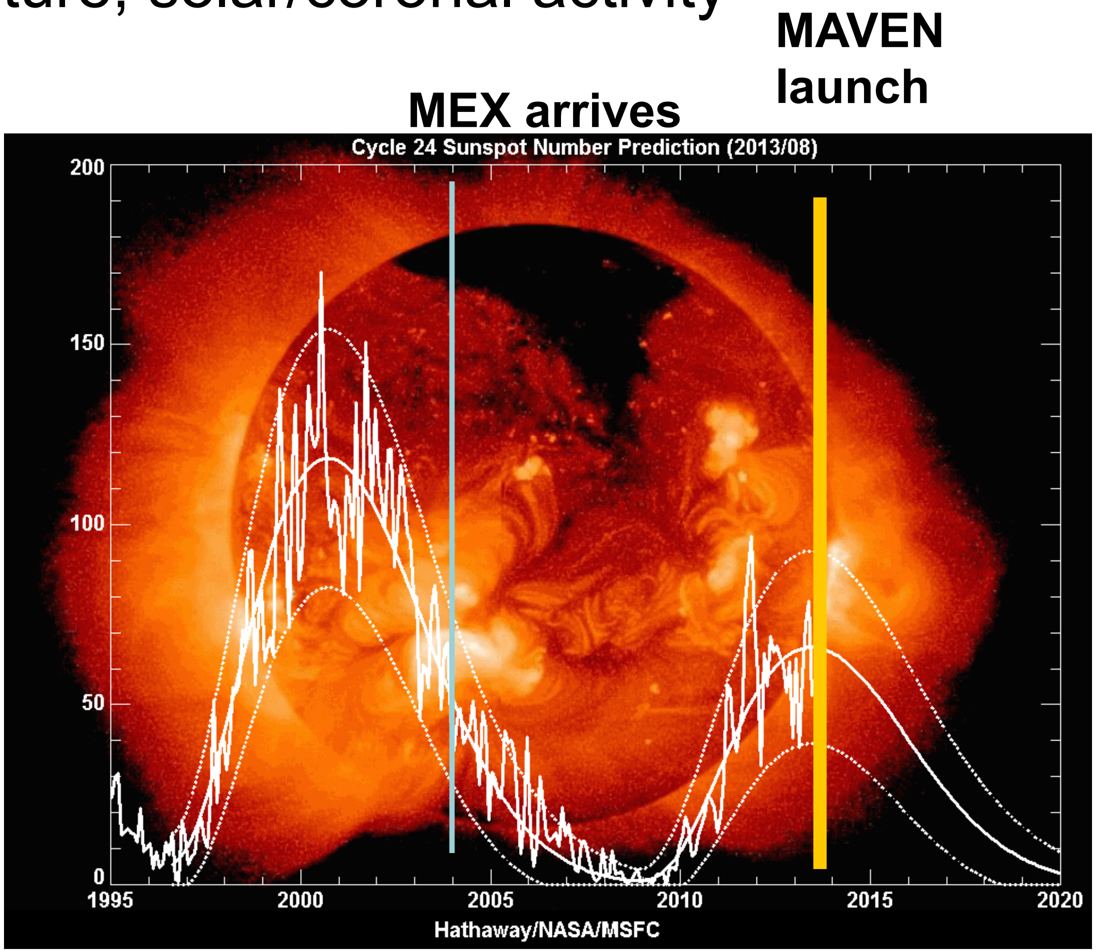


NASA website images from comet Enke passage, and cartoon of the CME interacting with the draped cometary magnetic fields

The responses of Mars to the large ranges of conditions is a primary theme of this new Mars mission



Solar Cycle Settings of all observations need to be considered in drawing conclusions: EUV, solar wind structure, solar/coronal activity



In particular, many MEX observations occurred during an unusually quiet solar period. Its extended operation plus new measurements on MAVEN mission will be a big opportunity.

Where the MAVEN mission will make a huge difference:

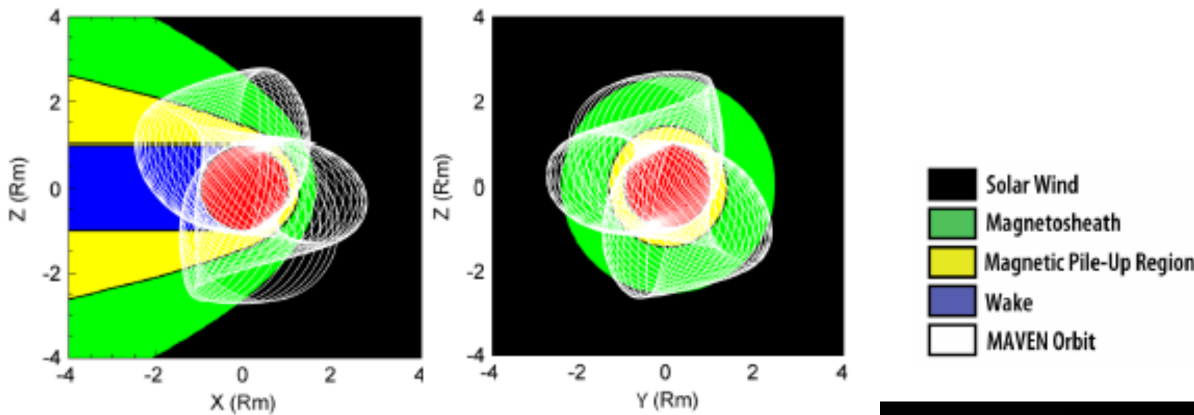
-We will see if sputtering really occurs and its importance relative to other escape processes (some of which may be new to us)

-We will observe how Mars' atmosphere responds to solar events-especially in ways that might enhance escape (e.g. Higher EUV–enhanced thermal and photochemical escape, and atmosphere ion production? CMEs-more sputtering and ion escape? Other processes e.g. related to crustal magnetic field interactions with solar wind, to SEPs?)

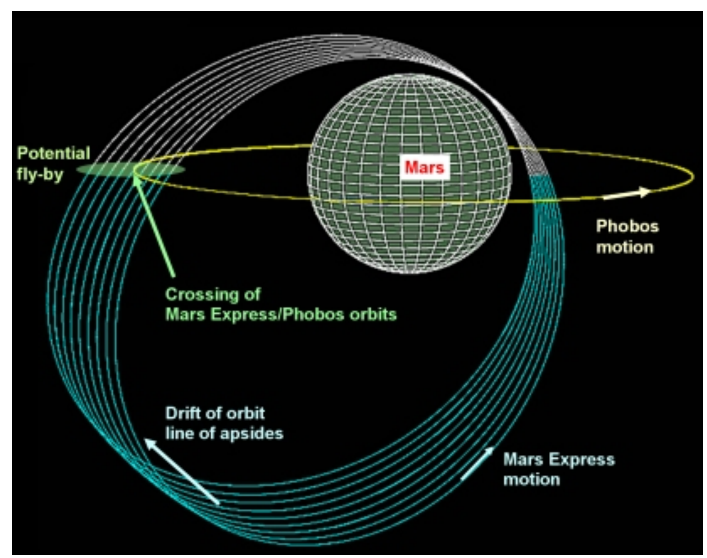
- We will use the results to constrain estimates and models of escape over time due to still-active processes.
These will tell us if we can explain how Mars got where it is today-with implications for Earth and other planets as well.

Supporting information of interest to MAVEN

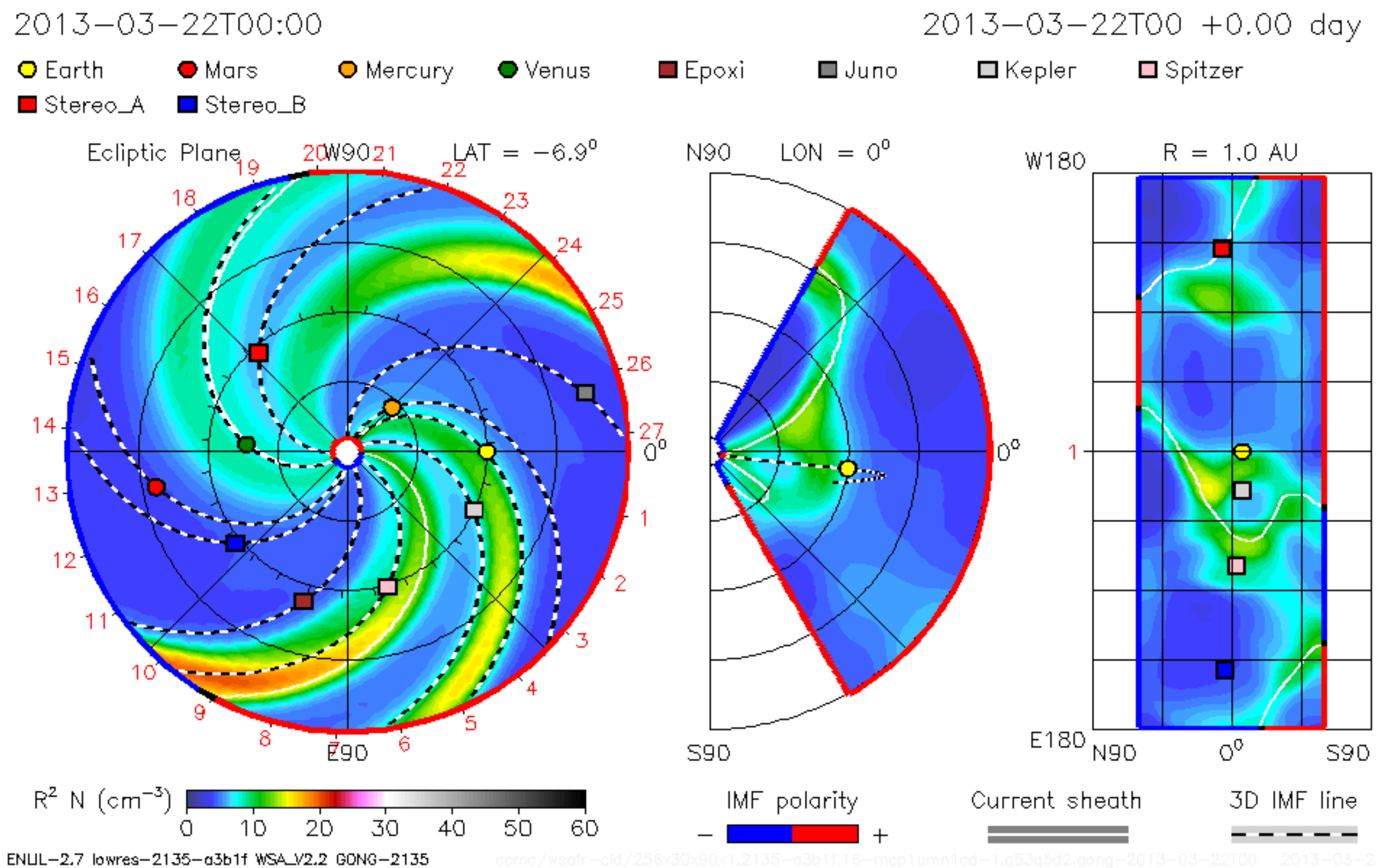
ESA's Mars Express ASPERA-3 measures solar wind and atmospheric ions in a complementary orbit



Collaborations including measurement comparisons are planned

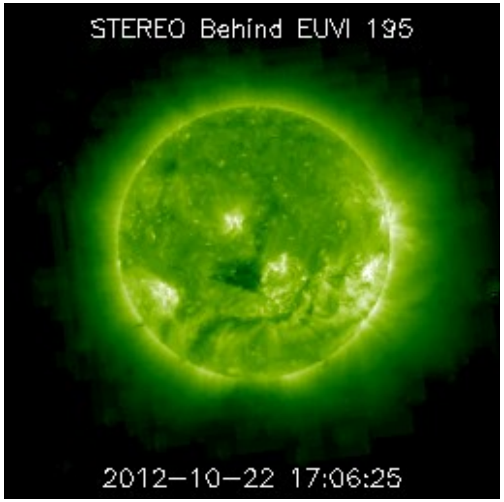


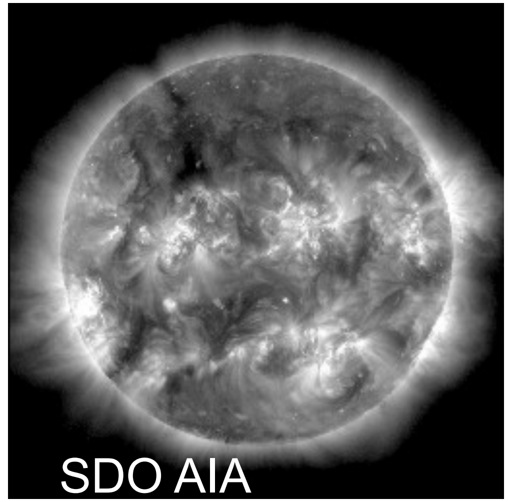
NASA Space weather monitoring assets include models Of CME shocks out to Mars orbit, based on SOHO and STEREO mission imaging (Space Weather Center, GSFC)

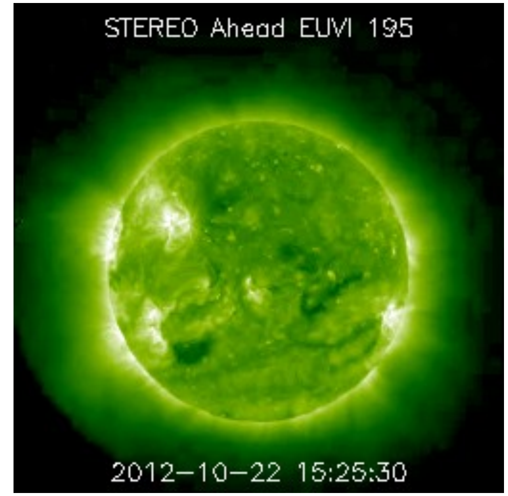


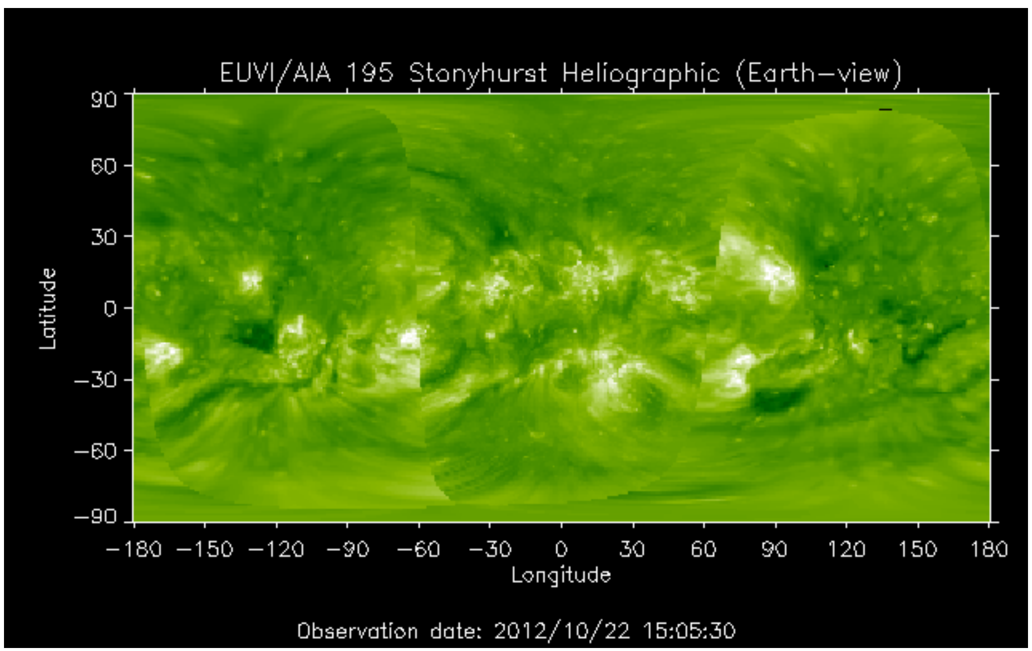
swc.gsfc.nasa.gov

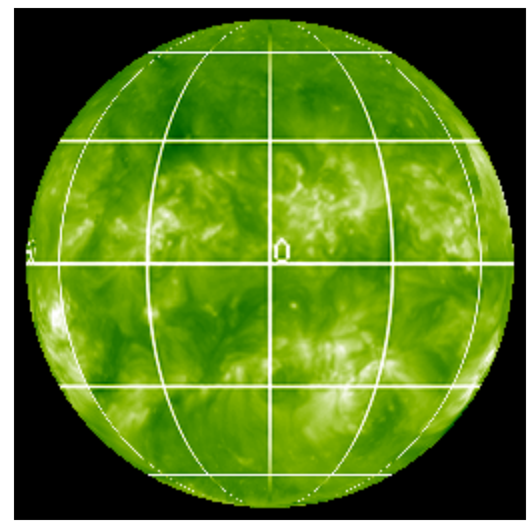
Since 2011 we have been able to watch solar activity anywhere







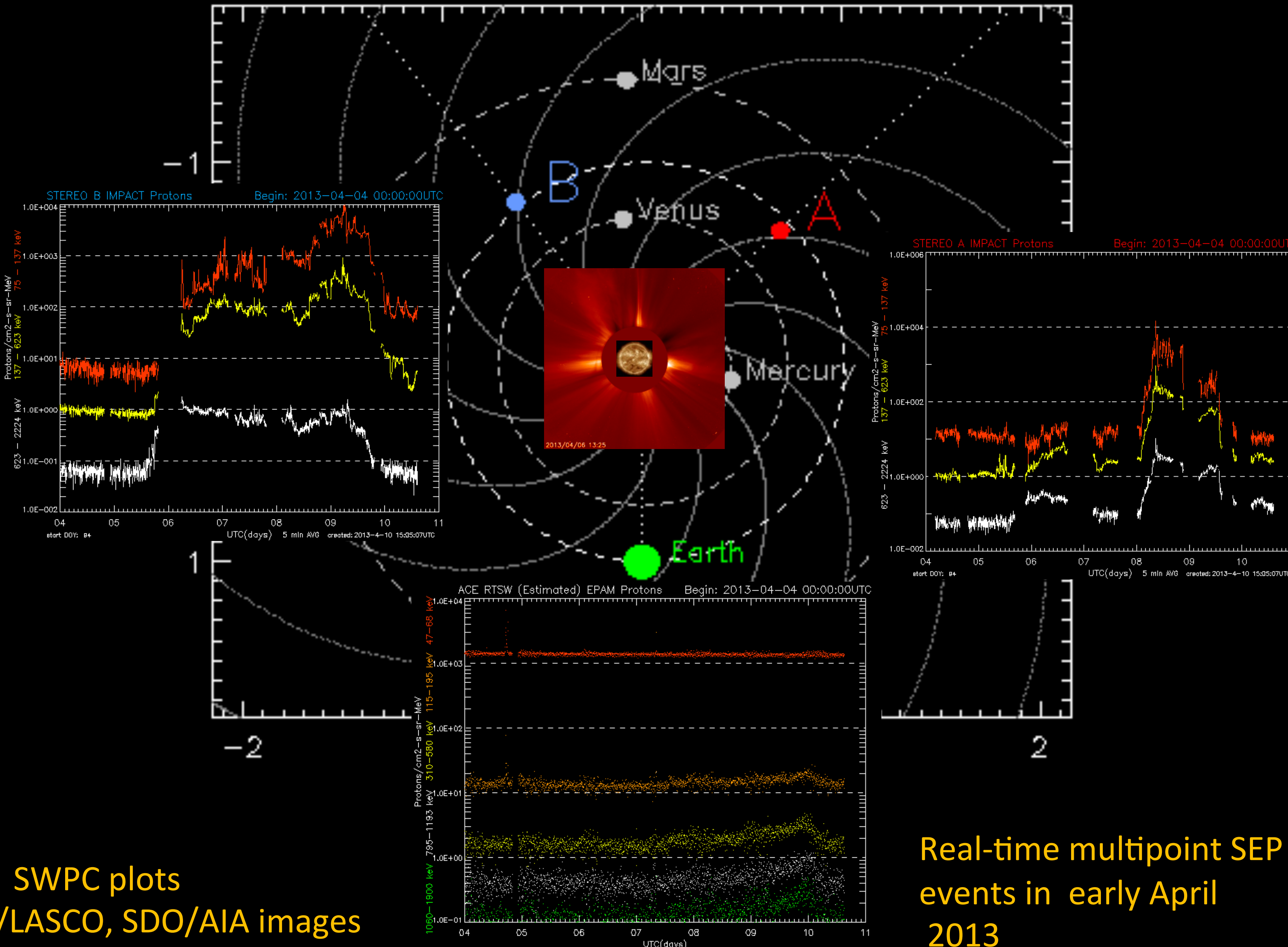




Bill Thompson, GSFC
STEREO Science Ctr.

SDO and STEREO are part of the Heliophysics Great Observatory

STEREO +ACE real-time multipoint measurements at 1 AU give the latest state of space weather ‘now’ (NOAA RT data plots, images from SOHO, SDO)



NOAA SWPC plots
SOHO/LASCO, SDO/AIA images
http://stereo.ssl.berkeley.edu/multistatus.php

Real-time multipoint SEP events in early April 2013