MAVEN

Mars Atmosphere and Volatile Evolution Mission

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History of the Mars Atmosphere Derived From MAVEN Observations

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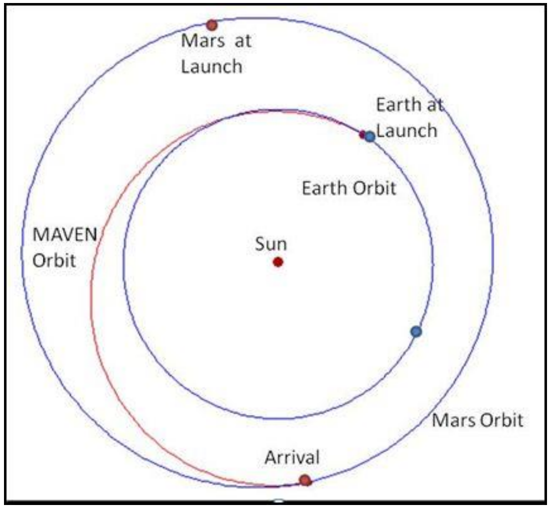
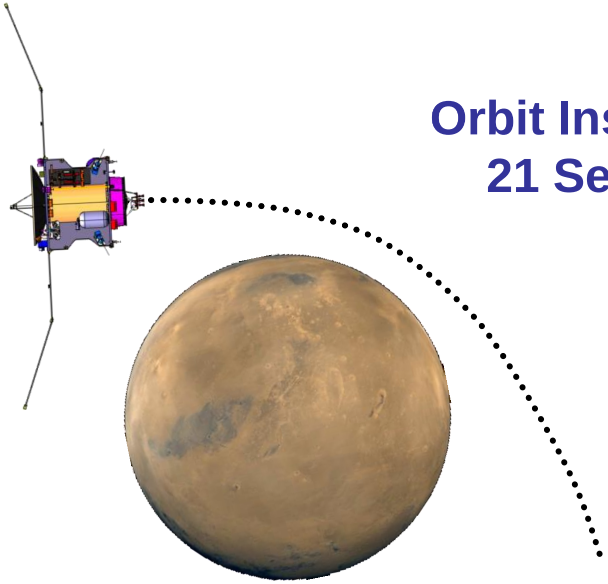
University of Colorado
13 July 2017

MAVEN Mission Profile

Launched on 18 Nov. 2013; Atlas V-401, from Cape Canaveral

Ten-Month Ballistic Cruise to Mars





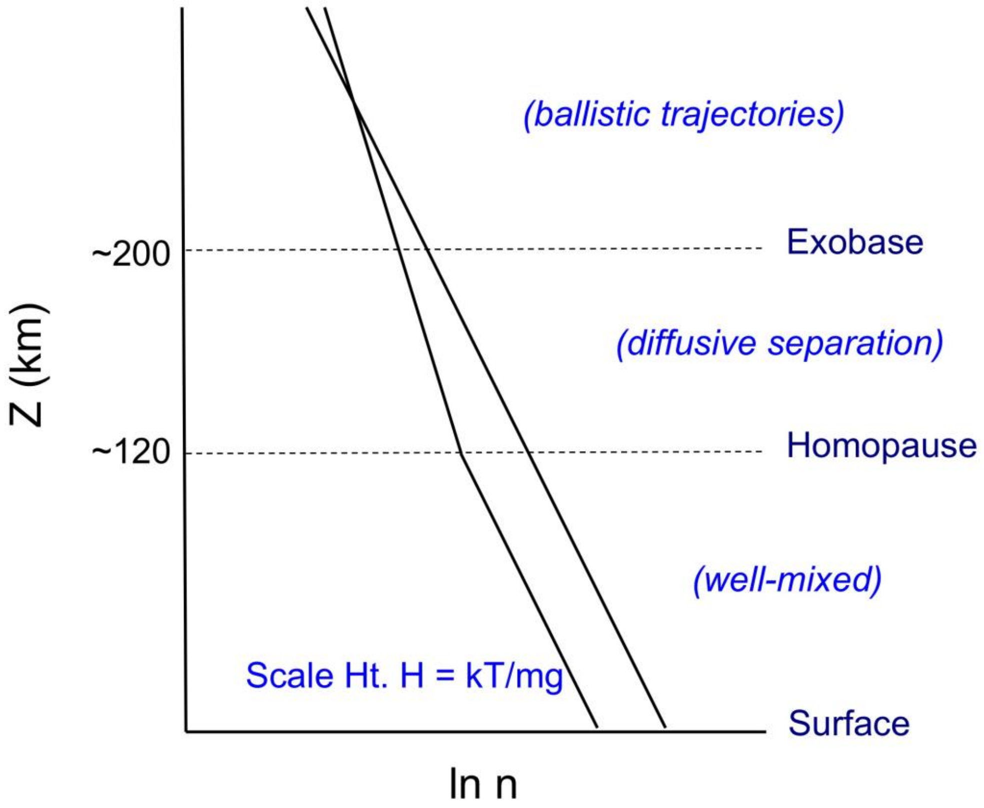
Orbit Insertion on 21 Sept 2014

One Year of Primary Science Operations, Now in Extended Mission

Orbit shown to scale

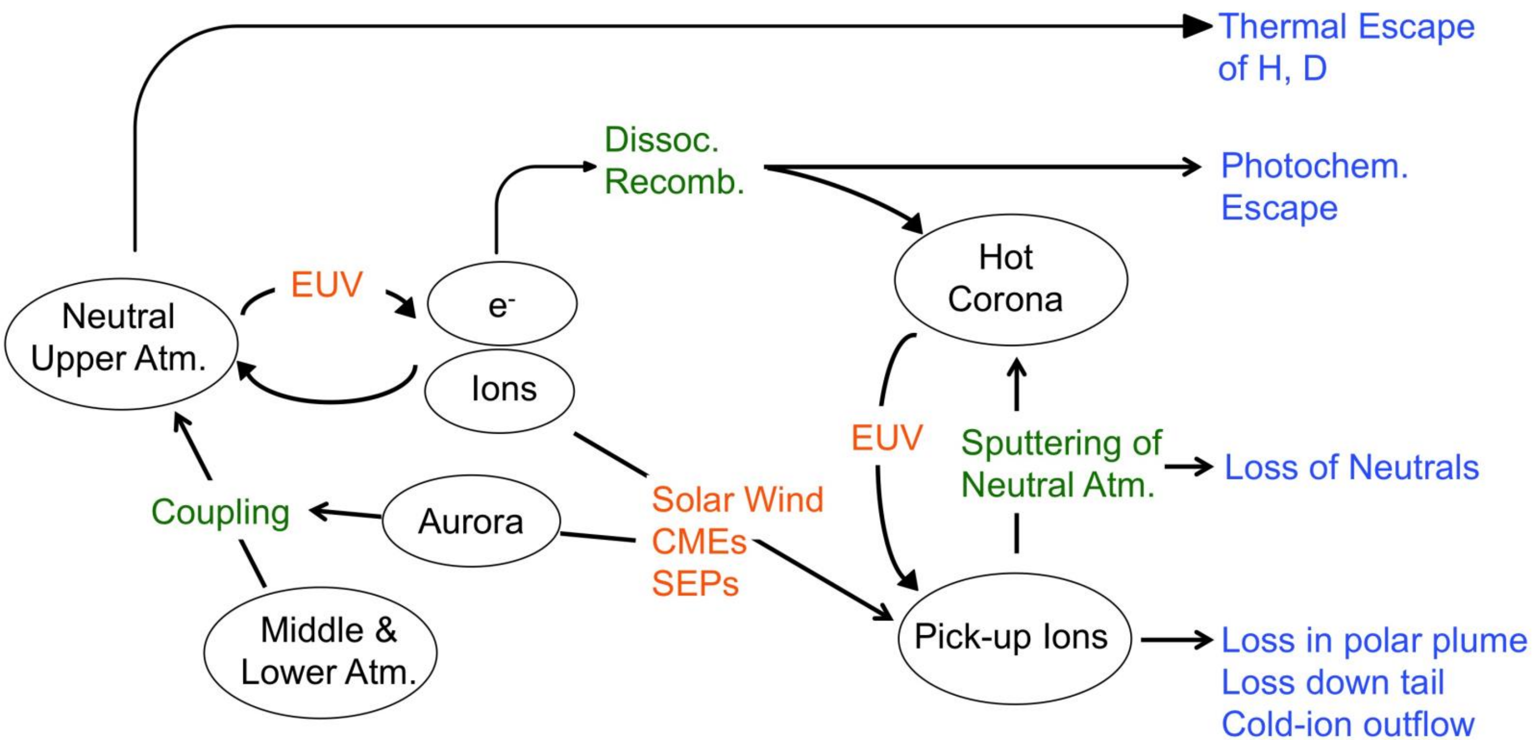
Basic Structure of the Mars Atmosphere

- The Mars upper atmosphere is an extension of the lower atmosphere
- Dynamical mixing between the two allows each to affect the other



Processes Leading to Escape in the Mars Upper Atmosphere*

What controls the behavior of the Mars upper atmosphere, and how do processes there lead to loss of gas to space?



** Shorthand for Mars upper atmosphere, ionosphere, solar-wind interactions, and the consequent loss of gas to space*

Outline of Presentation

- Examples of fundamental discoveries made by MAVEN
- Synthesis of results on loss to space
  - Observations of key loss mechanisms and drivers
  - Best estimate of current loss rates at the present epoch
  - Integrated loss through time
- Ongoing/continuing observations

(Not discussed in detail today: Detailed observations of behavior that allow us to understand individual processes and behavior)

Mars Diffuse Aurora

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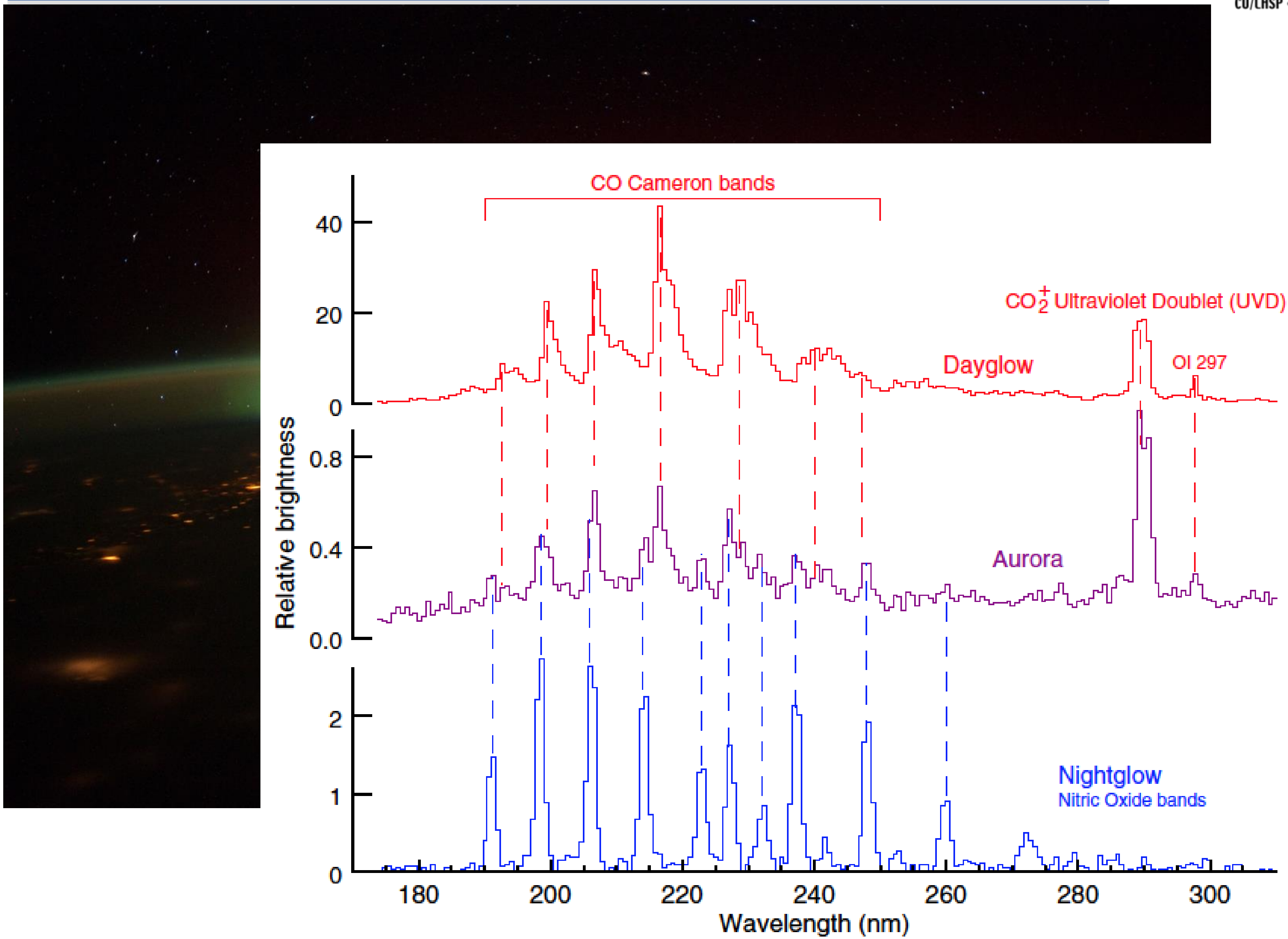
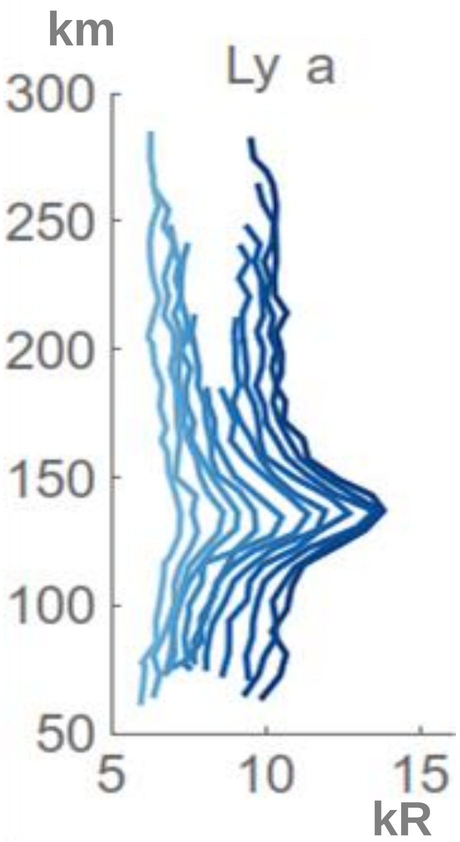
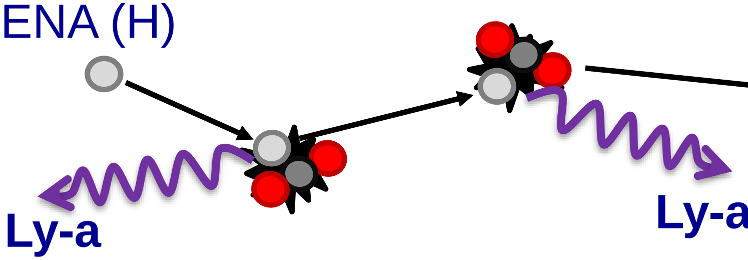


Mars Proton Aurora

- Unexpected bumps in H Lyman alpha profiles occurred simultaneously with penetrating high-energy solar wind protons.
- The protons emit through repeated charge exchange with background gases



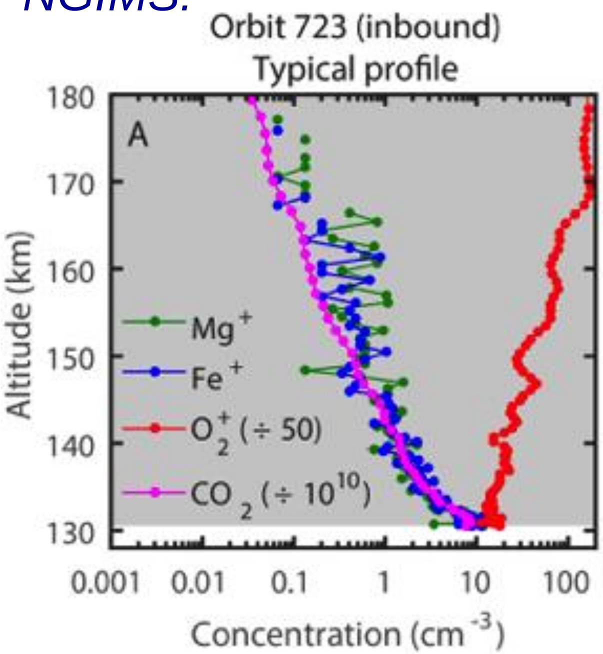
Penetrating
ENA (H)



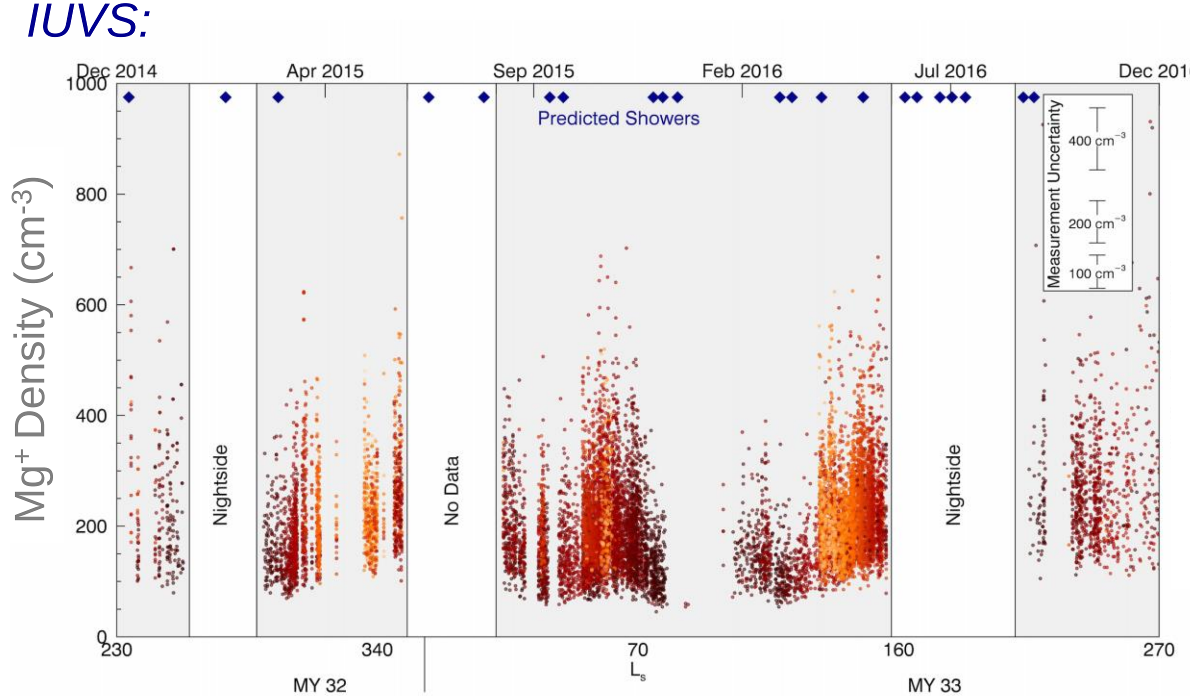
Each penetrating p / H can undergo many collisions, emitting many Ly-a photons

Detection Of Long-Lived Metal-Ion Layer In The Ionosphere

NGIMS:



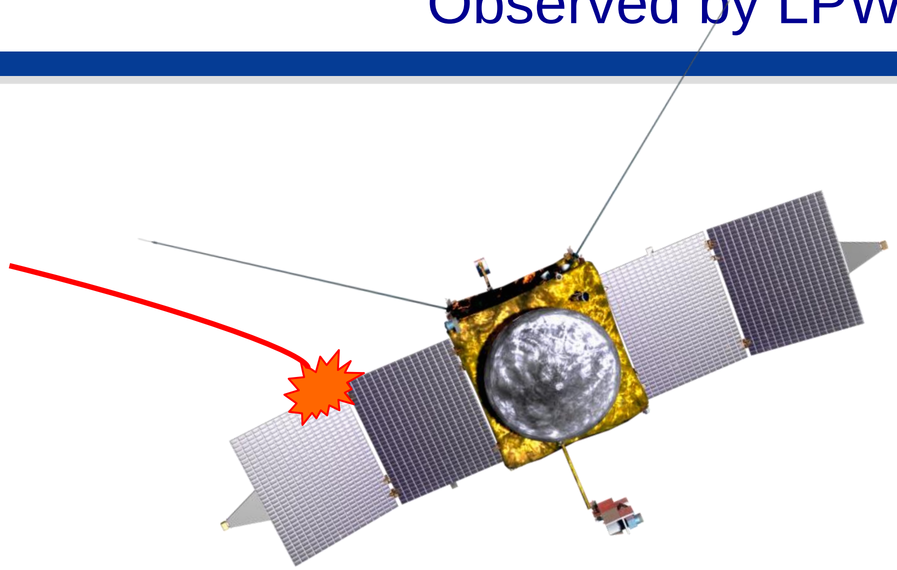
IUVS:



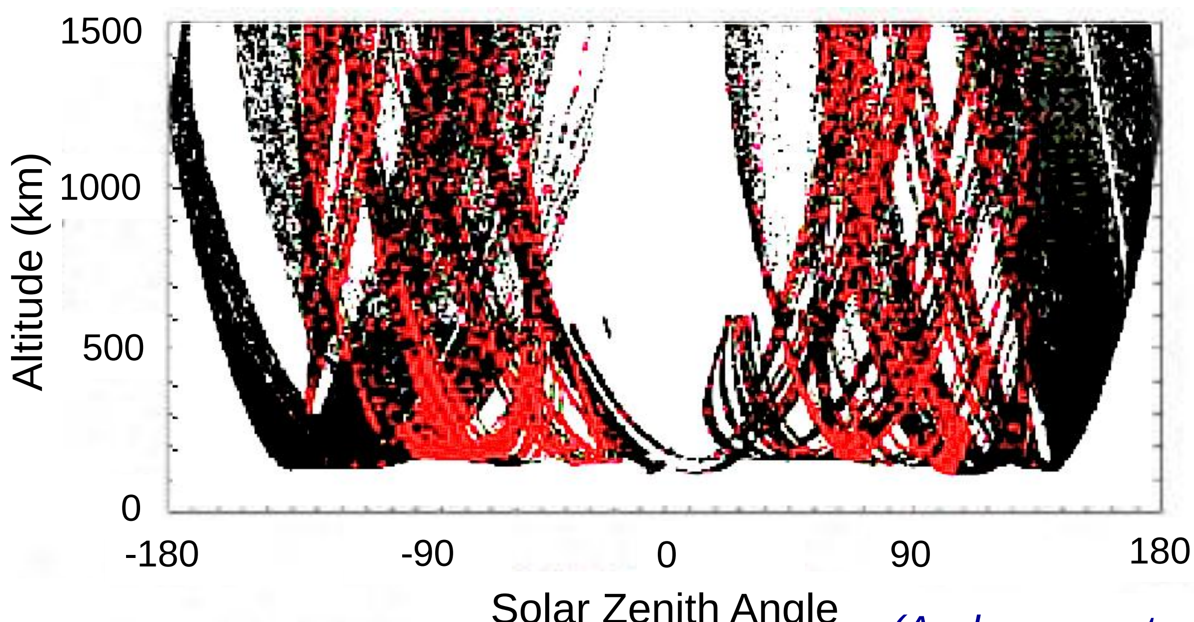
Results may have important implications for ionospheric chemistry and atmospheric escape.

(Grebowsky et al., 2017; Crismani et al., 2017)

Discovery of Dust Cloud In Near-Mars Space, Observed by LPW



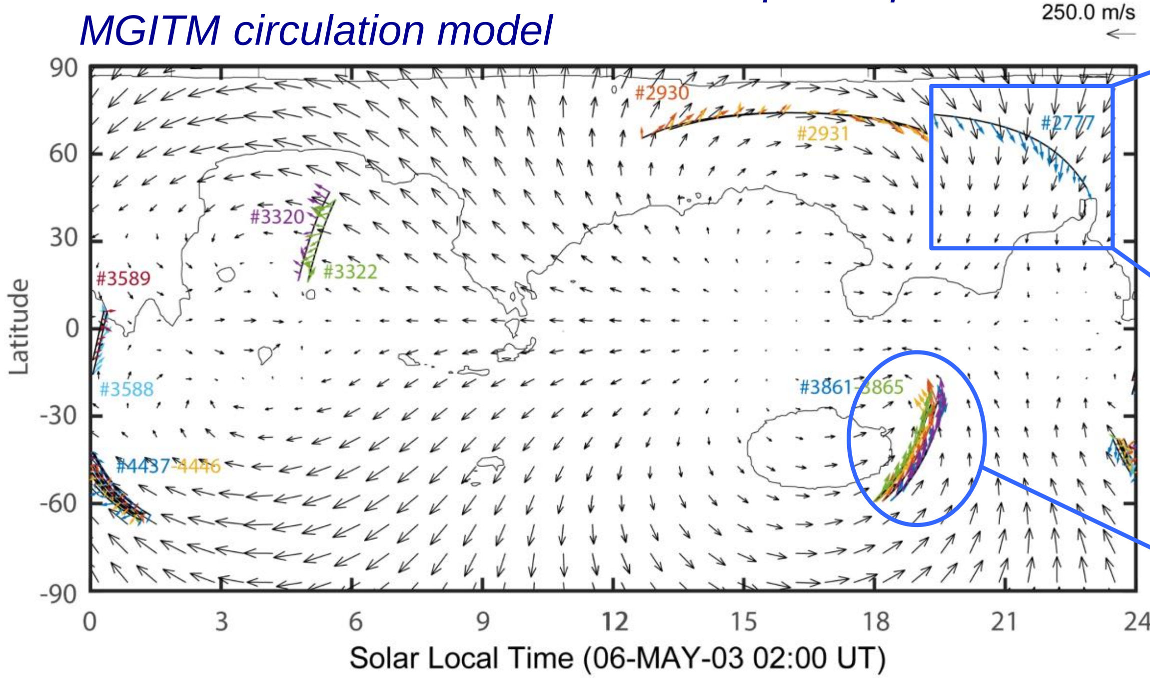
Observed distribution of dust impacts:

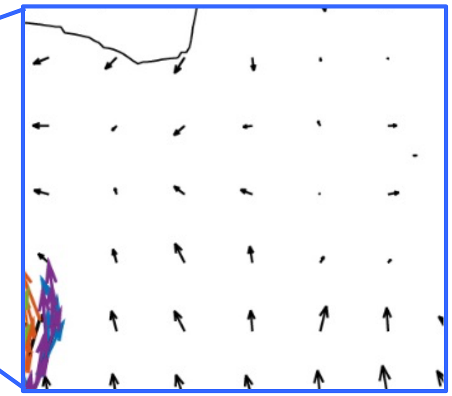


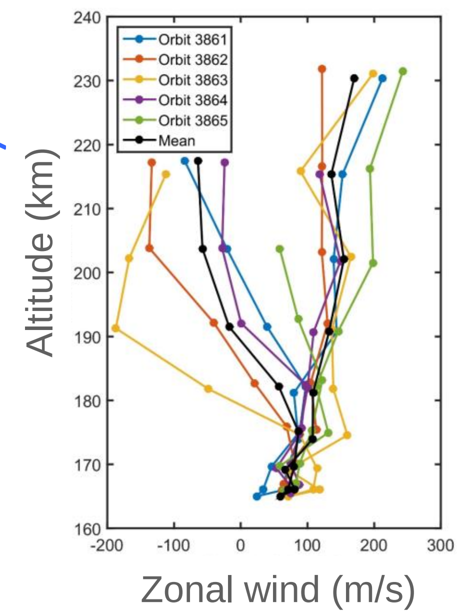
(Andersson et al., 2015)

NGIMS Measurement of Neutral and Ion Winds

Neutral wind measurements to date plus representative MGITM circulation model



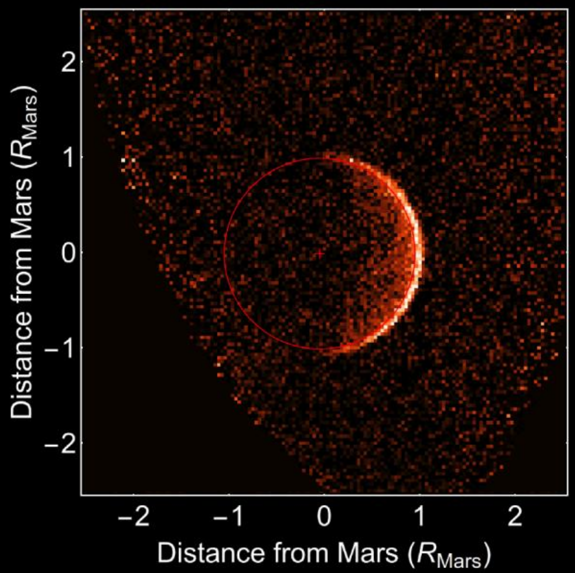




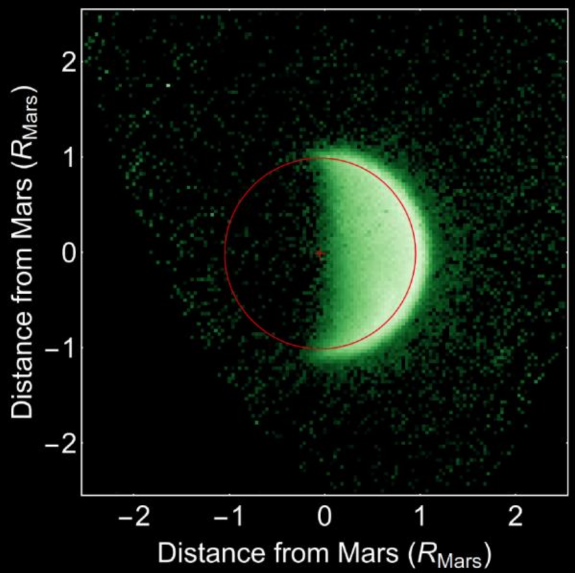
- NGIMS yaws left/right during periapsis pass to derive winds, implemented on all orbits one day/month
- Measure both neutrals and ions, on consecutive days
- Results show both similarities to model circulation and differences, plus significant longitudinal variability
- First synoptic measurements of upper-atmospheric winds

(M. Benna et al.)

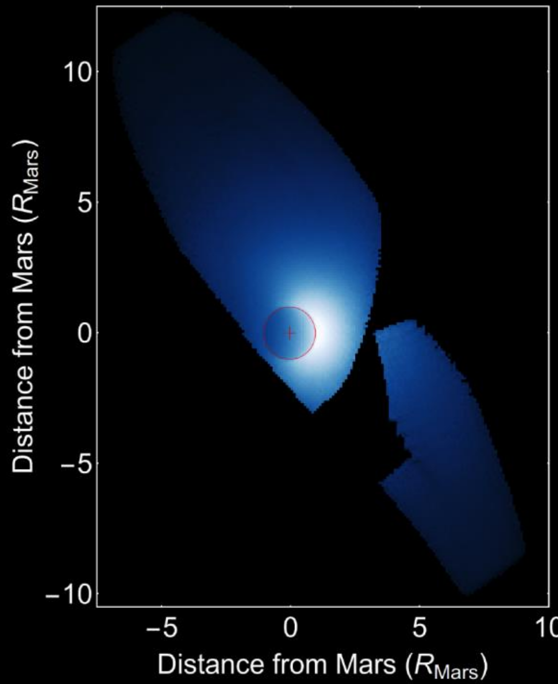
Atomic Components Of H_2O And CO_2 On Their Way To Escaping



Atomic Carbon

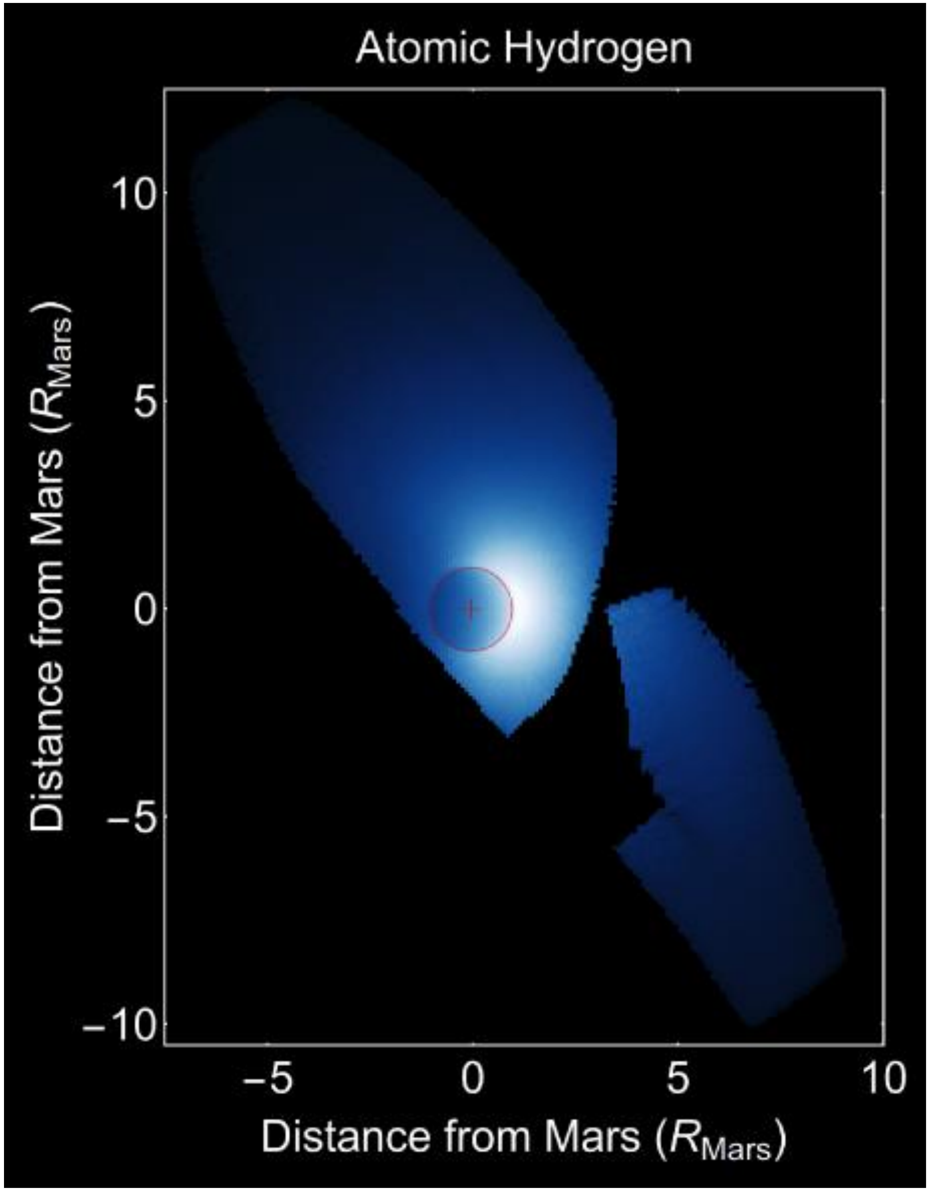


Atomic Oxygen



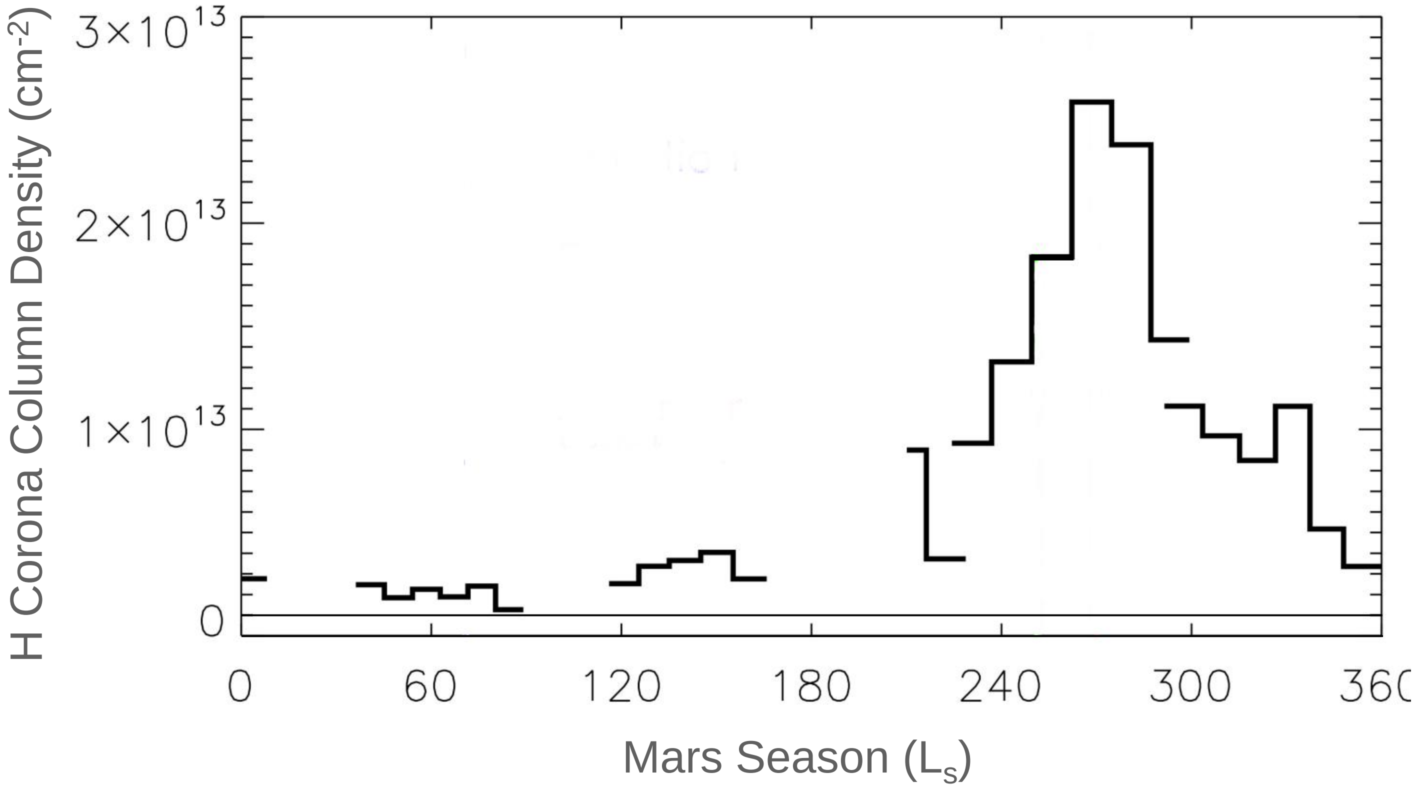
Atomic Hydrogen

Hydrogen Loss To Space



- An extended corona of hydrogen surrounds Mars, to greater than 10 Mars radii.
- Source of H is H_2O in the lower atmosphere; H_2O is broken apart by sunlight, and H migrates to upper atmosphere
- H is light enough that it can escape to space by thermal (Jeans) escape

Hydrogen Loss To Space

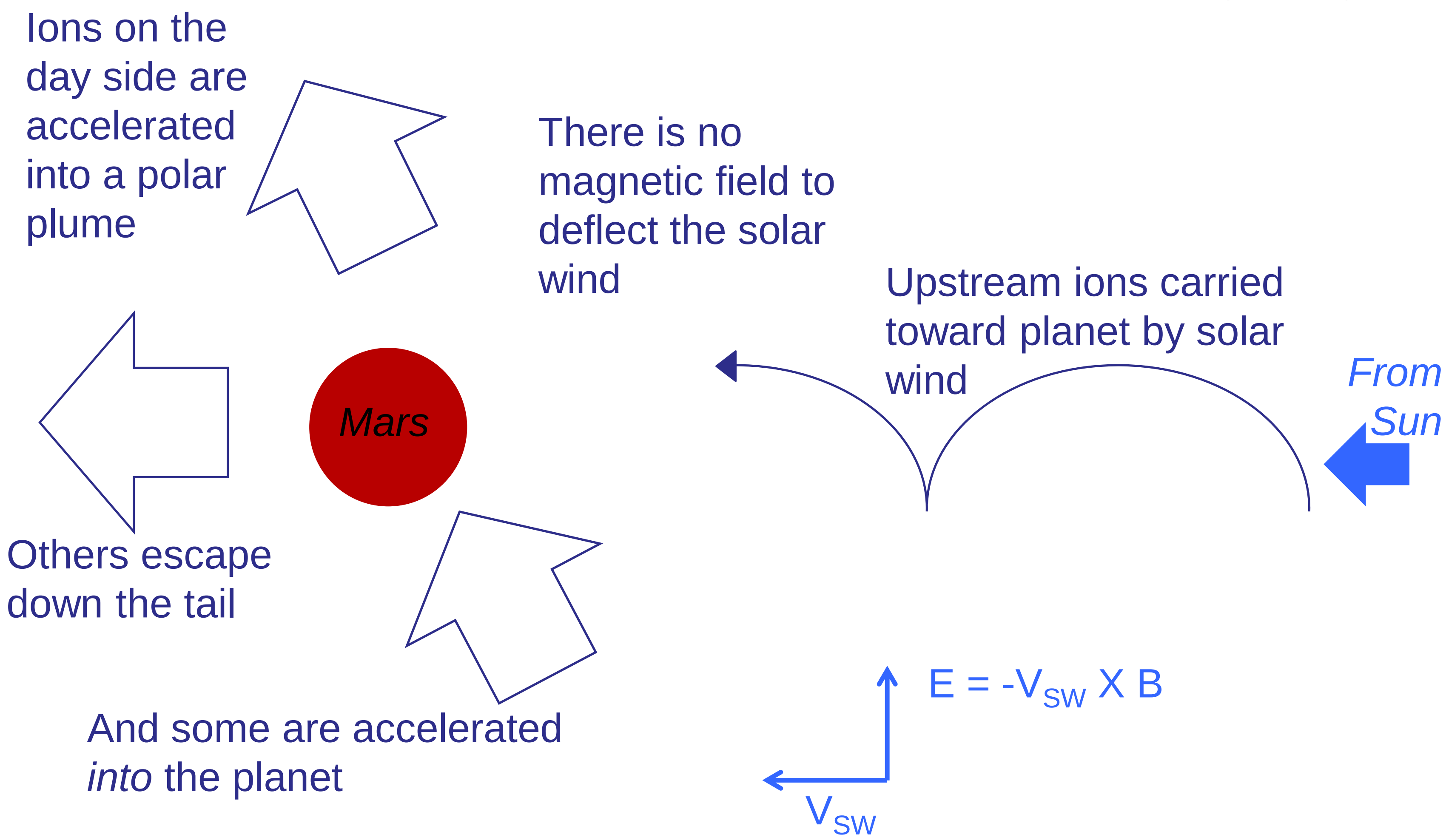


Column abundance of H in the extended corona shown throughout a Mars year

- Loss rate between ~250 – 1800 g H/sec
- If constant for 4 b.y., equivalent to loss of a global layer of H_2O between 3.4-24 m thick

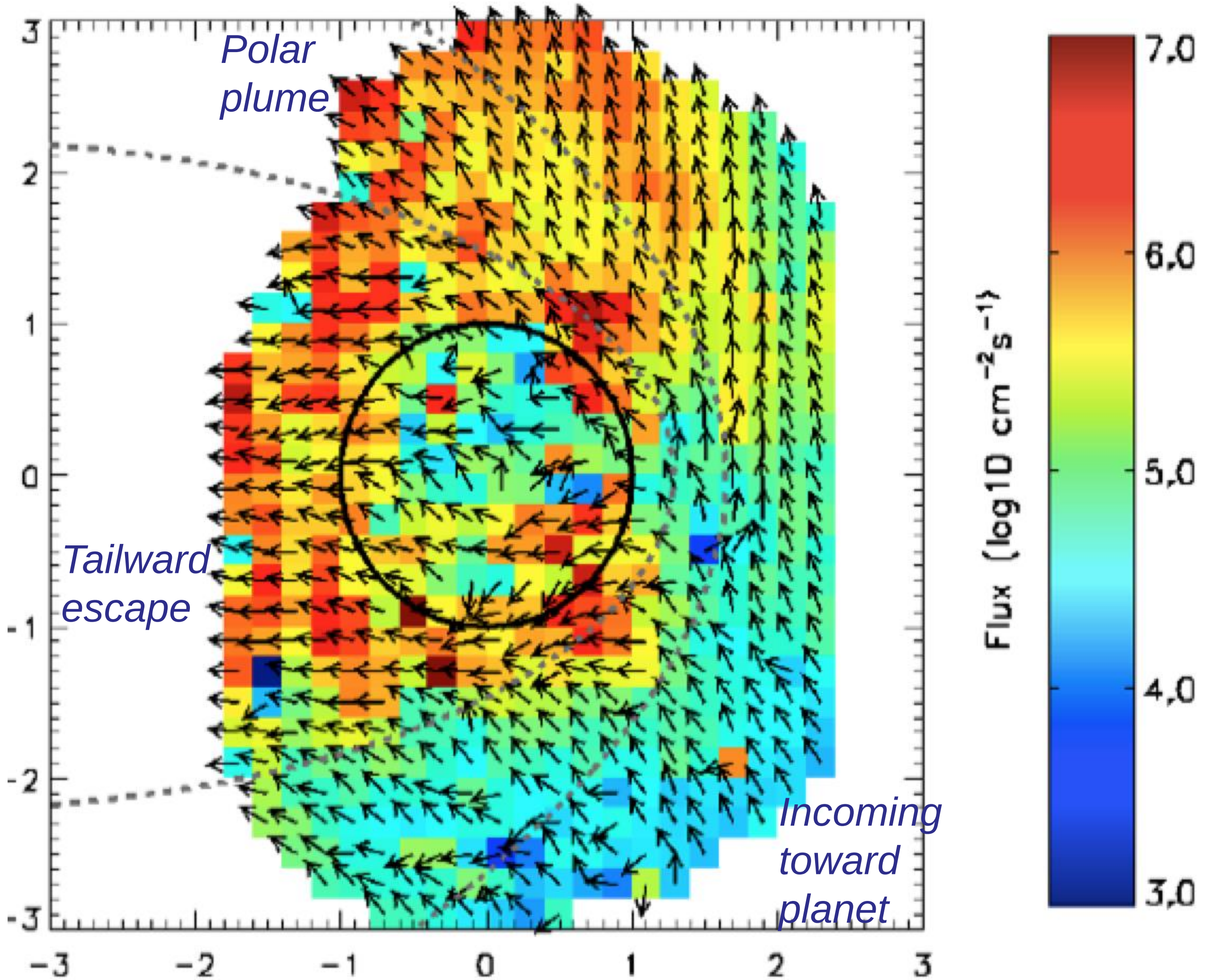
(Halekas et al., 2017; Chaffin et al., 2016)

How Ions Escape: Acceleration By The Solar Wind

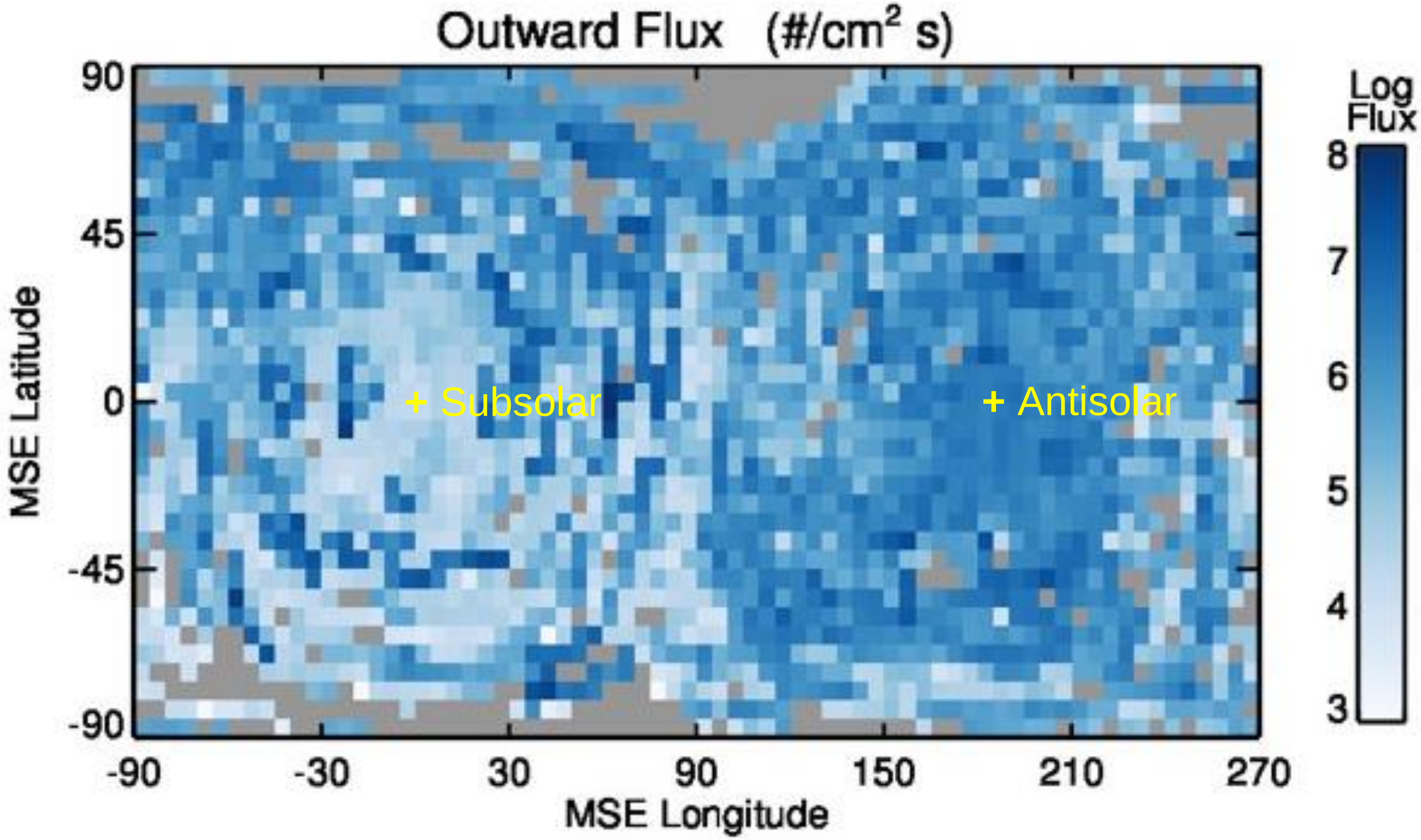


Magnetic field of impinging solar wind generates electric field that accelerates ions

MAVEN Data Show These Same Escape Pathways For Oxygen Ions

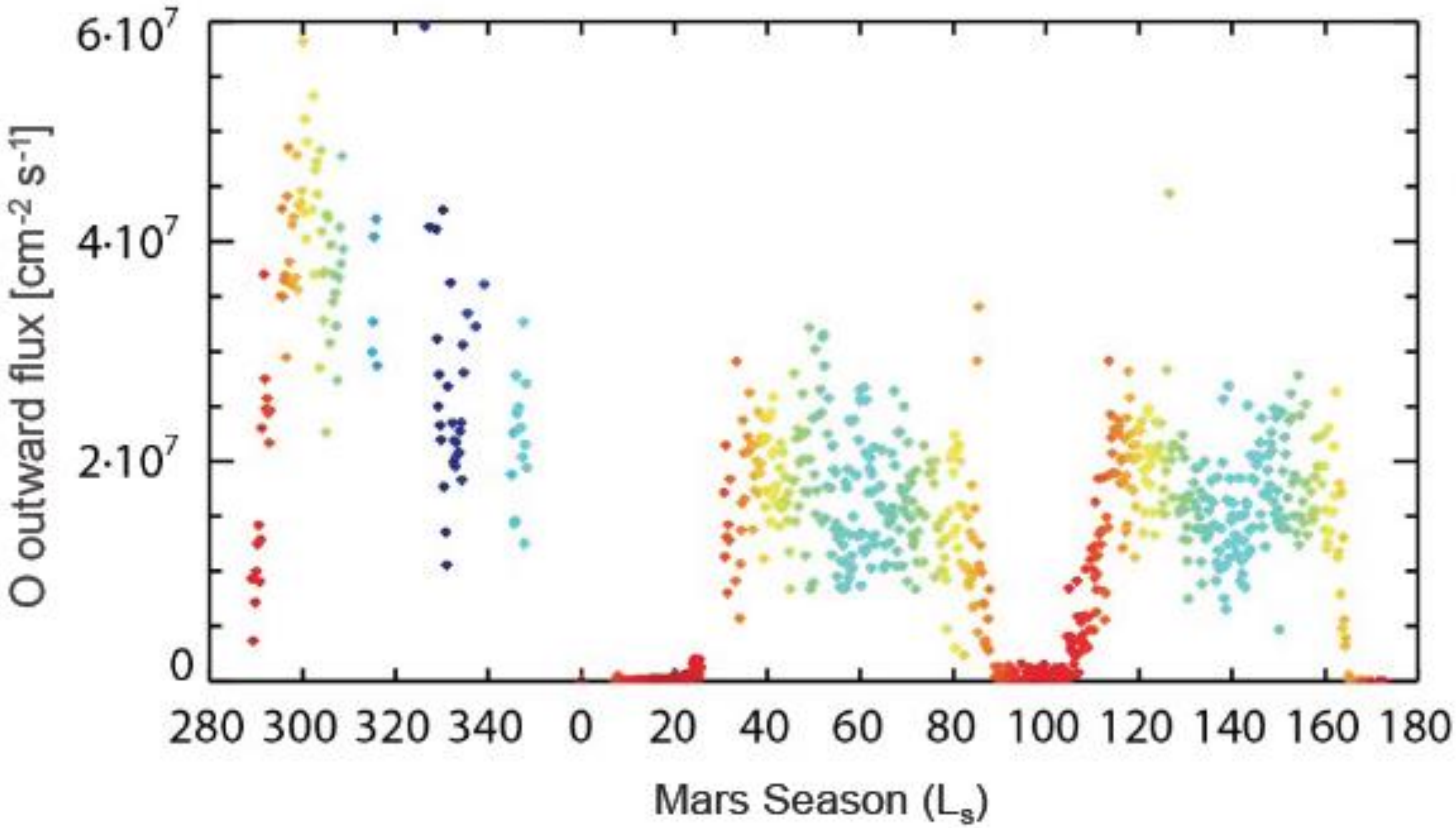


How Much Oxygen Escapes As Ions?



- Loss rate ~ 130 g O/sec
- Mean loss rate would remove all of the present-day atmospheric O (mainly from CO_2) in ~ 3 b.y.

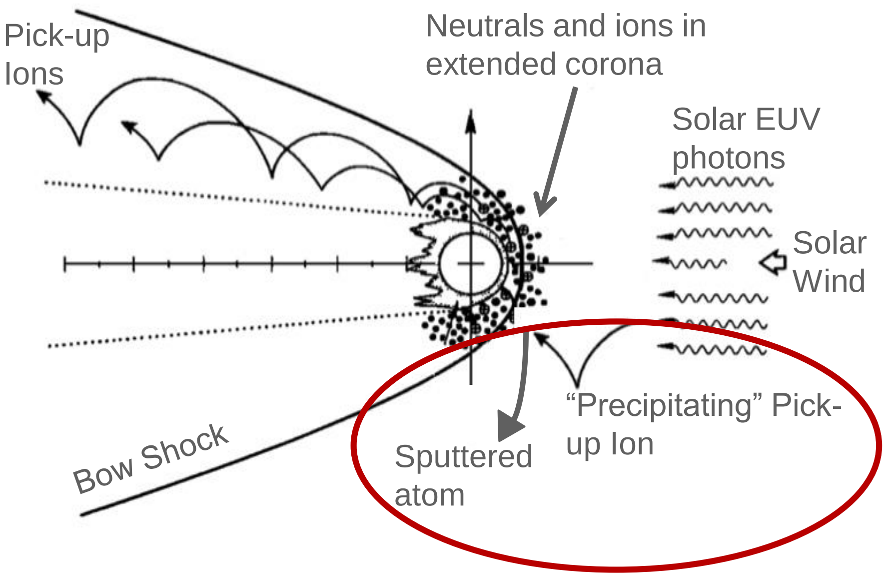
Photochemical Loss

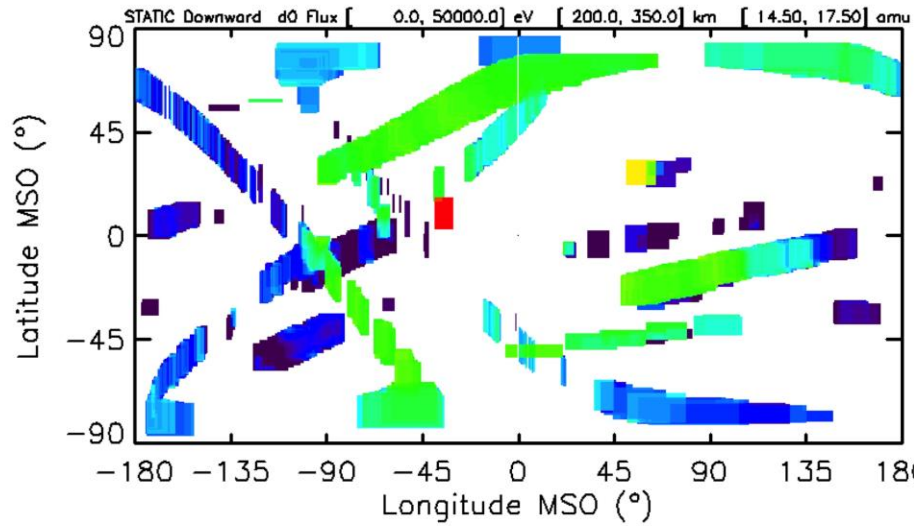


- Loss rate ~ 1300 g O/sec
- Mean loss rate would remove all of the present-day atmospheric O (mainly from CO_2) in ~ 300 m.y.

(Lillis et al., 2017)

Sputtering Loss of O





Spatial distribution of measured sputtering ion characteristics

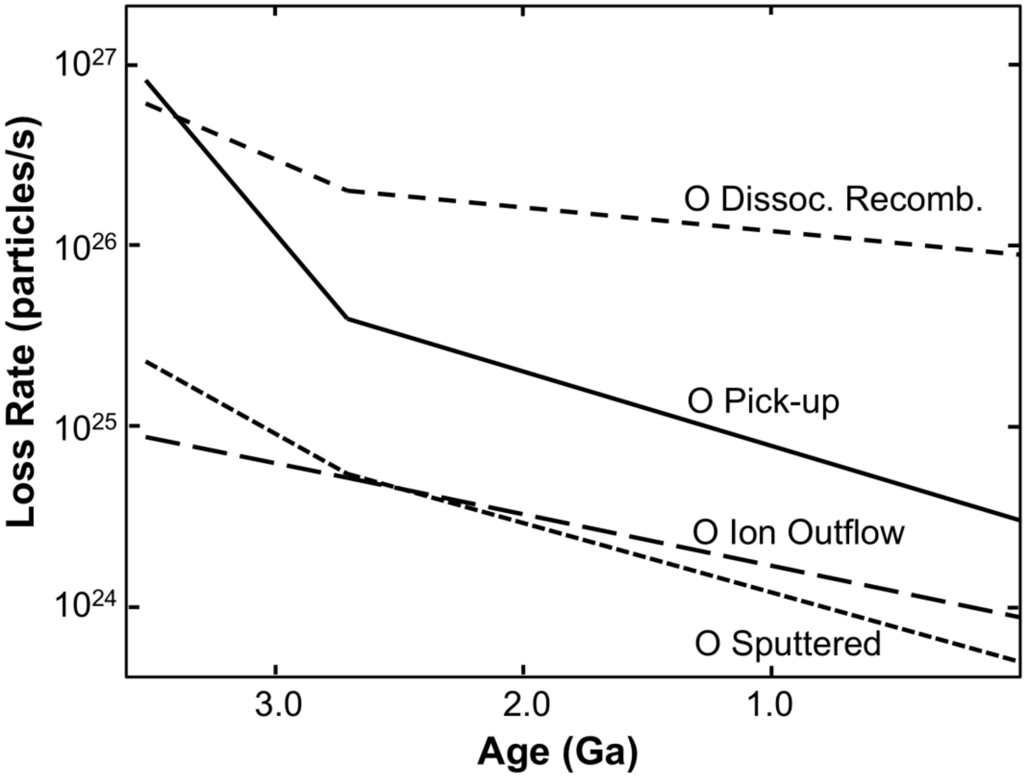
- Loss rate ~ 80 g O/sec
- Mean loss rate would remove all of the present-day atmospheric O (mainly from CO_2) in > 4 b.y.

(Leblanc et al. 2015, 2017)

Adding Up The Loss Rates

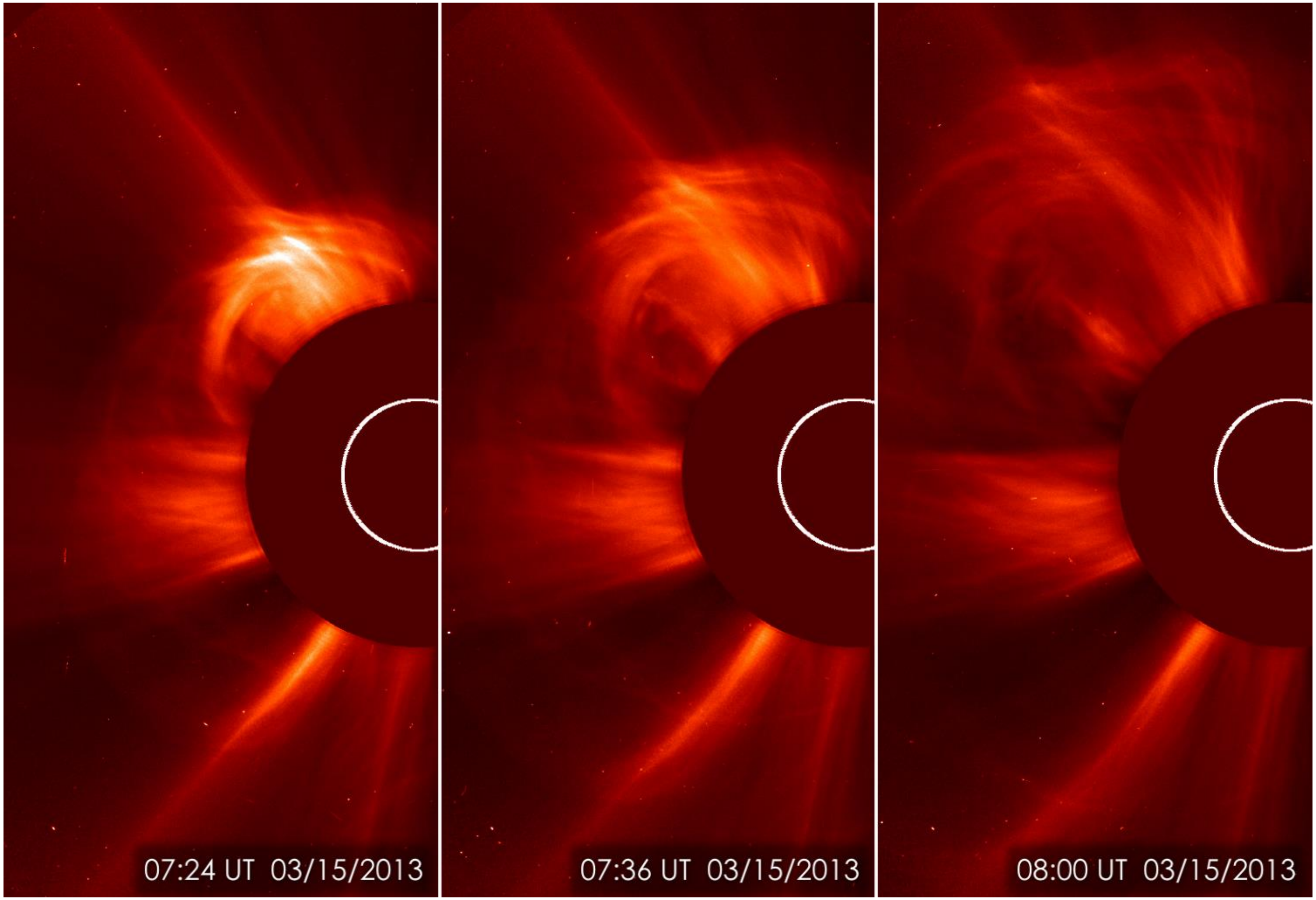
- **Total loss rate from Mars today**
  - Total measured loss rate of ~ 2-3 kg/s
- **Hydrogen loss (from H_2O):**
  - Mars would have lost a global equivalent layer of water between ~ 3.4 – 24 m thick in 4 billion years
- **Oxygen loss (from CO_2 and H_2O):**
  - Mars would have lost equivalent of either ~ 2.4 m of H_2O or ~75 mbar of CO_2 in 4 billion years
- ***But, loss rates almost certainly not constant through time***

Atmospheric Loss Rates Were Greater Early In History



- Loss rates were greater in the past when the solar EUV and solar wind were more intense
- History of EUV and solar wind are derived from examining sun-like stars, effects at Mars modeled based on physical processes; we use the model from Chassefiere and Leblanc (2013)
- *Integrated loss of O equivalent to loss of > 15 m H_2O or > 0.5 bar CO_2*

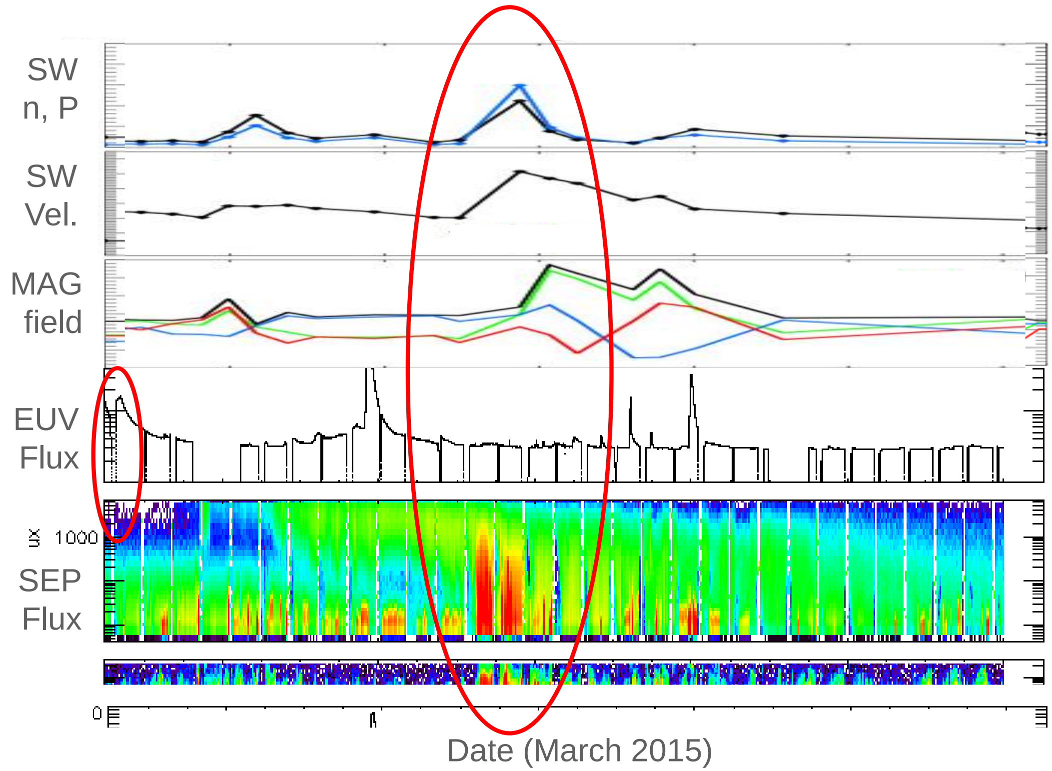
Solar Storms Can Enhance Loss From Mars' Atmosphere



Solar coronal mass ejection as observed from SOHO spacecraft, 2013

MAVEN Observes Enhanced Loss During Solar Storms (1 of 4)

The 8 March 2015 Interplanetary Coronal Mass Ejection:



- 8 March 2015 event is the largest event we've seen to date
- It's actually only a moderate-strength event
- Flare on 6 March, solar-wind arrived at Mars on 8 March.

MAVEN Observes Enhanced Loss During Solar Storms (2 of 4)

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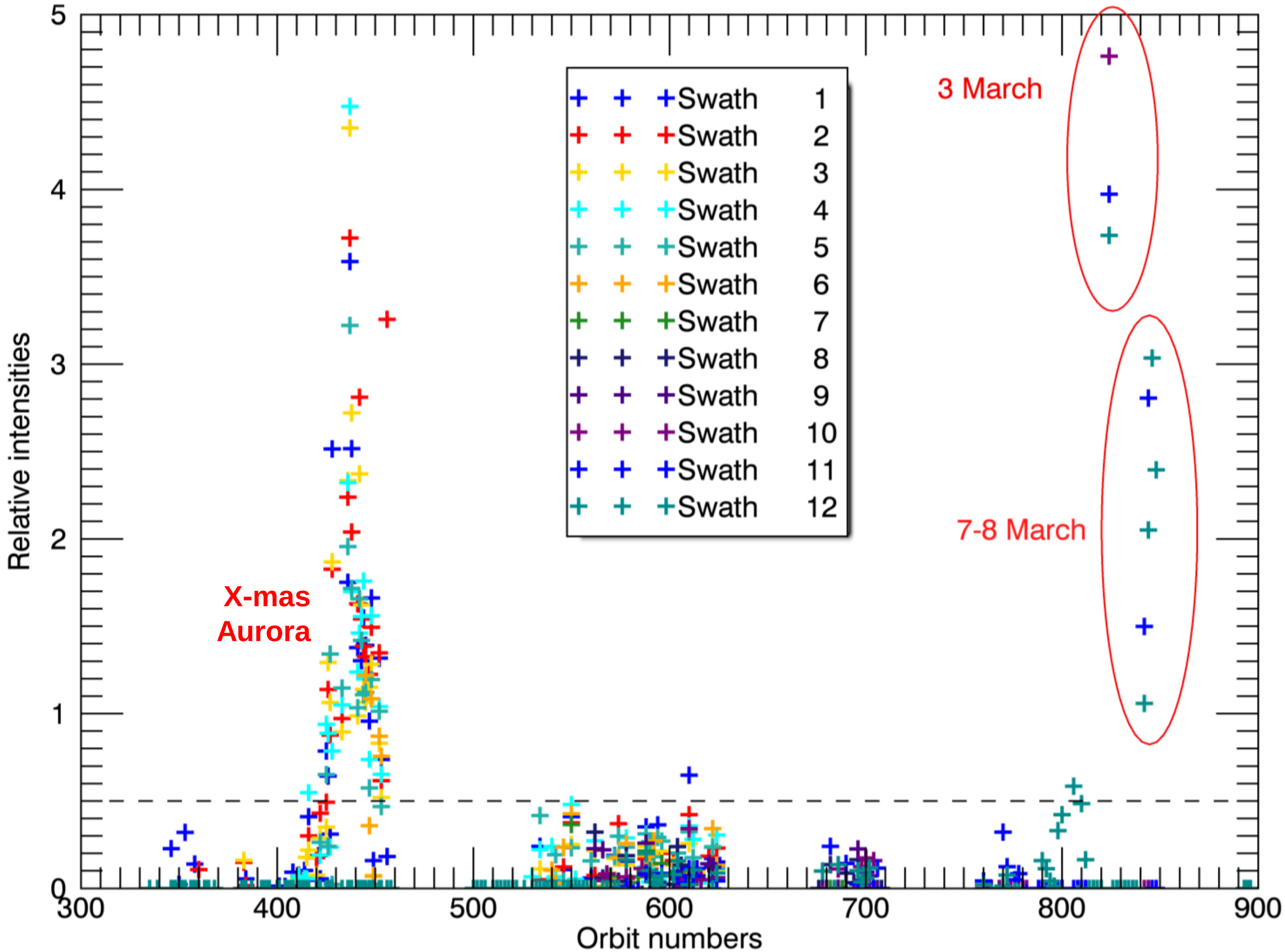
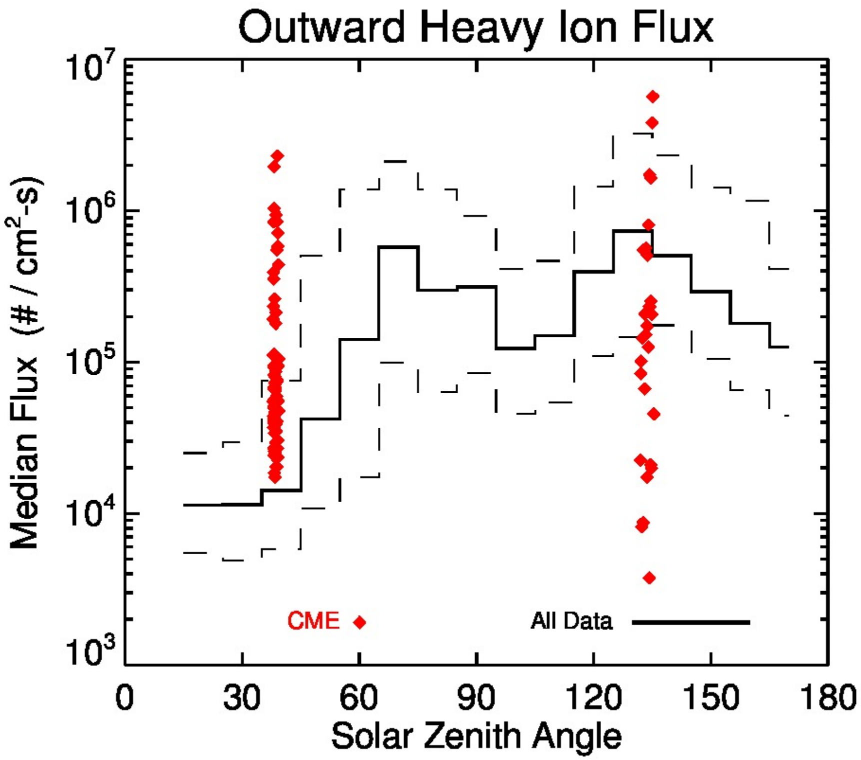
Aurora triggered by March events compared to the earlier Dec. 2014 aurora:



MAVEN Observes Enhanced Loss During Solar Storms (3 of 4)

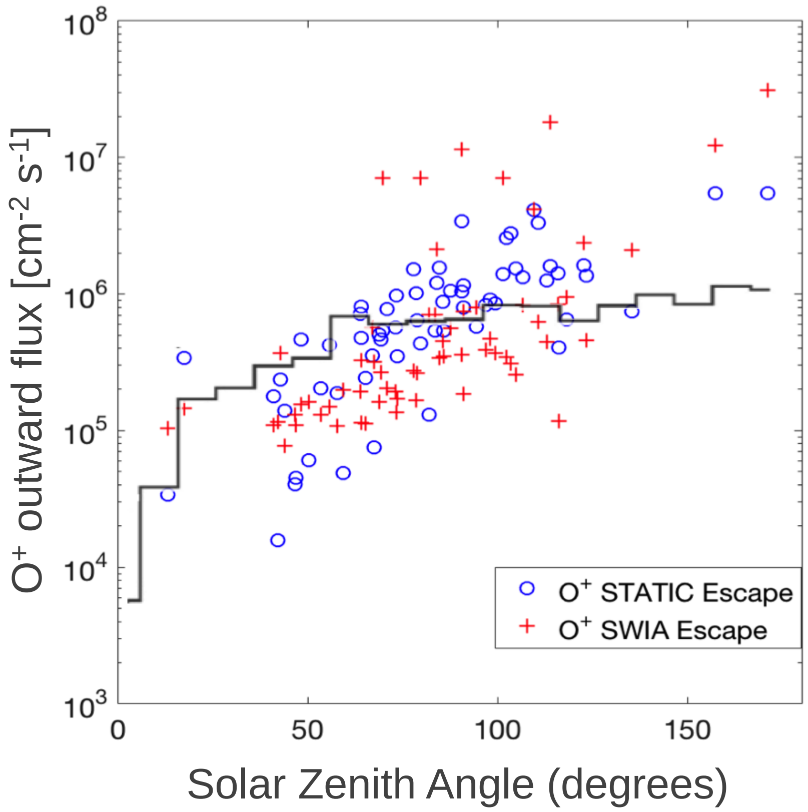
Enhanced loss triggered by this event:



- Measurements indicate minimal change to tailward flux, and significant enhancement of flux on sunward side
- Escape enhanced by ~20x for this moderate event, shown largely in MHD models that have been tested on MAVEN data

MAVEN Observes Enhanced Loss During Solar Storms (4 of 4)

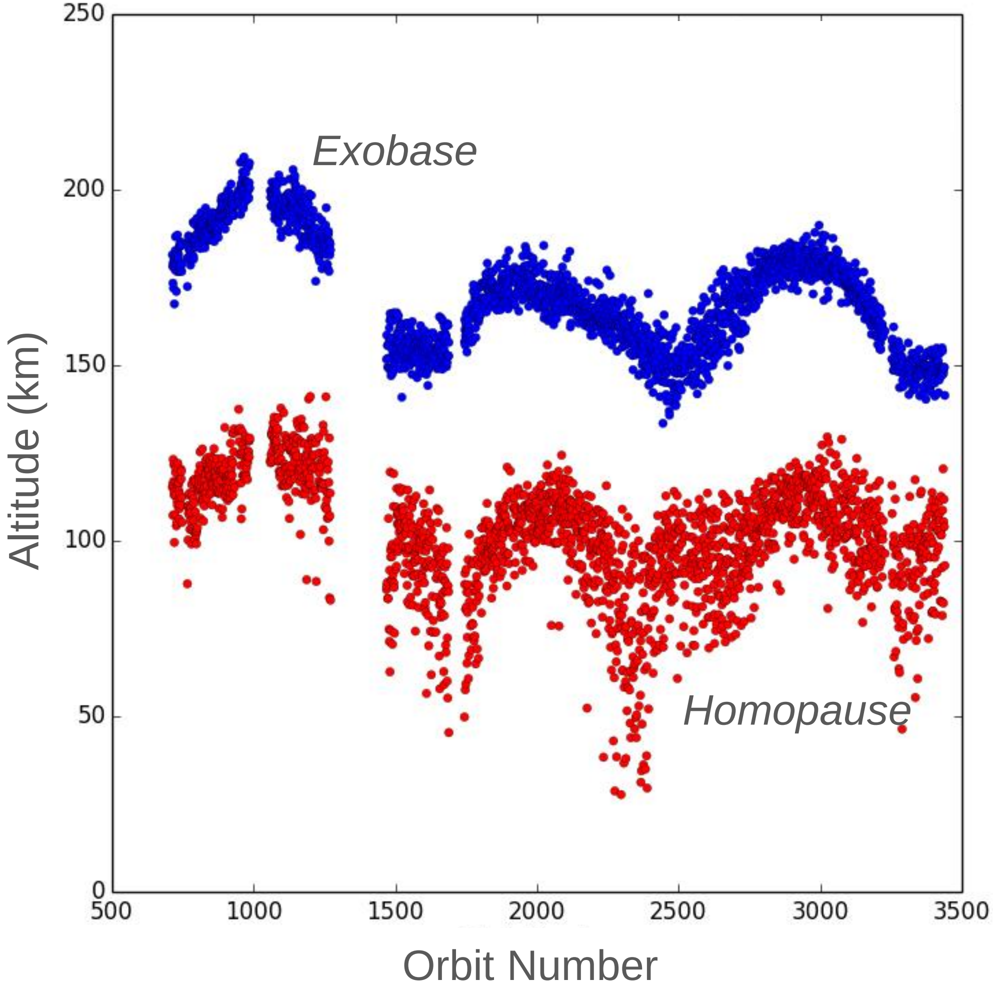
Enhanced loss observed in multiple smaller events throughout mission:



- Loss is enhanced downstream, as shown by observations of many smaller events
- Solar events likely to have been stronger and more abundant early in history; Sun may have had essentially continuous events
- Storm-induced loss could have dominated total loss

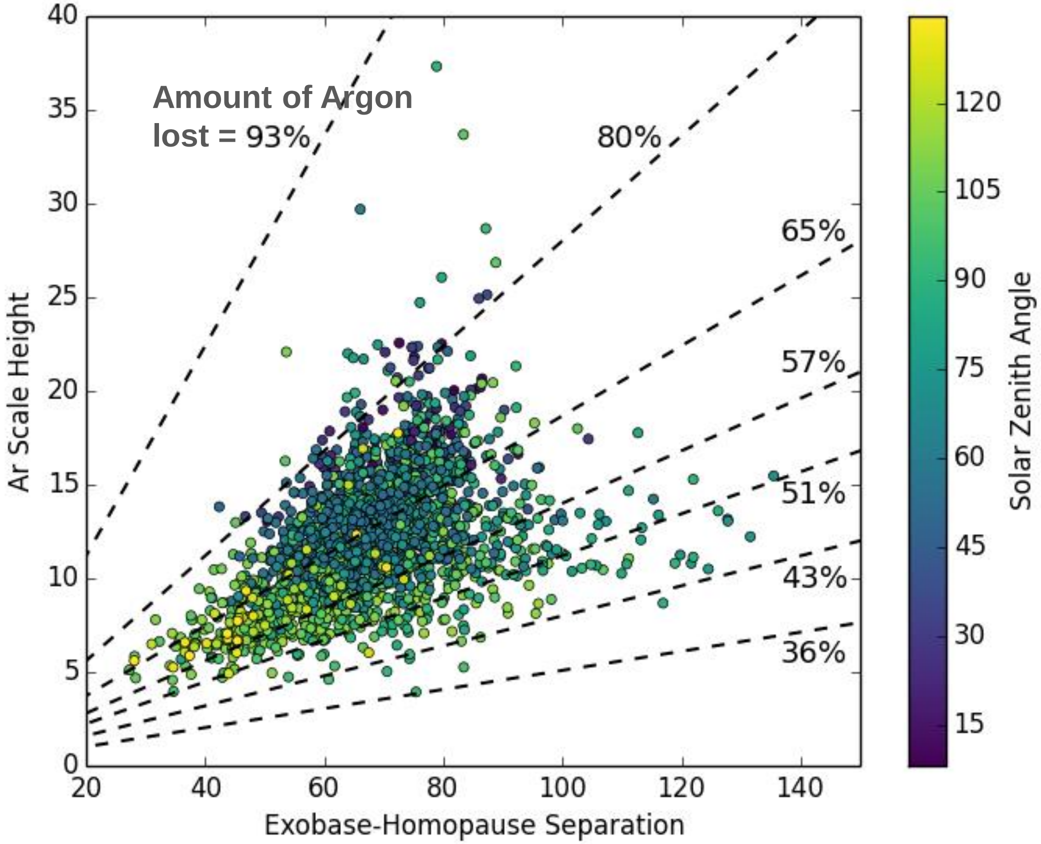
(Curry et al., 2017)

Determining Total Atmospheric Loss Using Argon Isotopes (1 of 2)



- *Exobase* altitude derived from measured number-density profiles and collision cross sections
- *Homopause* altitude derived from abundance ratios
  - Values lower than 80 km are due to non-simple structure of profile and probably are not real

Determining Total Atmospheric Loss Using Argon Isotopes (2 of 2)



Mean of loss of 66 % of Argon to space by pick-up-ion sputtering

Scaling to CO_2 yields similar fraction lost

- Model based on Rayleigh distillation, using upper-atmosphere diffusive separation and lower-atmosphere ratio to derive fraction of gas lost to space
- Incorporates time-dependent outgassing of juvenile gas and supply of gas by impacting objects

Major Results From The MAVEN Mission

Loss to space appears to be THE major process responsible for changing the Mars climate from an early warm, wet climate to the cold, dry climate we see today.

New results expected from ongoing observations:

- Results are based on one Mars year; not all years are the same
- Only part of the 11-year solar cycle has been observed
- New observations are expected to significantly enhance our understanding of upper-atmosphere processes
  - Neutral and ion winds
  - Low-energy ion outflow
  - Radio occultation measurements of electron density
  - Hi-res imaging of ozone and nitric oxide
  - Hi-res observations of structure around magnetic cusps