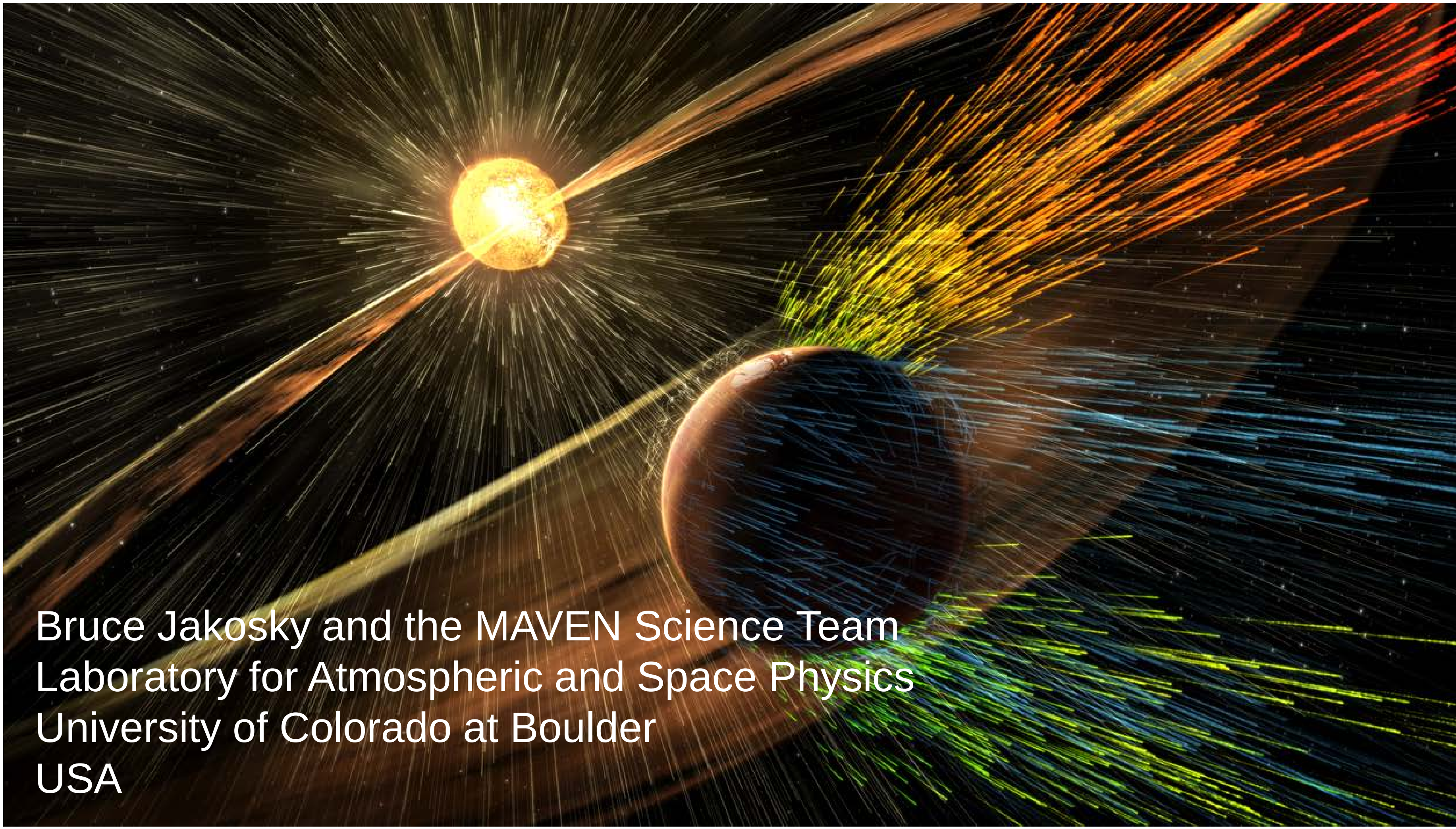
Mars Atmosphere and Volatile Evolution Mission (MAVEN)

Mars Atmospheric Loss at the Present and Integrated Loss Through Time As Observed by MAVEN



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Science Objectives For MAVEN And For This Talk

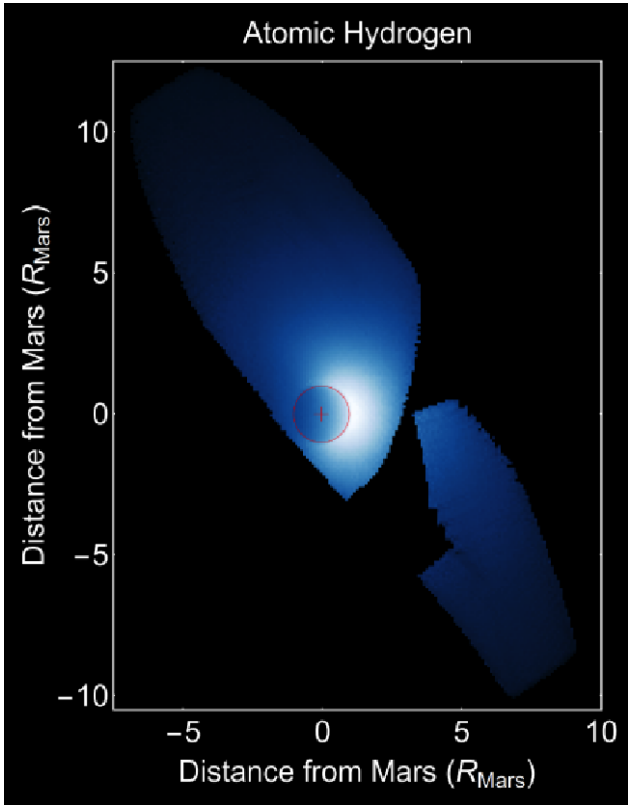
MAVEN science objectives:

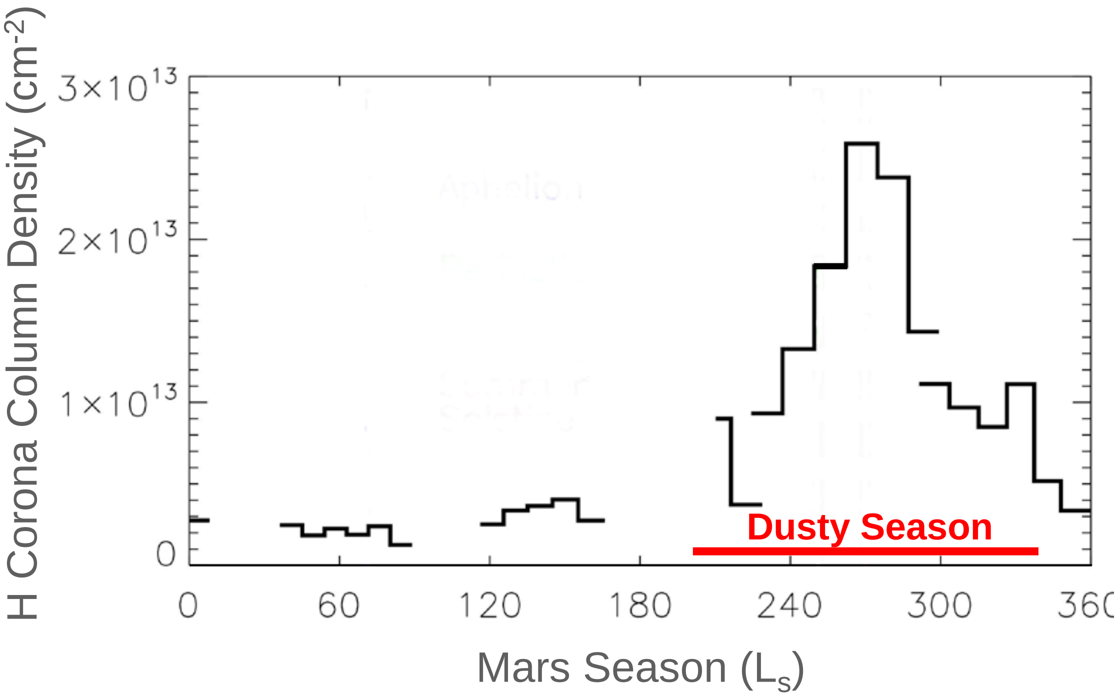
- Understand current behavior of Mars upper-atmosphere system and processes that drive it
- Understand current escape rates and processes that drive them
- Extrapolate through time to get integrated loss to space and thereby determine role of loss of gas to space in driving climate change

This talk:

- Examine present-day loss across all processes
- Extrapolation to get integrated loss through time
- Constraining loss using Ar isotopes

Loss To Space: H Corona and H Escape

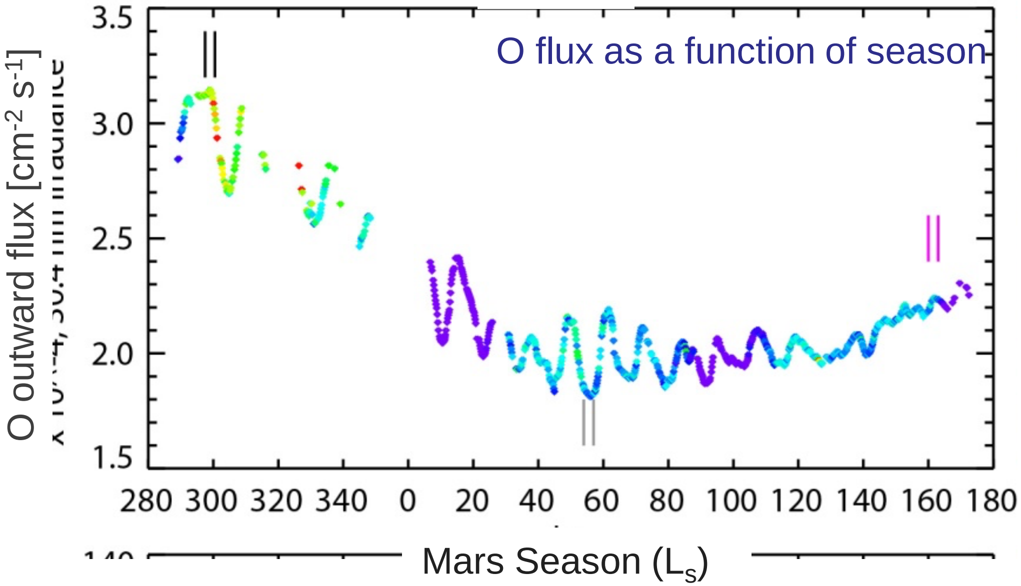


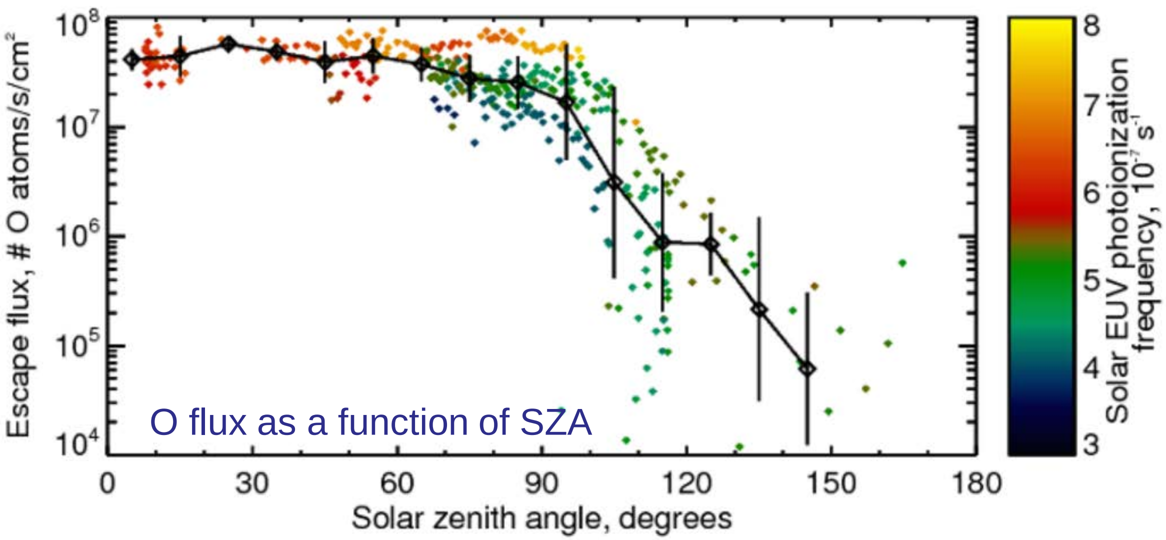


- Large seasonal variation appears to be due to atmospheric dust effects on atmospheric temperature and vertical distribution of H_2O in lower atmosphere
- Strong dependence of loss rate on dust and water content implies potential for significant interannual variability and dependence on Mars' axial obliquity

(Halekas, 2016; Chaffin et al. 2016)

Loss To Space: Photochemical Loss Of O

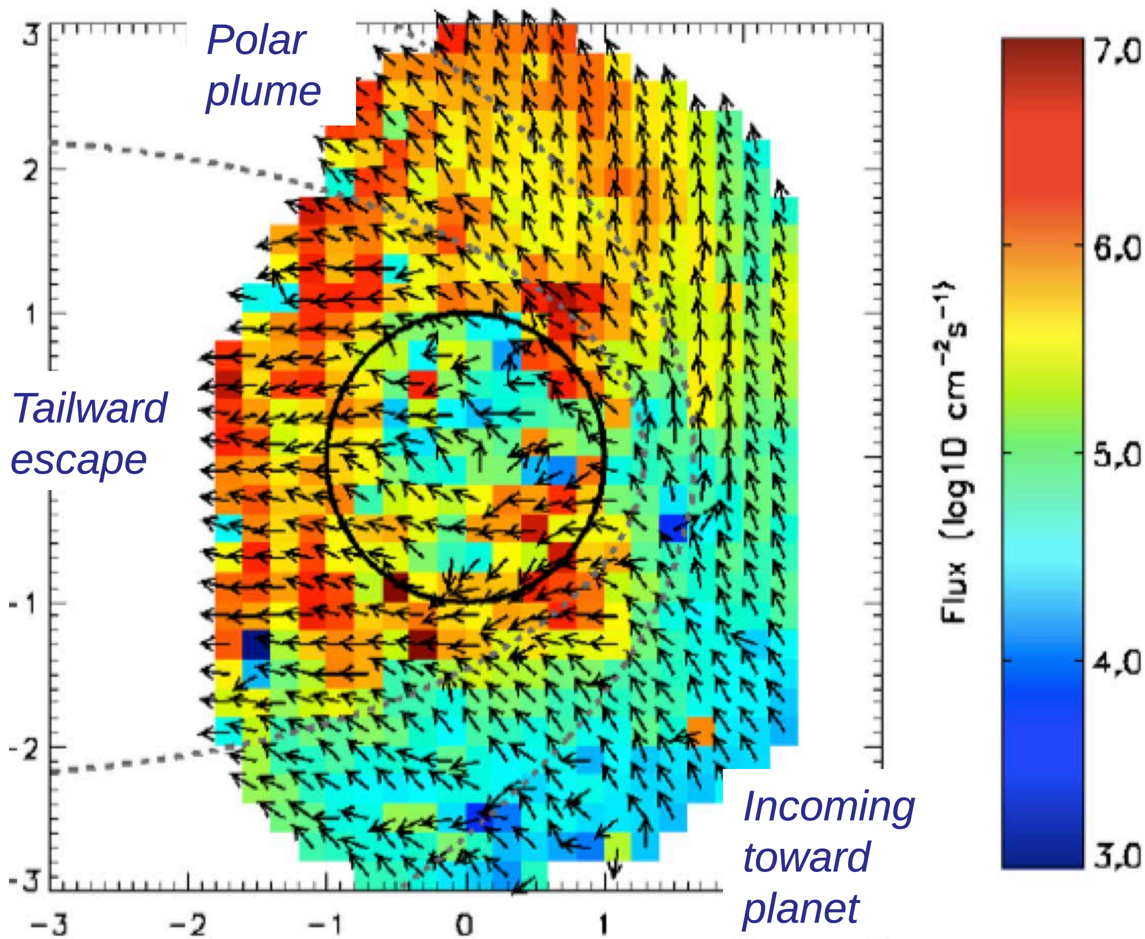




- Photochemical loss rate derived from observed properties of ionosphere
- Derived average loss rate ~ 1.3 kg O/sec, largest present-day loss process
- Range of possible responses at present epoch not yet identified
- This loss rate would remove all of the present-day atmospheric O (mainly from CO_2) in ~ 300 m.y.

(Lillis et al., 2018)

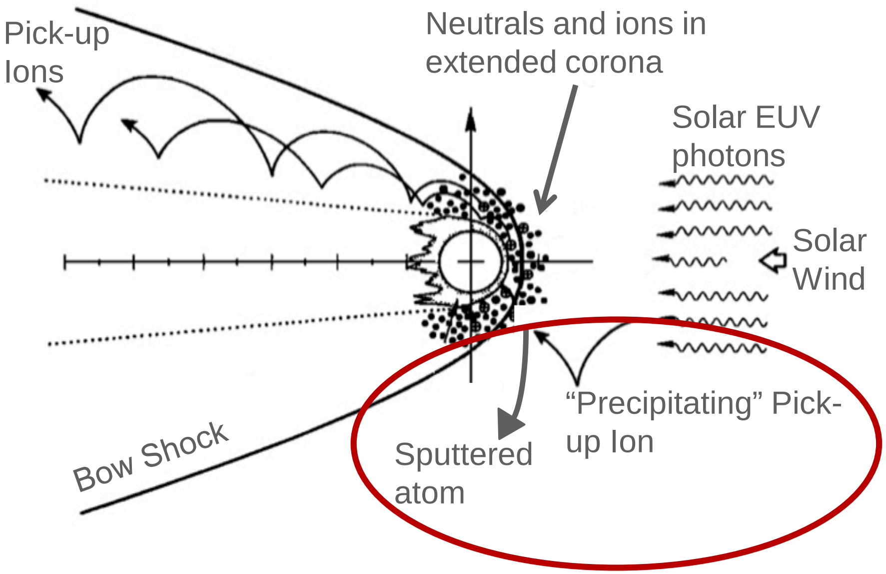
Escape Pathways For Oxygen Ions

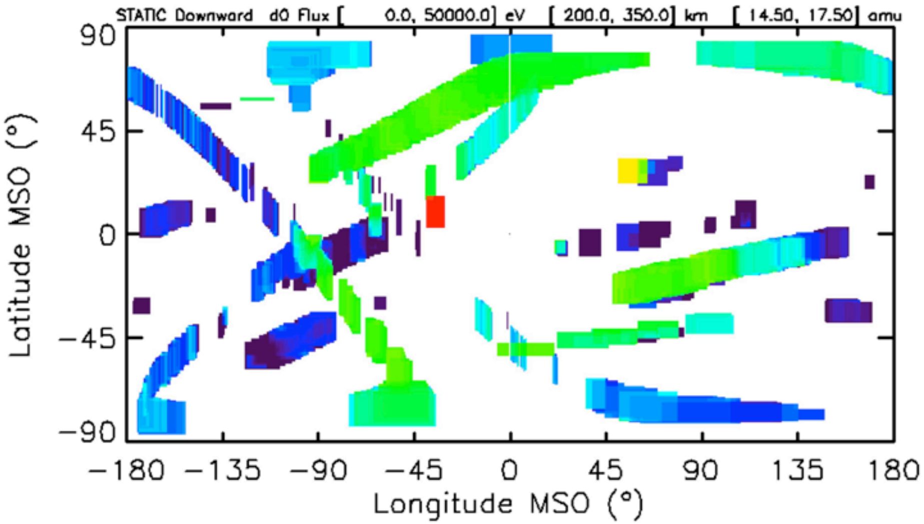


- Loss rate ~ 130 g O/sec
- Mean loss rate would remove all of the present-day atmospheric O (mainly from CO_2) in ~ 3 b.y.

(Y. Dong et al., 2015; Brain et al., 2015, 2018)

Sputtering Loss of O





Spatial distribution of measured sputtering ion characteristics

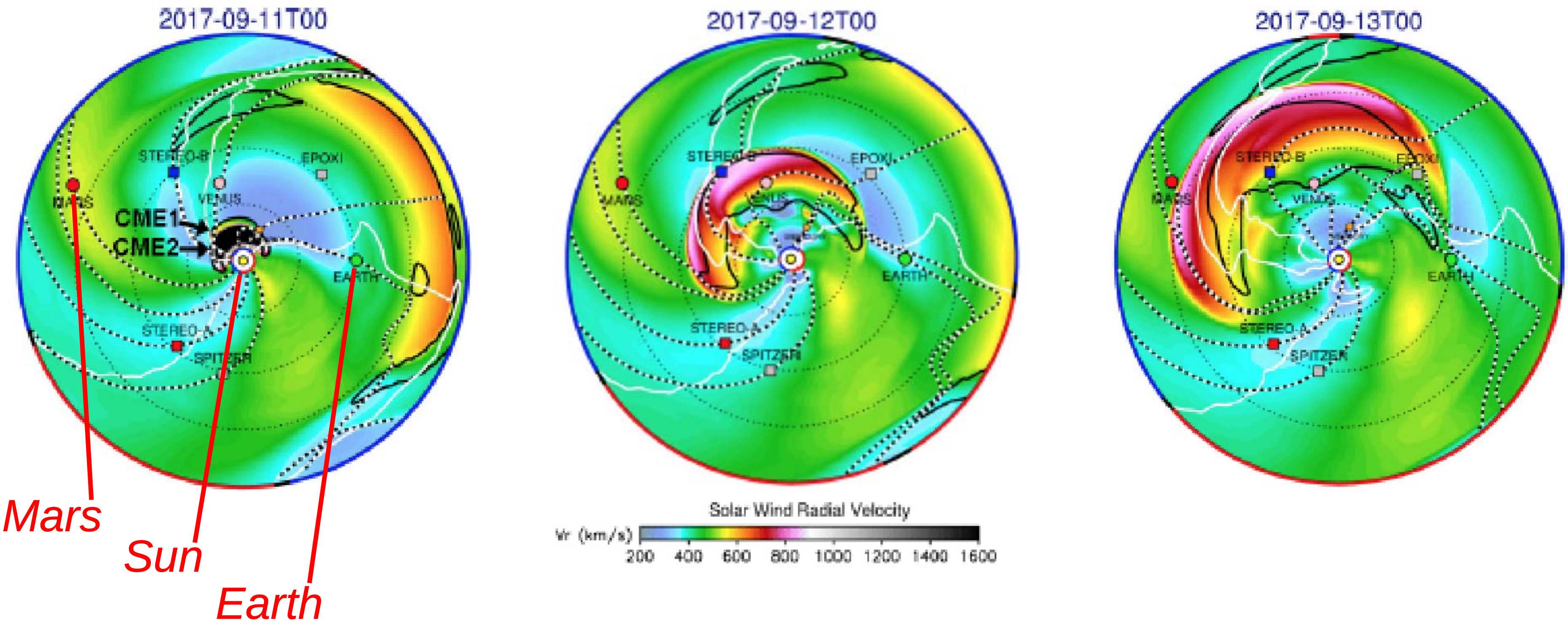
- Loss rate calculated from precipitating ions and properties of atmospheric "target"
- Loss rate ~ 80 g O/sec
- Mean loss rate would remove all of the present-day atmospheric O (mainly from CO_2) in > 4 b.y.

(Leblanc et al. 2015, 2017)

Summary Of Present-Day Loss Rates

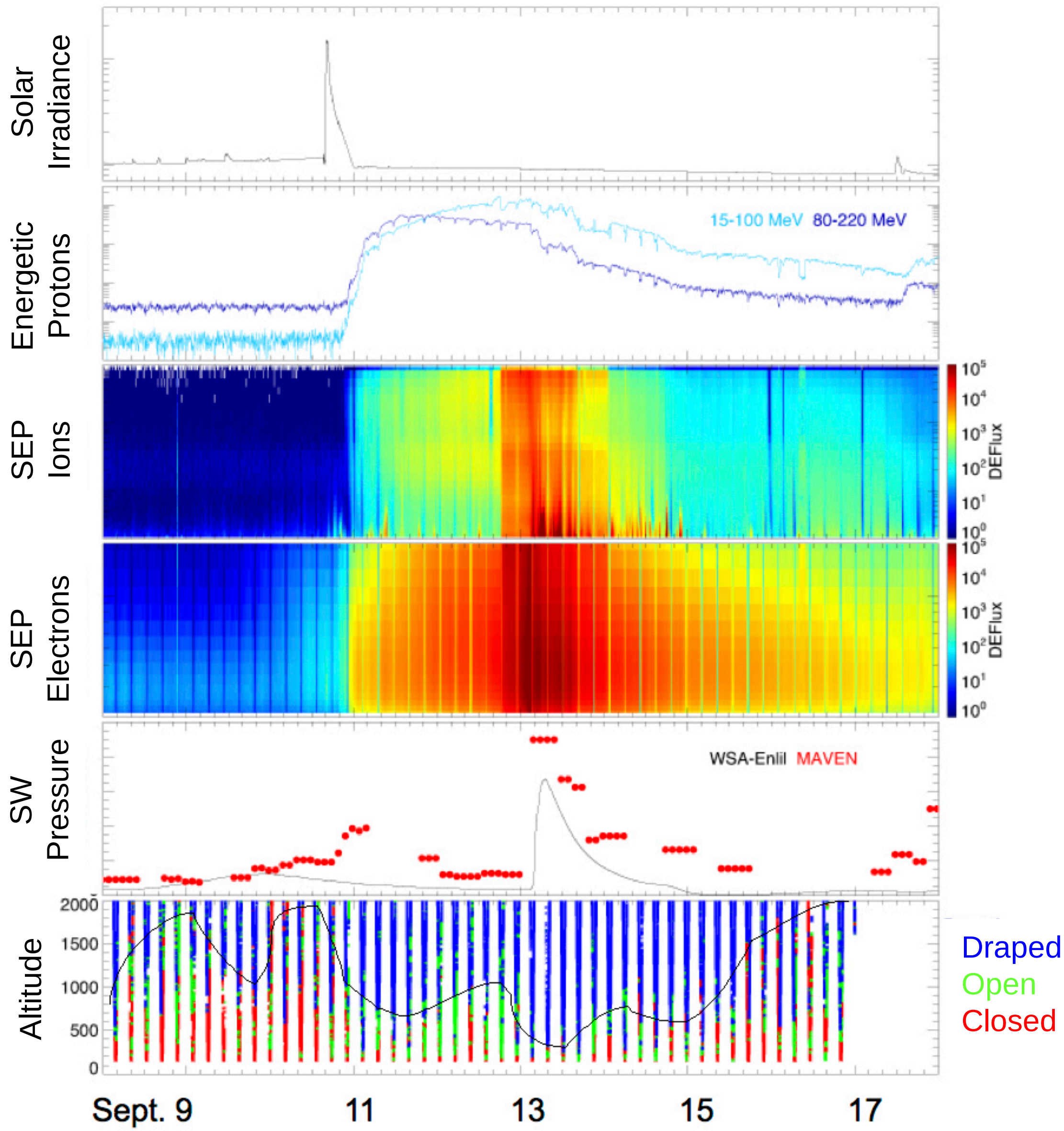
	H Jeans	O ion	O Dissoc Recomb	O sputtering	Total loss thru time
Present-day loss rate from MVN (s^{-1})	1.6-11 x 10^{26}	5 x 10^{24}	5 x 10^{25}	3 x 10^{24}	
4.2 b.y. at present rate, H_2O	3.6-25.2 m	0.2 m	2.2 m	0.14 m	
4.2 b.y. at present rate, CO_2		6 mbar	68 mbar	4 mbar	

Solar Event of 10 Sept 2017: Largest-To-Date Solar Event Observed By MAVEN



- WSA-ENLIL model output showing event, based on observations from multiple spacecraft
- Two ICMEs merge into one large one that hit both Mars and Earth
- Event was observed by multiple Mars spacecraft

Solar Event of 10 Sept 2017: MAVEN Observations Of The Event



Key observations of the event (shown top to bottom):

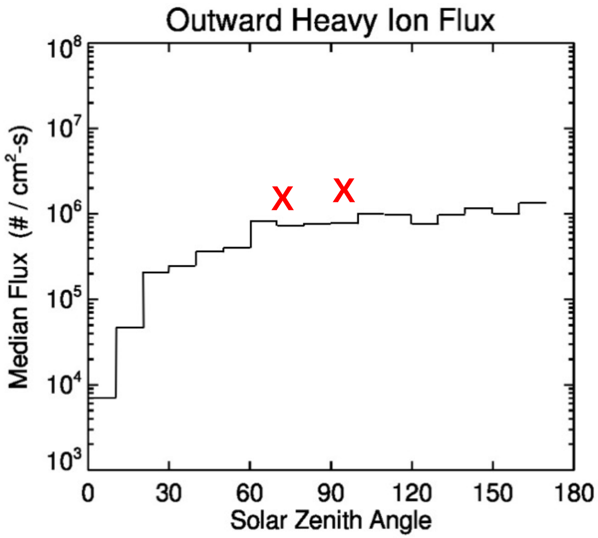
- Solar flare
- Arrival of high-energy protons
- Arrival of energetic ions and electrons
- Increase in solar-wind dynamic ram pressure
- Compression of solar-wind magnetic-field lines

Produced significant effects, including:

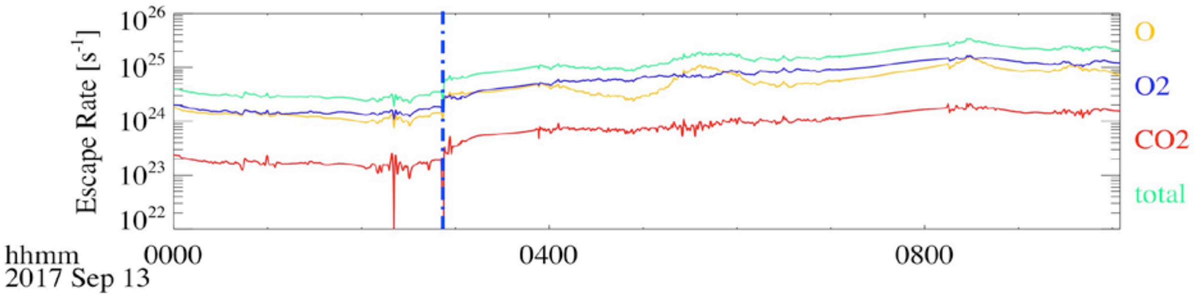
- Atmospheric heating
- Atmospheric aurora

(C. Lee et al., 2018)

Solar Event of 10 Sept 2017: Enhanced Heavy-Ion Loss



Ion flux during event, compared to average over a Mars year; ***X*** *shows average loss during event*

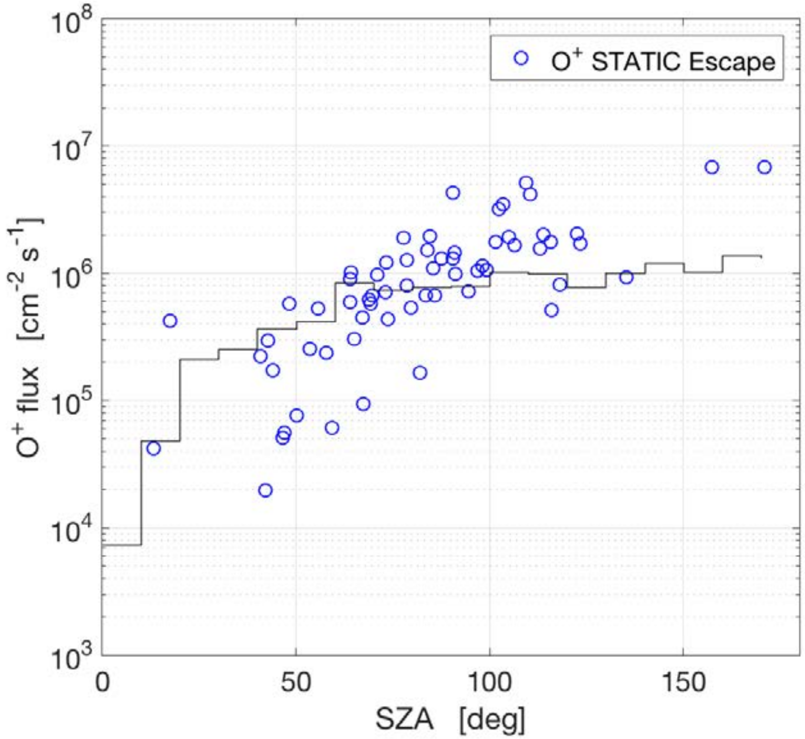


Heavy-ion loss into 4π derived from model validated against observations; 20x increase in loss rate

- Observations show an increase in loss, but are at a limited range of SZA, are at angles at which enhancement is small, and are not clean indications of enhanced loss
- Models validated against observations are used to calculate loss into all 4π solid angles; different models show 3-20x enhancement in loss during event
- *May represent the major loss mechanism early in Mars history, when solar events were stronger and occurred much more often*

(Ma et al., 2018)

Loss To Space: Enhanced Ion Loss Rates From Series Of Solar Storms Observed By MAVEN



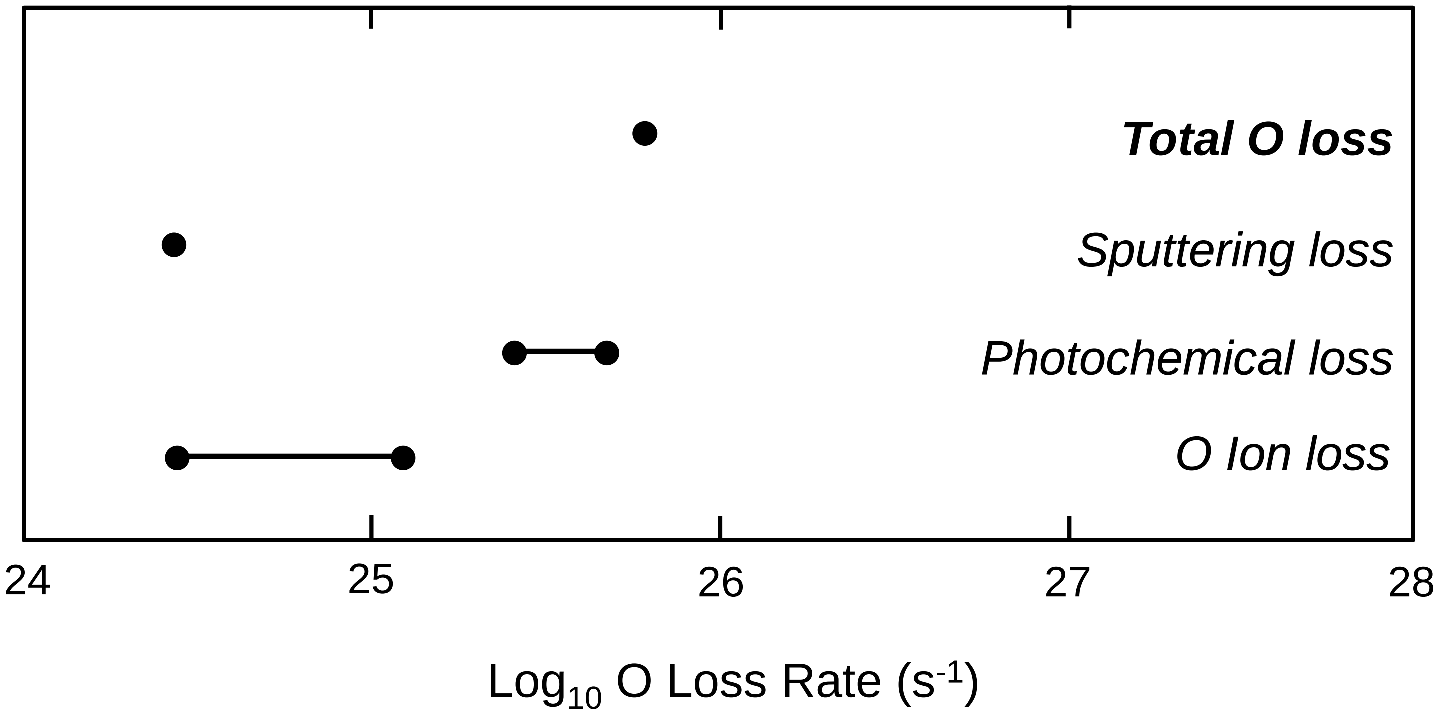
- Loss rate into all 4π directions cannot be determined for a single event from a single spacecraft
- Using multiple events, we can get a statistical indication of effects on total loss
- Figure compares O^+ loss rate at specific solar zenith angles from multiple solar events (circles) with average loss rate through year (histogram)
- Net effect is significant enhancement of loss due to solar events

(Curry et al., 2018)

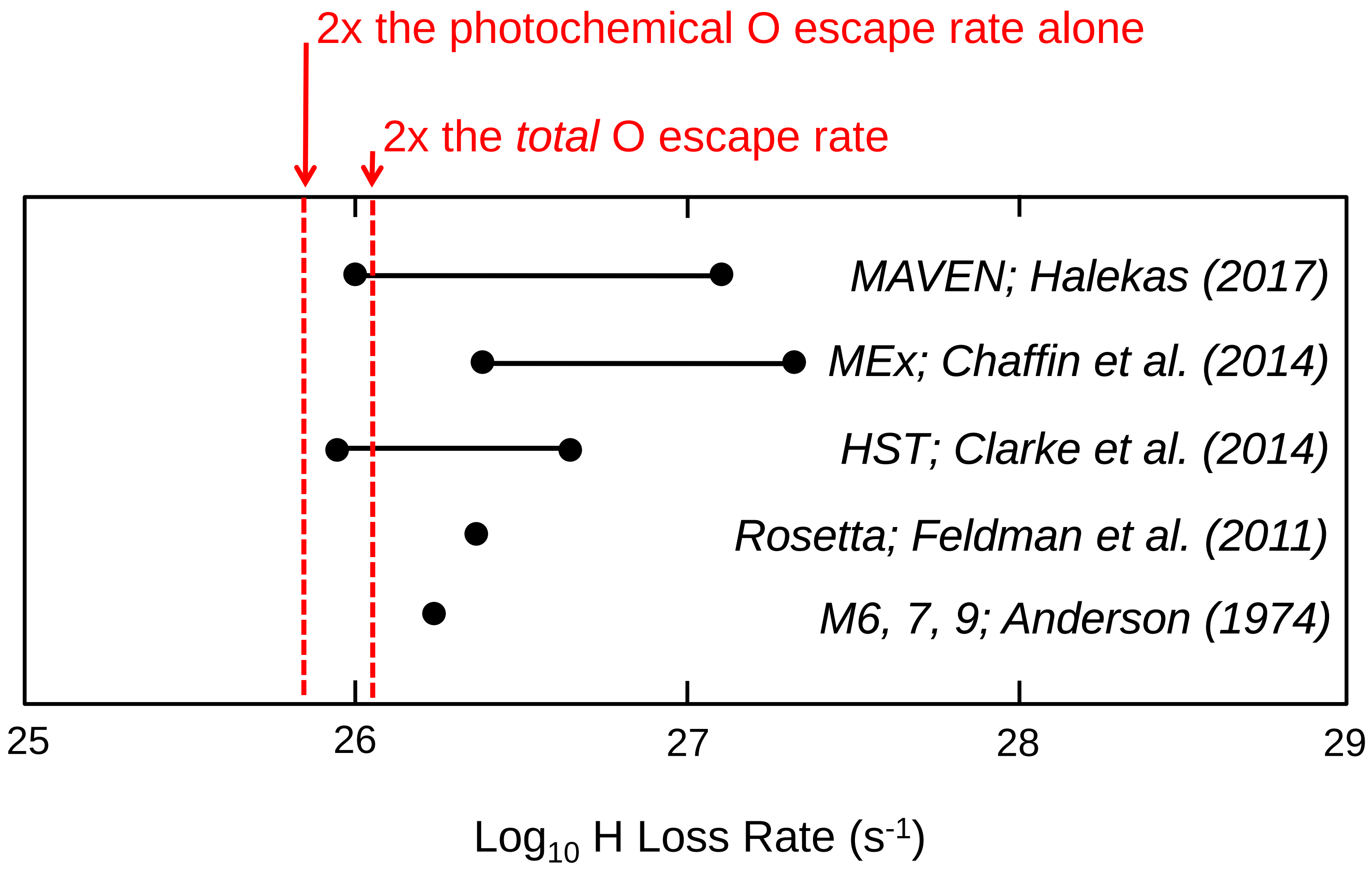
Are H And O Escaping In The Ratio Of 2:1

- McElroy (1972) and Liu and Donahue (1976) proposed escape in that ratio based on coupling of thermal escape of H and non-thermal escape of O
  - $O_2^+ + e \rightarrow O + O$ (dissociative recombination)
  - O_2 ultimately comes largely from photodissociation of H_2O
  - If thermal loss of H allowed build-up of O, then non-thermal loss of O would increase until they were in balance
  - Timescale to come to balance ~10^3 – 10^5 years
  - Escape rate of H derived from Mariner 6, 7, and 9 observations of H profile; dissociative recombination calculation for loss of O
- We can evaluate this hypothesis based on MAVEN observations and calculations of H and O loss rates

MAVEN Observations Of Escaping O



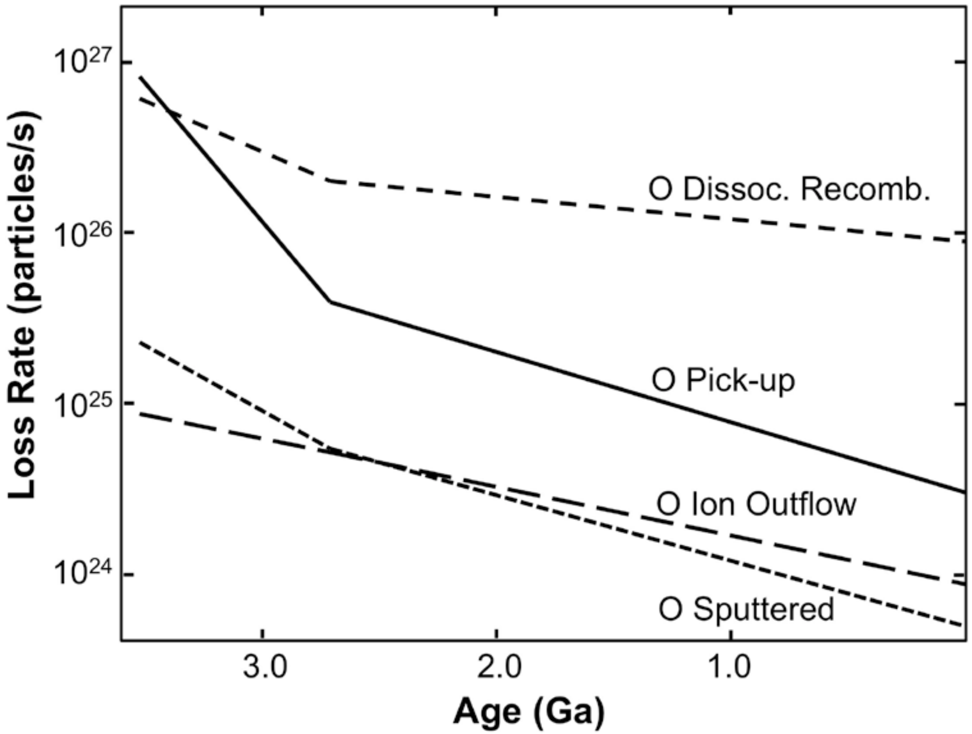
MAVEN Observations Of Escaping H



Why H And O Might ***NOT*** Be Escaping In Ratio Of 2:1

- MAVEN may not be observing all of the escaping O (e.g., cold-ion outflow not yet quantified)
- MAVEN year of observations may not be typical of current epoch
  - Year-to-year variability of dust cycle
  - Year-to-year variability of water cycle
- MAVEN has observed over only one portion of an odd solar cycle; loss may not be representative of full range of solar conditions, especially including effects of solar storms
- Changing orbital elements can drive changes in lower-atmosphere boundary conditions on 10^4- and 10^5-year timescales
- Coupling between multiple non-thermal loss processes may complicate feedback relationship between H and O escape
- O can come from either CO_2 or H_2O, and loss of C could balance some loss of O
- Chemical interaction of atmospheric gases with regolith/crust could provide a significant sink for H, O, or C, putting H and O out of balance

Atmospheric Loss Rates Were Greater Early In History



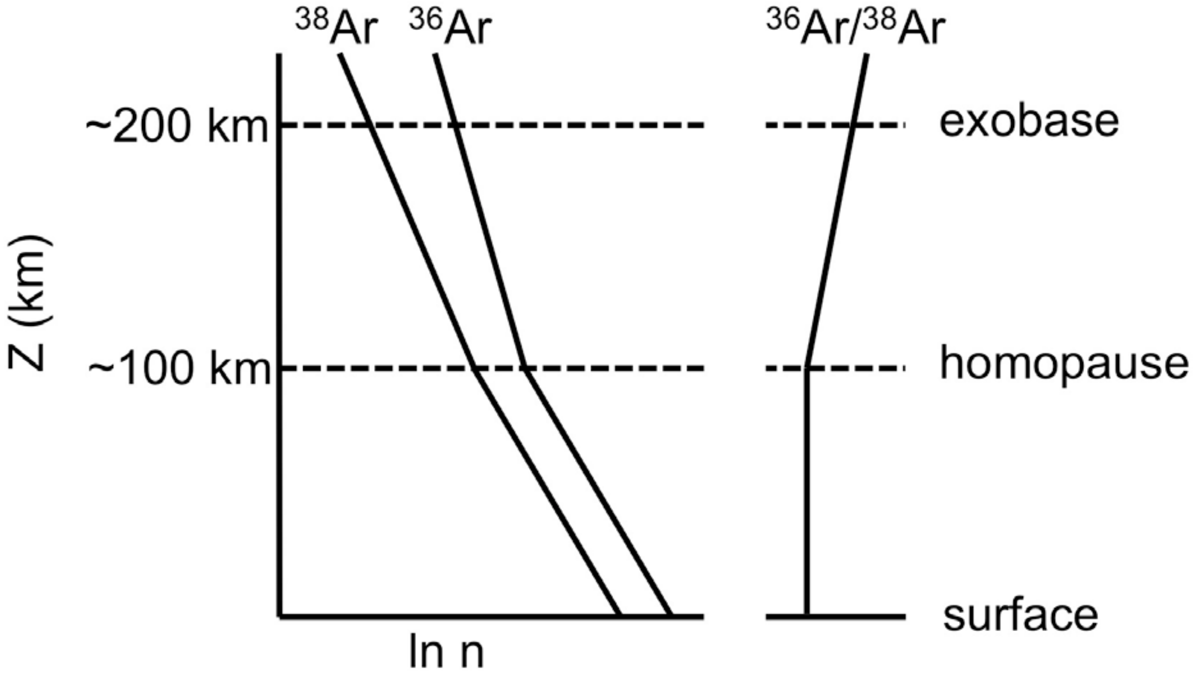
- Total measured loss rate today of ~ 2-3 kg/s
- Loss rates were greater in the past when the solar EUV and solar wind were more intense
- History of EUV and solar wind are derived from examining sun-like stars, effects at Mars modeled based on physical processes; we use the model from Chassefiere and Leblanc (2013)

Integrated Loss Through Time

	H Jeans	O ion	O Dissoc Recomb	O sputtering	Total loss thru time
Present-day loss rate from MVN (s^{-1})	1.6-11 x 10^{26}	5 x 10^{24}	5 x 10^{25}	3 x 10^{24}	
4.2 b.y. at present rate, H_2O	3.6-25.2 m	0.2 m	2.2 m	0.14 m	
4.2 b.y. at present rate, CO_2		6 mbar	68 mbar	4 mbar	
CO_2 loss, extrap. from L1992		630 mbar	113 mbar	7 bar	7.7 bar
CO_2 loss, extrap. from C2013		525 mbar	227 mbar	42 mbar	0.79 bar
CO_2 loss, extrap. from L2017			460 mbar		0.46 bar
H_2O loss, extrap. from L1992		22.1 m	3.6 m	227 m	253 m
H_2O loss, extrap. from C2013		18.8 m	2.9 m	1.4 m	23 m
H_2O loss, extrap. from L2017			16 m		16 m

- Extrapolation into past suggests that loss to space has been a major process in evolution of the atmosphere
- Not definitive, due to long list of assumptions

Direct Estimate Of Atmosphere Lost To Space Using Argon Isotopes (1 of 2)



- Due to mass separation above homopause, escape preferentially removes the lighter ^{36}Ar at exobase leaving behind the heavier ^{38}Ar
- For a measured fractionation between homopause and exobase, there is a unique relationship between fraction of gas lost isotopic enrichment
- Argon can be removed only by sputtering, so results apply only to sputtering loss

Direct Estimate Of Atmosphere Lost To Space Using Argon Isotopes (2 of 2)

MAVEN
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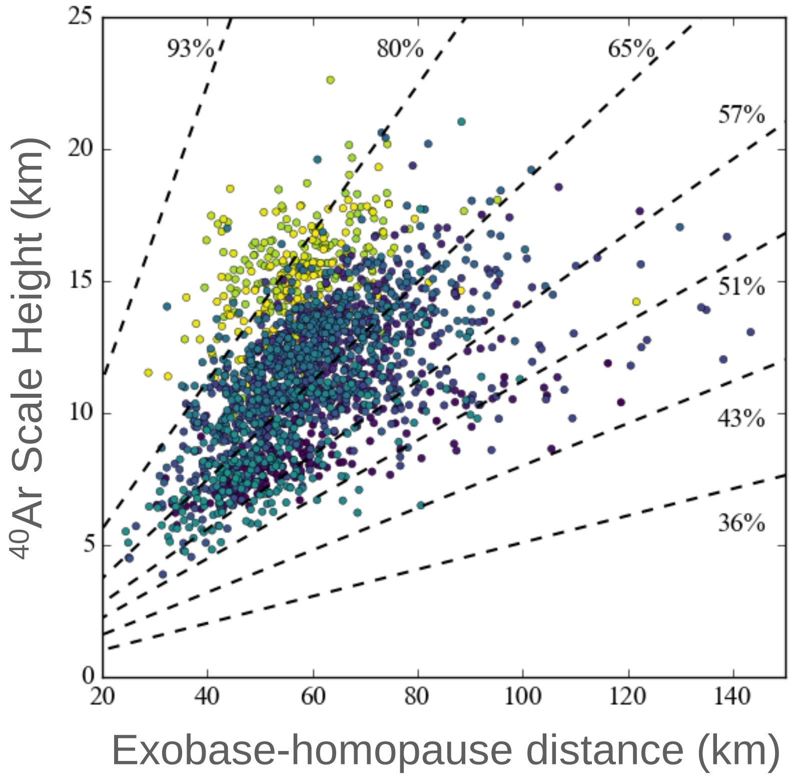

- *Dashed lines show fraction of gas lost to space*
- *Model includes outgassing of juvenile gas from interior, infall from accreting asteroids/comets, etc.*

- Upper-atmosphere structure derived orbit by orbit, used to estimate loss to space
- Average fraction lost is 66 ± 4.5 %
- ^{36}Ar is stripped to space only by sputtering
- CO_2 loss by sputtering is comparable, but CO_2 also has additional loss processes

(Jakosky et al., 2017)

Conclusions

- Loss to space is occurring today at rates that, by themselves, would be significant over geological time
- Extrapolation of loss rates into the past, although uncertain due to model uncertainties and assumptions:
  - Indicates that loss was significantly greater in the past (consistent across all models)
  - Suggests that loss was a major (if not the dominant) mechanism for changing the climate through time
- Analysis of Argon isotopes confirms that loss to space has been a major process

Issues/Questions

- What is the relationship between the MAVEN observations of one Mars year and the range of behaviors over the solar cycle? *(Note that in-process comparison with Mars Express data will help to address this issue.)*
- Do H and O escape in the ratio of 2:1 over timescales longer than a year? How about early in Martian history?
- Does O that is lost come partially from CO_2 or entirely from H_2O? If the former, where does the C go?
- What is the effect of changing obliquity on escape of H and O (due in part to changes in H_2O driven by different heating of the polar ice)?
- How much H, C, and O (from H_2O and CO_2) have been lost to the regolith or crust? How can we construct an integrated synthesis of volatile evolution?

How can we observationally constrain these processes?