Ion Outflows: Causes and Consequences

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Outline

Big Picture – Comparative planetology – atmosphere evolution

Water loss from Venus and Mars, cf. Earth. Contemporary outflow rates are the same. Understanding terrestrial processes can provide insight for the other planets.

Brief Review of Terrestrial Observations

Precipitating electron density is the single best controlling factor – but hardest to parameterize in models

Minimum flux (polar wind?), maximum flux (source limit?)

Questions for Models, Data and Theory

Generic questions can be classified as: requirement for coupled models, multi-fluid anisotropic global models, multi-spacecraft observations, and understanding of wave processes and how to characterize these in outflow and global models.

What Determines the Rate of Water Loss?

Hydrogen can escape more easily than any more massive particle

- If the hydrogen comes from water then why are all atmospheres not oxidizing?
- Implies hydrogen loss is controlled by oxygen loss – self regulation

Balance of rates applies on geological time-scales

- For Mars, Hunten and McElroy [JGR, 1970] argue that time scale is ~ 10^5 years, otherwise more O_2 would be present in the atmosphere
- No reason to expect balanced rates on short time-scales
- Measured oxygen loss rate does not reflect instantaneous water loss rate (but we often assume it does)

Some Numbers for Context

Assume oxygen loss rate of ~ 10^{25} s^{-1}

Corresponds to ~ 270 gs^{-1} of water loss (assuming oxygen loss equivalent to water loss)

4.5 billion years ~ 1.4 x 10^{17} s

Over age of solar system loss rate of 10^{25} s^{-1} gives 3.8 x 10^{19} g of water, or 3.8 x 10^{19} cm^3

Earth (6371 km radius): ~ 7 cm of water

Venus (6052 km radius): ~ 8 cm of water

Mars (3390 km radius): ~ 26 cm of water

Escape Velocities

	Escape velocity (km/s)	Proton Energy (eV)	Oxygen Energy (eV)
Earth	11	0.6	10
Venus	10	0.5	8
Mars	5	0.13	2

The high oxygen escape energy means plasma processes are required for escape at Earth and Venus.

At Mars dissociative recombination can result in energetic neutrals with energies above escape energy.

Unmagnetized Planets – Pathways for Loss

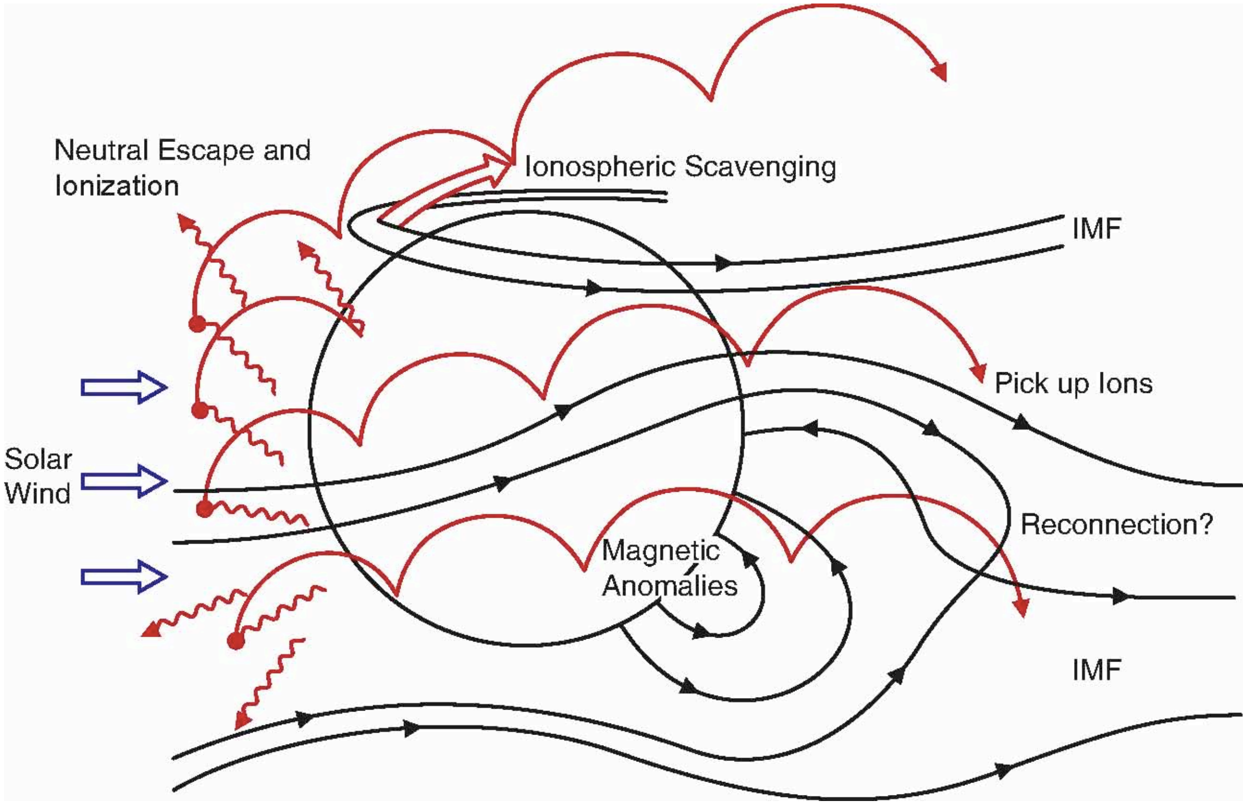
Direct neutral escape (mainly Mars)

Ionization (charge exchange or photoionization) and “ExB” pick up

Pick up induced sputtering

Direct solar wind - ionosphere interactions (scavenging)

Reconnection and auroral processes (Mars)



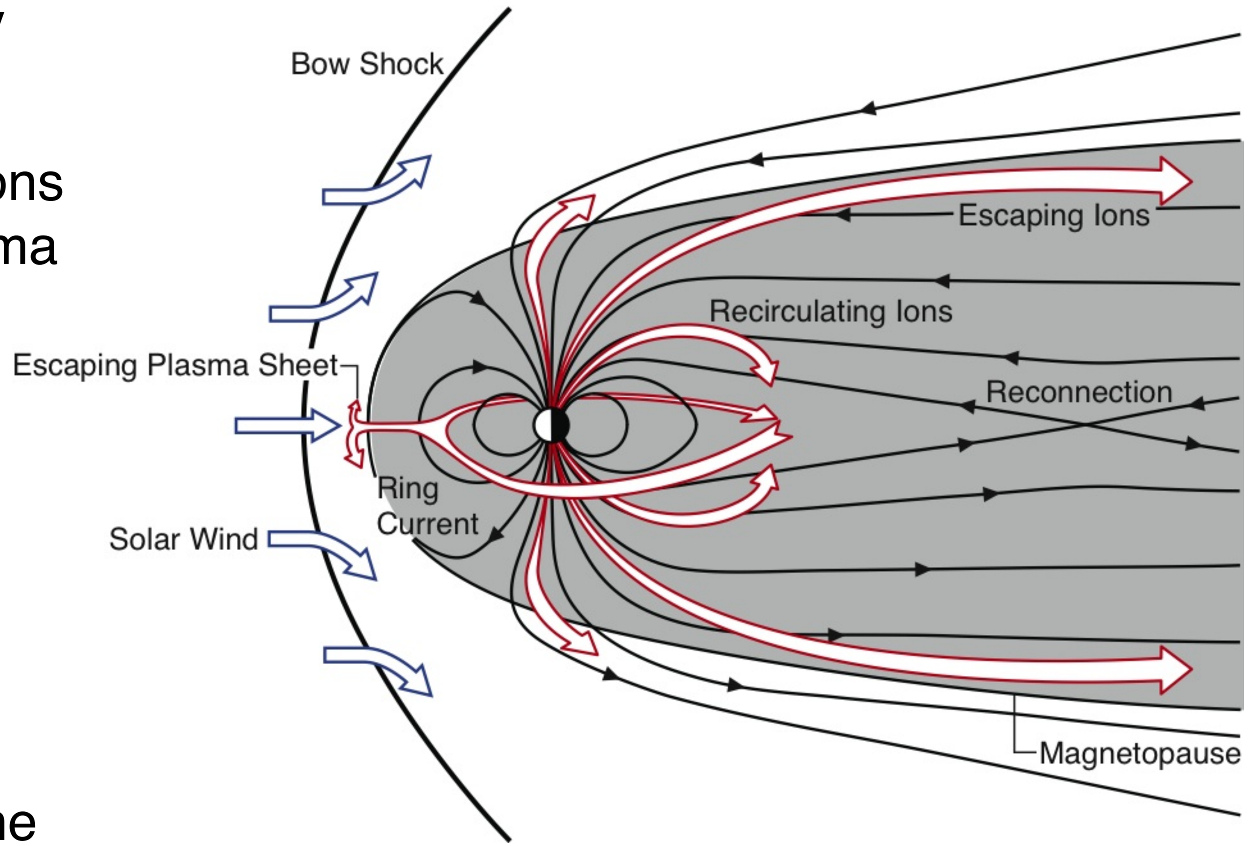
Earth – Pathways for Loss

Direct ion escape – cusp/cleft fountain (high energy heavies or protons)

Low energy and auroral ions recirculate, populate plasma sheet and ring current

Sunward convection and dynamical changes allow some escape through dayside magnetopause

Ions may also escape through charge exchange (not shown), or re-enter the atmosphere through pitch angle scattering (not shown)



Contemporary Oxygen Loss Rates

Earth [Yau and André, SSR, 80, 1-25, 1997]:

$\approx 1 \times 10^{25}$ s^{-1} ($K_p = 0$, $F_{10.7} \sim 85$) to $\approx 4 \times 10^{26}$ s^{-1} ($K_p = 6$, $F_{10.7} \sim 200$).

Venus [Nordström et al., 2013]:

During steady IMF: Heavies $(4.0 \pm 1.1) \times 10^{24}$ s^{-1}.

Mars:

Dissociative Recombination (neutrals) [Fox and Hać, Icarus, 2009]:
$\approx 2 \times 10^{26}$ s^{-1}.

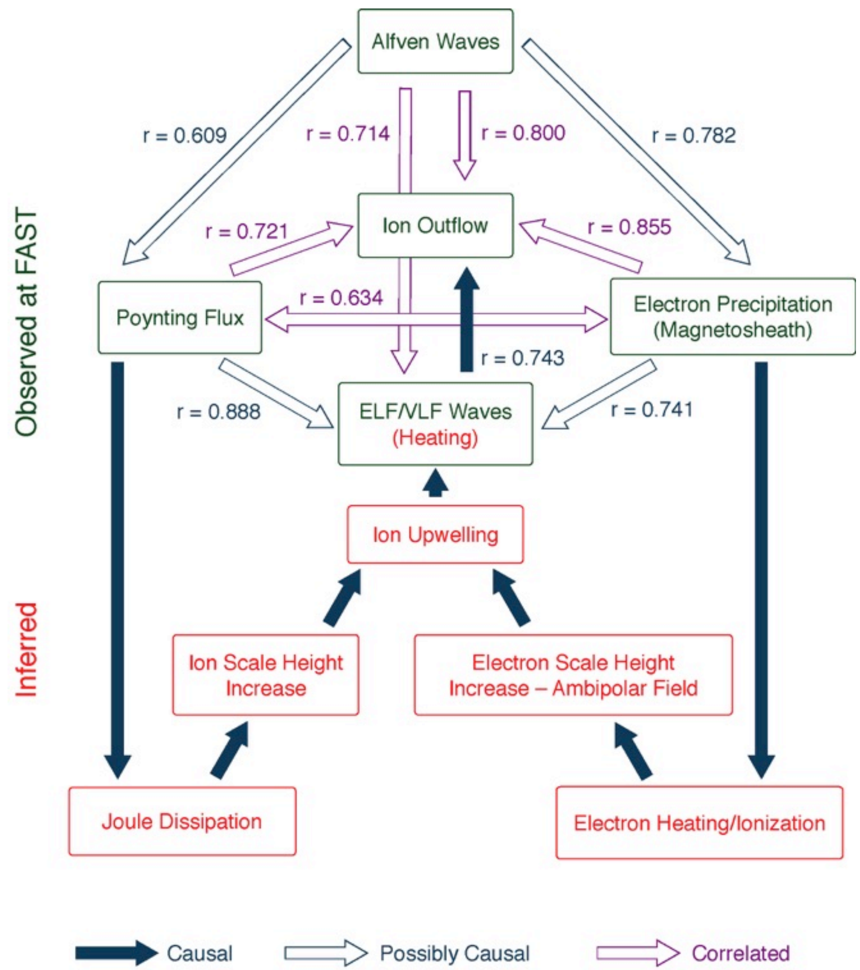
Mars Express Observations [Lundin et al., GRL, 2009]:
$\approx 3.5 \times 10^{24}$ s^{-1} (O^+ and O_2^+).

MAVEN ICME simulations [Jakosky et al.. Science, 2015] (all heavies):
1.46×10^{24} s^{-1} ($P_{sw} = 0.9$ nPa) to 3.34×10^{25} s^{-1} ($P_{sw} = 13.4$ nPa).

To lose an ocean of water need significantly higher solar wind dynamic pressure and solar EUV flux – “Young Sun” scenario.

Terrestrial Ion Outflows – Basic Pathway

Type 1



Type 2

Type 1 and Type 2 defined by Wahlund et al. [1992]

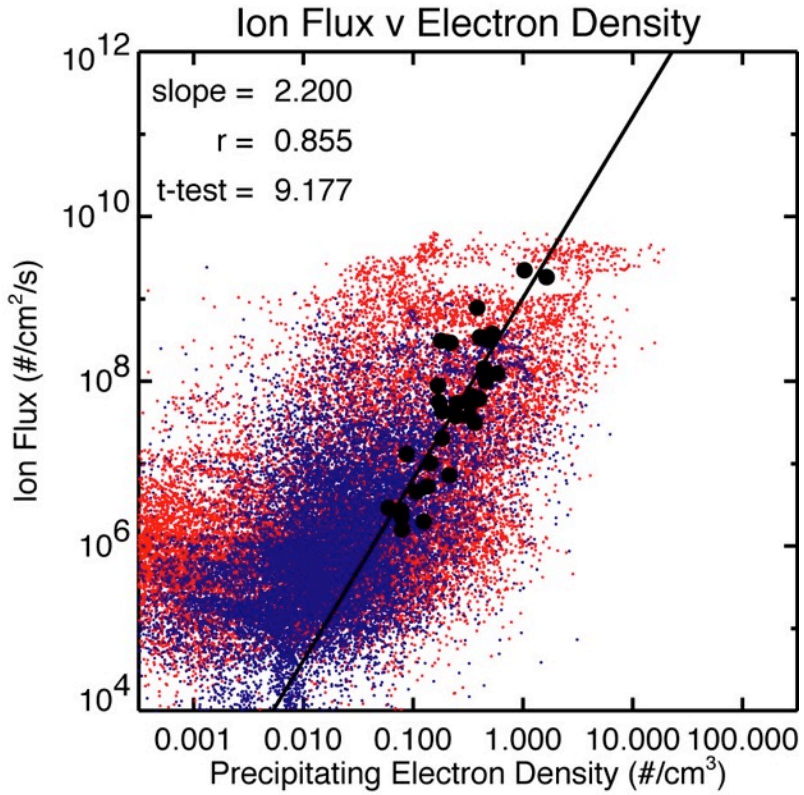
Multiple Linear Regression

Table of slopes and significance test for multiple linear regression
$\log_{10}$(parameter) v $\log_{10}$(ion number flux)

Poynting Flux	Electron Density	Alfvén Wave	ELF Amplitude	$F_{1,27}$ Test
0.78	1.30	0.53	-1.46	
Deleted	1.32	0.47	0.63	6.44
0.81	Deleted	0.88	-0.54	13.69
0.70	1.71	Deleted	-0.56	6.43
0.44	1.19	0.43	Deleted	1.94

Parameter can be deleted for $F_{1,27} < 4.21$ (95% confidence)

Day/Night Differences



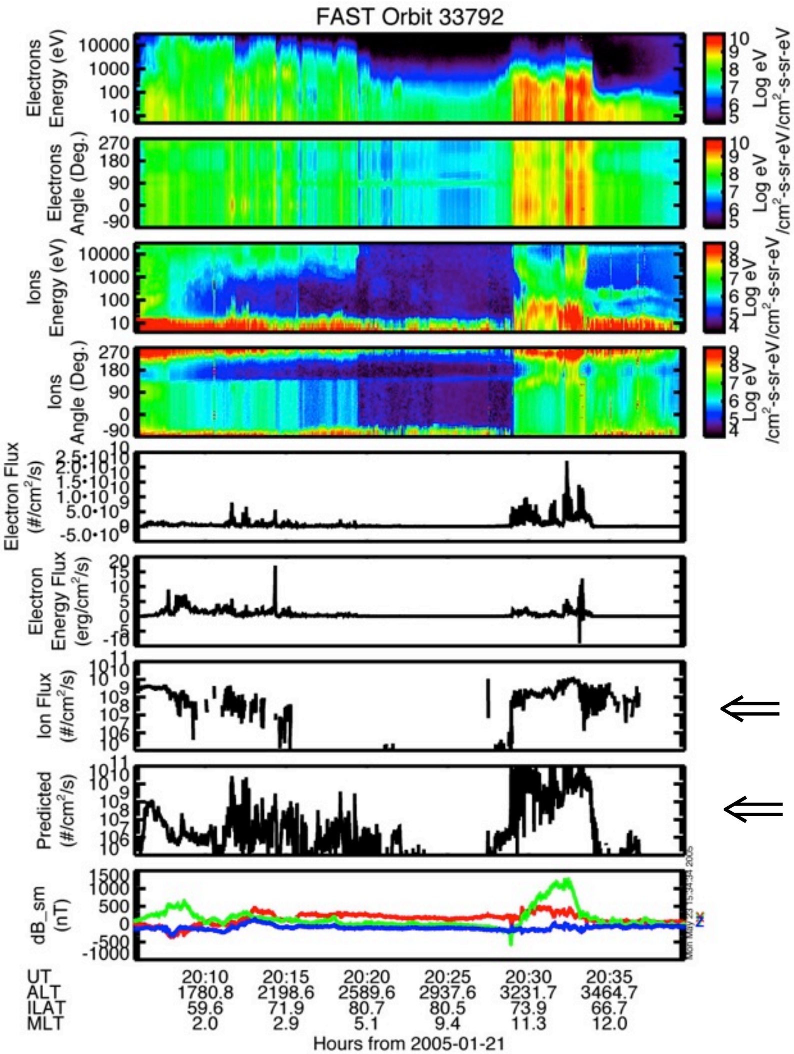
Both dayside and nightside data show evidence for a lower flux limit (polar wind?), and an upper limit.

These limits may depend on solar illumination and source plasma flux limits.

May also need more complicated functional forms than simple log-log regression line.

Day Night

Flux Saturation



Predicted fluxes based on electron data (no E-field).

Overall agreement, but evidence of flux saturation.

Cusp is near terminator on this day. Solar illumination?

⇐ Observed flux

⇐ Predicted flux

Questions – Thermosphere-Ionosphere

Models:

How well do they determine upwelling?

What is the role of wave instabilities?

How does chemistry affect the upwelling?

Data:

In situ measurements are difficult – low energy particles dominate the particle spectra.

Should include neutral measurements.

Issues with satellite drag.

Theory:

Polar wind type models appear to be well developed – but again how are waves included?

Ionosphere- Low Alt. Magnetosphere

Models:

Scaling laws are a method for including outflows in global models. But have limitations – polar wind limit, flux saturation limit, characteristic conic energy.

Thin ionosphere boundary condition in global MHD models is suspect – including thermosphere-ionosphere models is clearly the way forward. May also need to include "gap" physics (the region between the inner edge of the global model and the ionosphere), but this is computationally expensive.

Data:

Single spacecraft measurements have well characterized the in situ particles and fields (hence scaling laws). But do not resolve time versus space, or variation with altitude (e.g., Alfven-wave Poynting flux being converted to precipitating electron energy flux). Need multi-spacecraft measurements.

Theory:

How do we characterize wave effects? Ion and electron heating rates? Can local theory provide parameters that can be folded back into global models.

Higher Altitude Magnetosphere

Models:

How is the influx of ionospheric plasma handled in a global code? Unless the code is multi-fluid (different masses, and separate mass, momentum, and energy continuity equations), all species flow with the same drift ($\mathbf{u}_i = \mathbf{u}_e - \mathbf{j}\mathbf{x}\mathbf{B}/ne$).

Global models typically assume isotropic pressure. But an ion conic is highly anisotropic. How does this affect the transport?

Fundamental question: Where do the heavy ions actually go?

Data:

The magnetosphere is vast. Do the best we can.

Theory:

Mainly an issue of multi-species coupled models.

Summary

Comparative Planetology:

Contemporary heavy ion outflow rates are comparable for the terrestrial planets. Fundamental question for atmospheric evolution: “Where did the water go”?

Understanding similarities and differences in the processes may allow us to extrapolate to the early solar system.

Issues:

Thermosphere boundary conditions, wave heating processes, outflowing ion characteristics in global models, flux limitations.

Model Requirements:

Fully coupled models, preferably with multi-fluids (not just multi-species), pressure anisotropy, and “thick ionosphere” (that is, thermosphere-ionosphere models, and spatially resolved “gap” region).

Better understanding of wave processes and how they can be characterized in global models.

Data:

Multi-spacecraft observations are essential. Need to resolve time versus space, and evolution with altitude.