Atmospheric Loss on Earth

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Introduction

Solar wind driven outflows – atmosphere evolution

Driving question – water loss from the terrestrial planets.

Does contemporary oxygen ion outflow rate correspond to water loss?

Does an intrinsic magnetic field inhibit ionospheric escape?

Venus and Mars

At Mars neutrals can escape.

Heavy ion outflow rates ~ 10^{25} s^{-1} at Venus and Mars [Brain et al., 2017].

Outflow rate limited through solar wind dynamic pressure [Dubinin et al., 2017].

Earth outflows

Solar wind interacts indirectly with the Earth's ionosphere through magnetic field reconnection.

Global oxygen outflow rates: 10^{24} – 10^{26} s^{-1} [Yau and André, 1997].

Do these ions ultimately escape the terrestrial magnetosphere?

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 [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).

Mass Loss – Where Did The Water Go?

Conventional Wisdom: The Magnetic Shield Hypothesis

- Venus and Mars are dry, Earth is wet.
- Venus and Mars have no active dynamos, Earth does.
- Lack of intrinsic field means greater mass loss to the solar wind.

Counter Argument: Solar Wind – Magnetosphere Coupling

- Intrinsic magnetic field increases size of obstacle to solar wind flow.
- More momentum and energy available to drive loss processes.
- Magnetic reconnection couples polar ionosphere to solar wind.
- Energy deposition on open field lines allows for heating and outflow.
- Some of the outflowing plasma escapes – alternative mass loss process.

Some Numbers for Context

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

Corresponds to ~ 300 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
4.2 x 10^{19} g of water.

Earth (6371 km radius): ~ 8 cm of water [~ 7 mbar oxygen]

Venus (6052 km radius): ~ 9 cm of water

Mars (3390 km radius): ~ 30 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.

Unmagnetized Planets – Pathways for Loss

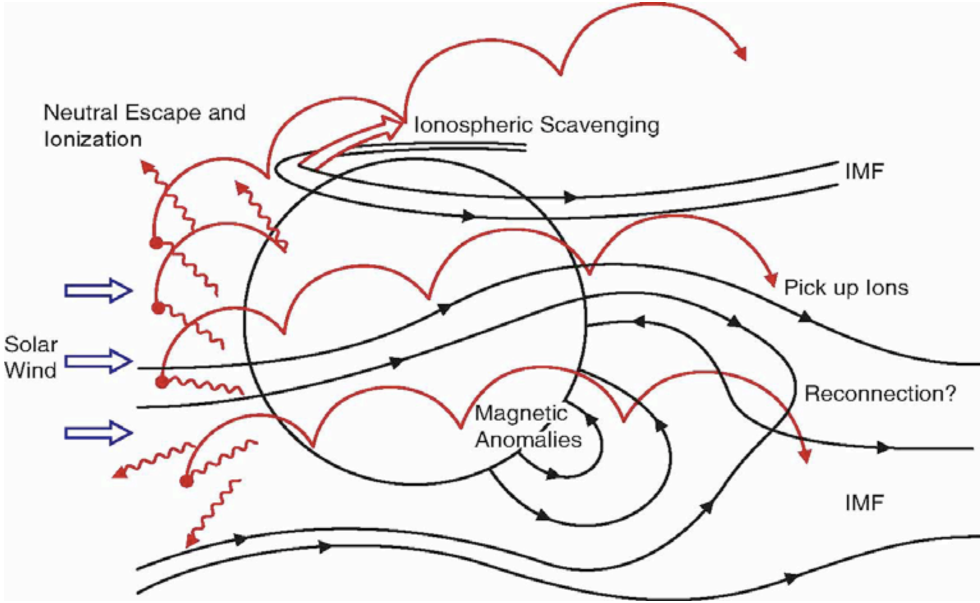
Direct neutral escape (mainly Mars).

Ionization (charge exchange or photoionization) and "ExB" pick up.

Pick up induced sputtering.

Direct solar wind - ionosphere interactions (scavenging).

Reconnection and auroral processes (Mars).

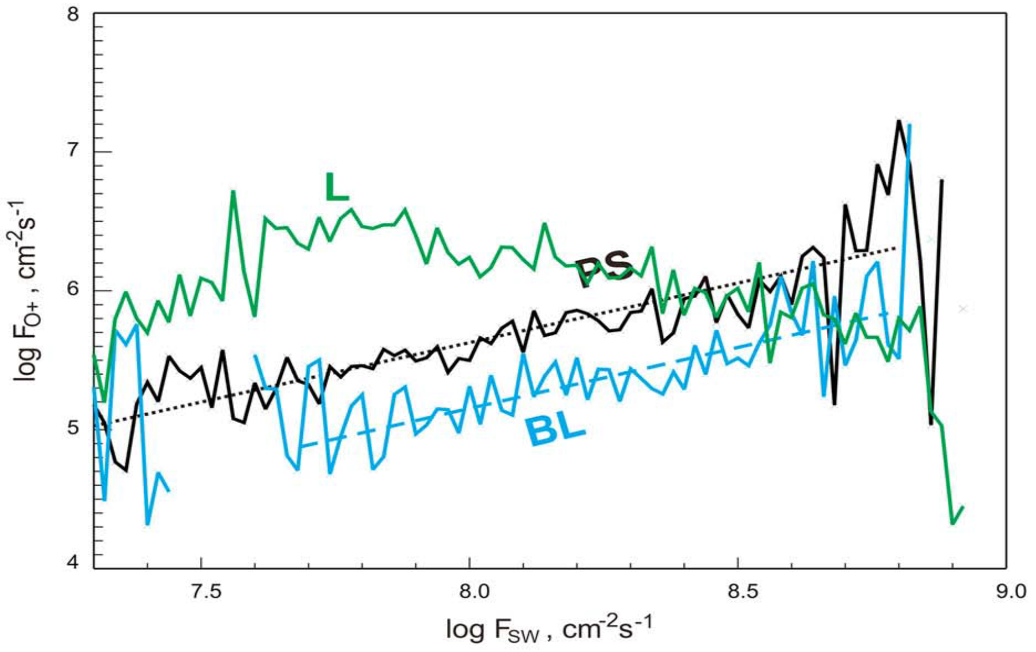


Limiting flux – Solar Wind Dynamic Pressure

The solar wind is the ultimate source of momentum for escaping ions, but once the ions are escaping their flux is constant.

Equating the momentum flux of the solar wind and escaping ions: $n_{sw} m_p A_{sw} v_{sw}^2 \approx n_i m_i A_i v_i v_{sw}$

This was explored by Dubinin et al. [2017], who found a linear relation between ion fluxes and solar wind flux.



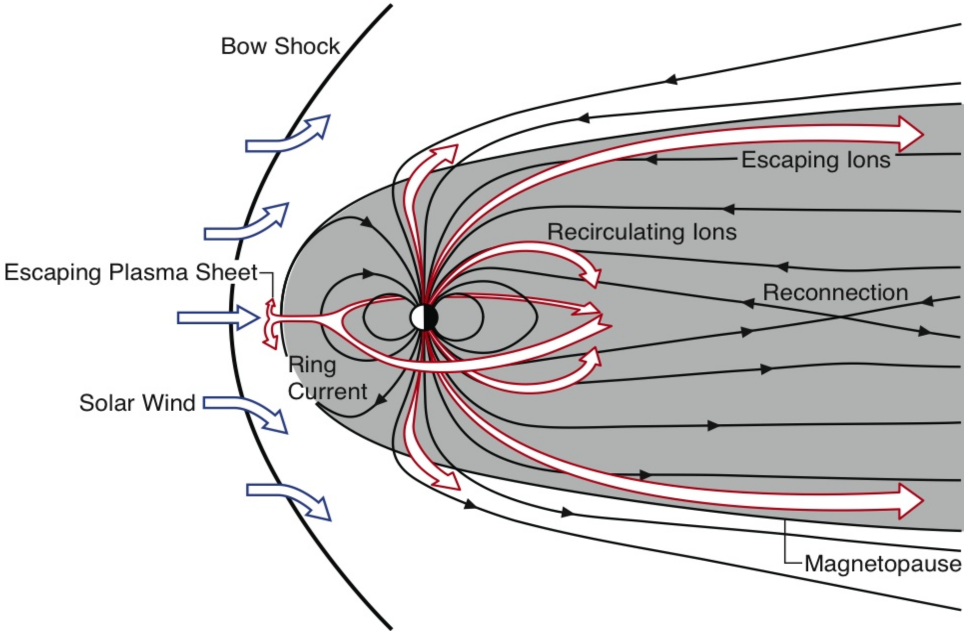
Earth – Pathways for Loss

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

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

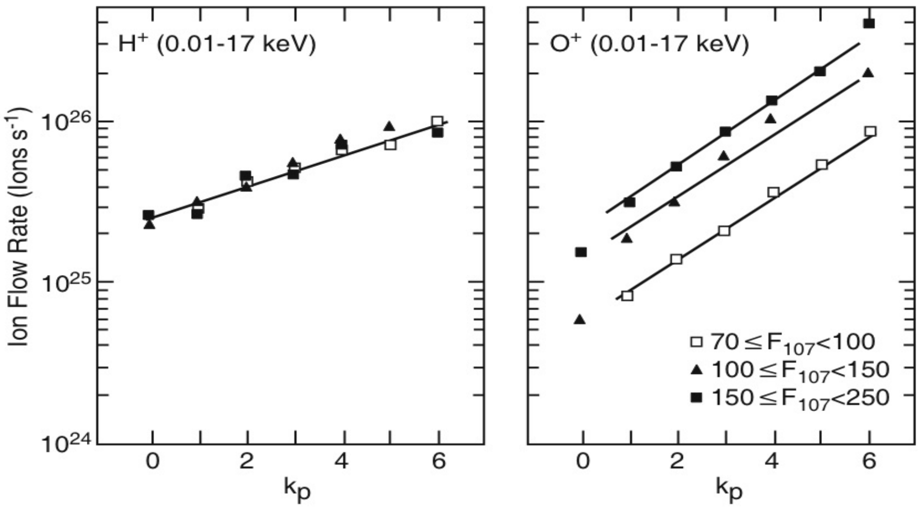
Sunward convection and dynamical changes allow some escape through dayside magnetopause.

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



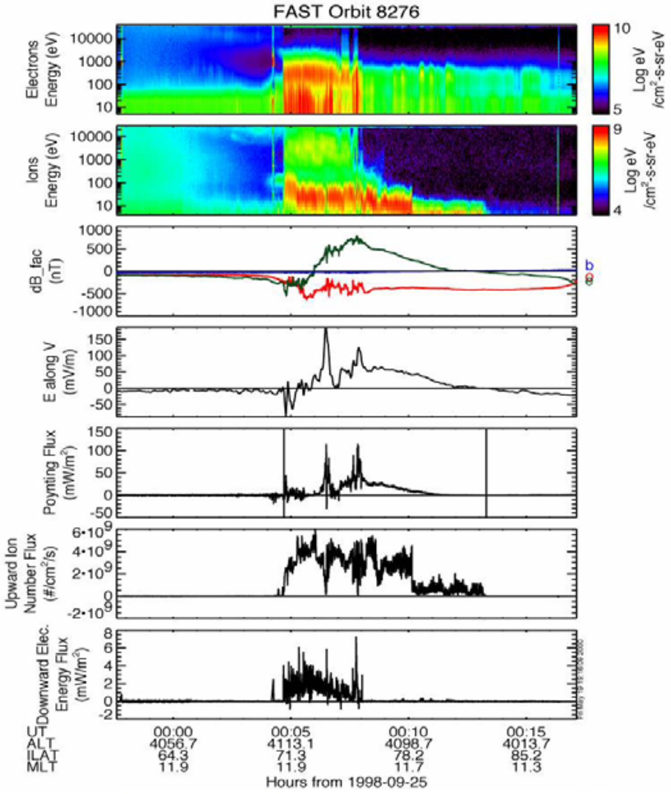
Terrestrial Outflow Rates

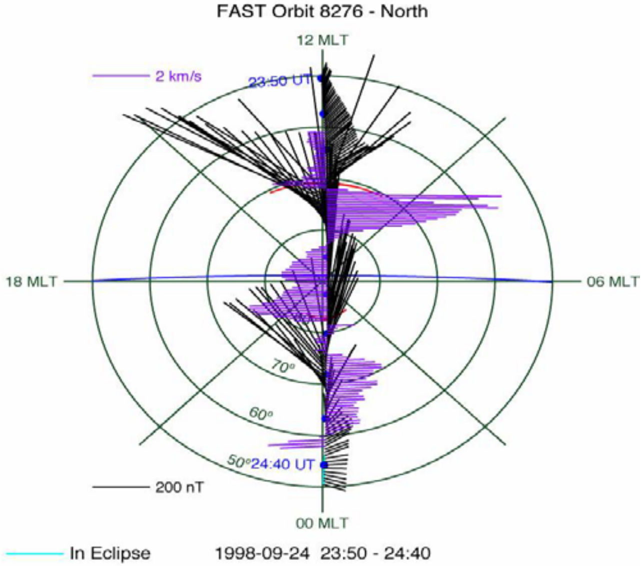
Yau and André, SSR, 80, 1-25, 1997



Integrated fluxes – comparison with local data depends on area.
Area above 56 degrees ILAT ~ 3×10^{18} cm^2 (both hemispheres).

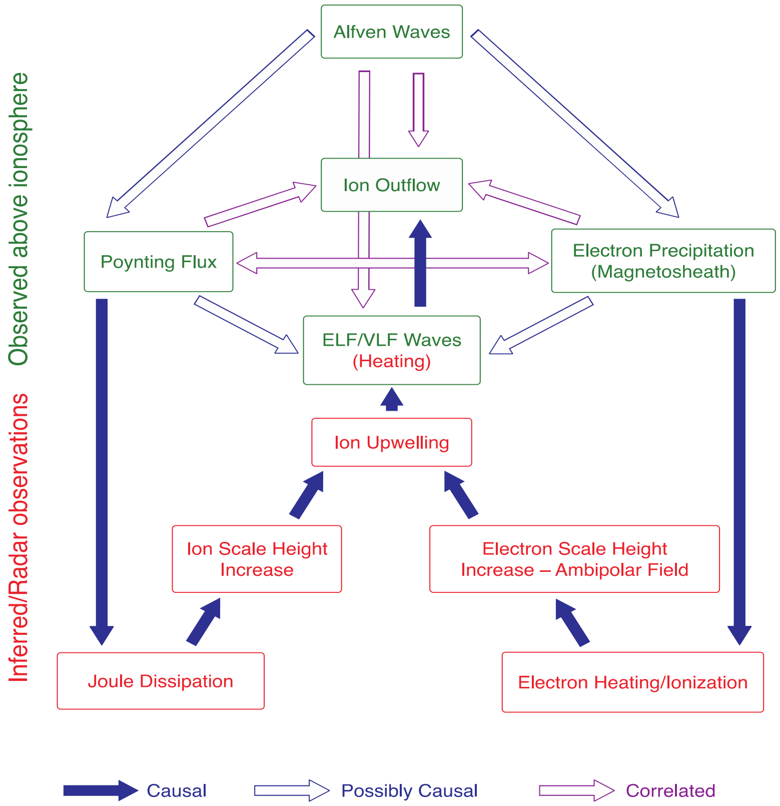
Cusp Region Ion Outflow





Strangeway et al. [2005]

Outflow Mechanisms

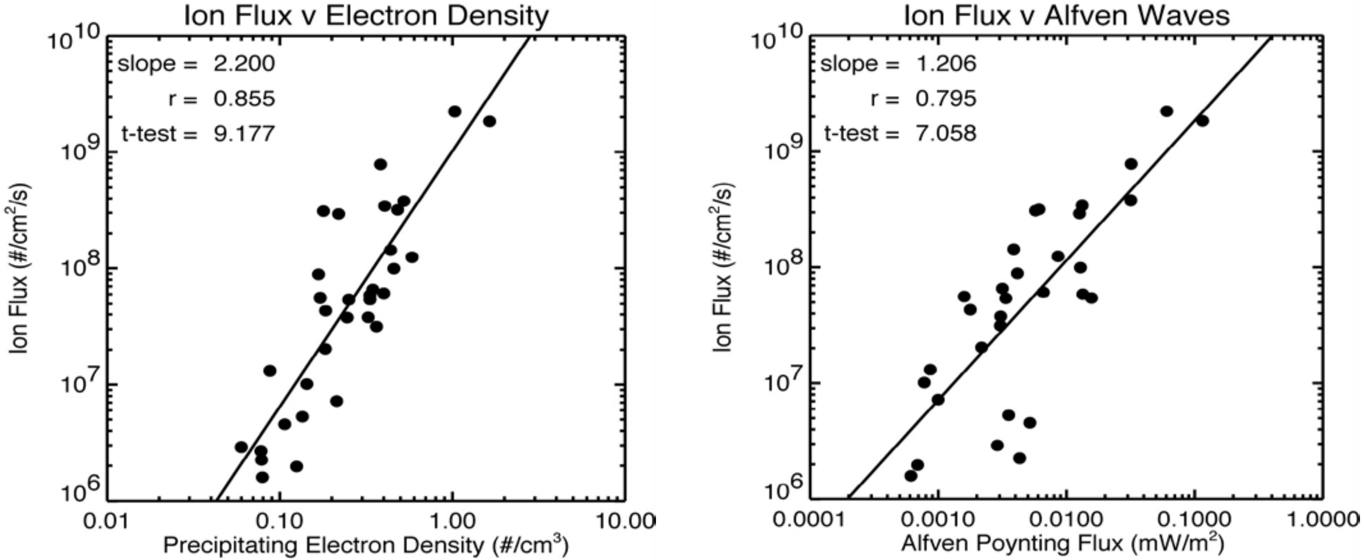


Type 1
(Ion heating)

Type 2
(Elec. Heating)

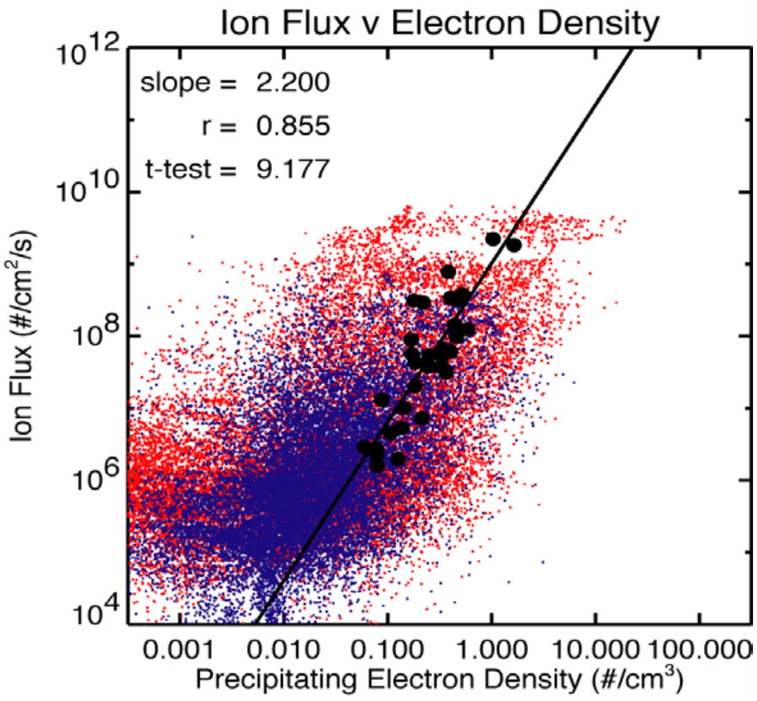
Type 1 and Type 2 defined by Wahlund et al. [1992] using radar observations.

Scaling Laws - Electron Precipitation, Alfvén Waves



Precipitating electrons (LHS) are the single best predictor of outflow fluxes, but hard to model. Alfvén waves (RHS) appear to be a useful proxy.

Day/Night Differences



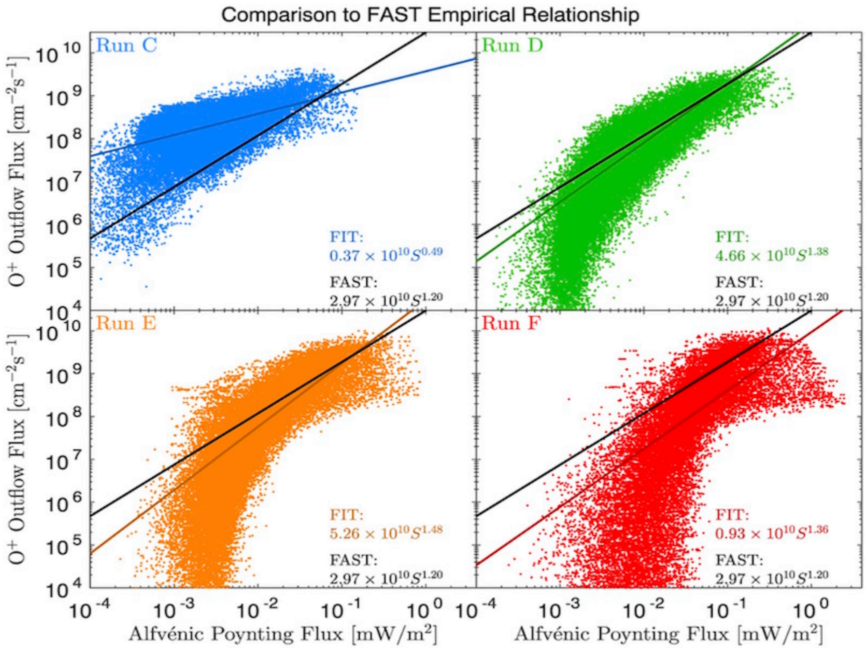
Day Night

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.

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

Terrestrial Outflow Models



Recently Varney et al. [2016] have developed a model that improves on models that use scaling laws to determined outflows.

They included transverse wave heating in their coupled model.

Transverse heating is required to increase ion energy above escape energies.

Results compare well with FAST scaling laws, but again show evidence of flux saturation.

Also need to determine if ions are ultimately lost or recycled.

Summary

Solar wind driven outflows – atmosphere evolution:

- Contemporary ion outflow rates are comparable for all three terrestrial planets $10^{24} – 10^{26}\ s^{-1}$.
- Not clear that an intrinsic magnetic field inhibits ionospheric escape – but how much of the escaping ions ultimately leave the magnetosphere?
- Need substantially higher outflow rates for the early solar system to result in significant water or atmosphere loss.
- EUV and solar wind may be stronger for the early solar system (Venus and Mars), but so is the solar-wind magnetosphere interaction (Earth).

Fundamental Question:

- How do the outflows vary with solar wind parameters?

Backup Material

Mars – Dissociative Recombination

Dissociative recombination can enhance neutral oxygen escape [Fox and Hac, 2009].

$$
\begin{aligned}
O_2^+ + e &\rightarrow O(^3P) + O(^3P) + 6.99\ \text{eV}, \\
&\rightarrow O(^1D) + O(^3P) + 5.02\ \text{eV}, \\
&\rightarrow O(^1S) + O(^3P) + 2.80\ \text{eV}, \\
&\rightarrow O(^1D) + O(^1D) + 3.06\ \text{eV}, \\
&\rightarrow O(^1D) + O(^1S) + 0.83\ \text{eV}.
\end{aligned}
$$

Exothermic energy is partitioned equally between the reaction products.

Only first two reactions enhance oxygen escape at Mars.

Does not affect oxygen escape at Venus.

DR loss rates ≈ 2 x 10^{26} s^{-1} [Fox and Hac, 2009], an order of magnitude larger than typically cited rates for sputtering (e.g., 2 x 10^{25} s^{-1} [Luhmann and Kozyra, 1991]).

DR loss process largely independent of solar wind conditions, but will depend on solar EUV.

Solar Wind Interaction – Mechanisms

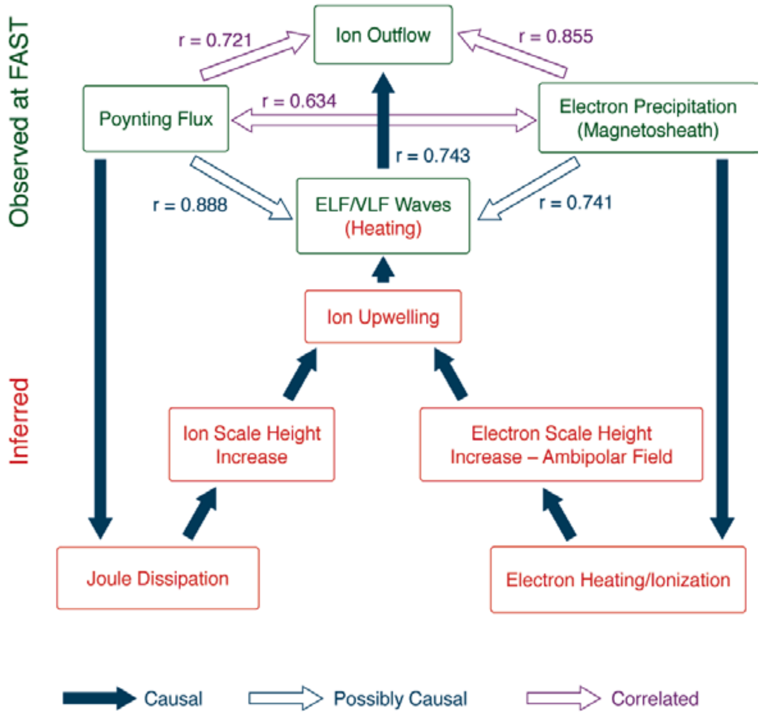
A magnetized plasma behaves like a fluid (magnetohydrodynamics, MHD), but with the addition of magnetic forces (Maxwell stress) to the momentum and energy equations of the fluid.

Magnetic stresses can be applied to the Earth's magnetosphere through a process known as reconnection, where field lines from the solar wind "reconnect" with field lines from the Earth's magnetosphere.

Electromagnetic energy can be transferred as Poynting flux through either large scale current systems ("DC") or MHD waves (Alfvén waves).

Outflow Mechanisms

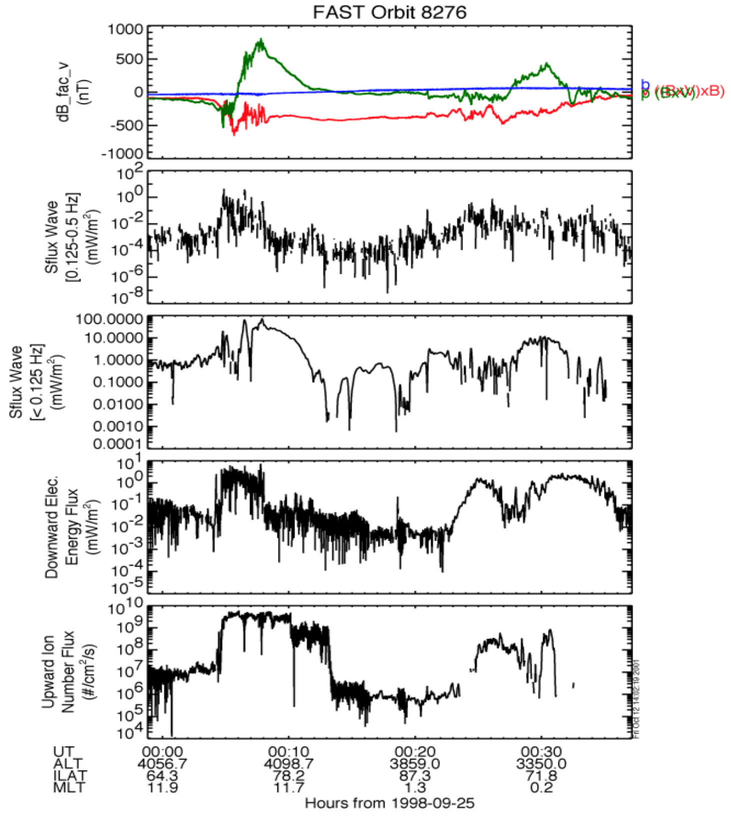
Type 1



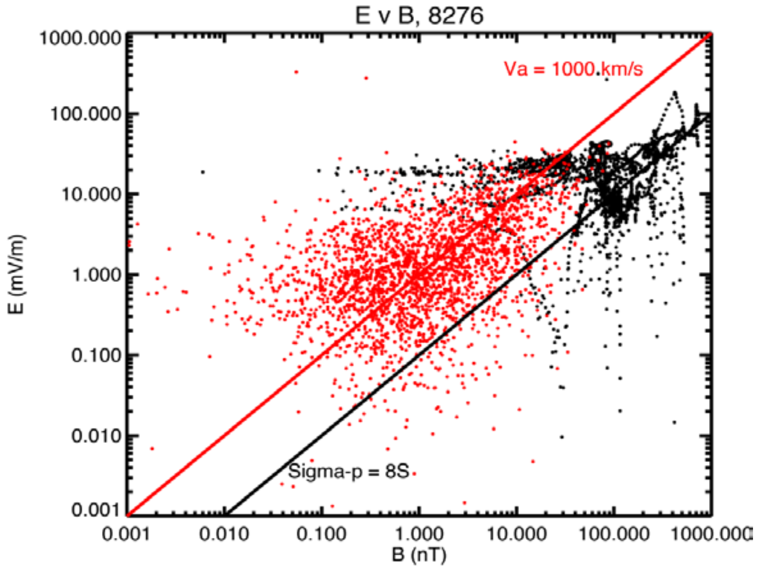
Type 2

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

Alfvén Wave Parameters



At FAST altitudes low frequency signals (< 0.125 Hz) are “quasi-static” – DC Poynting flux



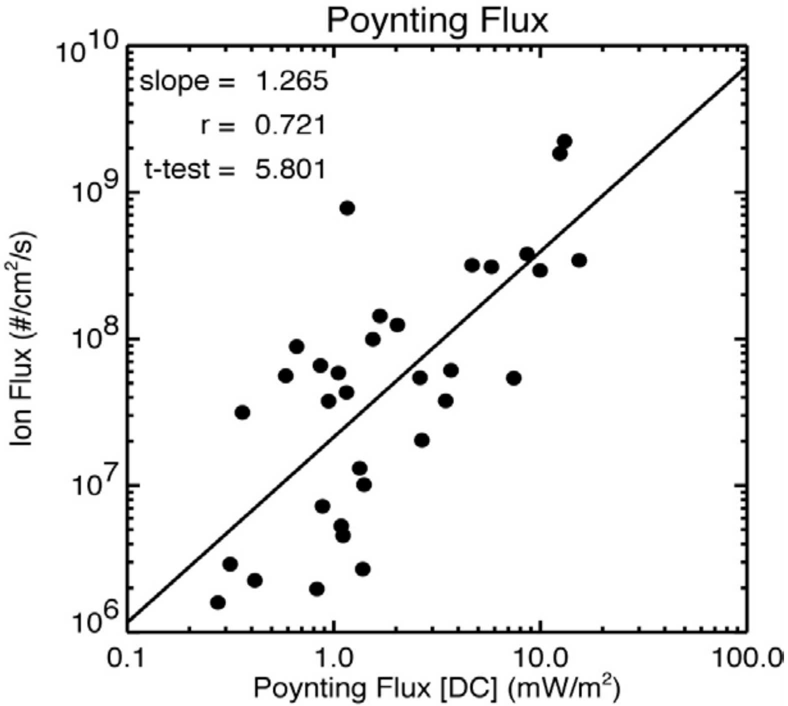
Multiple Linear Regression

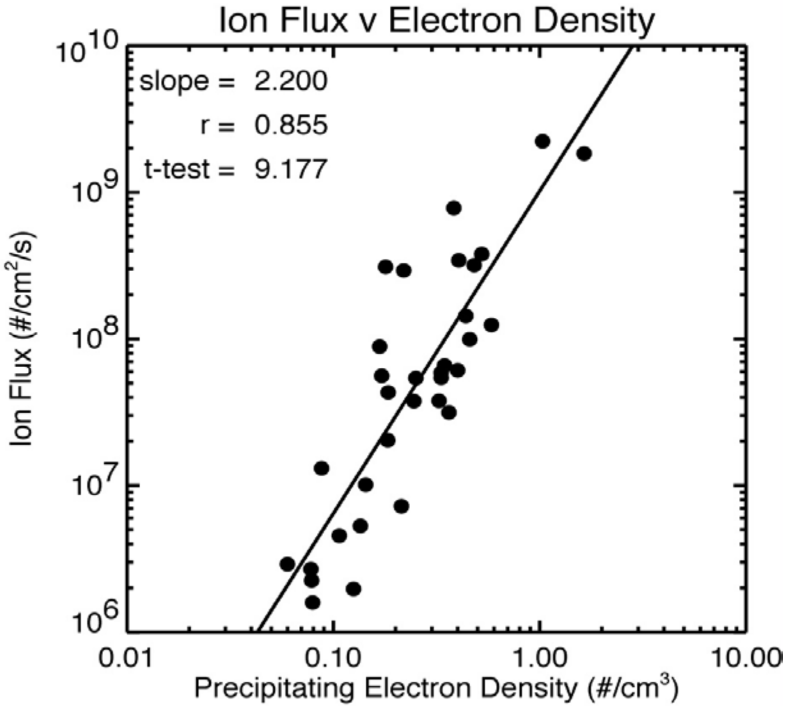
Table of slopes and significance test for multiple linear regression
$\log_{10}$(parameter) v $\log_{10}$(ion number flux)

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)

Scaling Laws

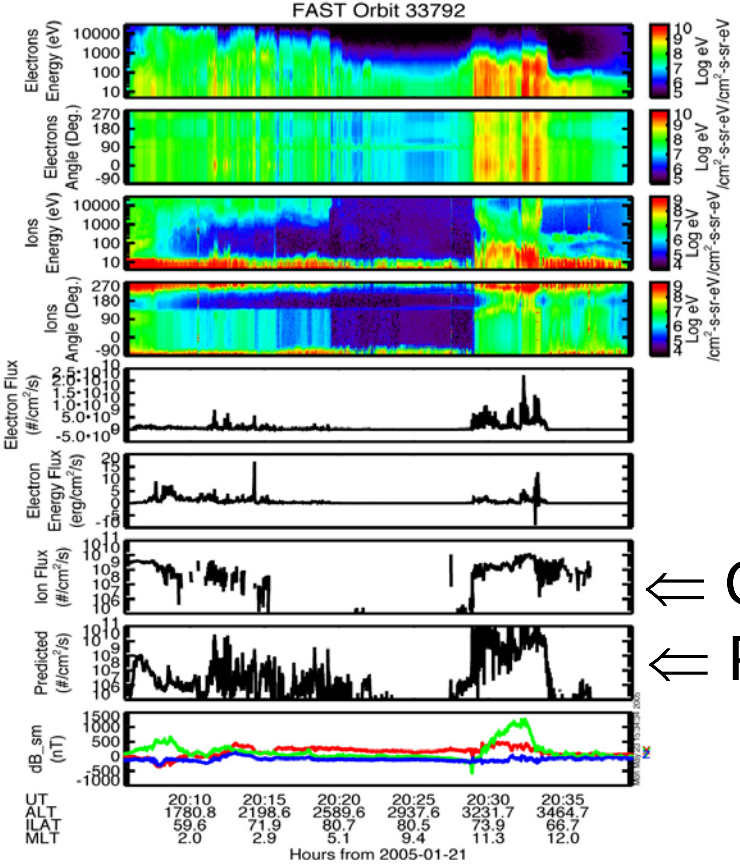




$f_i = 2.14\text{x}10^{7\pm0.24}\ S^{1.27\pm0.45}$

$f_i = 1.02\text{x}10^{9\pm0.34}\ n_{ep}^{2.20\pm0.49}$

Flux Saturation



⇐ Observed flux

⇐ Predicted flux

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?