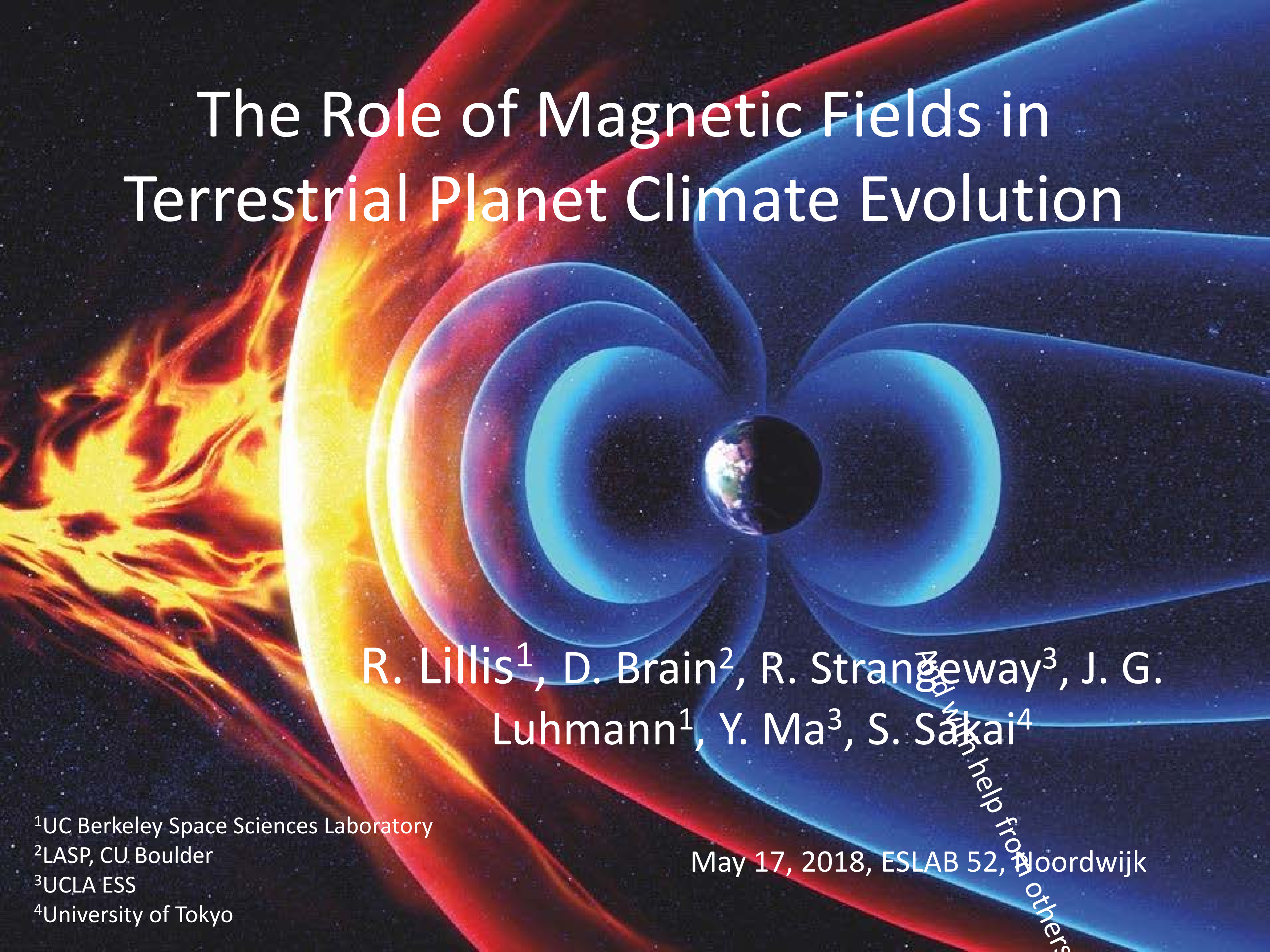


The Role of Magnetic Fields in Terrestrial Planet Climate Evolution

R. Lillis[1], D. Brain[2], R. Strangeway[3], J. G. Luhmann[1], Y. Ma[3], S. Sakai[4]

and with help from others

[1]UC Berkeley Space Sciences Laboratory
[2]LASP, CU Boulder
[3]UCLA ESS
[4]University of Tokyo

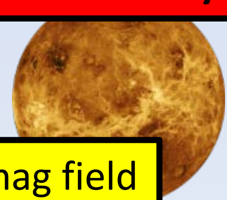
May 17, 2018, ESLAB 52, Noordwijk

What is a meaningful comparison?

- A simple side-by-side climate comparison between Venus, Earth and Mars is of limited use. They differ in so many more ways (other than magnetic field) that affect climate.

	Venus	Earth	Mars
Mass (% of Earth)	81%	100%	10.7%
Radius	6052 km	6378 km	3390 km
Density	5250 kg/m^3	5520 kg/m^3	3900 kg/m^3
Surface gravity	8.9 m/s^2	9.8 m/s^2	3.81 m/s^2
Av. Dist. from Sun	108 million km	150 million km	229 million km
Rotation period	243 Earth days	24 hours	24.6 hours
Orbit period (year)	224.7 Earth days	365.2 days	678 days
Surface temp.	465 °C	15 °C	-63°C
Surface pressure	90 bar	1 bar (sea level)	0.007 bar
Albedo (reflectivity)	0.76	0.37	0.15
Lower Atmosphere	96% CO_2 , 3% N_2	78% N_2 , 21% O_2	96% CO_2 , 3% N_2
Obliquity of axis	178°	23.5°	25.2°

Hot & heavy

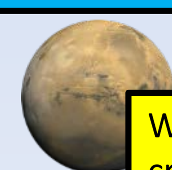


No mag field

Just Right

Dipole field

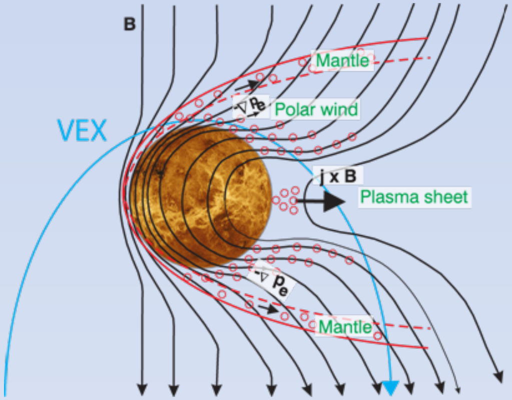
Cold & thin



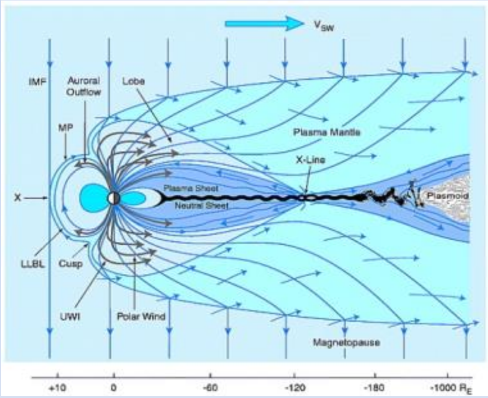
Weak crustal field

Why should B-fields matter to terrestrial planet climate evolution?

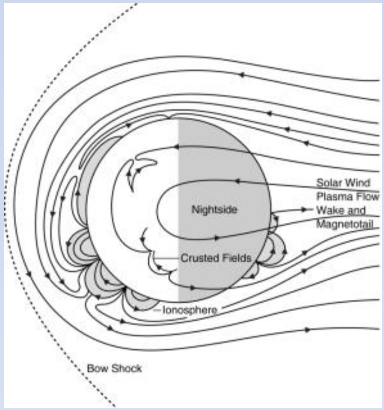
- B-fields **<u>don't</u>** affect sources of atmosphere or the bulk neutral atmosphere itself.
- B-fields **<u>do</u>** guide plasma into, within, and out of, partially-ionized upper atmospheres.
- Over time, planetary magnetic fields (intrinsic and induced), and their strength, geometry and topology can profoundly impact the total pressure and composition of terrestrial planet atmospheres, and hence the evolution of their climates.

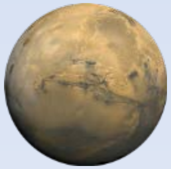


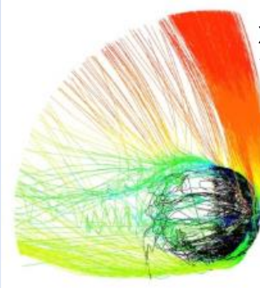
Dubinin & Fraenz, 2015



Moore & Horowitz, 2007



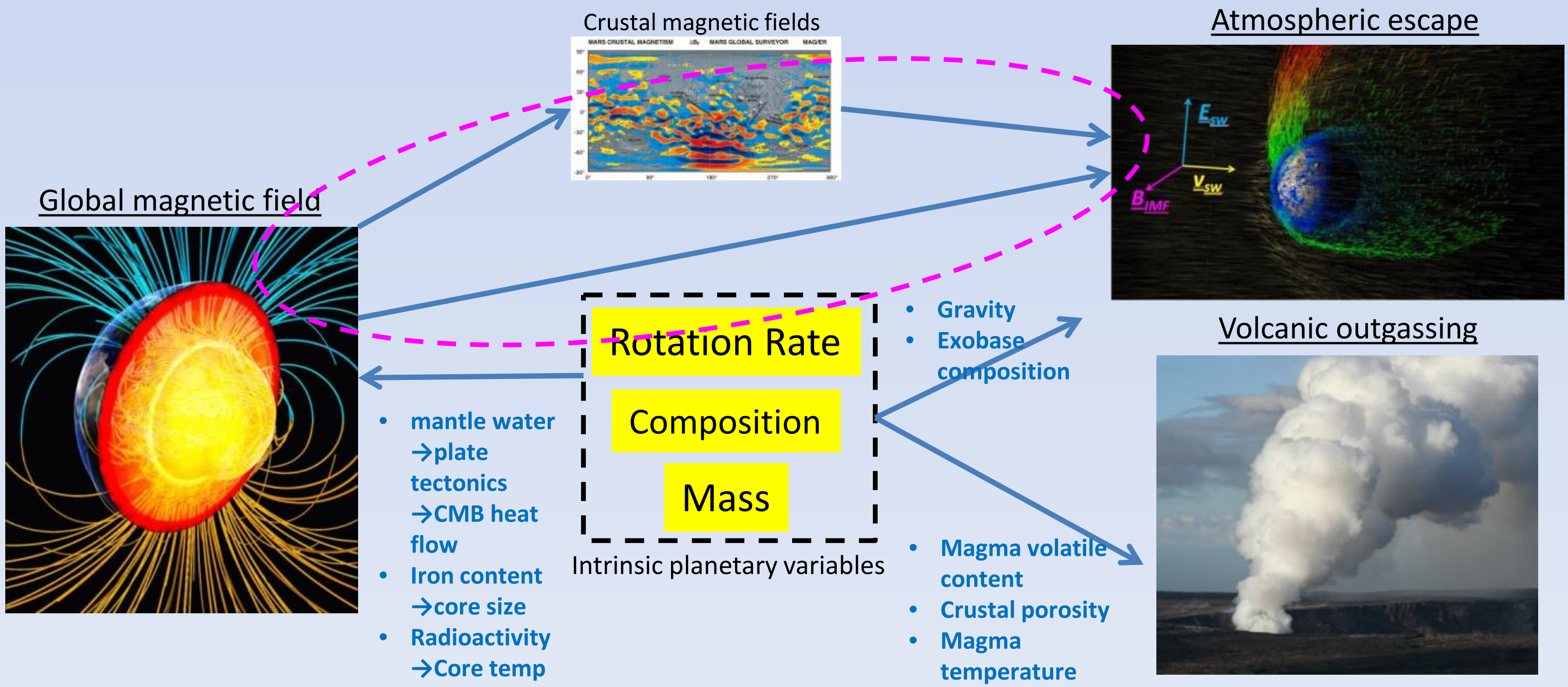




X. Fang O^+ ion tracing

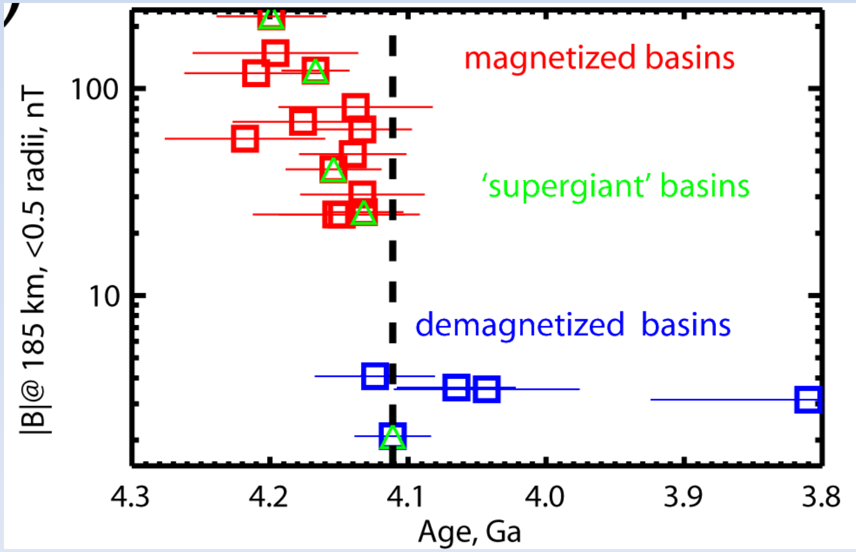
Magnetic fields don't exist in a vacuum (well, you know what I mean)

- Could ask the question *ceterus paribus*.
- But magnetic fields are not an independent, *a priori* planetary variable.
- A geodynamo is the result of interior physical processes whose boundary conditions are determined by intrinsic planetary variables.
- ***<u>The same variables</u>*** that contribute to atmospheric sinks and sources.

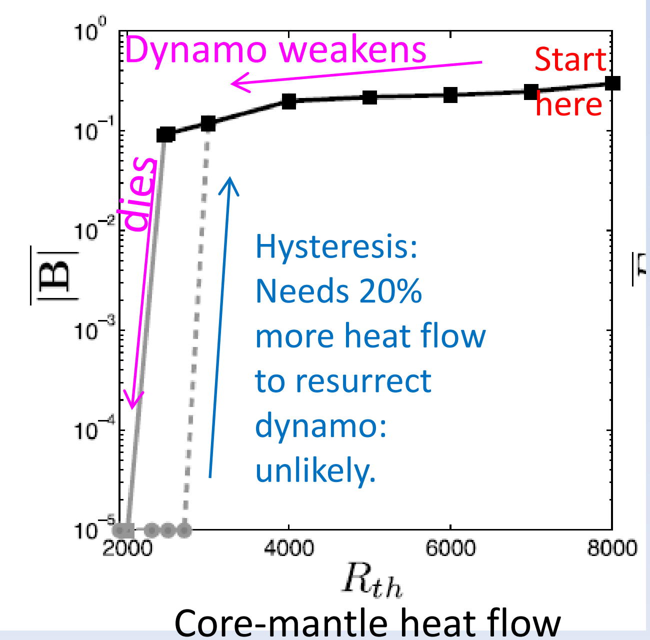


Magnetic fields don't exist in a vacuum (well, you know what I mean)

- Could ask the question *ceterus paribus*.
- But magnetic fields are not an independent, *a priori* planetary variable.
- A geodynamo is the result of interior physical processes whose boundary conditions are determined by intrinsic planetary variables.
- ***The same variables*** that contribute to atmospheric sources & sinks.
- Planets can transition from magnetic to non-magnetic (probably not the other way).



Mars dynamo evolution: Lillis et al., 2008

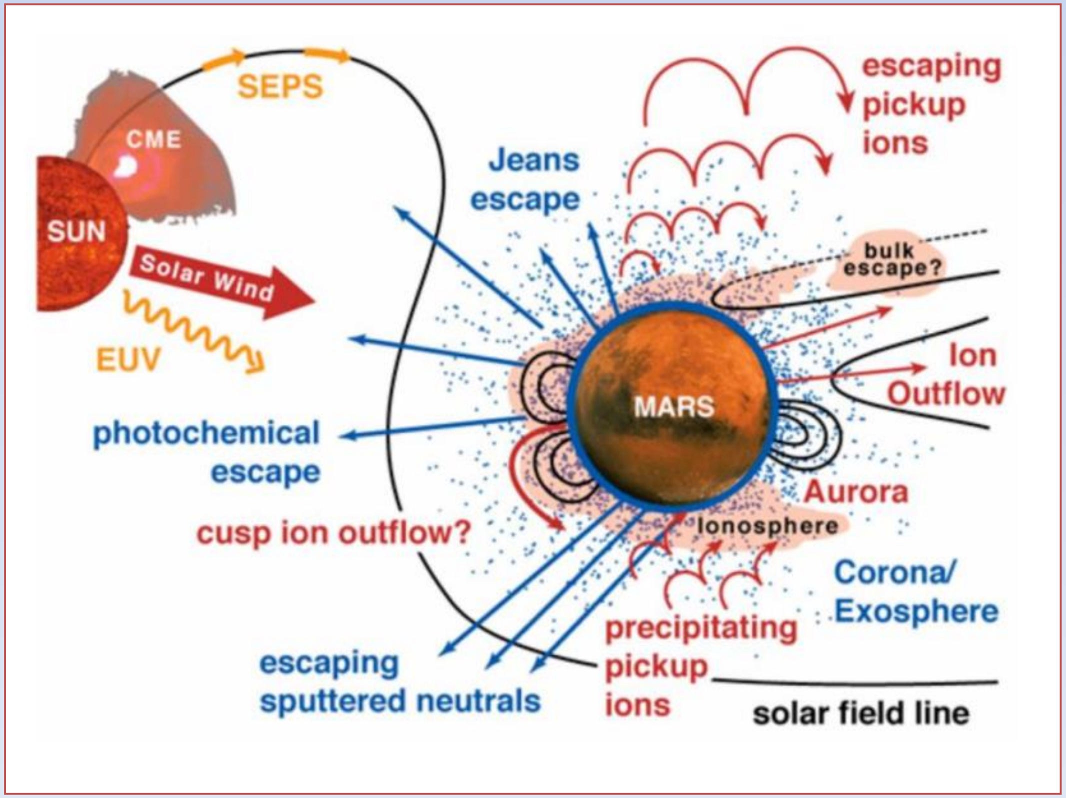


Core-mantle heat flow

Kuang et al., 2008

How should escape be affected?

- Absence/presence of magnetic fields should affect all escape processes involving ionized atoms/molecule motion near and above the exobase.
- Character & magnitude of effect of B-field depends on other variables (e.g. solar wind pressure, IMF direction, gravity)



How should escape be affected?

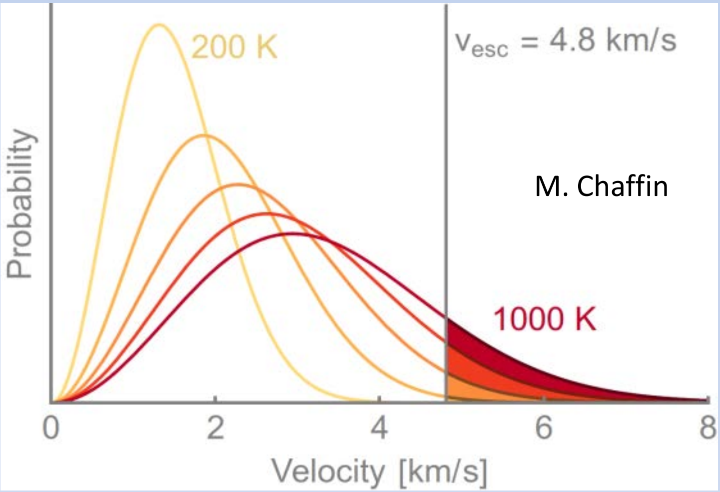
- Absence/presence of magnetic fields should affect all escape processes involving ionized atoms/molecule motion near and above the exobase.
- Character & magnitude of effect of B-field depends on other variables (e.g. solar wind pressure, IMF direction, gravity)

Categorize escape processes by the charge state of the escaping atom/molecule and the energization mechanism.

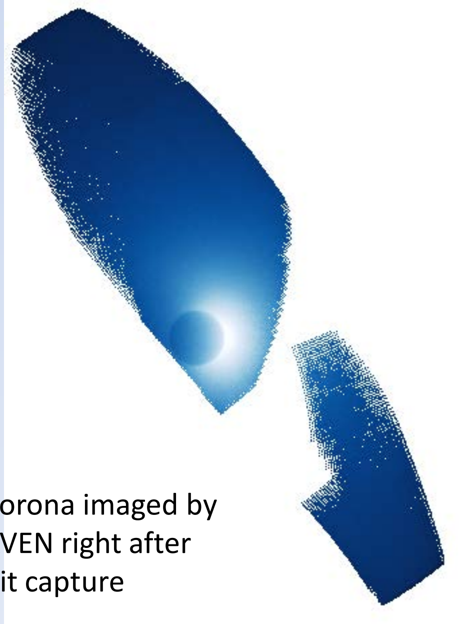
Escape Process	Effect of global magnetic field
Jeans Escape	Negligible
Photochemical escape	Small. Exobase chemistry and electron temperature affected by precipitating plasma.
Sputtering	Likely Negative. New oxygen ions cannot be precipitate except in certain auroral region near the poles.
Solar wind pickup	Likely negative. EI and CE inhibited. New O^+ ions created on closed field lines are trapped.
Ion outflow	Unclear. Outflow near magnetic poles may exceed total outflow in unmagnetized case due to far greater energization.
Bulk ion escape	Likely negative. Ionosphere-magnetosphere velocity shear would happen at much higher altitudes where densities are lower.

Jeans Escape

- **Definition**: high-energy tail of thermal atom distribution can exceed escape velocity.
- **Direct Dependencies**: T_{exo}, n_{exo}, g, m
- **Main responsible factors**:
  - Solar Irradiance (heats lower atmosphere and drives dust & H_2O vapor cycle).
  - Solar EUV (drives thermosphere temperature)
  - Total water content of atmosphere
- **Effect of intrinsic magnetic fields** :
  - Joule heating of neutrals by ions could raise thermospheric temperatures.
  - Heavy ion precipitation can heat neutrals during large solar events (Fang, 2103; Regoli this meeting)
  - However, solar photons dominate heating most of the time.
- **Overall judgment**: Negligible under current solar conditions. May matter for very active star (e.g. early sun).



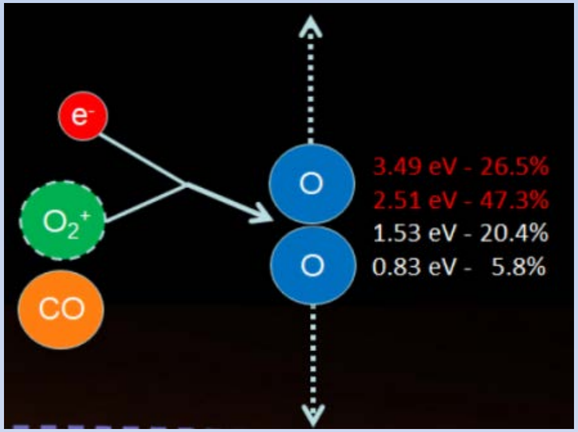
M. Chaffin

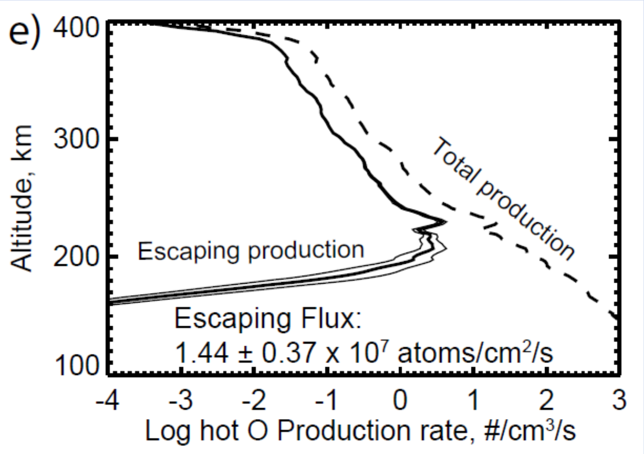


H Corona imaged by MAVEN right after orbit capture

Photochemical escape

- **Definition**: Exothermic reactions provide escape energy to neutral reaction products. Escape is from near and above the exobase.
- **Direct Dependencies**: g, n_n, T_n, n_e, T_e, n_i, T_i
- **Main responsible factors**:
  - Thermosphere composition
  - Solar EUV irradiance
- **Effect of intrinsic magnetic fields** :
  - electron impact ionization (EII) can alter O_2^+ production and T_e. EII is confined to polar regions if a global field is present.
  - Likely minimal since solar EUV photons dominate ionization and therefore hot O production.
- **Overall judgment**: B-fields likely don't matter much.

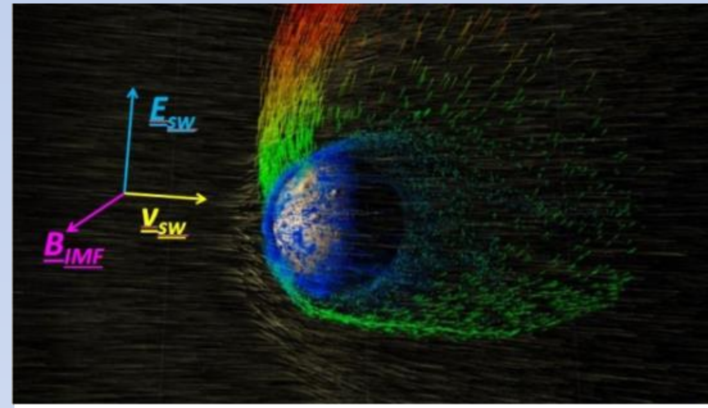


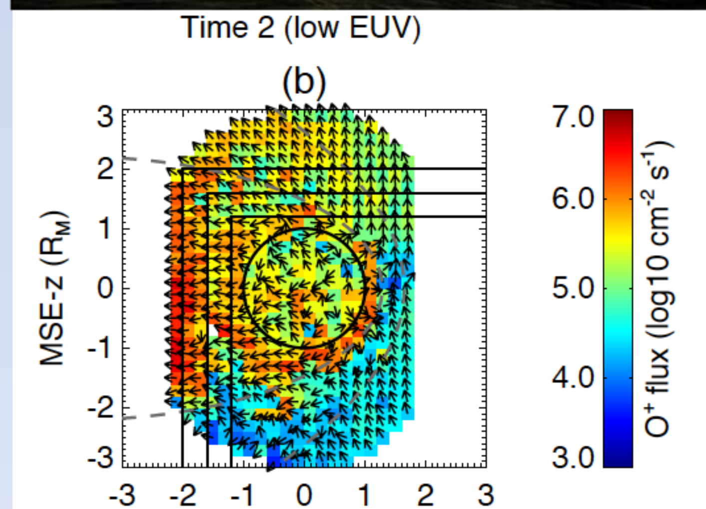


Lillis et al., 2017

Pickup Ion Escape

- **Definition**: SW convection E-field accelerates planetary ions to > V_{esc}
- **Direct Dependencies**: g, m, V_{SW}, B_{IMF}
- **Main responsible factors**:
  - Solar wind velocity & density.
  - Solar EUV (ionizes & controls oxygen corona)
  - Local magnetic field configuration
- **Effect of intrinsic magnetic fields**:
  - Reduce ionization of O by charge exchange and electron impact.
  - Photoionized O^+ ions created on closed magnetic field lines are trapped and cannot easily escape
- **Overall judgment**: B-fields likely inhibit pick up ion escape.

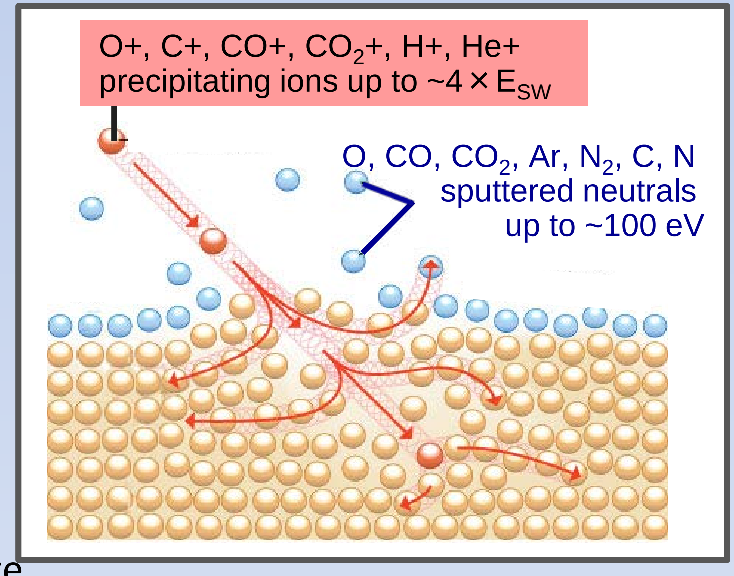


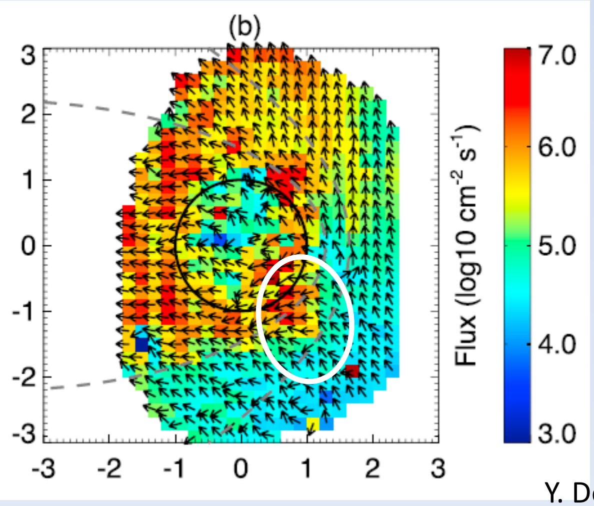


Sputtering Escape

- **Definition**: precipitating heavy ions transfer escape energy to cold neutrals
- **Direct Dependencies**: *g, m,* precipitating O^+ flux spectrum (V_{SW}, B_{IMF})
- **Main responsible factors**:
  - Solar wind velocity & density.
  - Solar EUV (ionizes & controls oxygen corona)
  - Local magnetic field configuration
- **Effect of intrinsic magnetic fields**:
  - Reduce ionization of exospheric O by charge exchange and electron impact.
  - Photoionized O^+ ions created on closed magnetic field lines are trapped and cannot easily the impact the atmosphere.
- **Overall judgment**: B-fields likely inhibit sputtering escape.

S. Curry

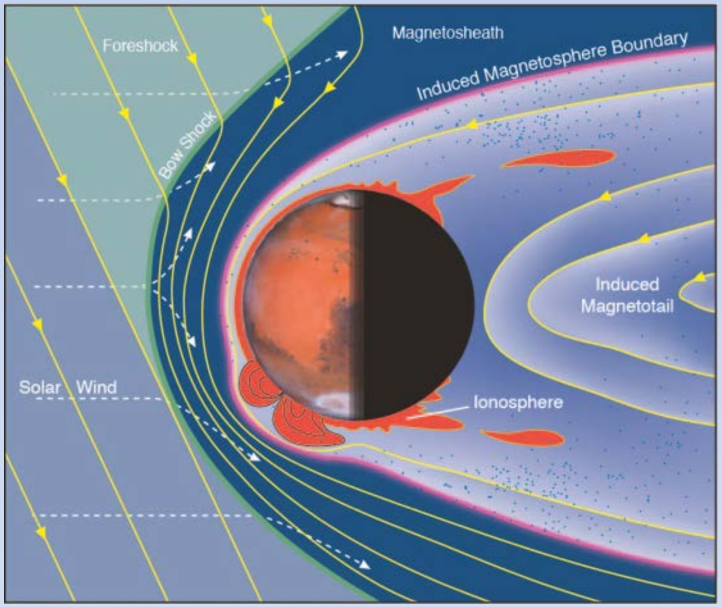




Y. Dong

Bulk Ion Escape

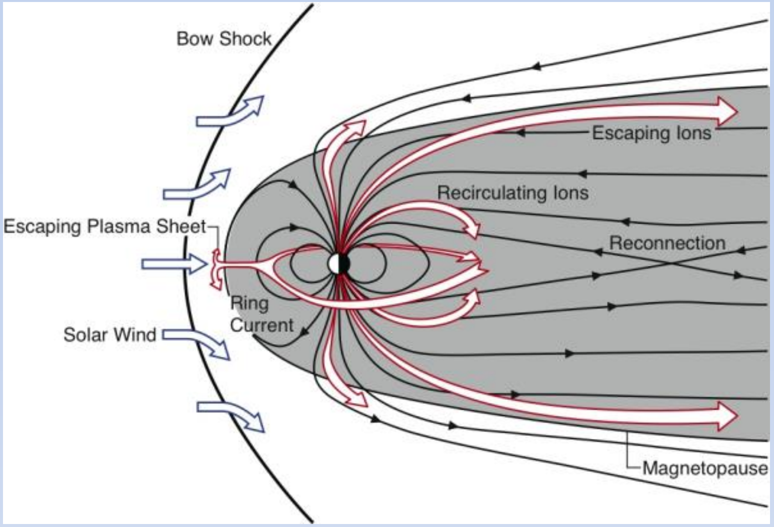
- **Definition**: plasma shear instability between ionosphere and magnetosphere removes coherent 'blob' of ionosphere plasma.
- **Direct Dependencies**: V_{SW}, B_{IMF}, n_{ion}, n_{ion}
- **Main responsible factors**:
  - Flow velocity difference at plasma boundary
- **Effect of intrinsic magnetic fields**:
  - Ionosphere-magnetosphere velocity shear would happen at much higher altitudes where densities are lower, reducing escape.
- **Overall judgment**: B-fields likely inhibit bulk ion escape.



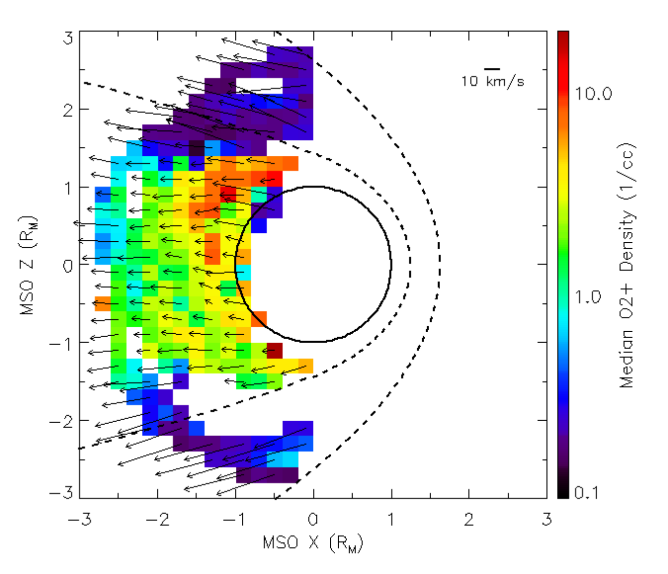
Bartlett, Cambridge University press

Ion Outflow

- **<u>Definition</u>**: topside ionospheric plasma is energized and flows out on open field lines
- **<u>Direct Dependencies</u>**: g, v_{ion}, topology
- **<u>Main responsible factors</u>**:
  - Energization mechanism (wave heating, Poynting flux, electron precipitation etc.)
  - Local magnetic field configuration
- **<u>Effect of intrinsic magnetic fields</u>**:
  - Restricts escape to open field lines at the poles.
  - ***But***, intrinsic magnetic field increases size of obstacle to solar wind flow: more momentum and energy available to drive loss processes.
  - polar ionosphere-magnetosphere coupling can lead to several kinds of escape.
- **<u>Overall judgment</u>**: No evidence that magnetic field acts as a shield.
  - Downtail ion escape rates are comparable for Earth and Mars (previous talks: Strangeway and Haaland, Dandouras).

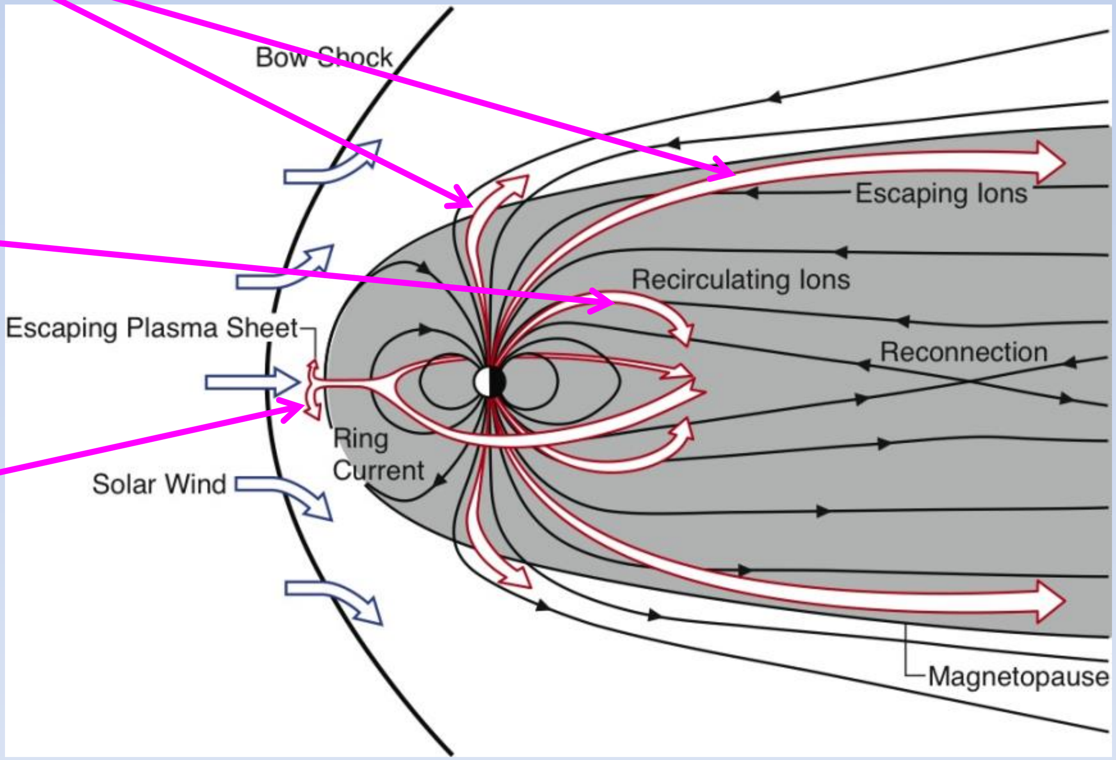


Cambridge University press



Ion outflow processes at Earth

- Direct ion escape: cusp/cleft fountain, polar wind outflow of light ions, variable auroral outflow.
- 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).

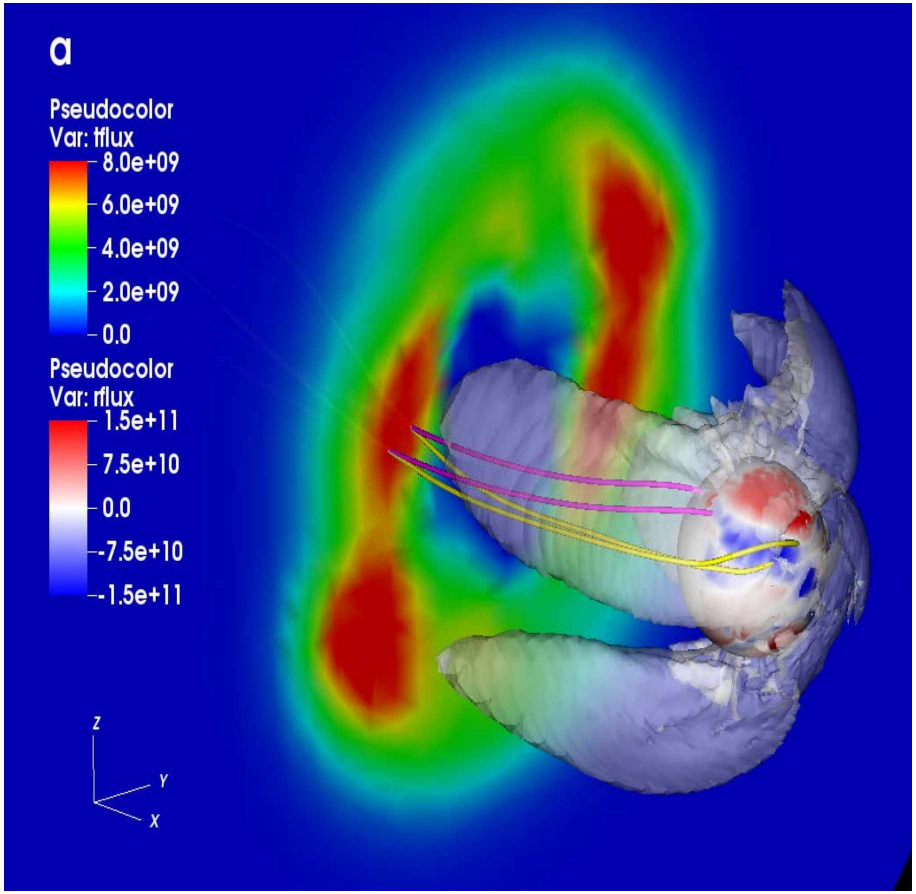


Slide from R. Strangeway

A weak intrinsic magnetic field

Tailward flux of heavy ions

- Four escape routes
  - High latitude
  - Along open field lines
  - On the neutral line
  - Associated with reconnection



Slide courtesy of S. Sakai.

100 nT at the surface

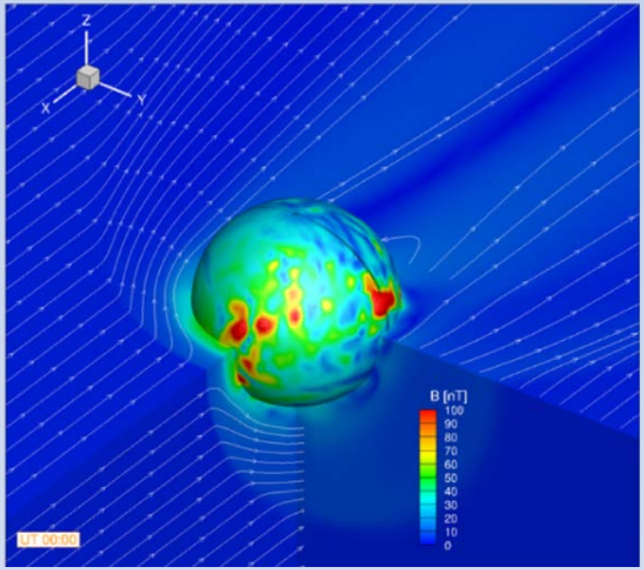
A weak intrinsic magnetic field

- Ion escape rates of heavy ions

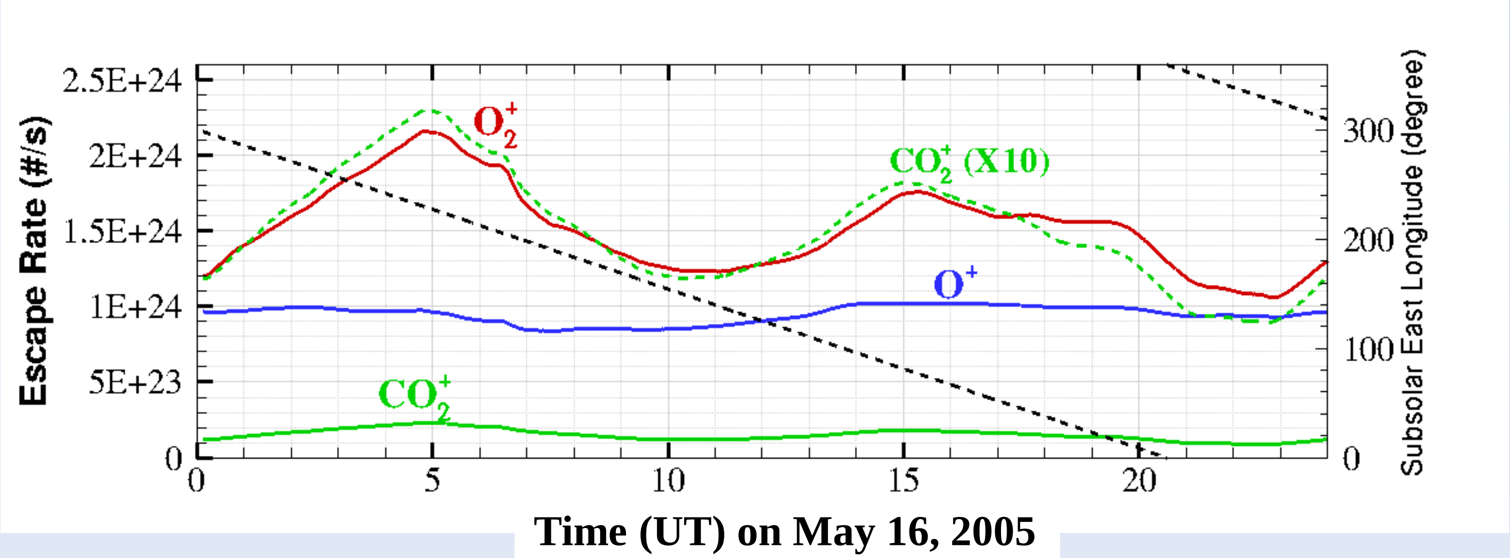
	Total escape rate [s^{-1}]
No dipole	~2.9×10^{24}
With dipole	~3.7×10^{24}

  - Total escape rates of heavy ions increased by 25—30% when a weak intrinsic magnetic field is considered.
- The ratio of escape rate
  - No dipole $O_2^+ : O^+ : CO_2^+ = 1 : 0.84 : 0.0010$
  - With dipole $O_2^+ : O^+ : CO_2^+ = 1 : 0.21 : 0.014$
  - The escape rate of O_2^+ and CO_2^+ significantly increased.
    - Heavy ions present at lower ionosphere are carried to the tail along the field lines opened by the reconnection or cusp.

Effect of crustal magnetic fields on escape



For May 16, 2005 (Ls=212). From the Time-dependent MHD Simulation of *Ma et al., [2014, GRL*]



Overall effect of magnetic fields?

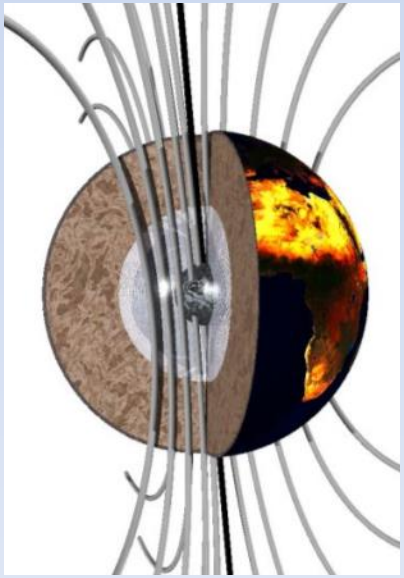
Escape Process	Effect of global magnetic field
Jeans Escape	Negligible
Photochemical escape	Small. Exobase chemistry and electron temperature affected by precipitating plasma.
Sputtering	Likely Negative. New oxygen ions cannot be precipitate except in certain auroral region near the poles.
Solar wind pickup	Likely negative. EI and CE inhibited. New O^+ ions created on closed field lines are trapped.
Ion outflow	Unclear. Outflow near magnetic poles may exceed total outflow in unmagnetized case due to far greater energization.
Bulk ion escape	Likely negative. Ionosphere-magnetosphere velocity shear would happen at much higher altitudes where densities are lower.

- Magnetic fields retard some escape processes, but may enhance ion outflow.
- Character & magnitude of effect of B-field depends on planetary attributes (gravity, exobase composition) and stellar outputs (solar wind pressure, solar EUV, IMF strength).
- ***Therefore, in addition to the evolution of the magnetic field itself, its relative importance evolves over time with the planet and its star***.

BACKUP SLIDES

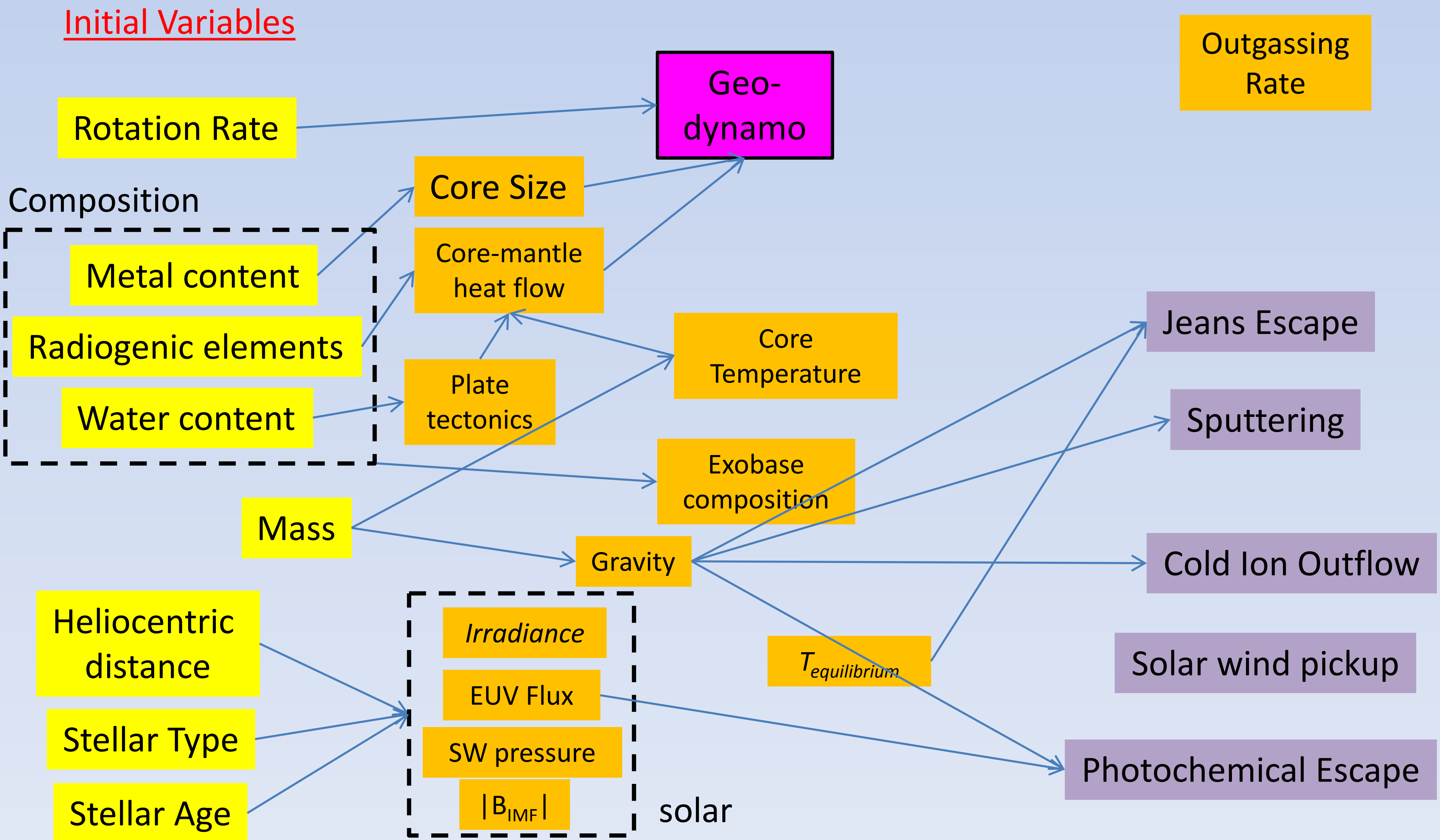
What keeps a dynamo going?

- Differential rotation and turbulent convection in a conducting fluid can serve to amplify and maintain an initial magnetic field[1].
- Requires sufficient core-to-mantle heat flow, ~5-20 mW/m^2 i.e. a superadiabatic temperature gradient between the core and mantle[2].
- Possible explanations:
  - Early Episode of plate tectonics[2]
  - Initially T_{core} - T_{mantle} > 150K [3].
  - Inner core solidification[4].
  - Elliptical excitation of the core [5].



[1]Larmor, 1919 , [2]Nimmo and Stevenson, 2000, [3]Williams and Nimmo, [4]Schubert et al., 2000, 5 Arkani-Hamed, 2011

Planetary variables play a complex role in magnetic fields and atmospheric escape



Outline

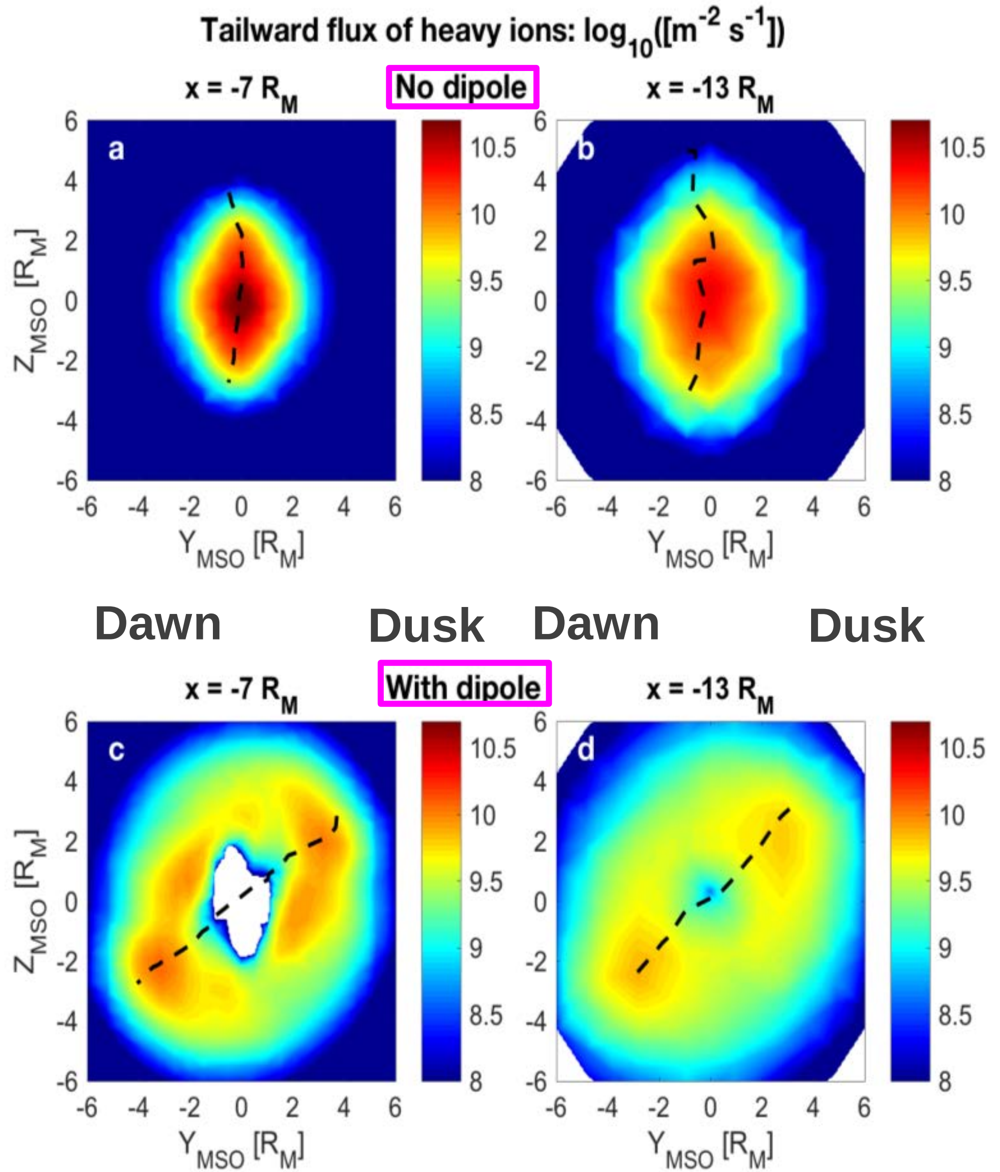
- What are useful comparisons between planets with and without magnetic fields?
- Magnetic fields in the broad context of planetary evolution.
- Escape processes and their dependence on magnetic fields.
- Summary

A weak intrinsic magnetic field

東京大学 THE UNIVERSITY OF TOKYO

Tailward flux of heavy ions

- Four escape routes
  - High latitude
  - Along open field lines
  - On the neutral line
  - Associated with reconnection



100 nT at the surface

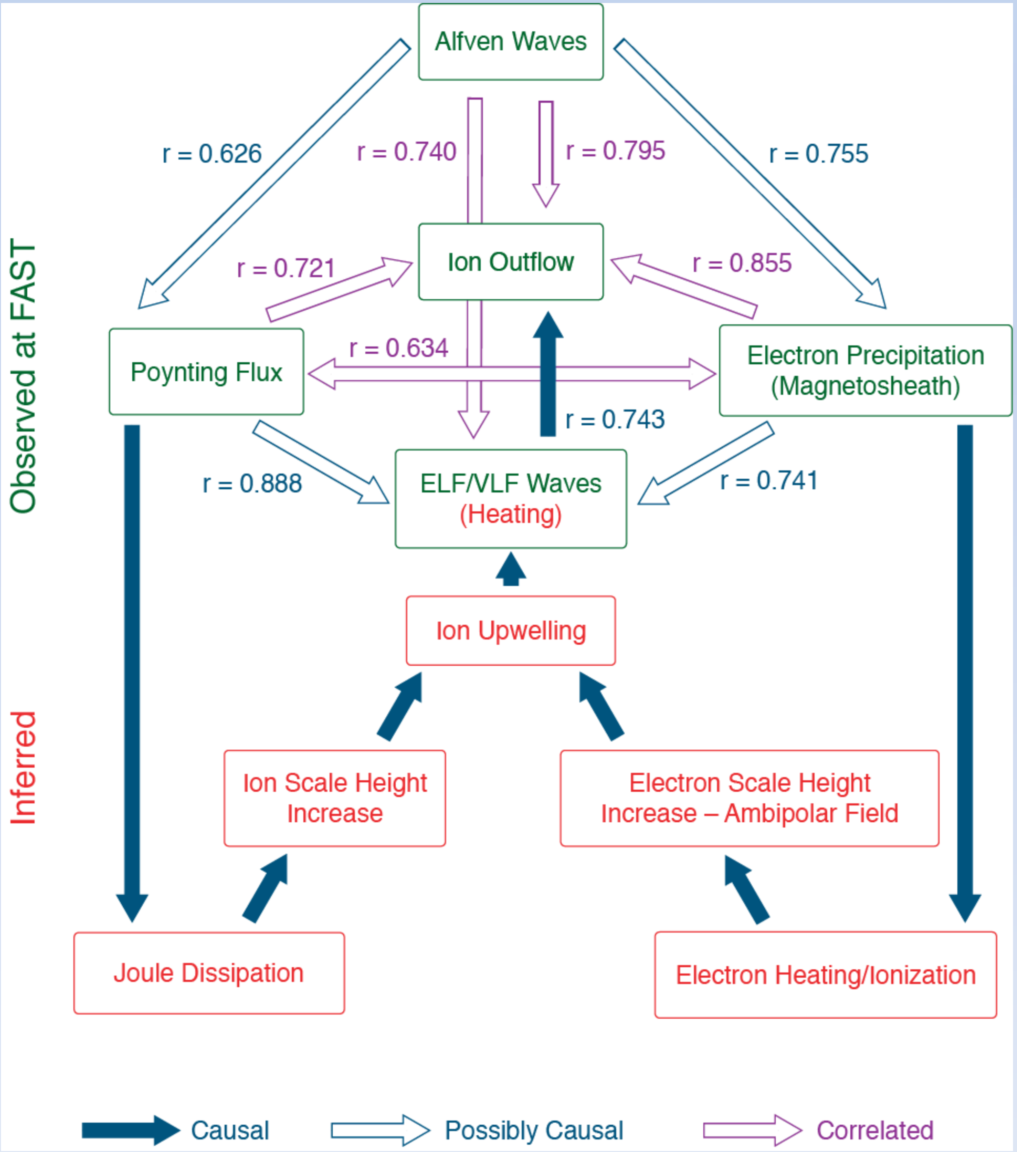
Slide courtesy of S. Sakai.

Does a magnetic field retard or promote ion outflow?

- 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.

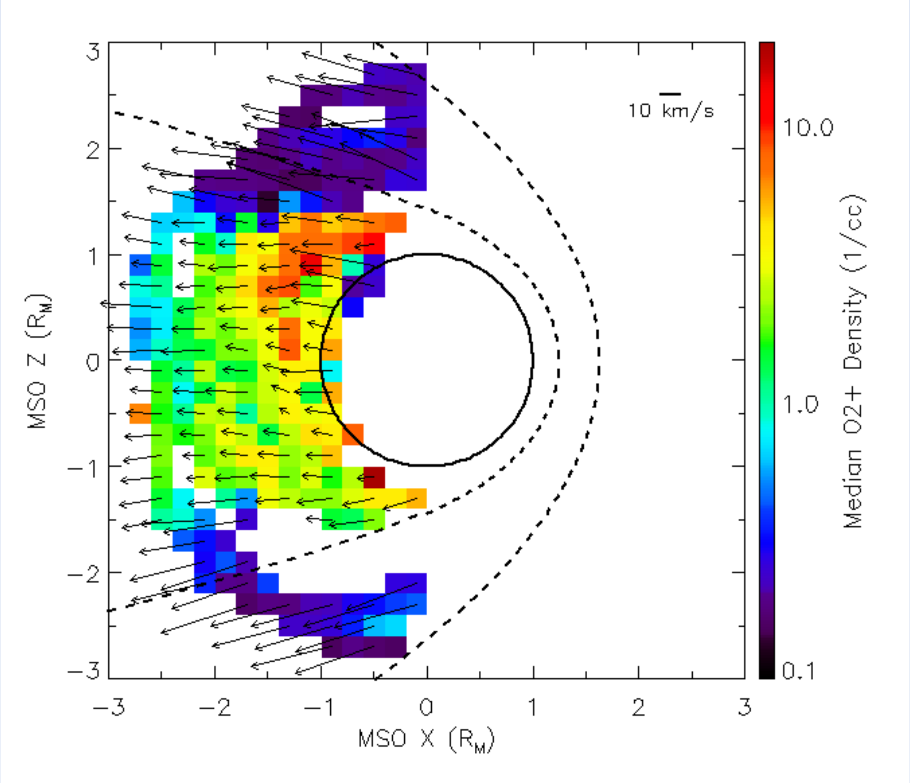
Slide from R. Strangeway

Ion outflow processes at Earth



Slide from R. Strangeway

Ion outflow at Mars



Slide from D. Mitchell

- Complex pattern of loss is well organized by magnetic topology (measured by SWEA and MAG), revealing multiple acceleration mechanisms.
- O_2^+ and O^+ are lost in about a 2:1 ratio, consistent with an ionospheric source region near the exobase.
- The cold oxygen ion loss down the tail is ~10^{25} ions/s, which represents a significant fraction of the total oxygen ion loss.