Proceedings of Symposium on Planetary Science 2021

Effects of an intrinsic magnetic field on atmospheric escape from a Mars-like planet

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Ion loss to space has played an important role in atmospheric escape and climate change on Mars because of intense solar activity during a younger, more active phase of the Sun. Although the existence of an intrinsic magnetic field on ancient Mars is also a key factor in ion loss, its effect remains unclear. Based on multispecies magnetohydrodynamics (MHD) simulations, we investigated ion loss dates and processes from Mars under extreme solar conditions and the existence of a dipole field with different strengths. The effects of a dipole field on ion loss depend on whether the dipolar magnetic pressure is strong enough to sustain the solar wind dynamic pressure. When the dipole field is existent but weak, it facilitates the cusp outflow and increases the loss rates of molecular ions (O_2^+ and CO_2^+) by a factor of six through the high-latitude magnetotail. When the dipole field is strong enough, the loss rates of molecular ions are decreased by two orders of magnitude, and peaks of the escape flux are located near the equatorial plane due to the magnetic reconnection in the northern-dusk or southern-dawn lobe regions. The pickup process on the extended oxygen corona created by the strong EUV flux contributes to the total O^+ loss. Therefore, the effects of the dipole field are less pronounced for O^+. Under more moderate solar EUV conditions, the effects on O^+ loss can be stronger and thus contribute to climate change.

Direction of the upstream interplanetary magnetic field (IMF) also significantly changes the magnetospheric configuration, influencing the atmospheric escape mechanism. This paper moreover investigates effects of IMF on the ion escape mechanism from a Mars-like planet that has a weak dipole magnetic field directing northward on the equatorial surface. The northward (parallel to the dipole at subsolar), southward (antiparallel), and Parker-spiral IMFs under present solar wind conditions are compared based on multispecies MHD simulations. In the northward IMF case, molecular ions escape from the high-latitude lobe reconnection region, where ionospheric ions are transported upward along open field lines. Atomic oxygen ions originating either in the ionosphere or oxygen corona escape through a broader ring-shaped region. In the southward IMF case, the escape flux of heavy ions increases significantly and has peaks around the equatorial dawn and dusk flanks. The draped IMF can penetrate into the subsolar ionosphere by erosion, and the IMF becomes mass-loaded as it is transported through the dayside ionosphere. The mass-loaded draped IMF is carried to the tail, contributing to ion escape. The escape channels in the northward and southward IMF cases are different from those in the Parker-spiral IMF case. The escape rate is the lowest in the northward IMF case and comparable in the Parker-spiral and southward IMF cases. In the northward IMF case, a weak intrinsic dipole forms a magnetosphere configuration similar to that of Earth, quenching the escape rate, while the Parker-spiral and southward IMFs cause reconnection and erosion, promoting ion escape from the upper atmosphere.

22nd Symposium on Planetary Sciences, 03-06
Online, 18 February 2021

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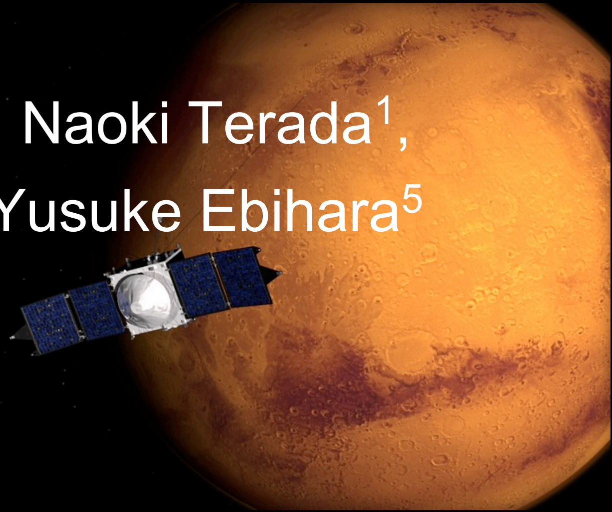

Atmospheric escape: Magnetic fields

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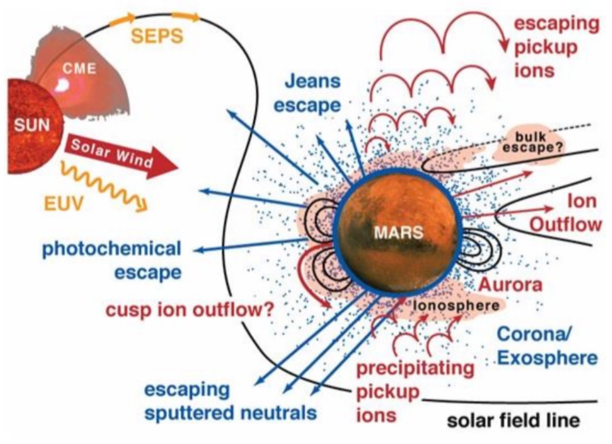
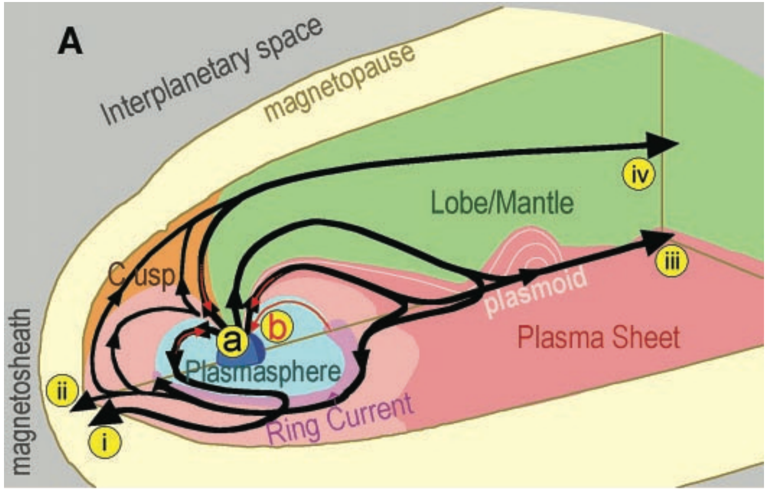
Unmagnetized planet (Mars)



Atmospheric escape from Mars (LPI/LASP)

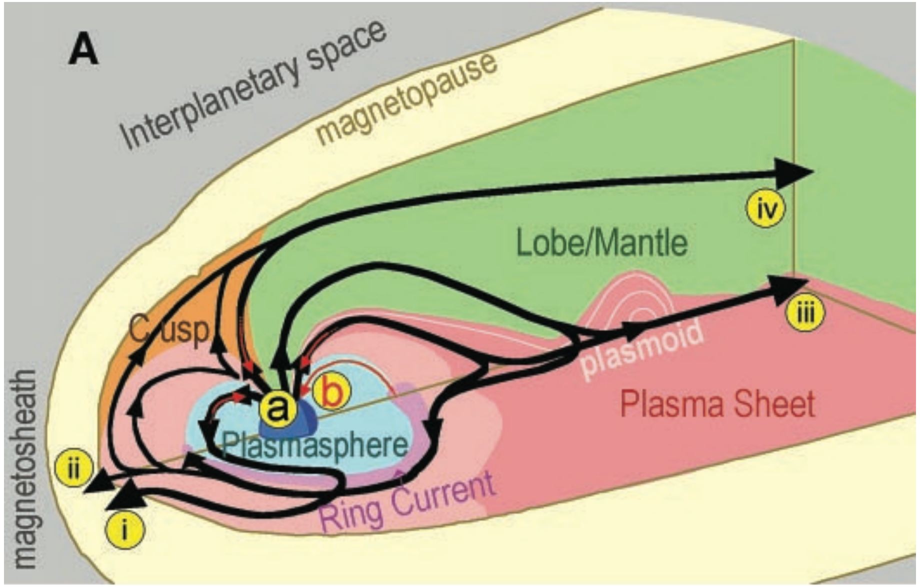
Magnetized planet (Earth)

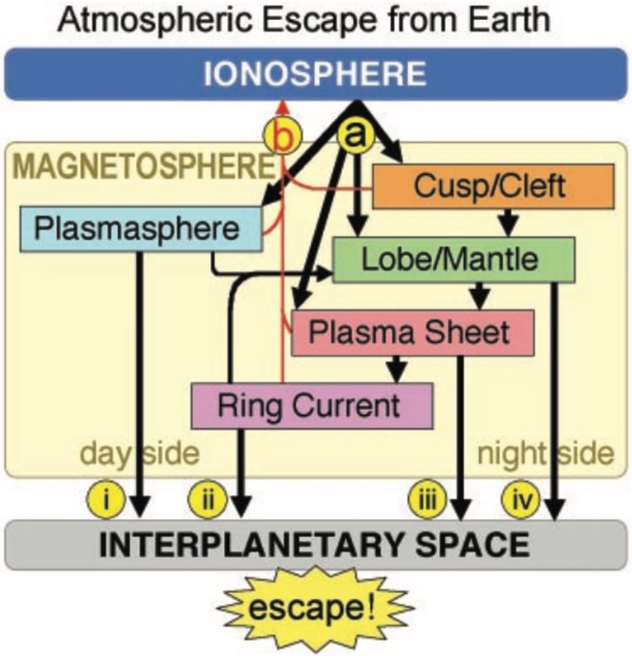


Atmospheric escape from Earth (Seki+, 2001)

- Escape mechanisms are quite different between unmagnetized and magnetized planet.
- Ion escape is important in revealing the atmospheric escape processes, especially heavy species.

Atmospheric escape: Case of Earth





Atmospheric escape from Earth (Seki+, 2001)

- Mainly four ion escape routes
  - Dayside: i) the plasmasphere or ii) ring current via cusp, lobe and plasma sheet
  - Nightside: iii) the plasma sheet or iv) lobe via cusp

Atmospheric escape: Solar activity

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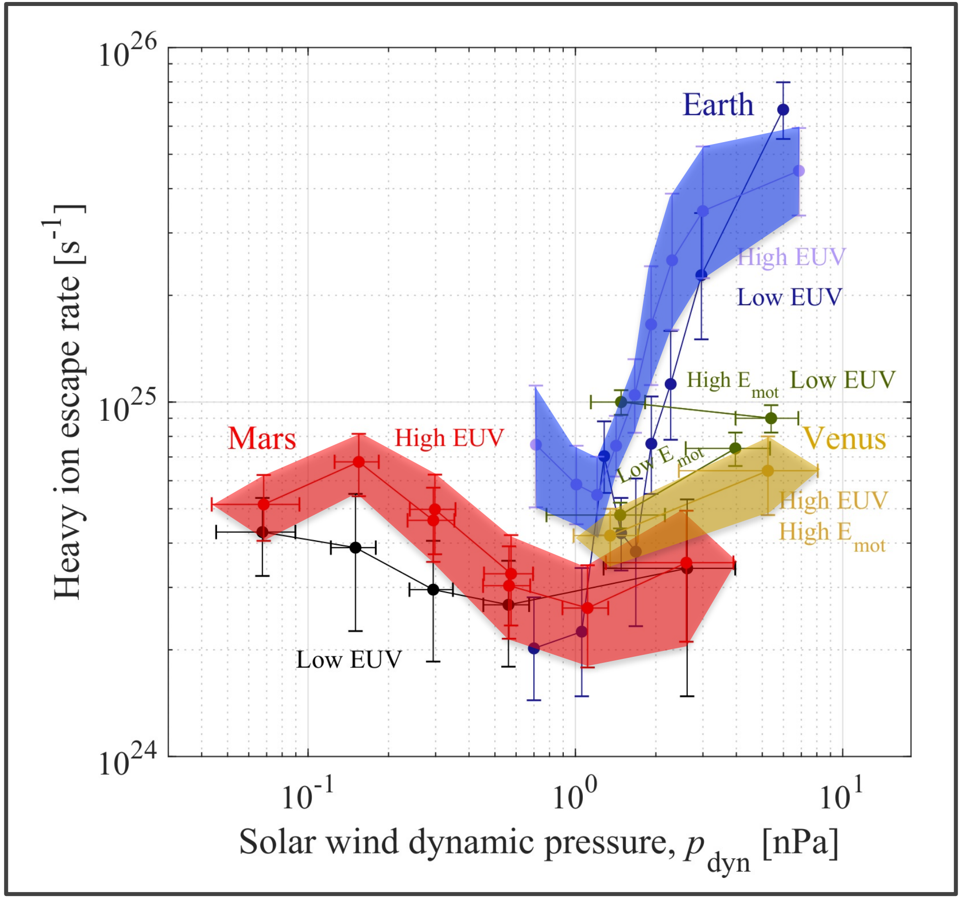
Dependence on solar wind dynamic pressure

- Mars: Negligible or inverse dependence
- Venus: Weak positive dependence
- Earth: Strong positive dependence

Based on
Masunaga+ (2019)
Ramstad+ (2018)
Schillings+ (2019)



Comparison of escape rate in each planet (Ramstad & Barabash, 2021)

Ancient Mars

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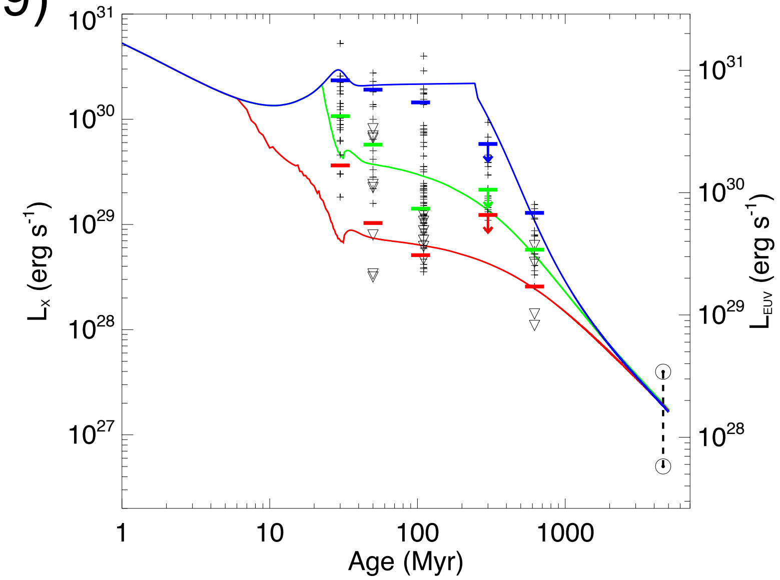
- X ray & EUV (XUV) environment
  - Solar activity was higher than the present.
  - High XUV facilitates the enhancement of ion escape (Jakosky+, 2015; Lee+, 2018; Dong+, 2018; Terada+, 2009)
- Atmosphere
  - At least 1-bar atmosphere
  - Present Mars has only atmosphere of ~0.007 bar.

  → Atmosphere was lost to space?
    - Based on the isotope ratio
    - Jakosky & Phillips (2001), Jakosky+ (2017), Kurokawa+ (2018)



XUV fluxes of G-type star over time (Tu+, 2015)

Magnetic fields at Mars

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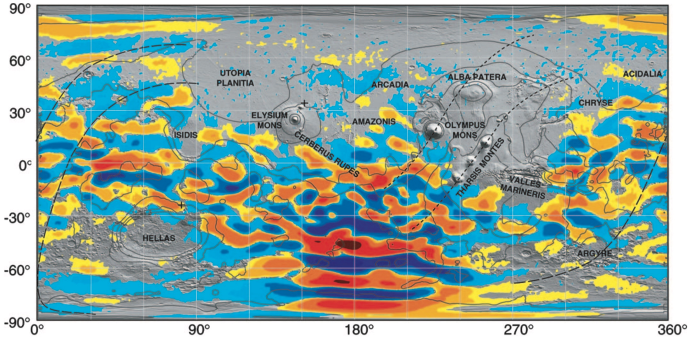
- Is/was there a global intrinsic magnetic field on Mars?

Mars	Present	Ancient
Magnetic field	Crustal	Global(?)



Crustal field map (Connerney+, 2005)

- The existence of crustal B field suggests that ancient Mars had an intrinsic global B field.
  - 5000 – 100000 nT (e.g., Collinson, 1997; Kirschvink+, 1997)
  - The dynamo ceased around 4.0 Ga.
- Our question is how the magnetic field affects the ion escape, that is, generates the climate change.

Motivation

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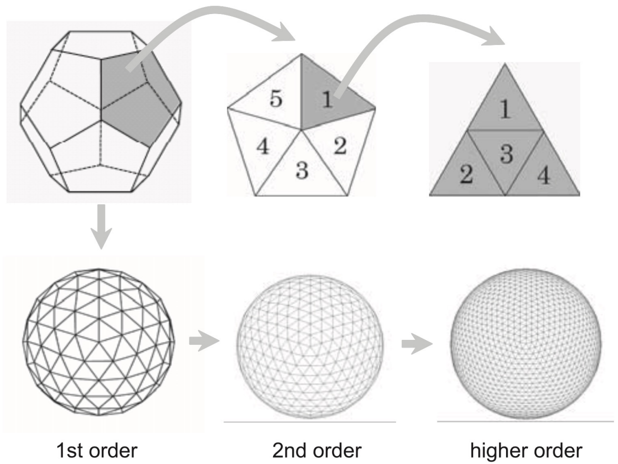
- What are key parameters for the ion escape?
  - Existence of magnetic field & its intensity
  - Solar activity
  - Solar wind conditions
  - Interplanetary magnetic field (IMF)
- The magnetohydrodynamic (MHD) simulations are conducted in order to investigate the ion escape rates and mechanisms with various above parameters.
- The effects on climate change are discussed.
- The content of presentation consists of
  1. Sakata et al. (2020)
  2. Sakai et al. (2018; 2021)

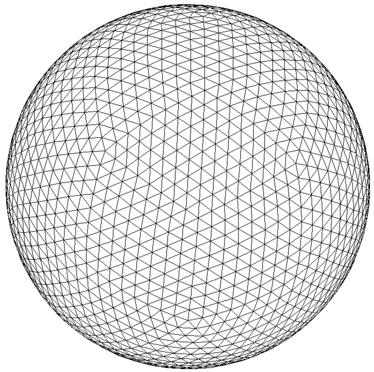
Model

- A model from Terada+ (2009)
  - Based on Tanaka (1998)
    - Total Variation Diminishing (TVD) scheme
  - 3-D multispecies & single-fluid MHD
  - Horizontal grid: Triangle unstructured grid (4th order)

Grid system made from a dodecahedron



Grid system (Moriguchi+, 2008)



4th order grid

Model

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- A model from Terada+ (2009)
  - Based on Tanaka (1998)
    - Total Variation Diminishing (TVD) scheme
  - 3-D multispecies & single-fluid MHD
  - Horizontal grid: Triangle unstructured grid (4^{th} order)
    - 1922 (on the sphere) × 336 (radial direction)
  - This model can treat from ionosphere to (induced) magnetosphere seamlessly.
    - 11 ion species in the ionosphere including CO_2^+, O_2^+, O^+, and H^+.
    - Including the chemical and collisional processes

Case 1: Ancient Mars
(Sakata et al., 2020)

Case1: Ancient XUV (XUV = 100)

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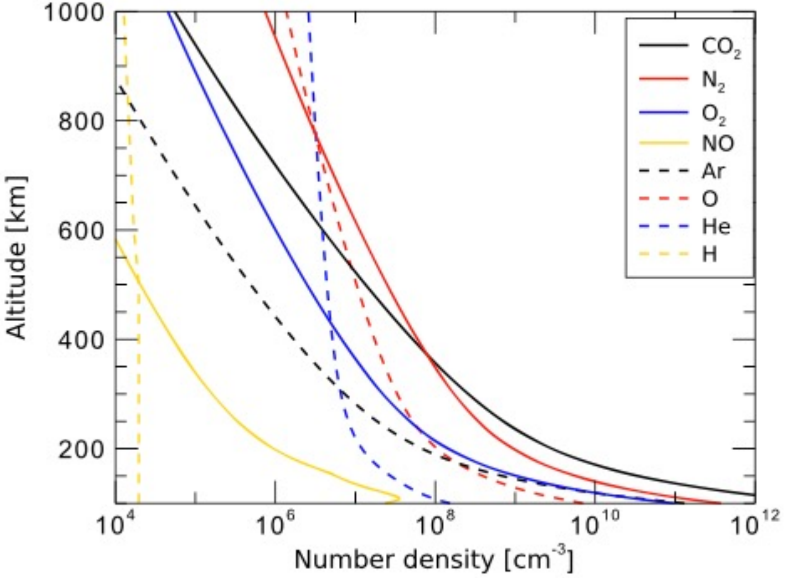
- Input parameters

Sub-cases	1	2	3	4	5
B_{eq} [nT]	0	100	1000	3000	5000
F_{XUV} (present = 1)			100		
$N_{s/w}$			1000 cm^{-3}		
$V_{s/w}$			2000 km/s		
B_{IMF}			60 nT (Parker-spiral)		
P_{dyn}			~6700 nPa		

- Background neutral atmosphere
  - Based on Kulikov+ (2007)



Neutral density profile from Kulikov+ (2007)
(Sakata+, 2020)

Case1: Ancient XUV (XUV = 100)

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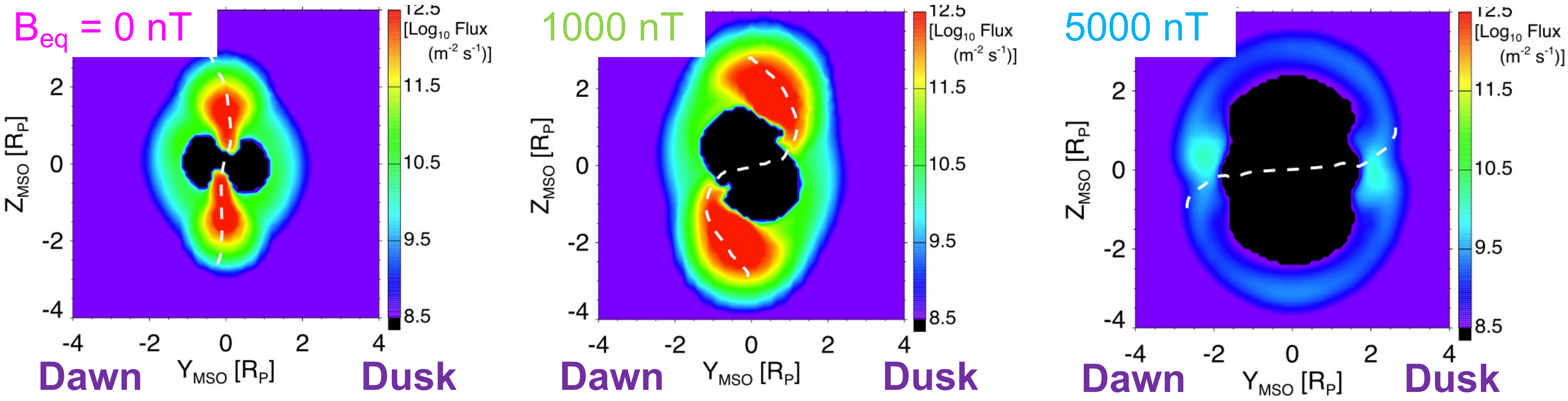
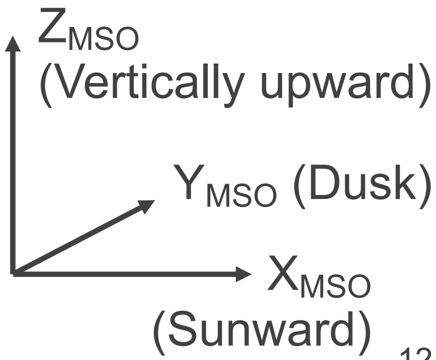
- Tailward fluxes of O_2^+ at x = -2 R_M

Tailward flux of O_2^+ (Sakata+, 2020)



- Different peak positions
  - 0 nT: On the neutral line in the meridional plane
  - 1000 nT: Tilted neutral line; magnetic pressure gradient from the cusp
  - 5000 nT: Near the equator; convection from dusk to dawn after a reconnection (for dawn peak)



Case1: Ion escape rates

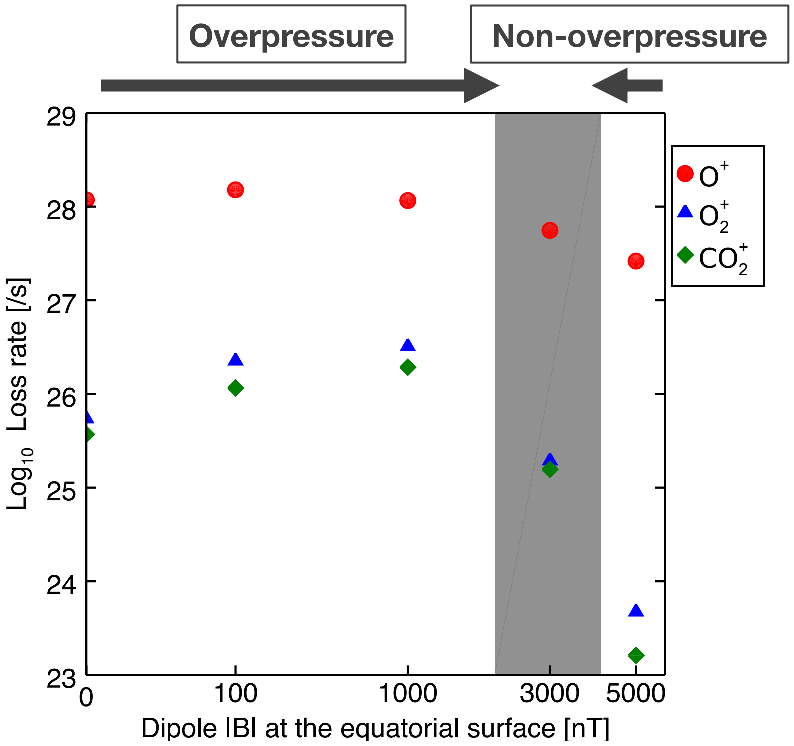
Molecular ions (O_2^+ & CO_2^+)

- Overpressure
  - Increase by a factor of 6.
- Non-overpressure
  - Decrease by two orders of magnitude

→ Intrinsic magnetic field enhance the escape from the cusp.

O^+

- Smaller effect of intrinsic magnetic field compared to molecular ions
- Mass-loading of enhanced oxygen corona by high XUV irradiance



Escape rate depending on B field (Sakata+, 2020)

The ratio of P_B to P_{dyn} is a key factor to determine the ion escape rate.

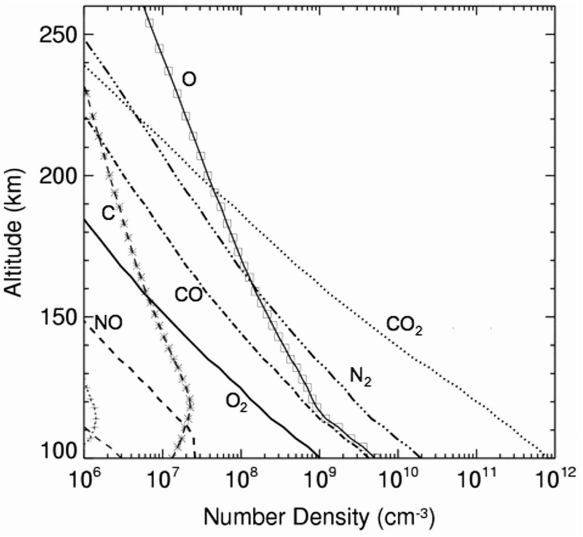
Case 2: Present Mars (Mars-like)

Sakai et al. (2018; 2021)

Case2: Present XUV

- Input parameters

Sub-cases	1	2	3	4
B_{eq} [nT]		100		0
F_{XUV} (present = 1)			1	
$N_{s/w}$			$3\ cm^{-3}$	
$V_{s/w}$			400 km/s	
B_{IMF}			2 nT	
Direction of B_{IMF}	Northward (Parallel)	Parker-spiral	Southward (Antiparallel)	Parker-spiral
P_{dyn}			0.8 nPa	



Neutral density profile (Terada+, 2009)

- Background neutral atmosphere
  - Based on Terada+ (2009)

Case2: Present XUV

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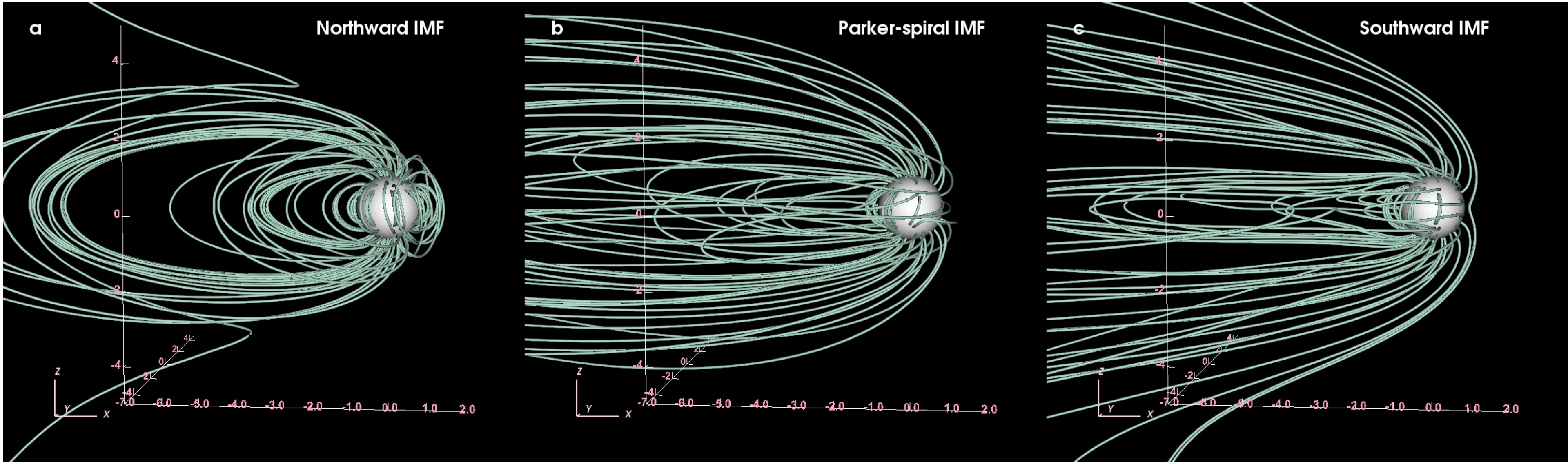
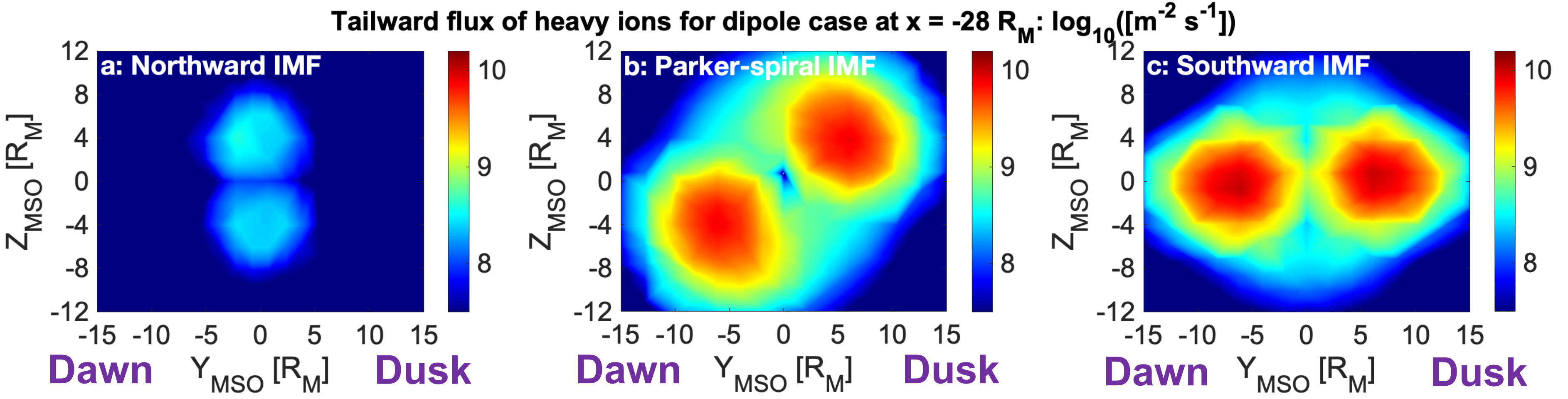
- Magnetosphere

Magnetic field lines in each IMF case (Sakai+, 2021)



- N-IMF: A weak intrinsic magnetic field forms a magnetosphere similar to Earth.
- S-IMF: Intrinsic field lines stripped off by the IMF erosion

Case2: Present XUV



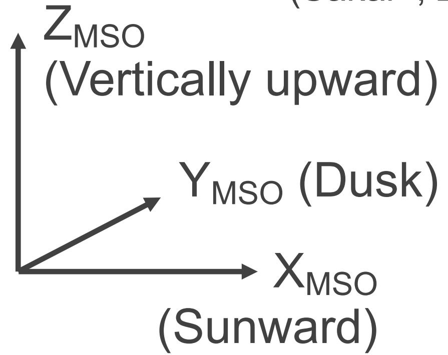
Northward IMF

Parker-spiral IMF

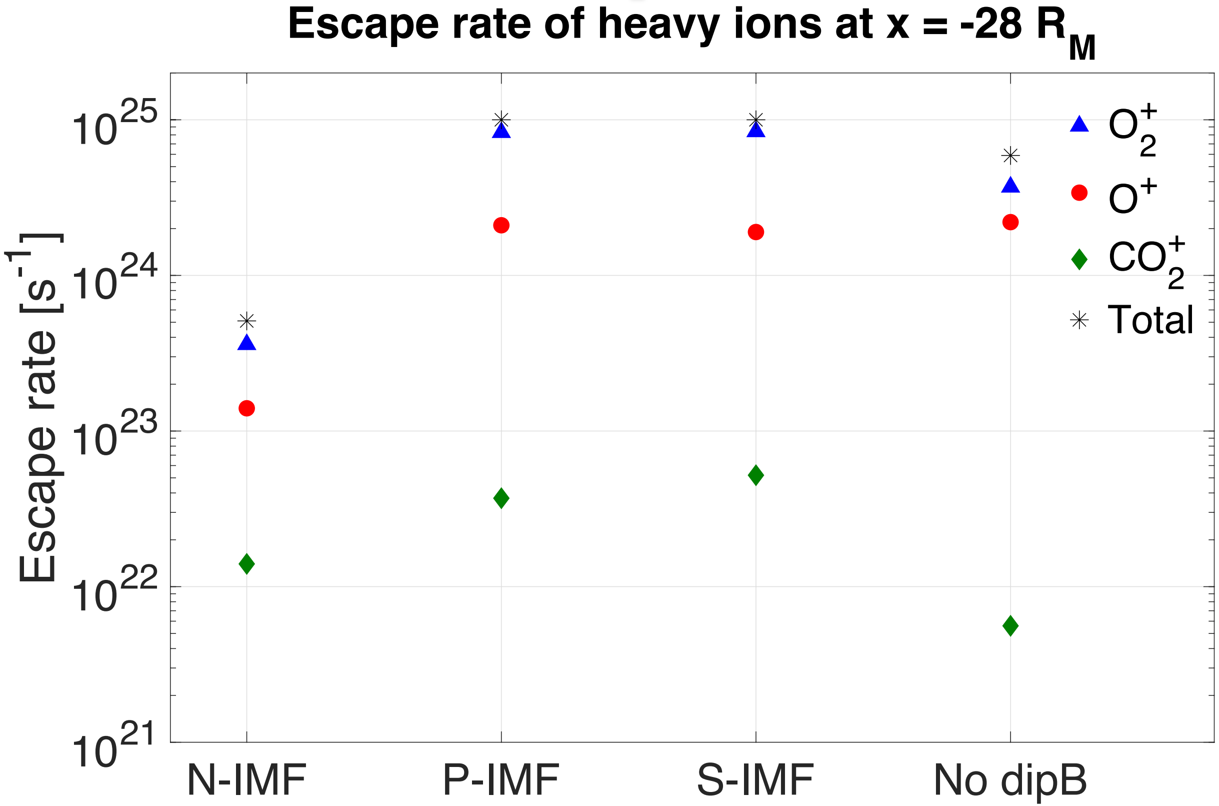
Southward IMF

Tailward fluxes of heavy ions (Sakai+, 2021)

- Different peak positions
  - N-IMF: High latitude; lobe reconnections
  - P-IMF: On the neutral sheet and high latitude; reconnections in the tail flanks
  - S-IMF: Equator; a mass-loading



Case2: Ion escape rates



- N-IMF w/ DB < P-IMF w/o DB < P-IMF w/ DB ≈ S-IMF w/ DB
- Northward IMF could protect the atmosphere.

(Sakai+, 2021)

Summary & Takeaways

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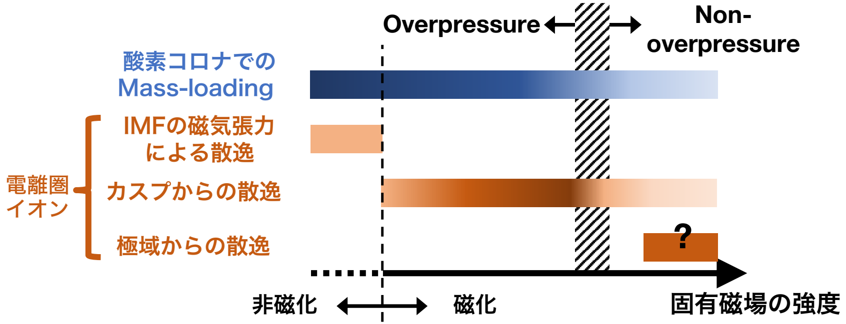
Investigated the effects of intrinsic magnetic field, solar wind condition, and IMF orientation on the ion escape using a multispecies MHD model.

- The ratio of P_B to P_{dyn} is a key factor to determine the ion escape rate.
  - Ion escape rate tends to increase in the overpressure state, but to decrease in the non-overpressure state.
  - The intrinsic B fields enhance the escape through the cusp.
- The parallel IMF could protect the atmosphere, while the parker-spiral and antiparallel IMF tend to strip off the atmosphere.

Ion escape rate highly depends on the B intensity, P_{dyn}, and IMF orientation, leading to figure out the climate change of ancient Mars.



Citations

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