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Effects of the IMF Direction on Atmospheric Escape From a Mars-like Planet Under Weak Intrinsic Magnetic Field Conditions

– Group Meeting of the Planetary Space Physics

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Macau University of Science and Technology

March.29, 2021.

Macau, China

Reference

JGR Space Physics

RESEARCH ARTICLE
10.1029/2020JA028485

Effects of the IMF Direction on Atmospheric Escape From a Mars-like Planet Under Weak Intrinsic Magnetic Field Conditions

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Key Points:

- The ion escape rate is the lowest in northward (parallel) interplanetary magnetic field (IMF) case and comparable in Parker-spiral and southward (antiparallel) IMF cases
- In the northward IMF case, ionospheric ions escape from limited regions of the high-latitude lobe reconnection with a draped IMF
- In the southward IMF case, IMF penetration into the dayside ionosphere and its subsequent transport to tail flanks cause efficient ion loss

Abstract Direction of the upstream interplanetary magnetic field (IMF) significantly changes the magnetospheric configuration, influencing the atmospheric escape mechanism. This paper 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 magnetohydrodynamics 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.

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Citation:
Sakai, S., Seki, K., Terada, N., Shinagawa, H., Sakata, R., Tanaka, T., & Ebihara, Y. (2021). Effects of the IMF direction on atmospheric escape from a Mars-like planet under weak intrinsic magnetic field conditions. *Journal of Geophysical Research: Space Physics*, *126*, e2020JA028485. https://doi.org/10.1029/2020JA028485

Received 15 JUL 2020
Accepted 17 FEB 2021

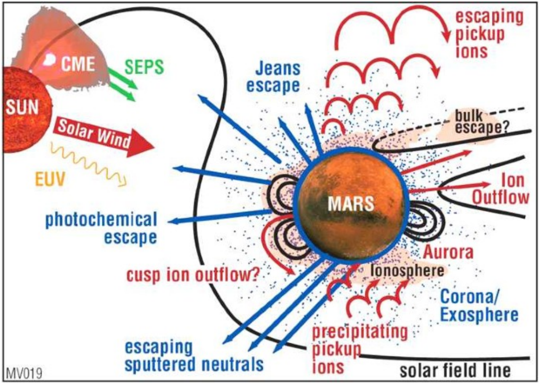
Sakai et al. 2021

Outline

Basic Concept of Atmospheric Escape

- The atmospheric escape can be separated into the neutral and ion escape:

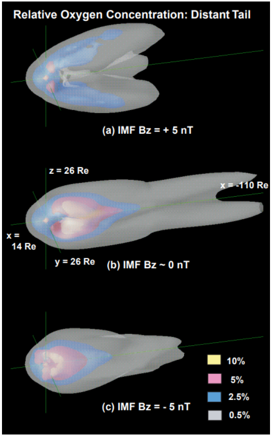
1. **Neutral escape**:
   Jeans escape, Hydrodynamical escape(Hydrogen), Photochemical escape;
2. **Ion escape**:
   Ion outflows, Pickup ions.
3. **For Mars:**
   - Ion outflows ★(O^+,O_2^+,CO_2^+);
   - Depends on:
     Solar Wind, solar X-ray, XUV irradiance, Magnetic field.



Martian Atmospheric Escape

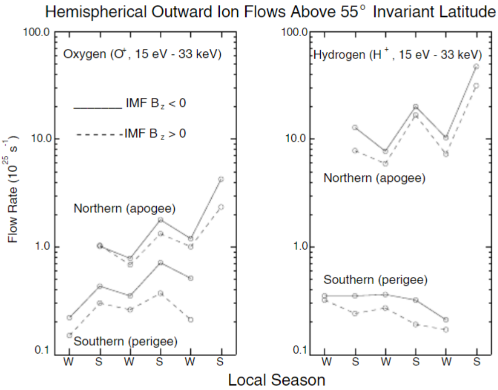
The Effect of the IMF Direction on the Ion Escape

- Earth: O^+ outflow: S-IMF>N-IMF;



Winglee 2000

- Earth: H^+,O^+ outflow: S-IMF>N-IMF;
- H^+: 1.5-2 times, O^+: 2.5-3 times;



Lennartsson, Collin, and Peterson 2004

Numerical Model

- It is useful for understanding how the IMF direction affect the escape mechanism for Mars-like planet.
- Model Description:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = \sum_i (m_i q_i - m_i L_i) \tag{1}$$

$$\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot \left(\rho \mathbf{V}\mathbf{V} - \frac{\mathbf{B}\mathbf{B}}{\mu_0}\right) + \nabla \left(P + \frac{B^2}{2\mu_0}\right) = -\nu_{it}(\rho \mathbf{V}) - \rho \mathbf{g} - \sum_i (m_i L_i)\mathbf{V} \tag{2}$$

$$\frac{\partial U}{\partial t} + \nabla \cdot \left[\left(U + P - \frac{B^2}{2\mu_0}\right)\mathbf{V} + \frac{\mathbf{E}\times\mathbf{B}}{\mu_0}\right] = -\mathbf{V} \cdot \left[\nu_{it}(\rho \mathbf{V}) + \rho \mathbf{g} + \sum_i (m_i L_i)\mathbf{V}\right]$$

$$+ \frac{k_B T_q}{\gamma - 1}\sum_i (q_i - q_{EII,i}) - \frac{k_B T_{EII}}{\gamma - 1}\sum_i q_{EII,i} - \frac{k_B T_L}{\gamma - 1}\sum_i L_i + \frac{\mathbf{V}^2 \sum_i (m_i q_i)}{3(\gamma - 1)} + \nabla \cdot (K \nabla T_L) \tag{3}$$

Where:

$$U = \frac{(\rho \mathbf{V})^2}{2\rho} + \frac{B^2}{2\mu_0} + \frac{P}{\gamma - 1}, \quad \mathbf{E} = -\mathbf{V}\times\mathbf{B} + \frac{1}{\mu_0 \sigma_e}\nabla \times \mathbf{B}$$

Parameter Settings

- Major ion species: CO_2^+, O_2^+, NO^+, CO^+, N_2^+, O^+, N^+, C^+, He^+, H^+;
- Standard values for present-day Mars:

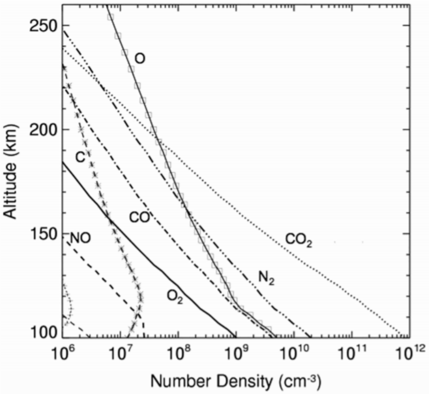
Table 1
Simulation Settings

Solar wind parameters	Northward IMF case	Parker-spiral IMF case	Southward IMF case
Solar wind density		$3\ cm^{-3}$	
Solar wind velocity		400 km/s	
Solar wind temperature		10^5 K	
Intrinsic magnetic field		100 nT at 100 km altitude on the equatorial surface	
IMF intensity		2.5 nT	
IMF direction	North	Parker-spiral	South

IMF, interplanetary magnetic field.

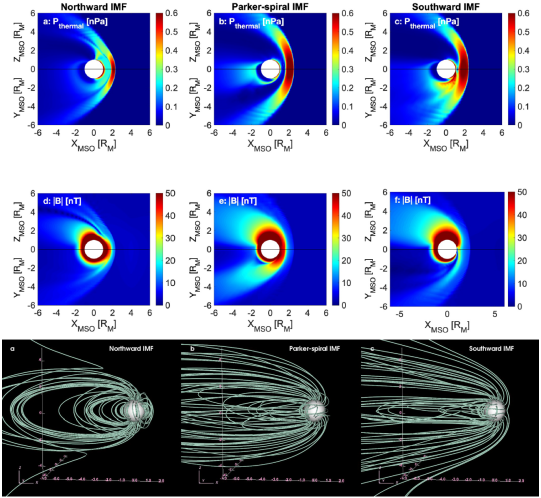
- Solar wind parameters following the MAVEN observations.

- Low solar activity(Viking):



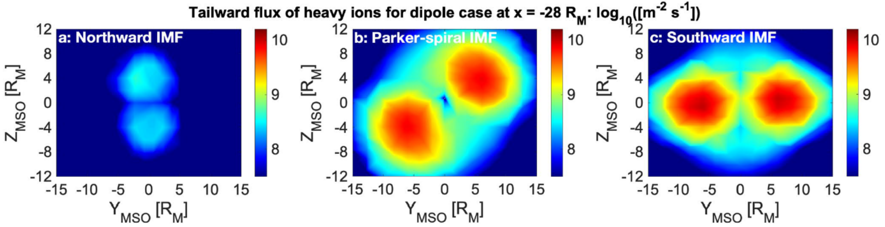
Terada et al. 2009

Magnetosphere Configuration



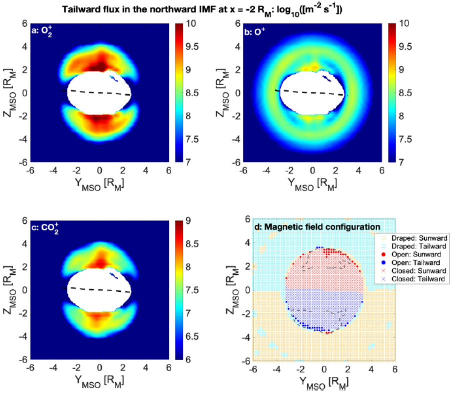
The Influence of the IMF Direction of the Heavy Ion Escape

- Heavy ions: O^+,O_2^+,CO_2^+;



IMF Direction	Location/Channel	Peak value of tailward flux
Northward	N/S Hemisphere	3×10^8 m^{-2} s^{-1}
Parker-spiral	Tail-flank	$\sim 5 \times 10^9$ m^{-2} s^{-1}
Southward	Equatorial tail flanks	$\sim 10^{10}$ m^{-2} s^{-1}

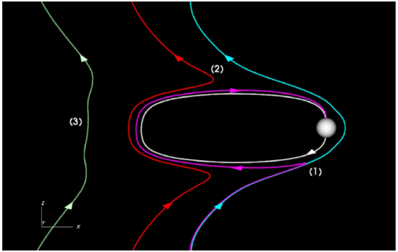
Northward IMF Case



(a)-(c): White region: the sunward flow, black line: $B_x = 0$; (d): Gray dashed line:O_2^+ flux contour lines of 10^9 m^{-2} s^{-1}.

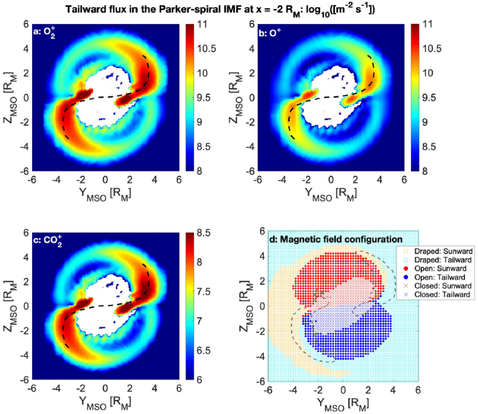
- High-latitude channel: [m^{-2} s^{-1}]

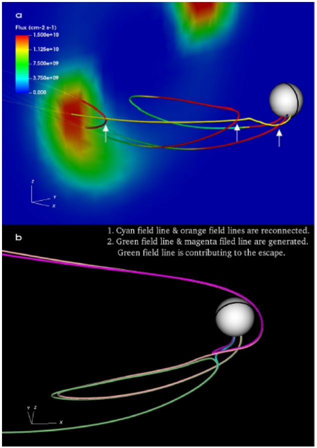
O_2^+	O^+	CO_2^+
$\sim 2 \times 10^{10}$	$\sim 10^9$	$\sim 6 \times 10^8$



- Ring-shaped channel: O^+, $\sim 3 \times 10^8$ m^{-2} s^{-1};
- Hot O corona, created by O_2^+ collide with the neutral atmosphere.

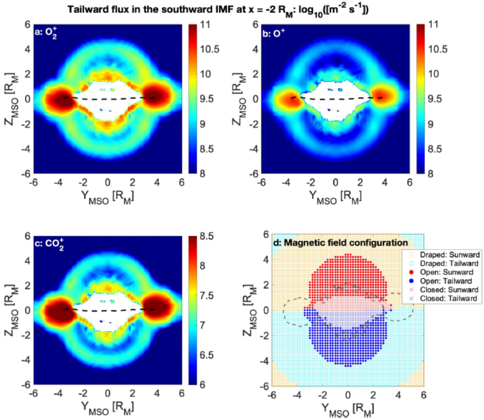
Parker-Spiral IMF Case



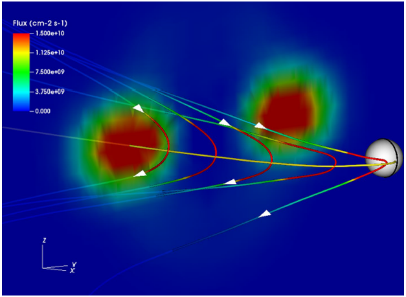


Tail-flank channel,Max of O_2^+ flux:
2×10^{11} m^{-2} s^{-1}.

Southward IMF Case



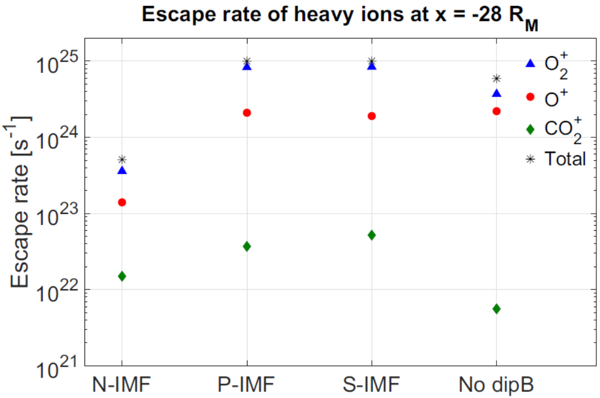
- Ion escape is driven by the mass-loading of ionospheric ions to the IMF:



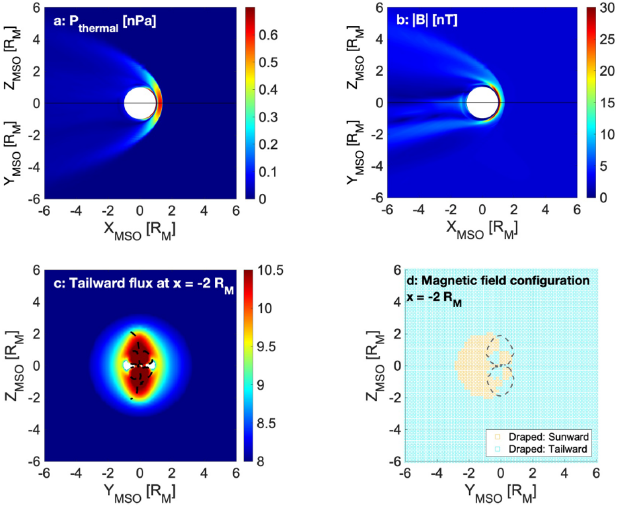
Equatorial channel,Max of O_2^+ flux: 2×10^{11} m^{-2} s^{-1}.

Ion Escape Rate in the Tail

IMF Direction	Total	O_2^+:O^+:CO_2^+
N-IMF	5.1×10^{23} s^{-1}	$69 : 28 : 3$
P-IMF	10^{25} s^{-1}	$79.4 : 20.2 : 0.4$
S-IMF	10^{25} s^{-1}	$81.6 : 17.9 : 0.5$



The Case of the Parker-Spiral IMF Without a Dipole Field



Conclusion

- Oxygen escape is important to understand H_2O and/or CO_2 escape,and these processes are related to Martian climate change;

IMF Direction	Channel	Oxygen Escape	Ion Escape Rate
N-IMF	high-latitude & ring-shaped	$\sim 8.8 \times 10^{23}$ s^{-1}	lowest
P-IMF	tail-flank	$\sim 1.9 \times 10^{25}$ s^{-1}	middle
S-IMF	equatorial	$\sim 1.9 \times 10^{25}$ s^{-1}	highest

- N-IMF forms a firm magnetosphere similar to that of Earth,resulting in the tendency of the magnetosphere to protect the atmosphere;
- P-IMF and S-IMF cause magnetic reconnection and erosion into the ionosphere, leading to more ion escape from the upper atmosphere;
- The IMF direction greatly affects the escape rate of oxygen ions;
- The ancient Sun was more active than the present-day Sun such that the IMF was more variable;
- Theses results would lead to revealing how Mars changed from a warm and wet climate in the past to a cold and dry climate in the present day.

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Thanks !