Novel Modeling of Mars' Ionospheric Electrodynamics

On the Formation of the Dynamo Currents

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Florida Institute of Technology, Melbourne, FL

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Outline

1 Introduction

2 Model of Mars' Ionospheric Dynamo Currents

3 Results for Daytime Ionosphere

4 Conclusions

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Earth and Mars's Magnetic Environment (I)

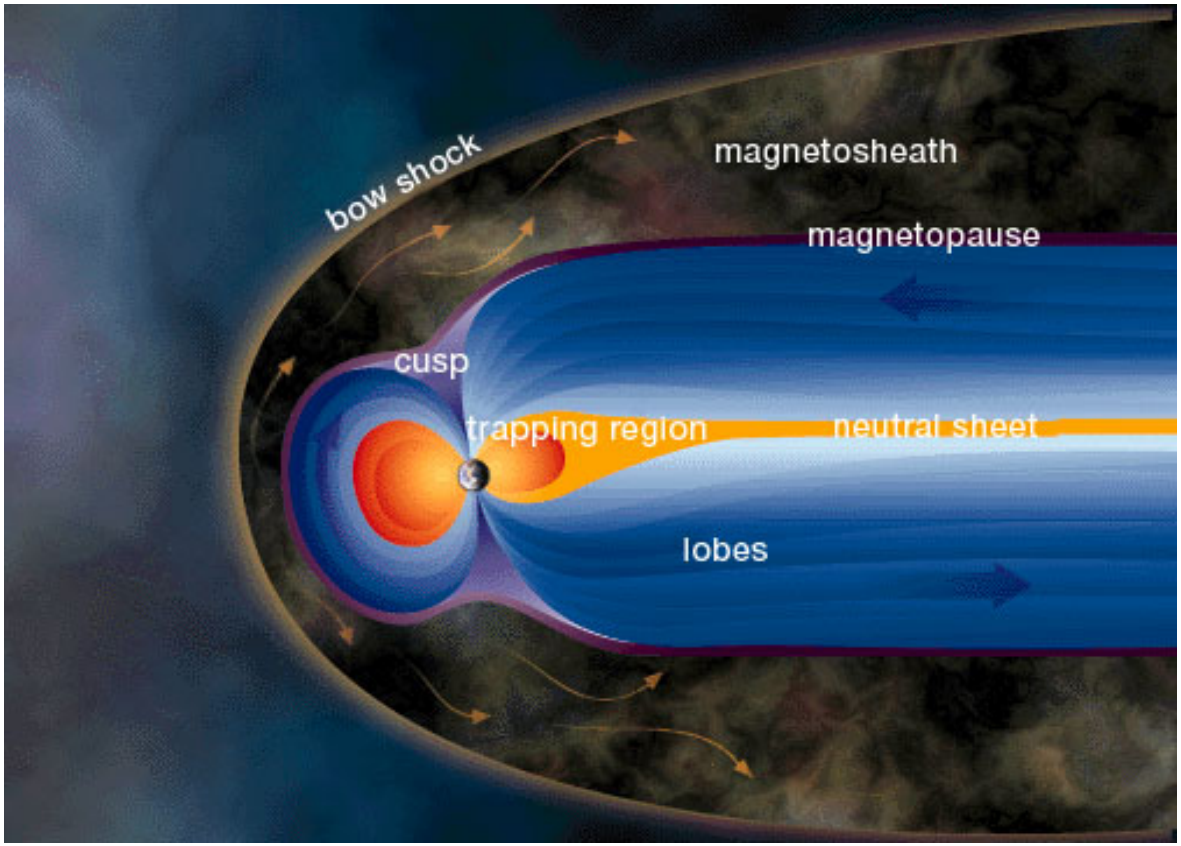


Figure: Image courtesy: NASA.

- Bow shock: Supersonic & superalfvénic speeds$\rightarrow$ $V_{SW}=\sqrt{\frac{\gamma P_i}{\rho_i}}$
- Magnetopause: Lorentz force $\rightarrow$ No penetration of solar wind protons

Earth's and Mars's Magnetic Environment (II)

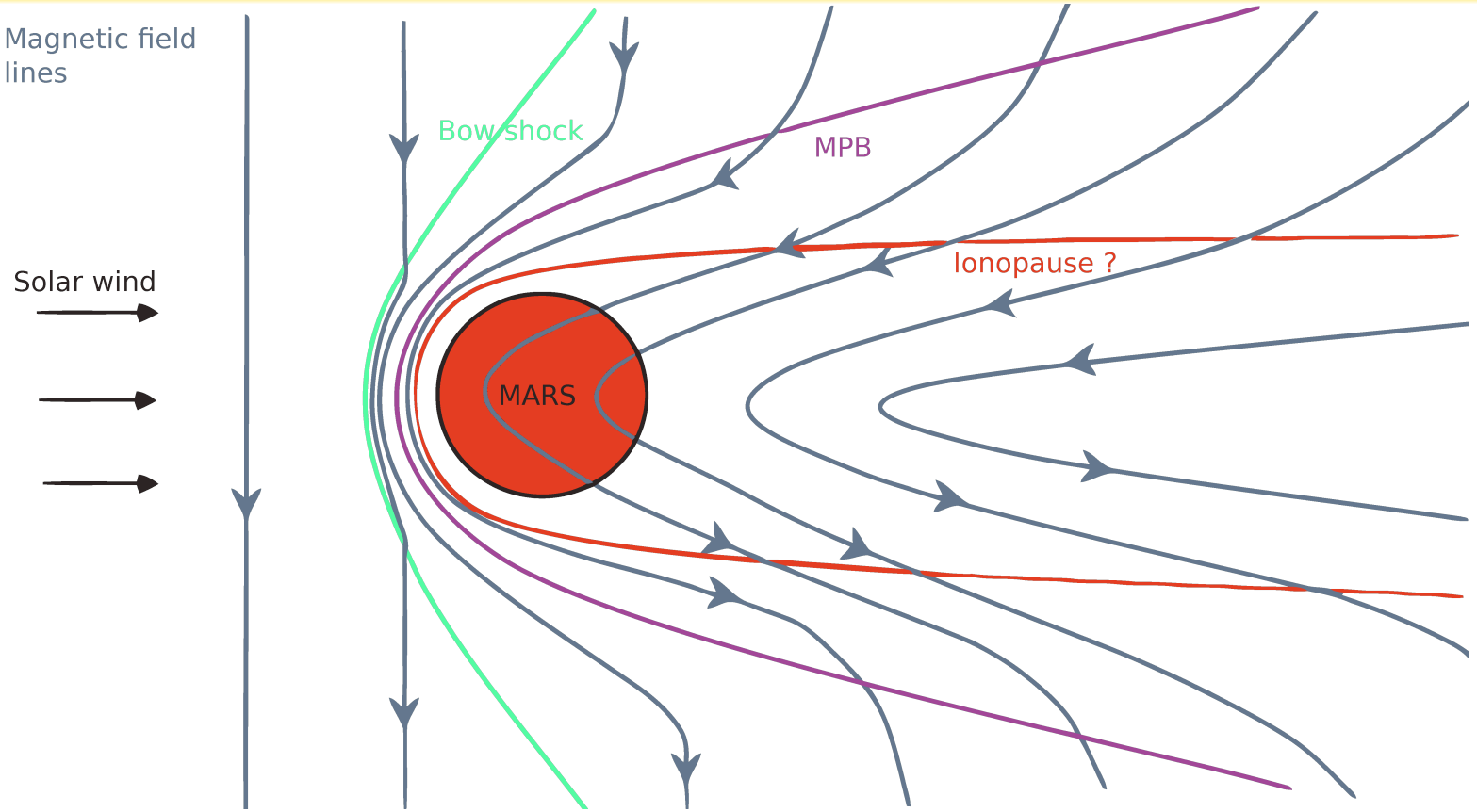


Figure: Image courtesy: DTU Space, [Luhmann and Russell, 1997].

- Bow shock: Supersonic & superalfvénic speed$\rightarrow V_{SW}=\frac{\gamma P_i}{\rho_i}$
- Magnetic Pile-up Boundary: Local deflection of solar wind protons $\rightarrow V_{SW}=0$
- Ionopause: Pressure balance: $\frac{\rho_{SW} V_{SW}^2}{2}=P_{\sigma}$

Mars' Magnetic Environment: A Unique Plasma Lab (I)

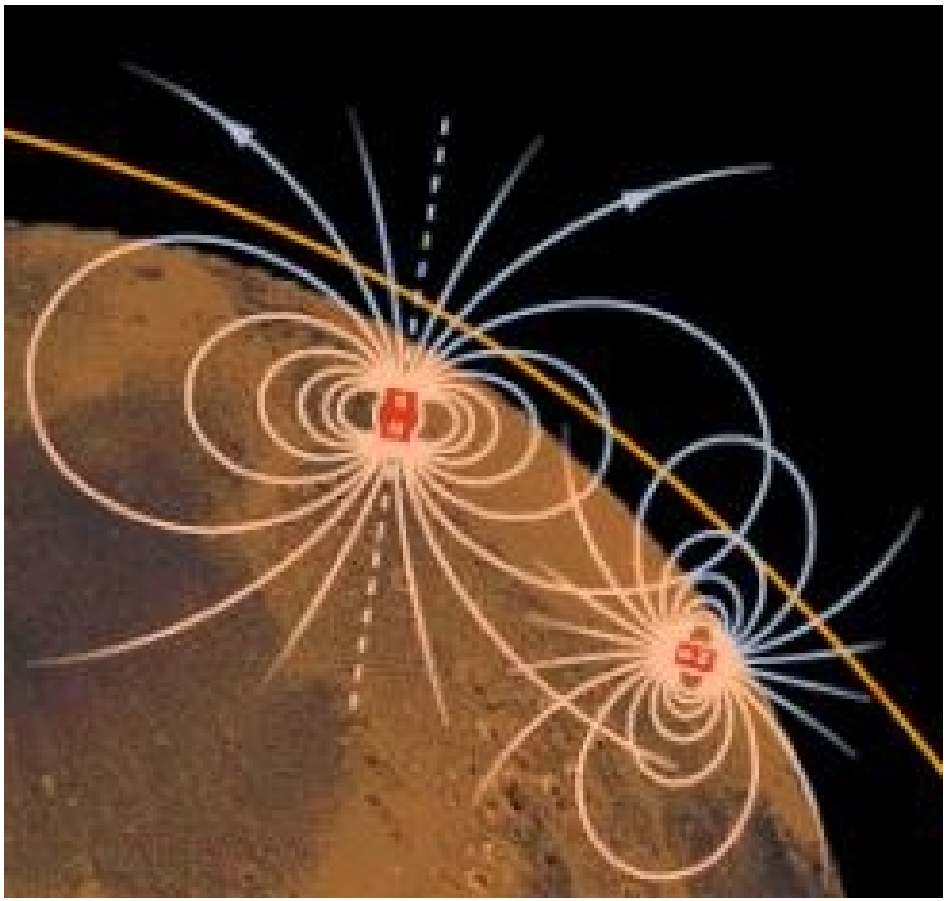


Figure: Image courtesy: NASA/JPL.

- No dipolar, "Earth-like" magnetic-field
- Remanent crustal fields
- Complex ionospheric composition (e & 71% O_2^+, 25% CO_2^+, 4% O^+, approximately)
- $P_{\male} \approx = 0.006 P_{\earth} = 600$ Pa
- Atmospheric composition ($\gtrsim$95% CO_2)
- Neutral winds

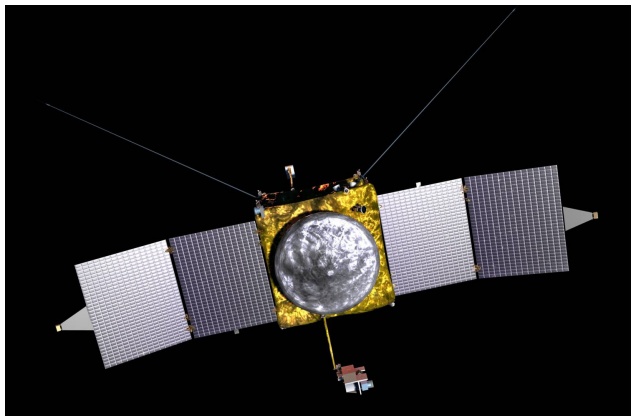


Figure: Mars Atmospheric Volatile EvolutioN (MAVEN). Image courtesy: NASA.

Pertinent Science Questions

- How can we characterize the interactions between the Martian climate and its ionosphere?
- How does an ionospheric current perturb the local magnetic field?
- What are the effects of the local magnetic perturbation on the following phenomena?
  - Atmospheric losses
  - Particle precipitations
  - Existence of auroras
  - Other processes?

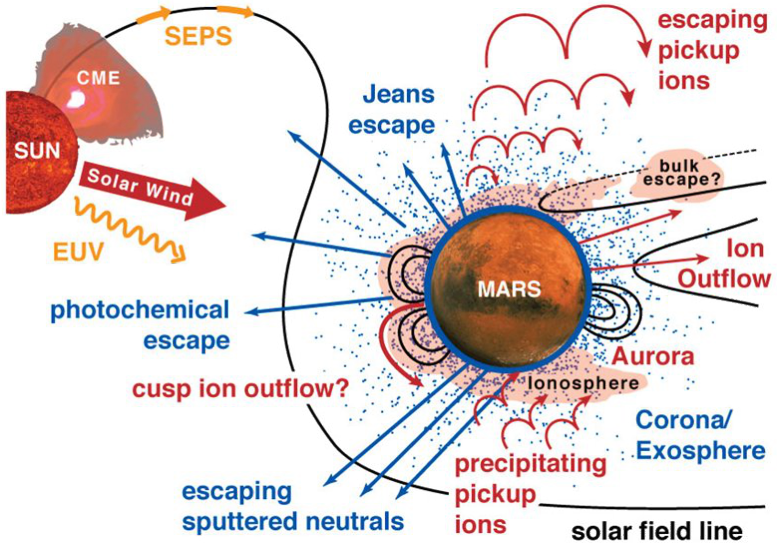


Figure: Schematic summarizing the loss mechanisms of the Martian atmosphere. Part of MAVEN's key achievement will be the determination of their relative importance throughout time [Jedrich, 2012].

Mars' Magnetic Environment: A Unique Plasma Lab (II)

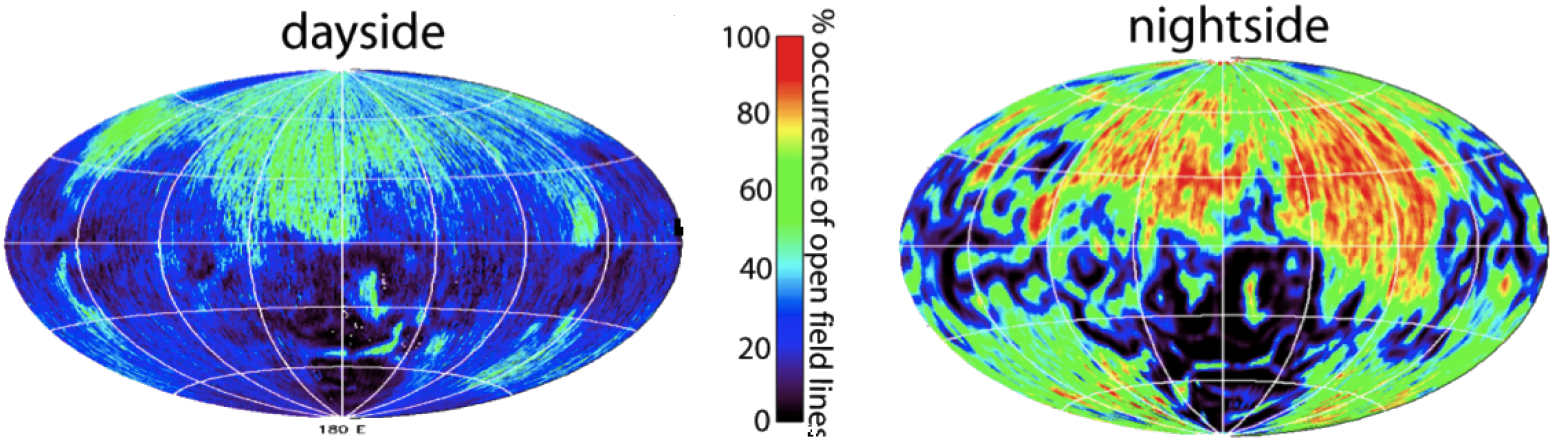
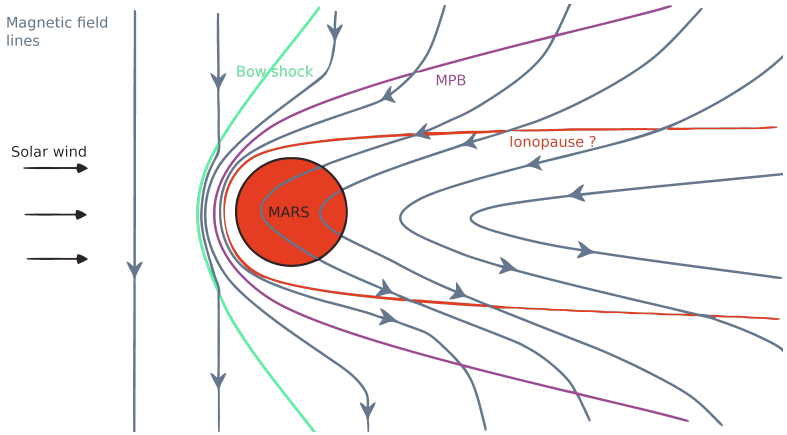


Figure: The percent occurrence of open magnetic field lines (i.e., connecting the IMF to the Martian atmosphere) at ∼400 km altitude on the nightside and dayside [Brain et al., 2007].

- Complex magnetic field configuration from remanent crustal fields with:
  - open/closed magnetic loop
  - strong/weak magnetic field magnitude
- Daytime/nighttime asymmetry with respect to the solar wind interaction



Mars' Dynamo Region (I)

- Definition: A **dynamo current** is generated by differential motions of positive and negative species.
- Mars' case:
  - ↳ positive ions → governed by collision with neutrals (demagnetized)
  - ↳ electrons → governed by gyromotion (magnetized)

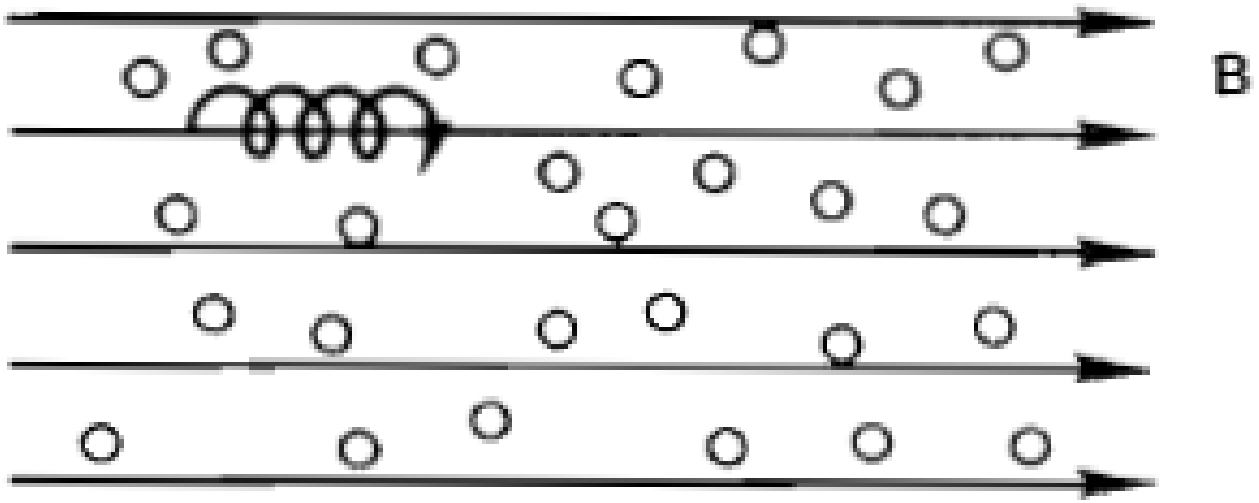


Figure: A charged particle in a magnetic field will gyrate about the same line of force until it makes a collision [Chen, 1984, p. 169]

Mars' Dynamo Region (II)

Estimates based on:

- O_2^+: most abundant ion
- CO_2: most abundant neutral
- electron

	Gyrofrequency	Coll. with CO_2
O_2^+	$\nu_{c,O_2^+} = \frac{eB}{m_{O_2^+}}$	$\nu_{O_2^+ - CO_2}$
e^-	$\nu_{c,e} = \frac{eB}{m_e}$	ν_{e-CO_2}

- H_L: the lower boundary of the dynamo region region is defined by the equality between the collision frequency of electron and neutrals and the electron gyrofrequency.

$$\nu_{c,e} = \nu_{e-CO_2}(H_L)$$

- H_U: the upper boundary of the dynamo region region is defined by the equality between the collision frequency of ion and neutrals and the ion gyrofrequency.

$$\nu_{c,O_2^+} = \nu_{O_2^+ - CO_2}(H_U)$$

$z \gtrsim H_U$	Magnetized ions Magnetized electrons	$\Rightarrow$ No dynamo current
$H_L \lesssim z \lesssim H_U$	Demagnetized ions Magnetized electrons	$\Rightarrow$ Ionospheric current
$z \lesssim H_L$	Demagnetized ions Demagnetized electrons	$\Rightarrow$ No differential current

Mars' Dynamo Region (III)

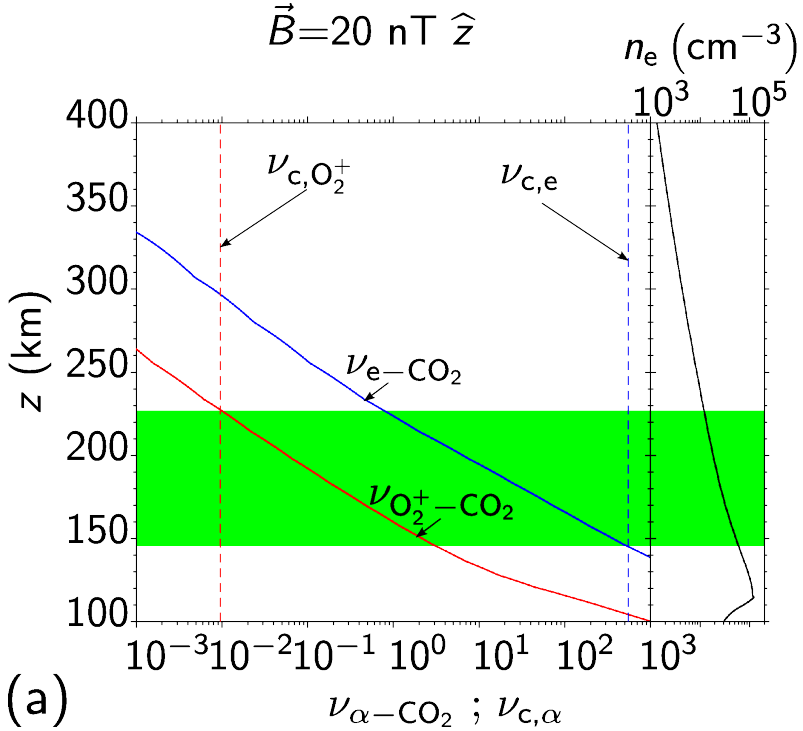


Figure: Expected locations of ionospheric currents (a) $\vec{B}$=20 nT $\hat{i}_z$ (typical); (b) $\vec{B}$=2000 nT $\hat{i}_z$ (near n_e peak).

Mars' Dynamo Region (III)

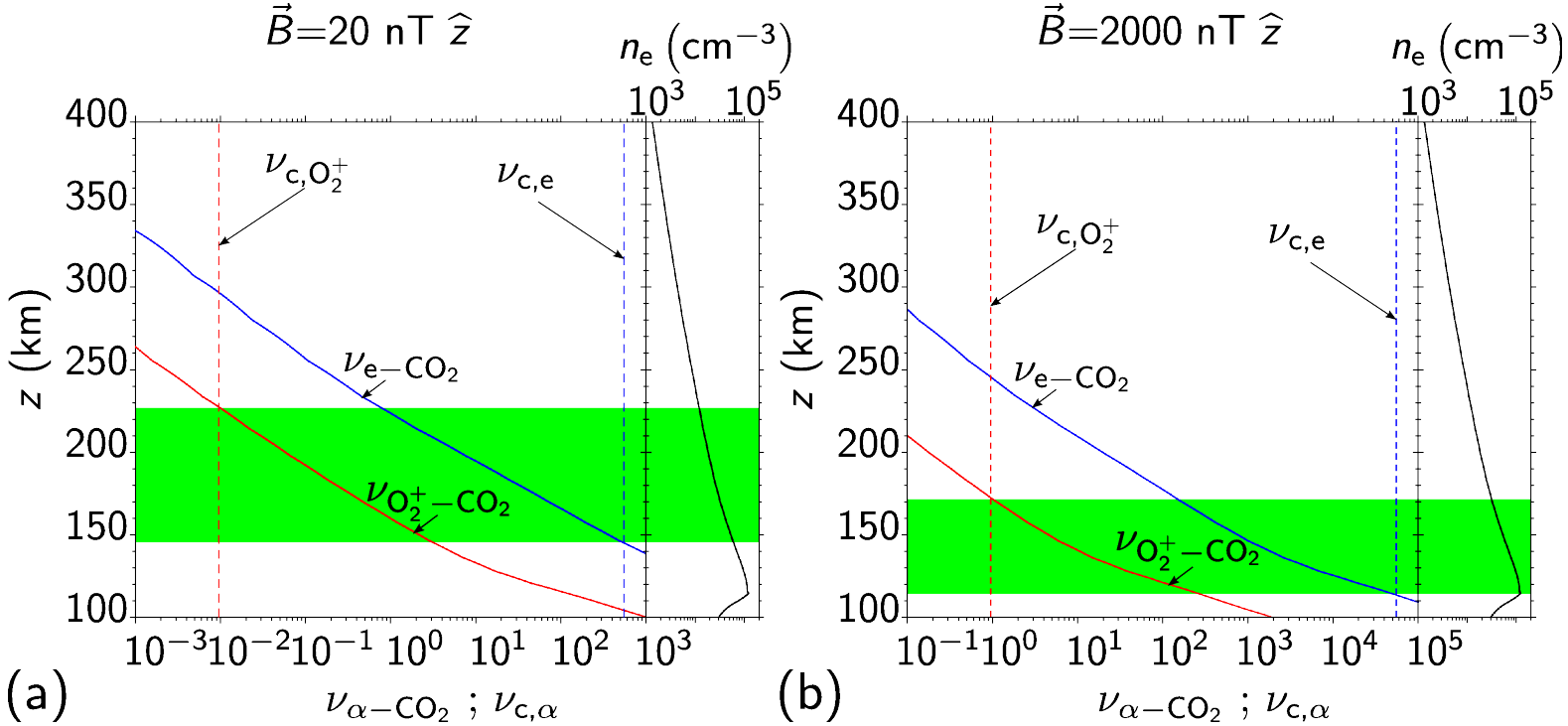


Figure: Expected locations of ionospheric currents (a) $\vec{B}$=20 nT $\hat{i}_z$ (typical); (b) $\vec{B}$=2000 nT $\hat{i}_z$ (near n_e peak).

Previous Modeling of Mars' E-M Environment

- Hybrid [Brecht and Ledvina, 2010; Brecht and Thomas, 1988]
  - ↳ Individual ions/neutralizing electrons
- Single fluid, multispecies [Ma et al., 2002, 2004]
  - ↳ 1 ion fluid/neutralizing electrons
- Multifluid, multispecies [e.g., Harnett, 2009; Harnett and Winglee, 2006; Sauer et al., 1997]
  - ↳ Multiple ion fluids/neutralizing electrons

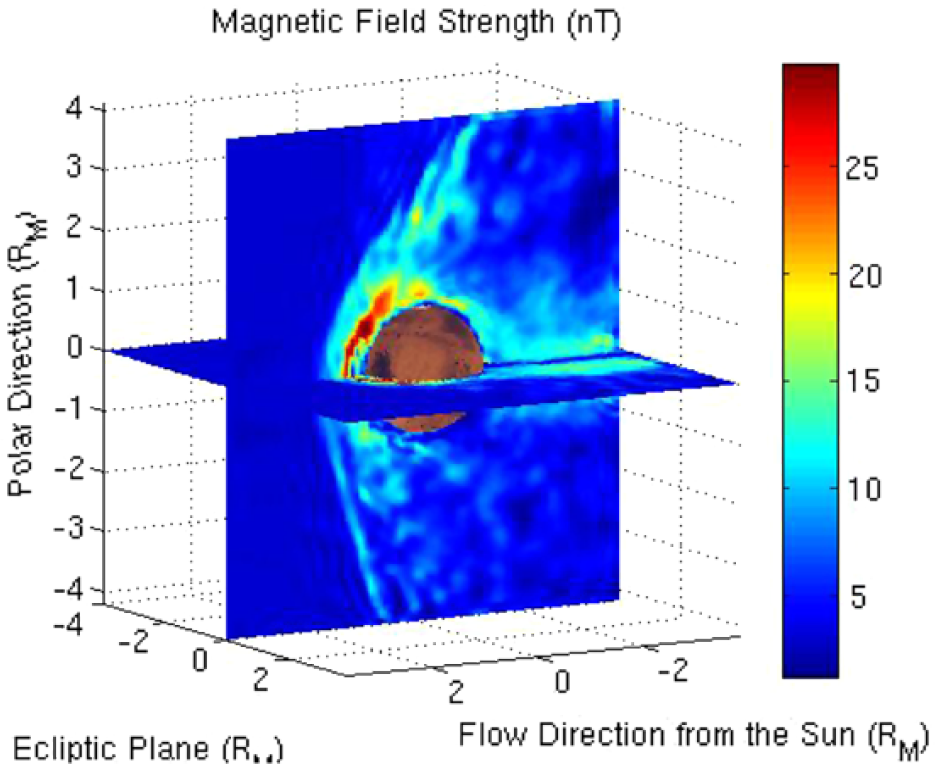


Figure: Magnetic field strength from a hybrid simulation of Mars [Ledvina et al., 2008].

Objectives of the Study

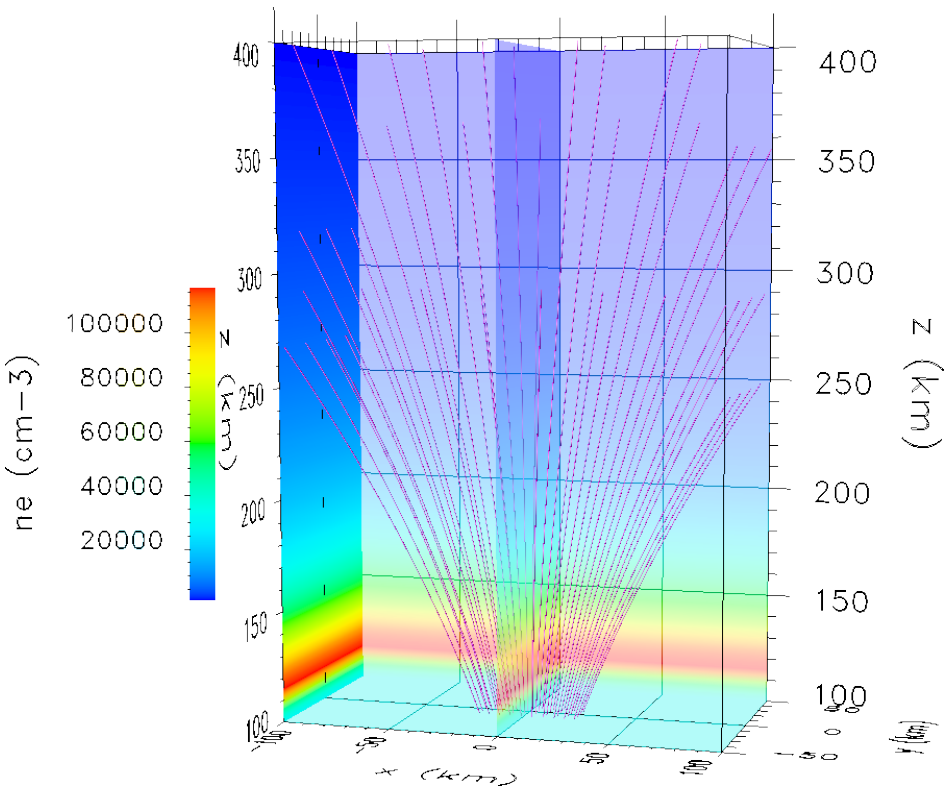


Figure: Model $\vec{B}$-field configuration near a magnetic cusp.

Development of a self-consistent model of Mars' ionospheric electrodynamics

- Multifluid (O_2^+, CO_2^+, O^+, & e)
- Neutral winds (CO_2, & O)
- Maxwell equations

Validation through the investigations of two case studies

- Uniform vertical field $\rightarrow \sim$cusp center
- B=20 nT–B=2000 nT
- Qualitative analysis (existence of dynamo currents, altitudes, dimensions,...)
- Quantitative analysis ($\vec{J}_{\max}$, $\vec{E}$)

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Multifluid Model Formulation (I)

- Daytime ionosphere (photochemical equilibrium)
- 3-D (Cartesian) multifluid model [Paty and Winglee, 2006]
- 200 km×100 km×300 km space scale with 3 km space resolution in z-direction
- Adaptive timestep: δt satisfies Courant et al.'s [1928] criterion
- 2-step Runge-Kutta method
- Initial conditions:
  - Horizontally uniform profiles
  - $\vec{V}_{\mathrm{n}}$=100 m/s $\widehat{x}$
  - $\vec{V}_{\mathrm{i}}$=100 m/s $\widehat{y}$
  - $\vec{B}$=20–2000 nT $\widehat{z}$

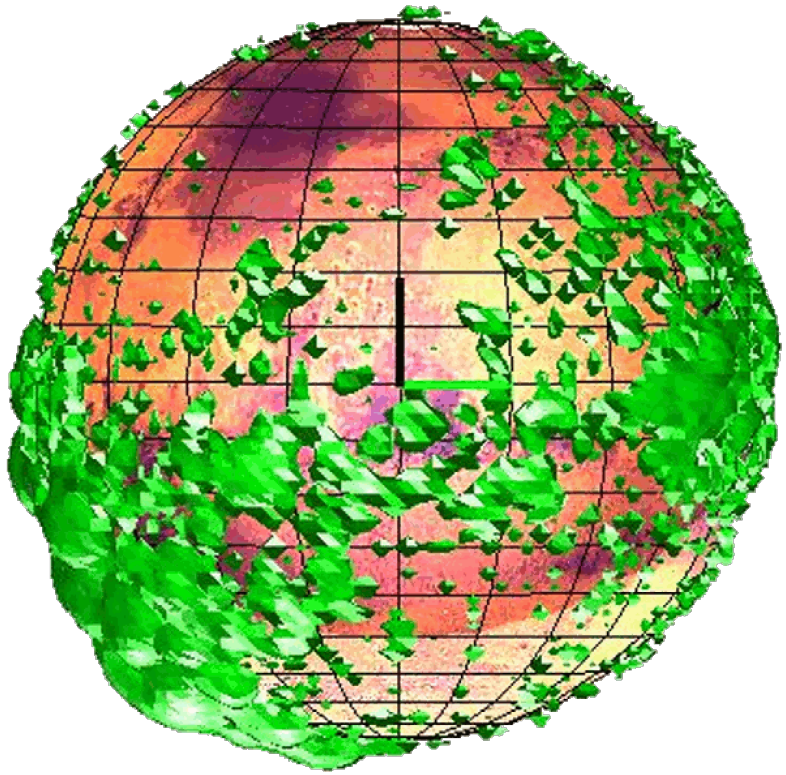
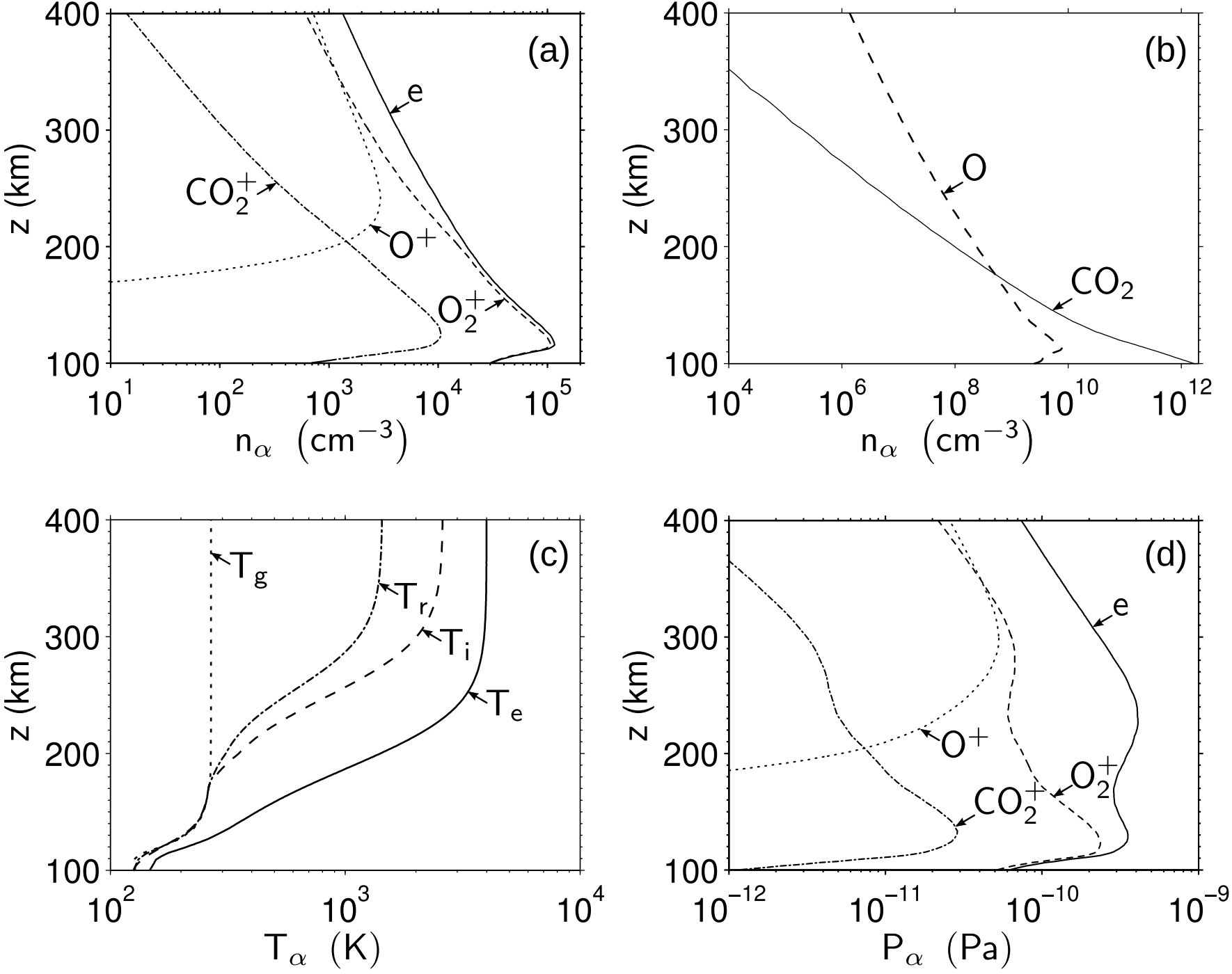


Figure: 100 nT surface levels of Mars' crustal fields using Purucker et al.'s [2000] magnetic field model [Brecht and Ledvina, 2010].



- Limited ion density profile records (from Viking I and II landers in... 1976)

Multifluid Model Formulation (II)

- Conservation of matter (O_2^+, CO_2^+, & O^+)
- Plasma approximation (e)
- Equation of state (O_2^+, CO_2^+, O^+, & e)
- Conservation of momentum (O_2^+, CO_2^+, & O^+)
- Plasma current definition (e)
- Maxwell–Faraday equation ($\vec{B}$)
- Maxwell–Ampère equation ($\vec{J}$)
- Generalized Ohm's law ($\vec{E}$)
- Fundamental equations
- Elastic ion–neutral collision
- Electron–neutral collisions

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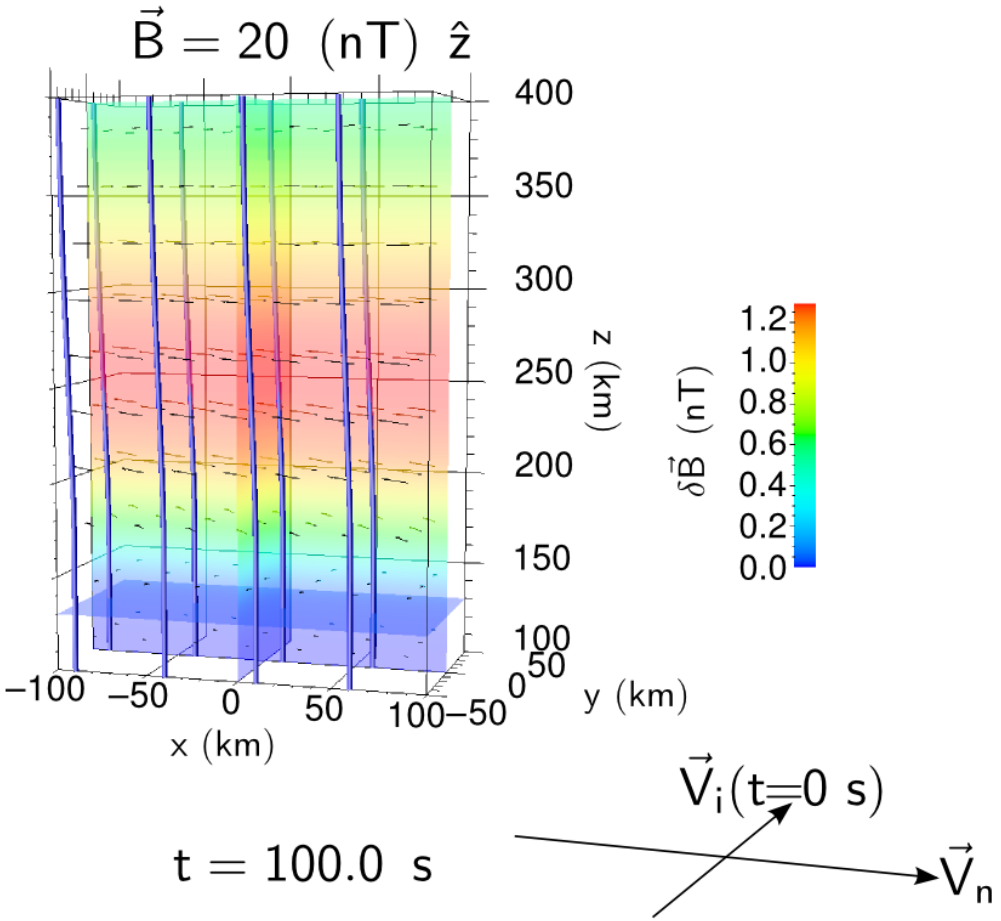
Magnetic Perturbations



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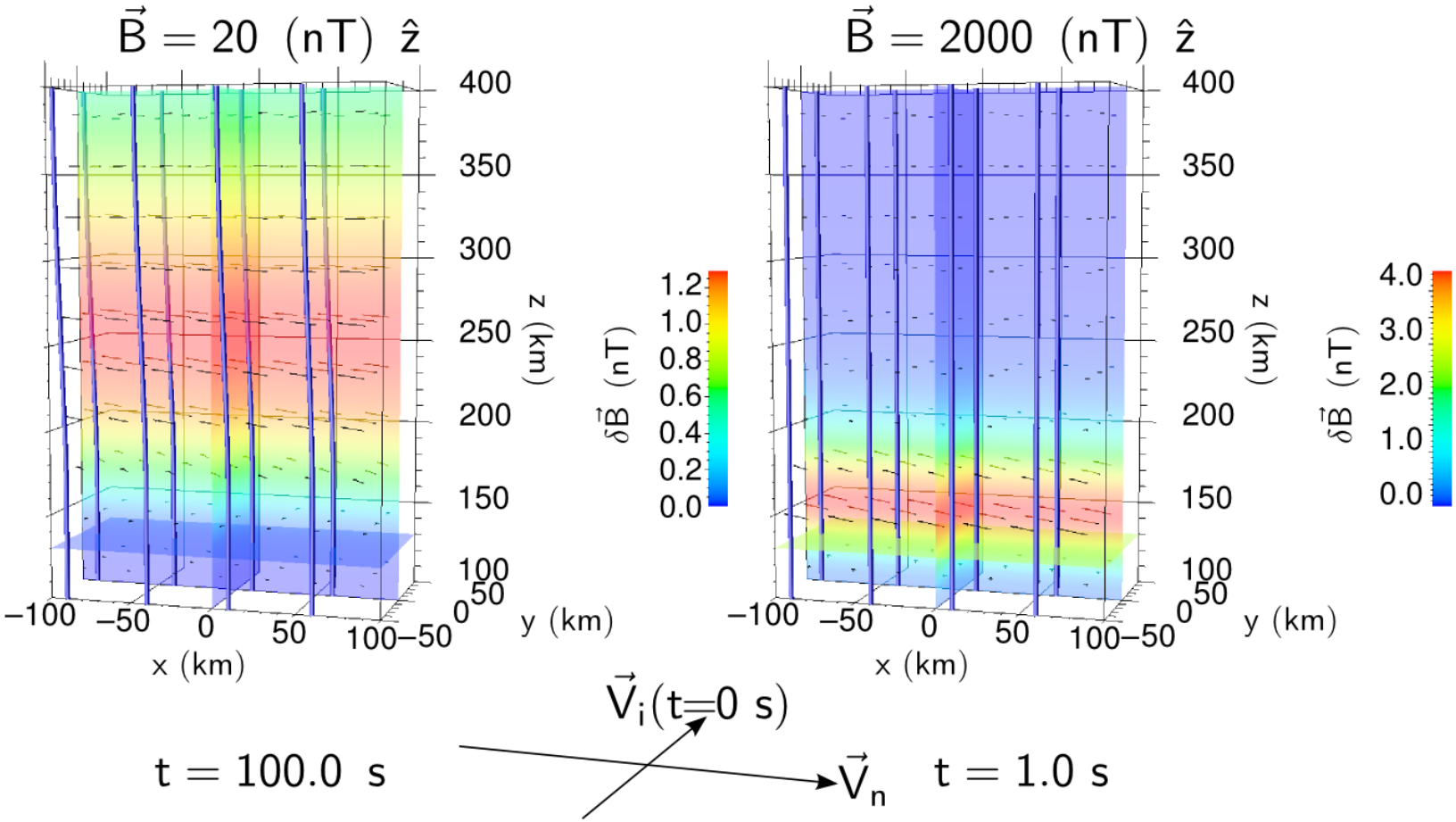
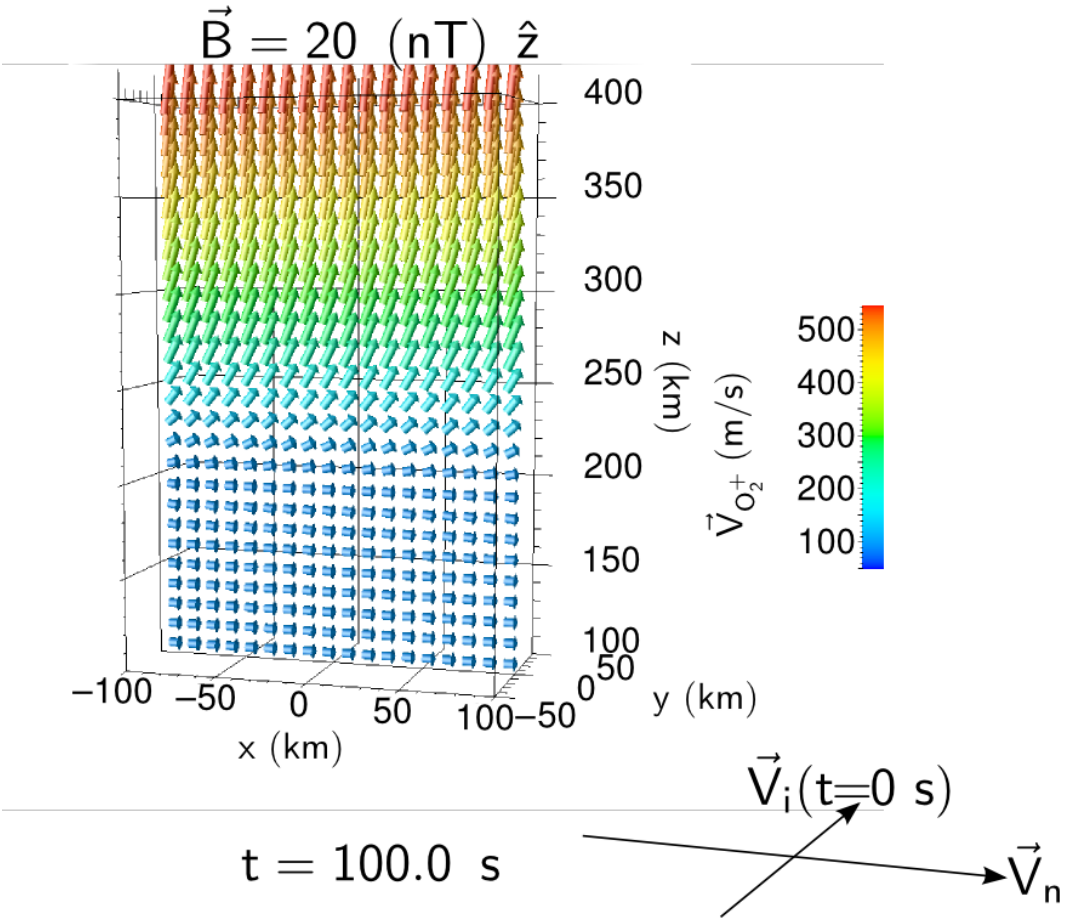
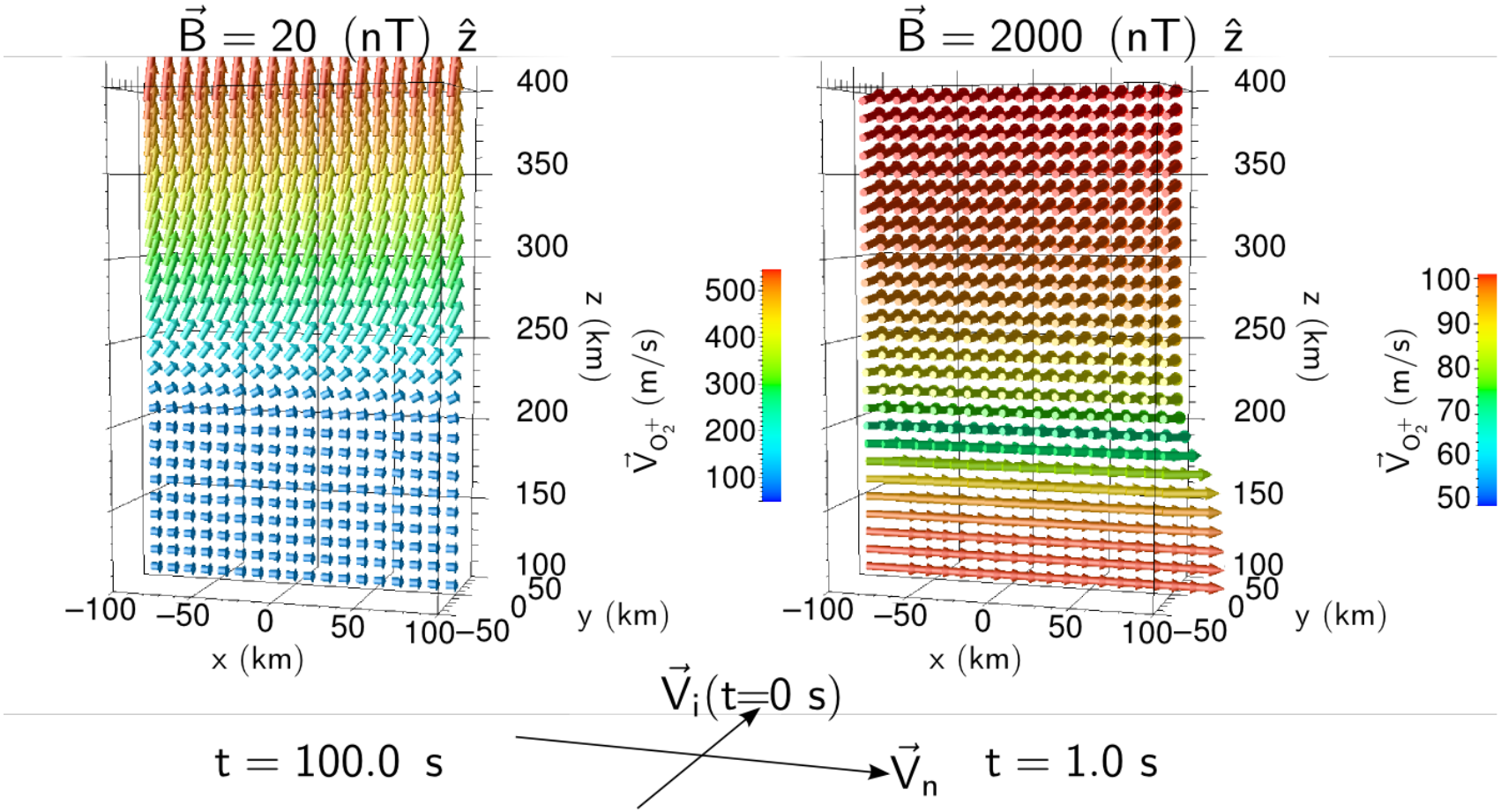


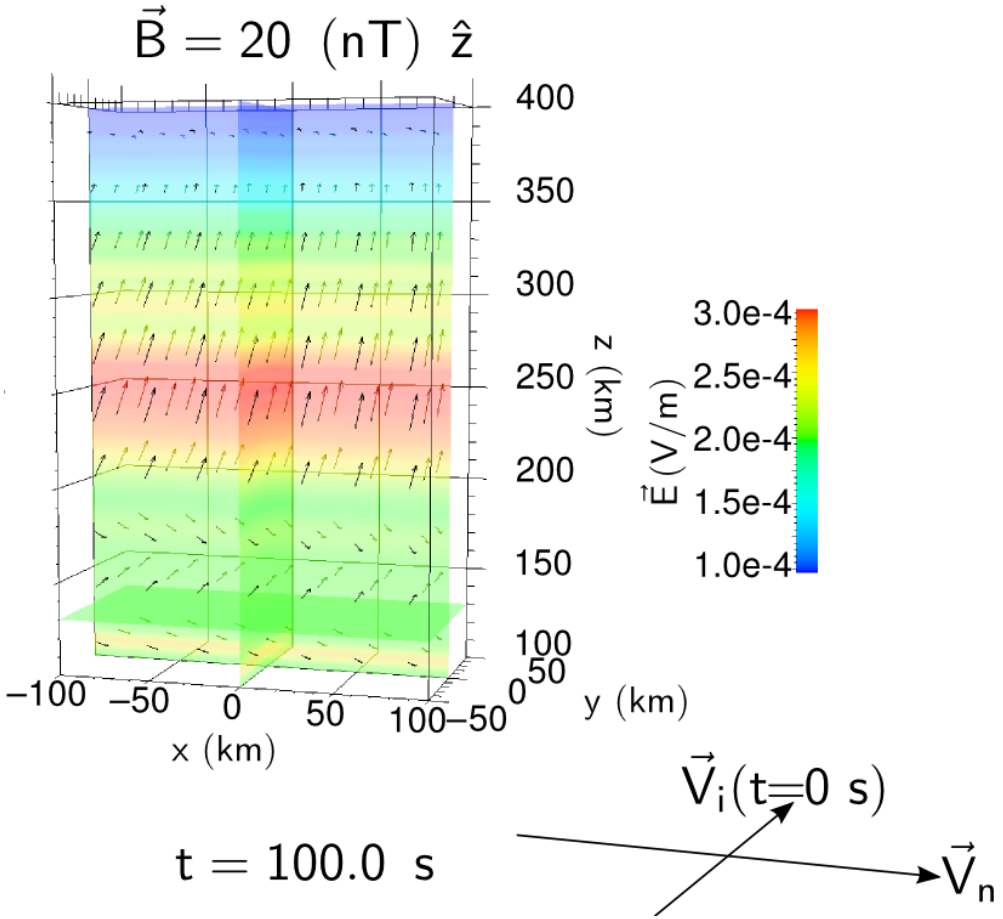
Ion Velocities



Ion Velocities



Electric Fields



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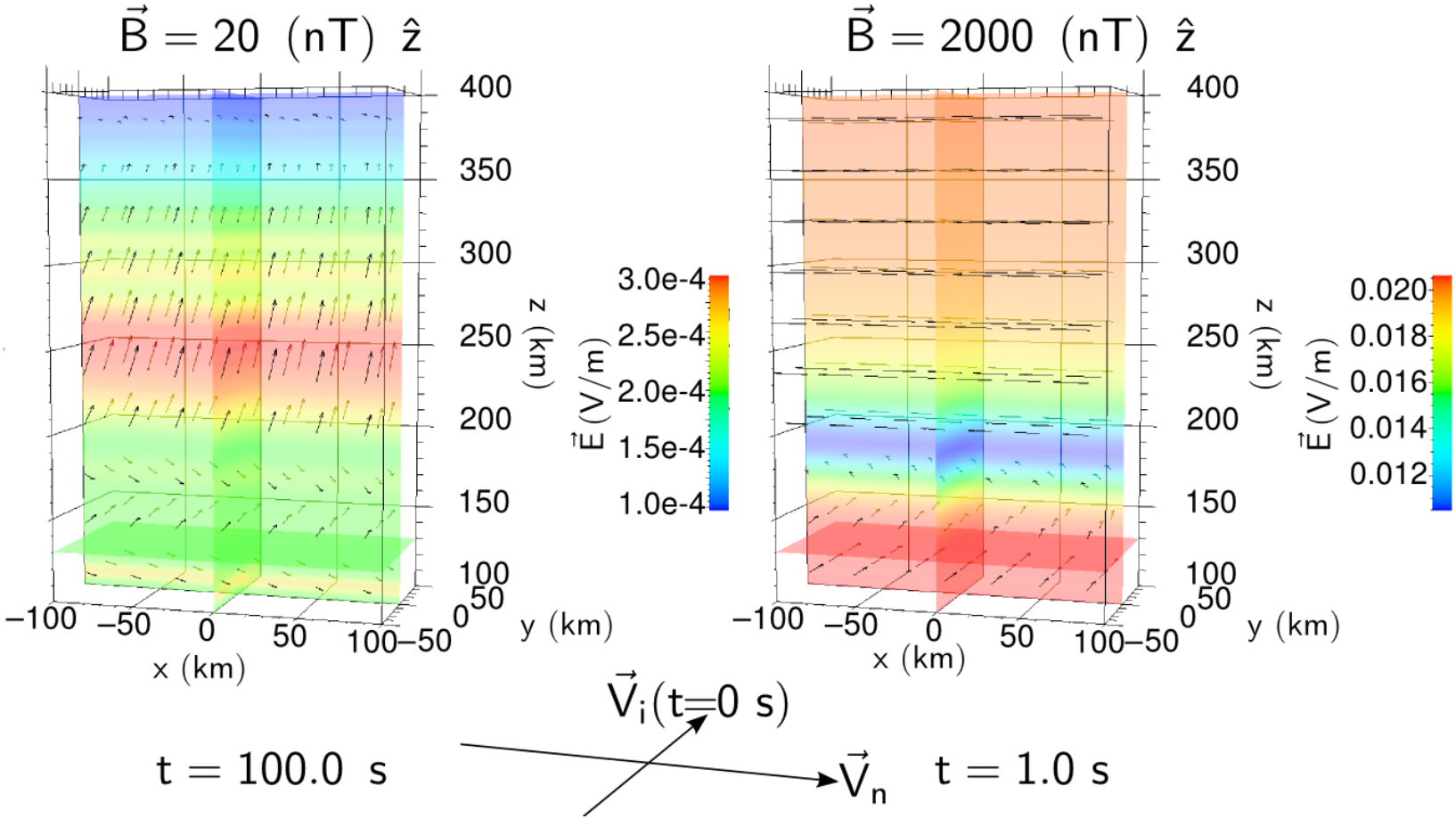
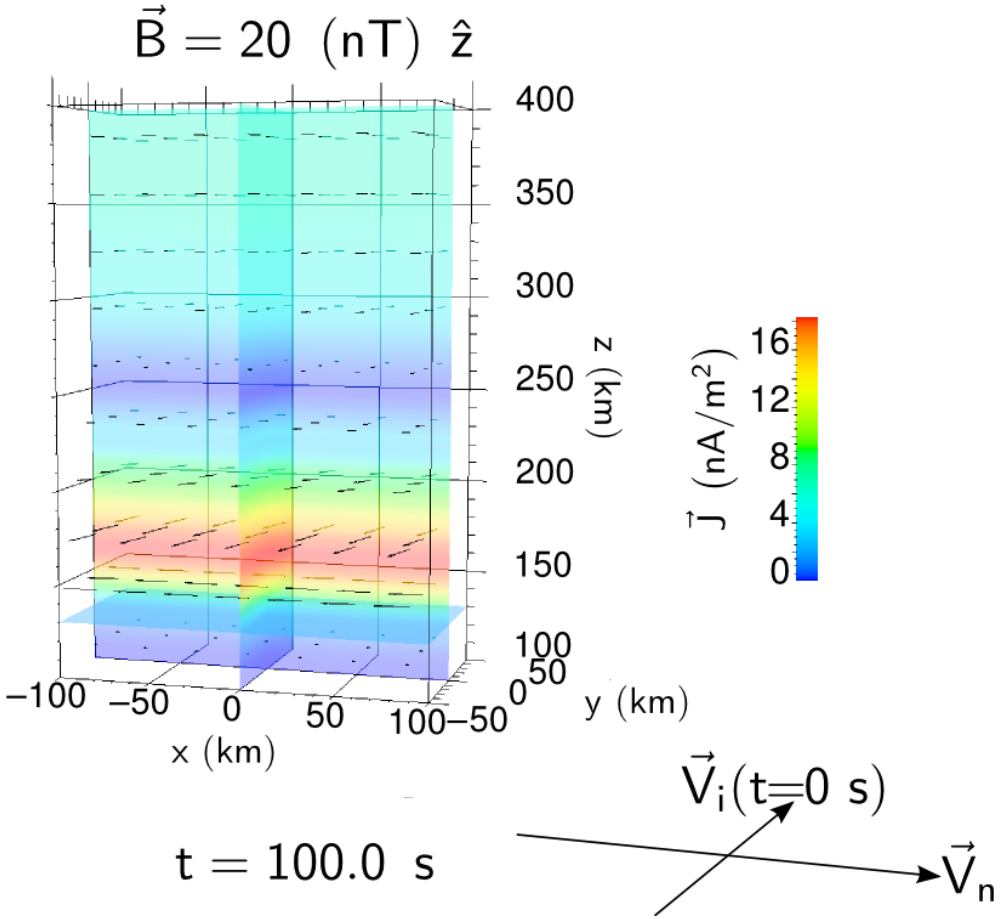
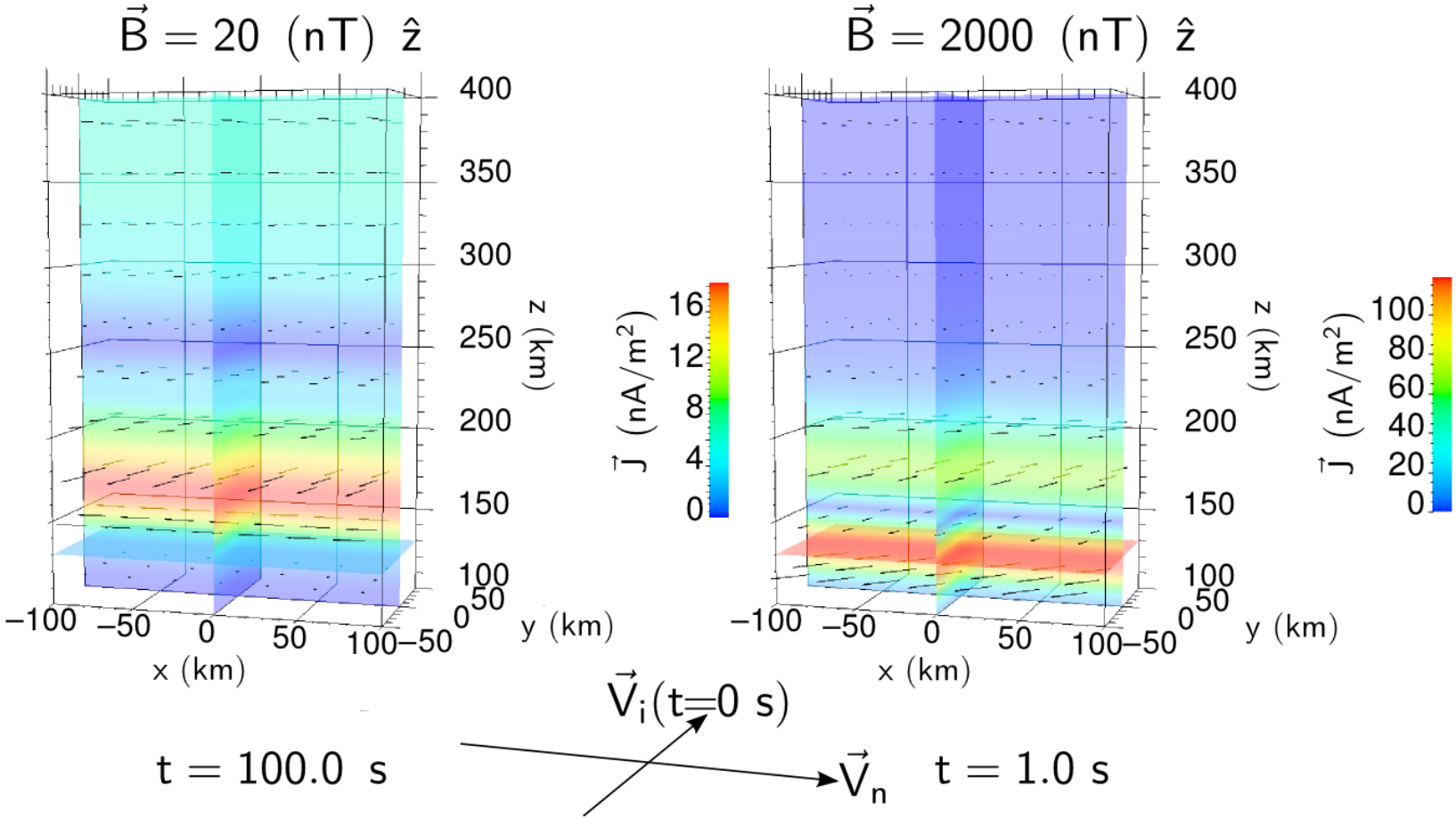


Dynamo Currents



Dynamo Currents



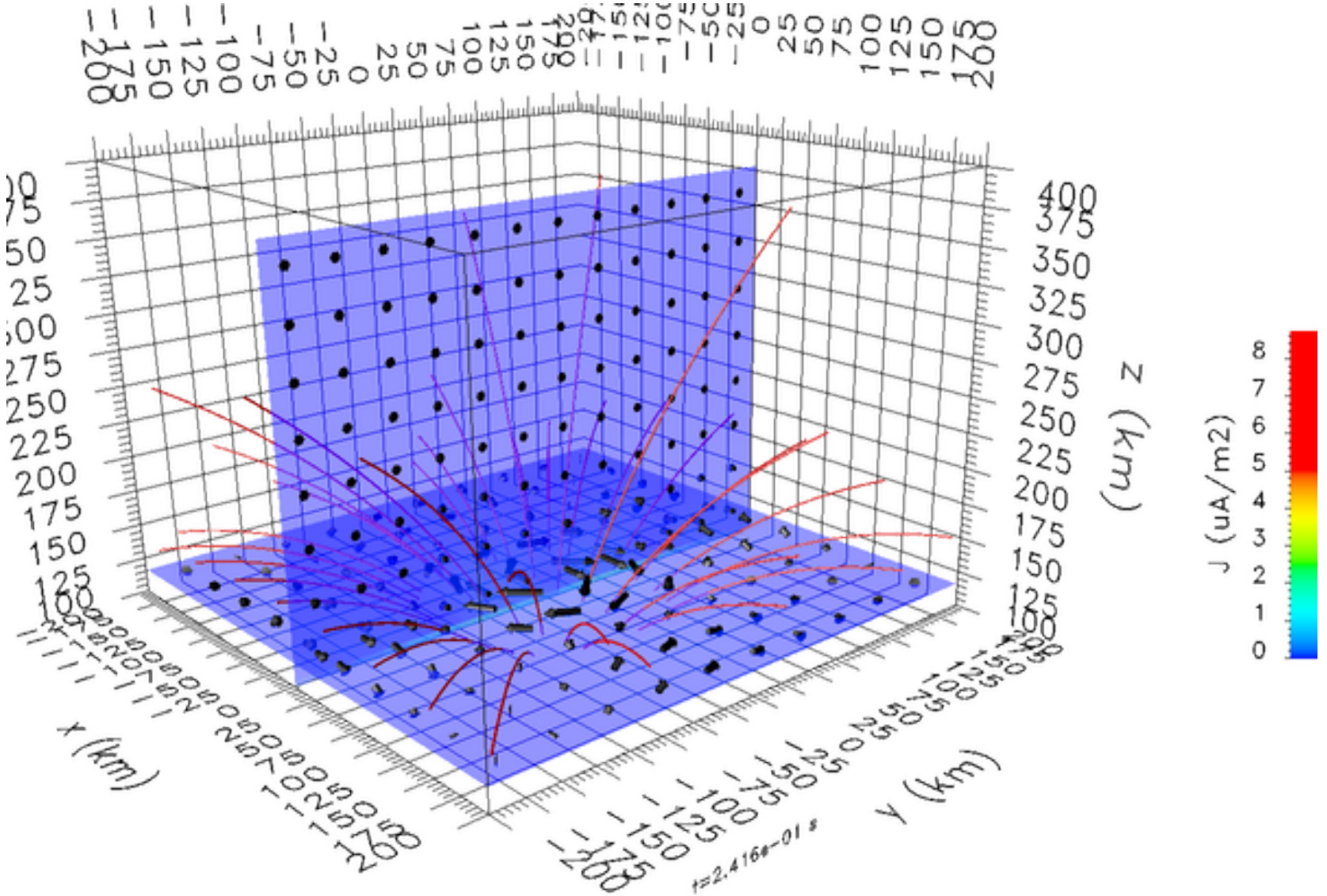
Quantitative Analysis

- The remanent crustal fields do generate electric currents
- The location of the dynamo region matches the prediction based on:

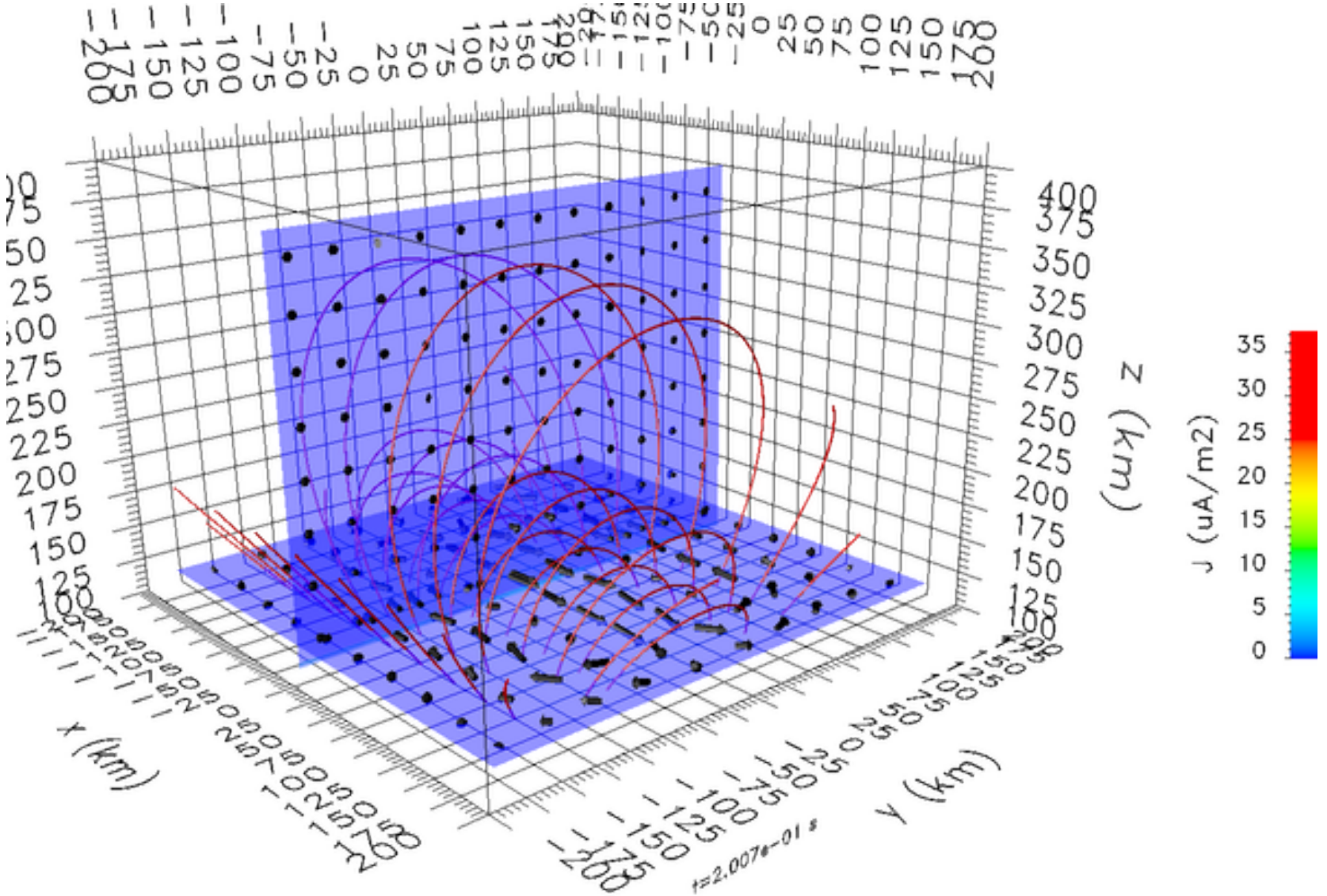
$$\begin{aligned} \nu_{c,O_2^+} &= \nu_{O_2^+ - CO_2}(H_U) \\ \nu_{c,e} &= \nu_{e-CO_2}(H_L) \end{aligned}$$

- The model results for $\vec{J}_{max}$ and $\vec{E}$ are consistent with theoretical calculations
- Mars' ionosphere can be efficiently modeled using a multi-fluid model and therefore our model can be used in more complex geometries
- The model lays the groundwork for new study of the interactions of the solar wind interactions with Mars' atmosphere

Magnetic Cusp



Magnetic Arcades



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Principal Contributions

The principal results and conclusions developed in this work can be summarized as follows:

- A new MHD multifluid model (M^4) of the Martian atmosphere has been introduced and validated.
- The first dynamic simulations of the dynamo region are produced.
- Simple uniform magnetic geometries are used for quantitative validation.
- Cusp and arcade geometries are used for regional studies of realistic magnetic topologies.
- Groundwork for new study of the interactions of the solar wind interactions with Mars' atmosphere is laid.

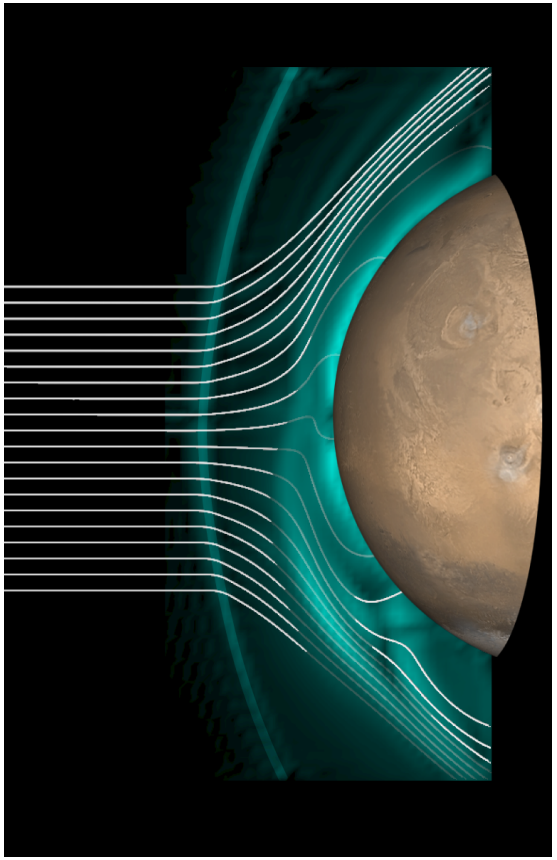

Figure: Example of magnetic field lines near Mars (Courtesy of E. Harnett and R. Winglee).

Acknowledgments

Thank You For Your Attention
Questions?

This work will be available online at:
`http://www.jeremy.riousset.com/`

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