Novel Modeling of Mars' Ionospheric Electrodynamics

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Abstract

Interactions between Mars' unique crustal magnetic fields and upper atmospheric electrons, ions and neutrals lead to the formation of currents in the ionospheric dynamo region. These interactions involve elastic and inelastic collisions between ions, electrons and neutrals in the presence of varying pressures, temperatures and densities. In addition, the complex magnetic topology of Mars leads to strong and weak, open and closed magnetic field regions in very close proximity. The resulting 'patchy' ionosphere varies on spatial scales of $\lesssim$ 100 km. These conditions make it impossible to derive an analytical solution of these ionospheric currents. Here we present a novel three-dimensional, multifluid, self-consistent, and dynamic model of the Mars ionospheric currents. These currents are driven by the coupling of atmospheric neutral winds to the ions and electromagnetic forcing of electrons. Our work is built upon a multifluid plasma dynamic model that tracks three ion species (O_2^+, CO_2^+, and O^+). This method applies equations for conservation of mass, conservation of momentum, charge neutrality, time dependent pressure for electron and ion species while simultaneously solving the generalized Ohm's Law and Maxwell-Ampere equation for the electric and magnetic fields. Incorporated into these equations are the aforementioned collisional interactions between the ions, electrons and neutrals. Our results demonstrate the feasibility of a self-consistent model of Mars' ionospheric electrodynamics, and investigate in particular the influence of thermospheric neutral winds, and magnetic topologies on the formation and evolution of ionospheric currents on Mars.

I. Introduction

Here we present the first stages of the development of the model, with particular attention on the model validation. The motivation for such a complex model is as follows:

- Ionospheric composition (e & 71% O_2^+, 25% CO_2^+, 4% O^+) $\Rightarrow$ multifluid model [5]
- Neutral winds $\Rightarrow$ 3-D model
- Complex magnetic field configuration (Figures 1 & 2) $\Rightarrow$ systematic validation approach
- 100 km$\times$50 km$\times$400 km space scale $\Rightarrow$ efficient numerical model

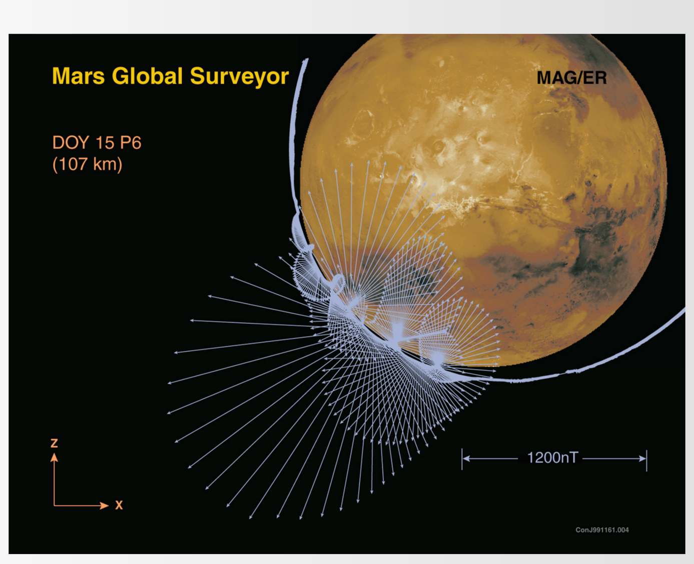

Figure 1: View of Mars' remnant crustal magnetic field. Figure courtesy of Jack Connerney.

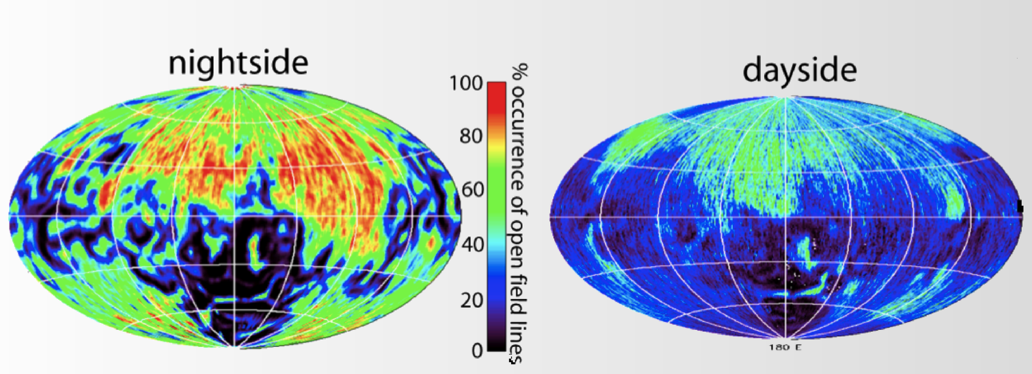

Figure 2: The percent occurrence of open magnetic field lines (i.e. connecting the IMF to the Martian atmosphere) at $\sim$400 km altitude on the nightside and dayside [2].

II. Model Formulation

- A 2-step Runge-Kutta method is used [1; 4; 6]
- Neumann boundary conditions are employed
- i=O_2^+, CO_2^+, O^+; e=electron

- Fundamental equations (implemented)
- Elastic ion–neutral collision (implemented)
- Electron collisions (in progress)
- Non-elastic collisions (in progress)

$$
\begin{cases}
\dfrac{\partial \rho_i}{\partial t} + \nabla\cdot\left(\rho_i \vec{V}_i\right) = (S_i - L_i)\, m_i \\
\rho_i \dfrac{\partial \vec{V}_i}{\partial t} = q_i n_i \left(\vec{E} + \vec{V}_i \times \vec{B}\right) - \nabla P_i - \dfrac{G M_M}{(R_M + r)^2}\rho_i \hat{r} + \rho_i \nu_{i-n}\left(\vec{U}_n - \vec{V}_i\right) + m_i S_i \left(\vec{U}_n - \vec{V}_i\right) \\
\dfrac{\partial P_i}{\partial t} = -\nabla\cdot\left(P_i \vec{V}_i\right) + (\gamma - 1)\vec{V}_i \cdot \nabla P_i + \sum Q_{i-n} \\
\dfrac{\partial P_e}{\partial t} = -\nabla\cdot\left(P_e \vec{V}_e\right) + (\gamma - 1)\vec{V}_e \cdot \nabla P_e + \sum Q_{e-n} \\
\dfrac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \\
\vec{J} = \dfrac{\nabla \times \vec{B}}{\mu_0} \\
\vec{V}_e = \sum_i \dfrac{n_i \vec{V}_i}{n_e} - \dfrac{\vec{J}}{n_e} \\
\vec{E} = -\sum_i \dfrac{n_i \vec{V}_i \times \vec{B}}{n_e} + \dfrac{\vec{J}\times\vec{B}}{q_e n_e} - \dfrac{\nabla P_e}{q_e n_e} + \dfrac{m_e}{q_e}\left(\sum_n \nu_{n-e}\vec{U}_n + \sum_i \nu_{e-i}\vec{V}_i\right) - \dfrac{m_e}{q_e n_e}\left(\sum_n \nu_{n-e} + \sum_i \nu_{e-i}\right)\left\{\sum_i n_i \vec{V}_i - \dfrac{\vec{J}}{q_e}\right\}
\end{cases}
$$

III. Model Validation

The validation of the model involves but is not limited to the following cases of study:

#	Collisions	$\vec{B}_{ext}$	$\vec{B}_{crust}$	Neutral wind
1	ν_{i-n} only	Uniform, $\uparrow$	No	No
2	ν_{i-n} only	Uniform, $\rightarrow$	No	No
3	ν_{i-n} only	Uniform, $\uparrow$	No	Uniform, $\rightarrow$, $\perp \vec{B}$
4	ν_{i-n} only	Uniform, $\rightarrow$	No	Uniform, $\rightarrow$, $\parallel \vec{B}$
5	ν_{i-n} only	Uniform, $\rightarrow$	No	Uniform, $\rightarrow$, $\perp \vec{B}$

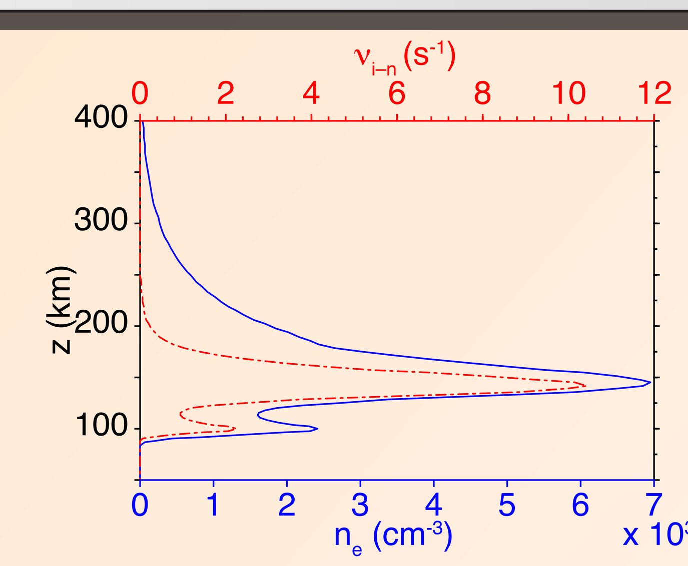

Figure 3: Electron density n_e and ion–neutral collision frequency ν_{i-n} vs. altitude z (nightside) [3].

IV. Preliminary Results

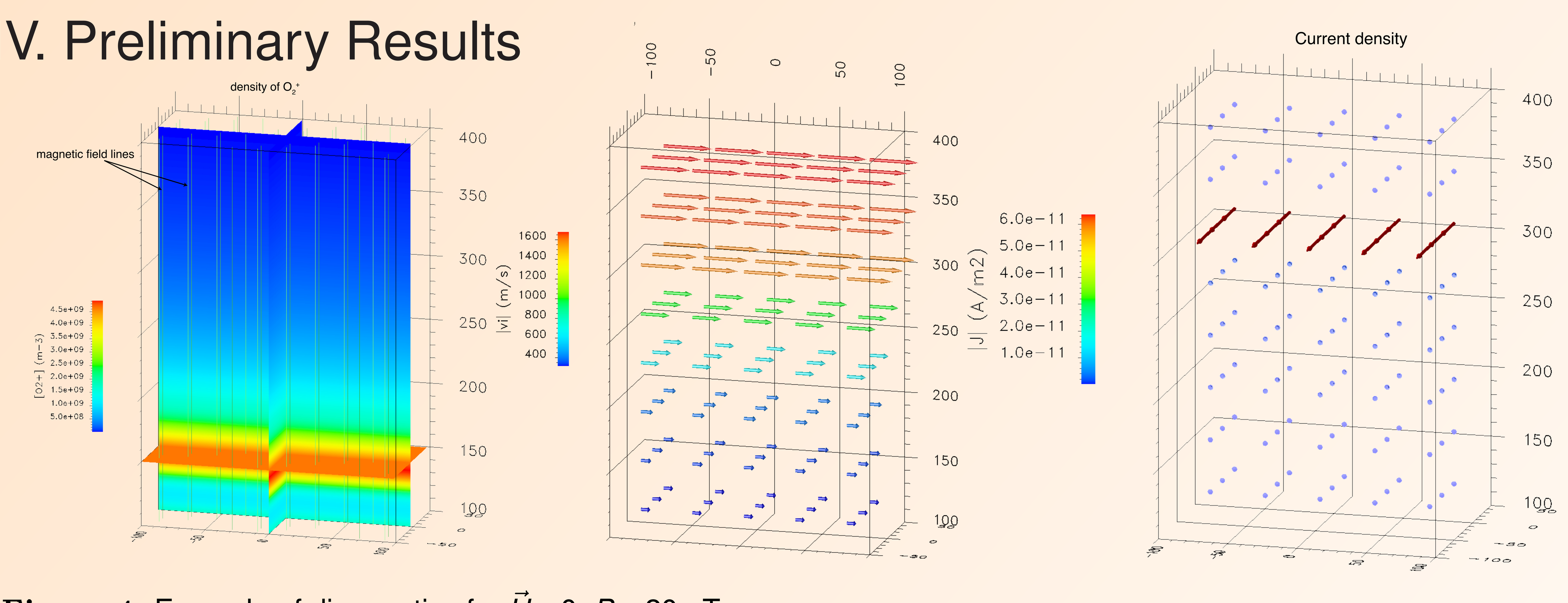

Figure 4: Example of diagnostics for $\vec{U}_n$=0, B_z=20 nT.

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V. Conclusions & Future Work

The results and conclusions resulting from this work can be summarized as follows:

- Mars ionosphere can be efficiently modeled using a multifluid model
- Early phase of validation has already started

This work consists in a first step towards the study of:

- the influence of Mars' remnant crustal magnetic fields on the ionospheric currents
- the impact of neutral winds of ionospheric dynamics
- the differences between dayside and nightside ionosphere as well as non-uniform ionization (see Figure 2)

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