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# The unusual electrodynamics of the ionosphere of Mars

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## Abstract

Mars has perhaps the most unusual magnetic environment in the solar system (Figure 1). Its inhomogeneous distribution of crustal magnetization leads to variations in magnetic field strength, local direction, and large-scale topology over horizontal and vertical lengthscales of 100 km or less. The local magnetic environment is also affected by interactions with the solar wind, so magnetic field strength and direction depend not only on position, but also on the time of day, subsolar latitude, and conditions in the interplanetary magnetic field and solar wind. Magnetic fields affect ionospheric properties and processes. Within the ionosphere, they affect large-scale (regular, steady) and small-scale (irregular, turbulent) plasma motion and thus plasma densities, currents, electric fields, and induced magnetic fields. Although many of these processes occur in the terrestrial ionosphere, they may operate in unusual ways in the unique environment of Mars. This presentation will focus on how plasma motion and electrodynamics in the ionosphere of Mars are qualitatively different from those seen at Earth.

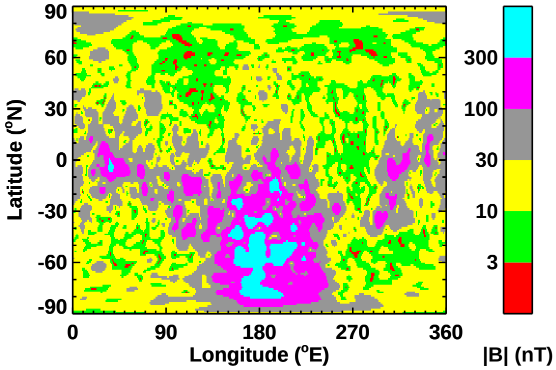

Figure 1: Crustal magnetic field strength at 150 km altitude on Mars. Based on model of Arkani-Hamed (2004).

## 1. Introduction

In the absence of any magnetic field, the motion of ionospheric plasma is described by the weak field limit of ambipolar diffusion. In this case, no currents flow and the plasma moves vertically in the neutral wind frame with a speed that results from the balance of gravity and pressure gradient forces with ion-neutral drag forces. In a strong magnetic field, the component of plasma motion along the magnetic fieldline is the same as in the weak field limit and plasma motion perpendicular to the magnetic fieldline is suppressed. Whether the field is weak or strong is determined by the ratio of the ion gyrofrequency, which is proportional to the magnetic field strength, to the ion-neutral collision frequency, which is proportional to the neutral number density. In many situations, the magnetic field strength varies slowly with altitude, whereas neutral number density decreases exponentially with increasing altitude, and this often leads to the weak field limit applying at low altitudes and the strong field limit applying at high altitudes. Regions of the Earth's ionosphere where plasma motion is significant are always in the strong field limit. This is not true on Mars, which prompts questions such as: How does the plasma velocity transition between the weak field and strong field limits? What three-dimensional plasma flow structures occur in an ionosphere with severe gradients in magnetic field strength and direction? The theoretical basis for models of plasma motion must be examined to answer these questions.

## 2. Theory

The steady-state equation for conservation of momentum for charged species $j$ can be written as (Withers, 2008):

$$0 = m_j \underline{g} - \frac{1}{N_j} \underline{\nabla} \left( N_j k T_j \right) + q_j \underline{E}' + q_j B \underline{\underline{\Lambda}}\, \underline{w_j} - m_j \nu_{jn} \underline{w_j} \tag{1}$$

where $m_j$ is mass, $\underline{g}$ is the acceleration due to gravity, $N_j$ is number density, $k$ is Boltzmann's constant, $T_j$ is temperature, $q_j$ is charge, $\underline{E}'$ is the electric field in the neutral wind frame, $B$ is the magnetic field strength, $\underline{\underline{\Lambda}}$ is a matrix representing a vector cross product with the unit vector parallel to the magnetic field vector, $\underline{w_j}$ is the velocity in the neutral wind frame, and $\nu_{jn}$ is the collision frequency for particles of species $j$ and neutrals.

This can be re-arranged to give:

$$\underline{w_j} = \frac{1}{N_j q_j}\left(\underline{Q_j} + \underline{\underline{S_j}}\,\underline{E'}\right) \qquad (2)$$

where $\underline{Q_j}$ and $\underline{\underline{S_j}}$ are functions of the variables in Equation 1. Using the definition of current density, $\underline{J}$, leads to:

$$\underline{J} = \underline{Q} + \underline{\underline{S}}\,\underline{E'} \qquad (3)$$

where $\underline{Q}$, effectively a source term, is the sum of the $\underline{Q_j}$ vectors and $\underline{\underline{S}}$, the conductivity tensor, is the sum of the $\underline{\underline{S_j}}$ matrices. The ratio $\kappa_j$, which equals $q_j B / m_j \nu_{jn}$, determines the directions of $\underline{Q}$ and $\underline{\underline{S}}\,\underline{E'}$. This is a generalized, frame-independent version of Ohm's law that includes the effects of gravity and pressure gradients. By contrast, typical derivations in textbooks and journals neglect gravity and pressure gradients and are not frame-independent.

Combination of Ohm's law with conservation of charge, Maxwell's equations, and suitable boundary conditions leads to an expression for $\underline{w_j}$ that reduces to either the strong field or the weak field limit as appropriate. A smooth transition occurs between the two limits. Currents, electric fields, and induced magnetic fields can also be obtained from this formalism. In particular, currents are most significant in the "dynamo region" that separates the weak field limit from the strong field limit.

## 3. Application

First, we shall illustrate the application of this theory using a simplified one-dimensional model of the ionosphere of Mars. Figure 2 shows the magnitude of the vertical component of ion velocity in a simplified one-dimensional model with an inclined magnetic field, demonstrating how the simulated ion velocity transitions smoothly between the weak field limit at low altitudes (high neutral number densities, many ion-neutral collisions per gyroperiod) and the strong field limit at high altitudes (low neutral number densities, few ion-neutral collisions per gyroperiod). Second, we shall describe progress on a project to study plasma motion in a realistic two-dimensional model of the ionosphere of Mars. As shown in Figure 3, some of the most strongly magnetized regions on Mars are characterized by arcade-like fieldline geometries.

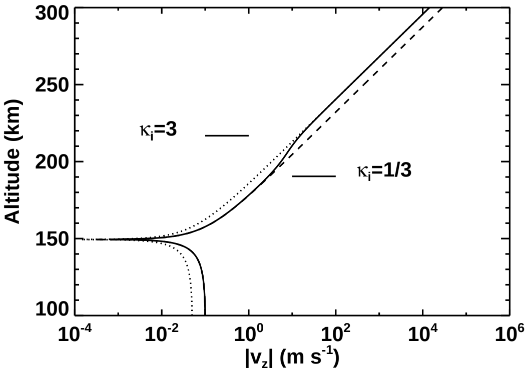

Figure 2: Magnitude of vertical component of simulated ion velocity (solid line) and corresponding limits for the weak field (dashed line) and strong field (dotted line) cases.

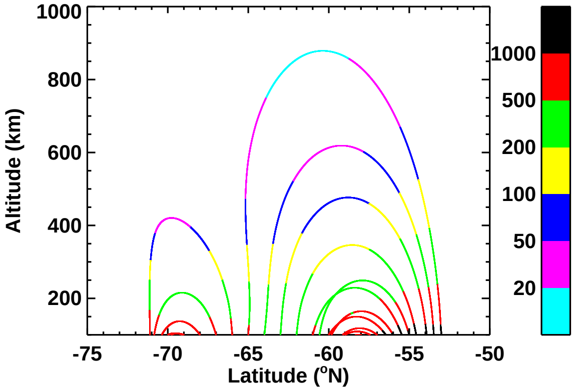

Figure 3: Series of magnetic fieldlines anchored at 180°E longitude. Colours indicate magnetic field strength in nT.

## References

[1] Arkani-Hamed, J. (2004), A coherent model of the crustal magnetic field of Mars, *J. Geophys. Res.*, *109*, E09005, 10.1029/2004JE002265.

[2] Withers, P. (2008), Theoretical models of ionospheric electrodynamics and plasma transport, *J. Geophys. Res.*, *113*, A07301, 10.1029/2007JA012918.