

A Hydrodynamic Model for Plasmasphere Refilling Following Geomagnetic Storms

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The refilling of the plasmasphere following a geomagnetic storm remains one of the longstanding problems involving ionosphere-magnetosphere coupling. Both diffusion and hydrodynamic approximations have been adopted for the modeling and solution of this problem. The diffusion approximation neglects the nonlinear inertial term in the momentum equation and so this approximation is not rigorously valid immediately after a storm. The principle focus of this work is the formulation and development of a hydrodynamic refilling model (that includes the nonlinear inertial term) using the flux-corrected transport method, a numerical method that is extremely well suited to handling nonlinear problems with shocks and discontinuities. In a previous study, this model has been validated against exact analytical benchmark problems and in this study, the model is used to describe plasmasphere refilling. The plasma transport equations are solved along one-dimensional closed magnetic field lines that connect conjugate ionospheres and the model currently includes three ions (H^+ , O^+ , He^+) and two neutral (O , H) species. In this study, each ion species under consideration has been modeled as two separate streams emanating from the conjugate hemispheres and the model correctly predicts supersonic ion

speeds and the presence of high levels of helium during the early hours of refilling. The ultimate objective of this research is the development of a three-dimensional model for the plasmasphere refilling problem, and with additional development, the same methodology can be applied to the study of other complex space plasma coupling problems in closed flux tube geometries.

Introduction

There are two kinds of ionospheric outflow in nature – the refilling of the plasmasphere following a geomagnetic storm [*Carpenter & Park*,1973] which occurs along closed field lines and polar wind outflow [*Khazanov*, 2009] which occurs along open lines. At its essence, these problems involve plasma escaping into vacuum in the presence of gravitational, electrostatic and magnetic force fields and collisional effects. A brief literature survey of the numerical models that have been developed for the modeling of ionosphere-magnetosphere coupling problems is provided in the next section.

Diffusion and Hydrodynamic Outflow Models: A Brief Literature Survey

Over the last several years, numerical studies have been undertaken to model and quantify ionospheric outflow and these studies have led to the development of ionosphere-plasmasphere coupling models. These models based on the solution of the plasma transport equations, fall within two broad categories. In one of these two categories, the nonlinear inertial terms in the plasma transport equations are neglected and thus low-speed, diffusion dominated flow can be modeled. Included in this category are the Sheffield University Plasmasphere Ionosphere Model (SUPIM) [*Bailey, et al.*, 1997], the Ionosphere-Plasmasphere Model (IPM) [*Schunk et al.*, 2004], and the Field-Line Interhemispheric

Plasma (FLIP) model [Young *et al.*, 1980]. The FLIP model has recently been integrated into the Ionosphere Plasmasphere Electrodynamics (IPE) model developed at the National Oceanic and Atmospheric Administration/Space Weather Prediction Center (NOAA/SWPC) to facilitate a better understanding of the connection between terrestrial and space weather.

The second category of models that exists in the literature is the so-called “hydrodynamic model,” where the nonlinear inertial terms are retained in the plasma transport equations. It was introduced by Banks *et al.* [1971] and has subsequently been worked on by many researchers [Khazanov *et al.*, 1984; Singh *et al.*, 1986; Rasmussen & Schunk, 1988]. The most well-developed hydrodynamic model of the low-latitude ionosphere is SAMI2/SAMI3 developed by Huba & Joyce [2000] and Krall & Huba [2013]. In the next section, a brief description of the ‘flux-corrected transport’ (FTC) method, (Boris & Book, 1976; Kuzmin *et al.*, 2012) used in this work, is provided.

Flux-Corrected Transport Method: A Brief Description

Ionospheric outflow problems are characterized by sharp discontinuities in the ion concentration profiles, resulting in gradients in the pressure as well as electric field profiles. Had it not been for these discontinuities, a second-order scheme such as the Lax-Wendroff [Hoffmann and Chiang, 2000] would have been adequate, where the numerical method itself does not introduce any diffusion in the problem. The fundamental philosophy behind the FTC method is that “diffusion” is artificially introduced “only” at spatial points where shocks and discontinuities are present. In partial fulfillment of the requirements of K. Chatterjee’s doctoral dissertation (to be completed by the end of 2018),

an FTC-based solution methodology has been developed for the plasmasphere refilling problem (including multiple ions and neutrals) following a geomagnetic storm. In this report, we discuss the preliminary results for the open line problem, which was simulated by increasing the curvature of the closed field line. An extended discussion of the results, along with associated figures, will be presented in a peer-reviewed American Geophysical Union (AGU) journal.

Discussion of Results

An FTC-based transport model was developed for the plasmasphere refilling model following a geomagnetic storm and this model was validated by analytical benchmarks. These results were presented in Utah/NASA Space Grant Consortium Meeting (2016). Subsequently, a multi-ion model (H^+ , O^+ , He^+) was developed for the refilling problem which also included two neutral (O , H) species. The model correctly predicted the following features consistent with results obtained from other models and experiments:

- A. Fast, supersonic outflow of H^+ ions (at a speed of around 30 km/s) from the conjugate ionospheres during the early stages of refilling.
- B. Counter-streaming of these H^+ ions, also observed during these early hours.
- C. As every ion species was modeled as two separate ion streams originating from the northern and southern hemispheres, equatorial shock formation, which exists in single stream models, were absent.
- D. The model correctly predicted He^+ ion peak, observed during the early hours of refilling.

- E. At the onset of refilling, O^+ dominance was assumed at a base altitude of 500 km. After the completion of refilling, the flux tube transitioned to H^+ dominance for almost the entirety of the length of the flux tube above the base altitude.
- F. At the completion of refilling, the ion streams were thermalized, and the ion drift velocities reduced to zero. The numerical solution matched the steady-state analytical solution for the hydrogen ion concentration, obtained under the assumption of a “ $L=4$ ” line of infinite length.

Summary and Future Work

Summarizing, we have developed a multi-ion, multi-stream, hydrodynamic refilling model for the plasmasphere following a geomagnetic storm. The numerical method used was the FCT method, extremely well-suited to handling nonlinear problems with shocks and discontinuities. In the immediate future, we intend to apply our model to problems with time-dependent boundary conditions. The ultimate objective of this research is the extension of this methodology to two and three dimensions, which would allow the modeling of plasma transport across field lines. With additional development, this model has the potential to be applied to other complex plasma coupling problems in open and closed flux tube geometries.

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