CURRENT COLLECTION AND CURRENT CLOSURE

IN THE TETHERED SATELLITE SYSTEM

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ABSTRACT

In this paper we address two aspects of the Tethered Satellite System: i) the current collection in the vicinity of the tethered satellite and ii) the appropriate physics for modeling the closure path of the tether current in the ionosphere.

Our approach to the issue of current collection has been based on numerical simulations performed with one and two dimensional codes. We have found that during transient current collection a positively charged body will attract an electron current which is greater than the steady state value by a factor > 40. The mechanism responsible for this is the influence of plasma ions while they are being evacuated from the sheath region. The duration of the enhancement for ionospheric conditions at 300km altitudes is on the order of a millisecond. During this transient phase some of the electrons in the sheath are accelerated to energies of twice the applied potential.

The structure of the evolved sheaths in the simulations indicates that electron collection is predominantly field aligned. The extent of the sheath transverse to the magnetic field is an electron Larmor radius, and is based on the attribution of the full potential drop to the cross field electron velocity. In the magnetic field aligned direction the sheath adjusts itself in extent to absorb the thermal ionospheric electron flux. We find that even in "steady state" there is a considerable fluctuation level in the sheath.Two other features that are important appear in the simulation. There is an ion void in the wake of the collecting body which strongly perturbs the electron population. Finally the settled sheath contains long lived electrons which are trapped electro-statically in the logitudinal direction and magnetically in the direction transverse to the field.

We have also examined a set of modified MHD equations for modeling the current closure in the Tethered Satellite System. These include ion inertia, quasi-neutrality, and simple drift motion for the electrons. The equations now support Whistler modes. A dimensional analysis indicates that the spectrum caused by the passage of TSS through the ionosphere may preferentially excite these modes.

Introduction

The electrodynamic operation of the Tethered Satellite system which is scheduled for flight in 1992 is crucially dependent on properties of a global circuit which regulates the current flow through the conducting tether. The elements which comprise this circuit are: the tether itself; the sheaths at the satellite and the orbiter; the electrical configuration which connects the end of the tether to the orbiter; and the closure path in the ionosphere. The circuit is also influenced by the presence of a neutral background around the satellite and orbiter, and possibly by the orientation of the orbiter to the magnetic field. In this paper we address two aspects of the overall problem: i) the characteristics and dynamics of the satellite sheath; and ii) the mechanisms for current closure in the ionosphere. Both of these problems have received considerable attention in the past, but recent theoretical and experimental results point to the fact that neither of these is well understood. The anticipated results which will come from the TSS mission will hopefully provide fresh data for unraveling the long standing fundamental physics question, first posed by Langmuir in 1921, of how a charged body behaves in a plasma.

Current Collection

We have modeled the behavior of a positively charged satellite moving through the ionosphere at orbital velocity with a Particle-in-Cell code. The calculation has been performed in the frame of the satellite. Our objective was to understand the morphology of the sheath structure and to predict the characteristic processes which can occur in the sheath region. To better understand the physics which is revealed by the simulation we also constructed a one dimensional un-magnetized fluid code to examine the transient behavior of an idealized problem of a charged sphere immersed in a plasma. Ma and Schunk(1989), and Calder and Laframboise(1990) have reported that in similar calculations the transient current collection can greatly exceed steady state behavior.

We have found that when the current in the tether is turned on, the transient response permits enhanced electron collection that exceeds the steady state by a factor as large as 40 (assuming an oxygen background). The process of sheath formation begins with collection of electrons nearest to the anode. When the electrons are first collected the ions have not evacuated the sheath region and must be expelled. During the time that ion expulsion is going on the electric field structure around the satellite enhances electron collection. The time scale for the transient is determined by the ion expulsion time which typically occurs on an ion acoustic timescale.

As observed in the one dimensional(spherical) simulations the buildup and relaxation of the electron current is relatively smooth. In contrast the two dimensional cases exhibited markedly unstable behavior. They were conducted for TSS like parameters which included voltages ranging from 20-200 Volts , a satellite with a 0.75 meter radius, immersed in a background plasma with a density of $10^{10}\#/m^3$, and a magnetic field of 0.35 Gauss. These simulations showed considerable field aligned structure and rapidly varying potentials that energized the electron population to twice the applied level, while some ions also acquired energies that were a good fraction of the applied potential (<25%). The scaling time for ion expulsion, however, agreed well with the one dimensional predictions.

The collection of electrons is predominantly field aligned and indicates that the total collected current will scale as:

$$I = 2 J_o \pi (r_s + \rho_e)^2, \quad (1)$$

$$J_o = n_e v_{the} |e|, \quad (2)$$

$$\rho_e = |e| (\phi/m_e)^{1/2} / (|e| B_o / m_e c) \quad (3)$$

and where r_s is the radius of the satellite, B_o is the earth's magnetic field and n_e, v_{the} are the ambient electron density and thermal velocity respectively. The overall scaling is similar to Parker and Murphy(1967), and shows a topology close to that predicted by Linson(1982).

The simulations clearly show that the ionospheric plasma flow past the satellite leads to a turbulent wake region. Some incoming ions are reflected from the potential sheath and have forward characteristics. While we have not been able to treat the effect of these ions in the simulation, the likely consequences are that they will preheat the plasma flowing towards the satellite raising the thermal velocity, v_{the}.

Another important feature of the sheath structure is the presence of trapped electrons which are magnetically insulated and circulate around the satellite. The prediction of discharge threshholds is sensitive to this feature. This has been examined theoretically by Linson and Papadopoulos(1982) and in recent experiments by Greaves et. al.(1990). The presence of neutral gas with densities $n_o > 10^{13}$ #/cc is likely to lead to a Penning-like discharge at the satellite, which further enhances the maximum current that can be collected . When a new electron ion pair is formed in the trapped region the electron will not be collected immediately, but will be trapped until the ion it was born with is expelled . The confinement time of the electrons is governed by ambipolarity and the expected longer electron lifetimes may yield avalanche like breakdowns at relatively low neutral densities.

Current Closure

The commonly anticipated current path in TSS is the propagation of field aligned Alfven wings into the lower ionosphere where collisionally dominated cross-field currents provide closure. Calculations which predict Alfven wave generation have been performed by Drell et. al.(1965), by Belcastro et. al. (1982), by Rasmussen et. al. (1985), and Barnett and Olbert (1986). Recently Urrutia and Stenzel (1990) have suggested that whistler waves are a more likely mechanism for providing the closure path nearer to the tether and have mapped the perturbed field patterns in a laboratory experiment. We have examined their hypothesis on the basis of an analytical model. In a usual MHD treatment of a current carrying plasma the electron and ion inertia is neglected. The equations used to describe this situation are:

$$\frac{1}{c}\,\partial \mathbf{B}/\partial t = -\nabla \times \mathbf{E}, \qquad (4)$$

$$4\pi\frac{\mathbf{J}}{c} = \nabla \times \mathbf{B}, \qquad (5)$$

$$\mathbf{E} = -\frac{\mathbf{v}}{c} \times \mathbf{B}_o, \qquad (6)$$

$$n_o M\, \partial \mathbf{v}/\partial t = \frac{\mathbf{J}}{c} \times \mathbf{B}, \qquad (7)$$

These equations can be manipulated to obtain an expression for the magnetic field . The result is an equation which predicts the existence of Alfven waves,

$$\partial^2 \mathbf{B}/\partial t^2 = \nabla \times \{ \mathbf{b}_o \times [\mathbf{b}_o \times \nabla \times \mathbf{B}]\} \bullet u_a^2,$$

where u_a is the Alfven velocity and $\mathbf{b}_o$ is a unit vector in the direction of the ambient magnetic field. We considered a simple modification to the MHD equations by retaining ion inertia. The first two equations, (4) and (5), remain the same, but in equation (5) $\mathbf{v}$ is replaced by $\mathbf{v}_e$ indicating that only the electrons are tied to field lines. For the ions we now consider the full Lorentz force law,

$$\partial \mathbf{v}_i/\partial t = (q_i/M_i) \bullet [\mathbf{E} + \frac{\mathbf{v}_i}{c} \times \mathbf{B}]. \qquad (9)$$

In addition we impose the restriction of quasi-neutrality requiring the electron and ion densities to be approximately equal. The relaxation of the condition that the ions be tied to field lines leads to a differential velocity between electrons and ions which can be found from Ampere's law (Equation. 5). The electron velocity can be expressed in terms of the ion velocity, the curl of the magnetic field, and the local plasma density. This in turn leads to a new equation for the electric field,

$$\mathbf{E} = -\frac{\mathbf{v}_i}{c} \times \mathbf{B}_o$$

$$+ \ (\nabla \times \mathbf{B}) \times \mathbf{B}_o/(4\pi |e| n_o). \qquad (10)$$

Equation (10) has a form almost identical to that of the MHD equations but for the presence of the second term. The retention of this additional term accounts for the presence of Whistler waves. The governing equation for the magnetic field is now:

$$\partial^2\mathbf{B}/\partial t^2$$
$$+\nabla x\{[\nabla x\partial\mathbf{B}/\partial t]x\frac{c\mathbf{B}_o}{4\pi|e|n_o}\}$$
$$= \nabla x\{\ \mathbf{b}_o x[\mathbf{b}_o x\ \nabla x\mathbf{B}\ ]\}\bullet u_a^2$$

A dimensional analysis reveals when the additional term introduced by the retention of ion inertia is important. If we were to normalize the equations in such a way that $T=\Omega_i t$ and $X=x\Omega_i/u_a$ then the equation for **B** depends only on X and T and has no numerical coefficients. The spatial ordering of both terms is also the same(but does depend on orientation). The characteristic distinction between the Alfven and Whistler terms is determined by the timescale. Consequently for:

$T>1$ The Alfven wave dominates

1 The Whistler wave dominates

The source term **S** which would appear on the right hand side in Equation (11) for a current carrying conductor would consist of the following expression :

$$\mathbf{S} = \nabla x\{[\partial\mathbf{J}_s/\partial t]\, x\, \frac{\mathbf{B}_o}{|e|n_o}\}\ . \qquad (12)$$

For TSS we would expect that the spectral content of the source term is determined by the time that the system spends on a magnetic field line , t=R/v. For orbital velocities of v=7.8km/sec and sheath sizes of R = 2 meters the characteristic dimensionless paramter is T=0.054 indicating the importance of the Whistler term. In relation to the experiment performed by Urrutia and Stenzel this would be the current pulse duration times the ambient ion Larmor frequency.

The analytic model that we have considered indicates that it is not permissible to neglect ion inertia terms for the situation posed by TSS. We are in the process of solving the equations presented above analytically. An alternate approach to solving this problem, both linearly and non-linearly is through simulations with a hybrid code. We have initiated a program to perform such calculations with a three dimensional code called QN3D which was developed at LLNL and at SAIC. The code was constructed by Horowitz and Anderson(1989) and numerically solves the modified MHD equations in discritized form for initial value problems. The code treats the electrons as a fluid, the ions with a particle-in-cell model, and assumes quasi-neutrality .

A set of outstanding issues for the current closure problem is: i) the inclusion of electron inertia along the magnetic field in both the analytic treatment and the simulation code; and ii) the proper matching of boundary conditions to the sheaths at the termination of the tether.

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