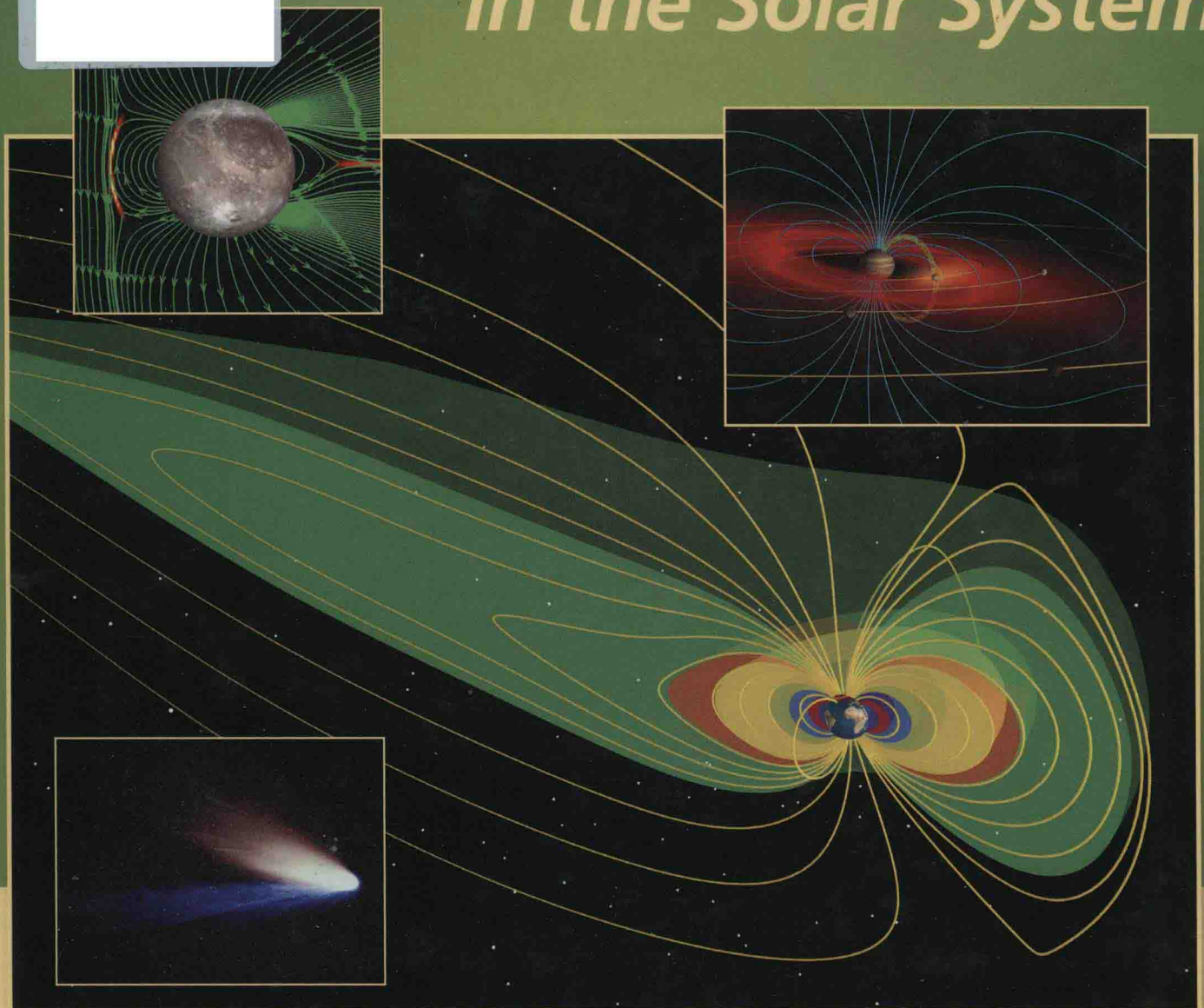


Magnetotails

in the Solar System



Andreas Keiling, Caitríona Jackman, Peter Delamere
Editors

Geophysical Monograph 207

Magnetotails in the Solar System

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PREFACE

Spacecraft observations have established that all magnetized planets in our solar system (Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune) interact strongly with the solar wind and possess well-developed magnetotails. Magnetotails are the site of many dynamic processes critical to the transport of mass, momentum, energy, and magnetic flux. The great differences in solar wind conditions, planetary rotation rates, ionospheric conductivity, and physical dimensions from Mercury's small magnetosphere to the giant magnetospheres of Jupiter and Saturn provide an outstanding opportunity to extend our understanding of the influence of these factors on magnetotail processes and structure.

It is not only the strongly magnetized planets that have magnetotails. Mars and Venus have no global intrinsic magnetic field, yet they possess induced magnetotails. Comets have a magnetotail that is formed by the draping of the interplanetary magnetic field. In the case of planetary satellites (moons), the magnetotail refers to the wake region behind the satellite in the flow of either the solar wind or the magnetosphere of its parent planet. The largest magnetotail of all in our solar system is the heliotail, the "magnetotail" of the heliosphere.

In the last decade there has been an abundance of new observations from spacecraft missions, such as MESSENGER, Geotail, Cluster, THEMIS, ARTEMIS, Galileo, New Horizons, Cassini, IBEX, and Deep Space 1. In addition, there have been great advances in the capabilities of simulations to allow modeling of many of the relevant processes. Hence, the time was ripe to address recent achievements of observational, theoretical, and modeling studies in a Chapman conference on "Fundamental Properties and Processes of Magnetotails," held in Reykjavik, Iceland, during 10–15 March 2013. The conference stimulated cross-disciplinary discussions among scientists specializing in all aspects of magnetotail physics.

To collect the discussions and results from the conference for the broader space science community, we endeavored on making this monograph, resting assured that the expertise would come from the expert attendees. While in the past the different types of magnetotails have been largely treated in separate books, our intention with this monograph was to take an integrated approach by treating the magnetotail as a fundamental phenomenon and incorporating the phenomenology and physics for all types of magnetotails in one book. As a result, this book should appeal to a broad

community of space scientists. In fact, it should also be of interest to astronomers who are looking at tail-like structures in our galaxy and beyond.

This book is largely, but not exclusively, based on reviews and tutorials presented at the above-mentioned Chapman conference. It is organized into three sections: Introduction, Tutorials, and Specialized Topics. To set the stage, the first section exposes with an excellent discussion an "unsolved" fundamental problem in magnetospheric physics: the magnetotail. The specific question asked is: "How is the configuration of highly stretched magnetic field lines created and maintained?" The problem is addressed via global stress balance but ultimately points to the lack of any quantitative theory, as of yet, to answer this question. We believe that this chapter is a "must-read" for anyone interested in magnetotails.

The second section covers the large range of magnetotails in our solar system. Each tutorial chapter focuses on one magnetotail, reviewing various phenomena specific to the magnetotail at hand. These chapters are ideal for those who want to become familiar with a specific magnetotail. With respect to the current literature, we find this to be quite a unique collection of tutorials.

Each magnetotail has its own individual and unique characteristics. By taking a comparative approach to a number of specific science questions, one can develop a greater understanding of magnetotail dynamics in these different environments. This is the approach followed in the third section, where each chapter focuses on a special region of the magnetotail or a specific phenomenon while comparing it among different magnetotails. Many facets of magnetotail physics are covered in this section.

We are truly grateful to the many people who made the Chapman conference a success and the book a reality. All the conference attendees brought the energy and enthusiasm that made the meeting fun and rewarding. The other program committee members (Jin-Bin Cao, Colin Forsyth, Mervyn Freeman, Denis Grodent, Xianzhe Jia, Larry Kepko, Norbert Krupp, James Slavin, Michelle Thomsen, and Tsugunobu Nagai) contributed greatly to the science aspect of this conference. AGU staff (Cynthia Wilcox, Shermonta Grant, and Lynn Erwin) and Beverly Smith-Keiling provided outstanding support throughout the organization of and during the conference. The authors of the 22 chapters provided the substance for this book, and the many volunteers (listed below) who reviewed those chapters have given the book

scientific credibility. The Icelandic hospitality welcomed us and made the field trips a true pleasure, visiting some of the local geological sites and, last but not least, a visit to the world-renowned Blue Lagoon. The National Science Foundation provided funding for many students to attend the conference. Additional funding, which helped with the costs of the conference center HARPA and the various field trips, came from the Institute of Geophysics and Planetary Physics (Los Alamos National Laboratory), the Space Sciences Laboratory (University of California, Berkeley), the Laboratory for Atmospheric

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Section I: Introduction

Magnetotail: Unsolved Fundamental Problem of Magnetospheric Physics

Vytenis M. Vasyliūnas

1.1. INTRODUCTION

Planetary magnetospheres are observed to extend in the antisolar direction to distances orders of magnitude larger than the magnetosphere's characteristic linear dimension on the dayside. That the supersonic solar wind interacting with a planet's magnetic field should create an extended wake along its direction of flow can be readily understood. What is remarkable about the observed planetary magnetotails is that they do not consist merely of sundry perturbations in the magnetic field and plasma but display a well-ordered structure: highly stretched-out, oppositely directed magnetic fields, separated by regions of enhanced plasma pressure (sketched in Figure 1.1). This configuration has by now become so familiar, from numerous papers on observations and model descriptions, that it is easy to overlook the underlying physical question: How is such a configuration created and maintained? In this chapter I show that, at the level of physical understanding as distinct from mere empirical representation, explaining the magnetotail constitutes a fundamental problem in magnetospheric physics that still remains unsolved, despite extensive empirical data (mainly at Earth but increasingly at other planets as well) and diverse qualitative theoretical concepts: There is as yet (to my knowledge) no predictive first-principles theory, comparable to the Chapman-Ferraro model which is the basis for understanding the dayside magnetosphere.

Section 1.2 summarizes the principal properties of magnetotails and identifies those that lead to the problem of global stress balance, which is described quantitatively

in section 1.3. The various proposed ideas of what maintains a magnetotail are reviewed in section 1.4.

Time variations, interesting and important as they are, are not dealt with; dynamical processes are mentioned only insofar as they illuminate some aspect of the basic problem. For simplicity, descriptions and illustrations generally presume that the planetary magnetic dipole is quasi-perpendicular to solar wind flow, which is the case for all magnetospheres observed to date (Earth, Mercury, Jupiter, Saturn) with the exception of Uranus and Neptune.

1.2. ESSENTIAL PROPERTIES

Evident in Figure 1.1 is the striking difference in the shape of magnetic field lines between the dayside and the nightside. Near the planet, the field lines are (nearly) dipolar at all local times. As one proceeds outward, on the dayside the field lines become more and more compressed as one approaches the magnetopause; on the nightside, to the contrary, they become stretched out and nearly aligned with the solar wind flow direction, the magnetic field direction reversing across the current sheet in the central region of enhanced plasma pressure and density (plasma sheet). In the lobes of the magnetotail above and below the plasma sheet, the magnetic field is approximately uniform, and the plasma pressure and density are very much lower than in adjacent regions.

Seemingly, there are processes that act to compress the magnetic field of the planet on the dayside and to pull it out on the nightside. The dayside process was identified already, for the magnetosphere of Earth, by Chapman and Ferraro in the 1930s: exclusion of the planet's magnetic field from the highly conducting plasma of the (then hypothetical) solar wind and its compression by the dynamic pressure of solar wind flow, a concept that by

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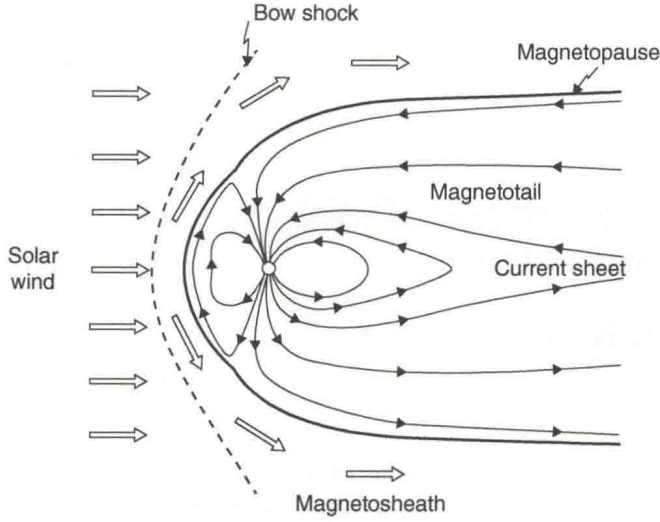


Figure 1.1 Schematic view of a magnetosphere, cut in the noon-midnight meridian plane. Open arrows: solar wind bulk flow. Solid lines within magnetosphere: magnetic field lines. The figure continues to the right out to distances in general much larger than the width of the figure. (In all figures of this chapter: sunward direction to the left; unless otherwise stated, magnetic field line directions appropriate for Earth or Mercury, reversed for Jupiter or Saturn.)

the 1960s had been developed into a well-defined mathematical theory [see, e.g., *Siscoe*, 1988, for review and references], capable of predicting quantitatively the location and shape of the magnetopause and the configuration of magnetic field lines. These predictions are mostly (with some exceptions, primarily during intense magnetic storms) in reasonable agreement with what is observed on the dayside of Earth's magnetosphere, but they disagree completely with what is observed on the nightside and especially in the extended magnetotail [see, e.g., *Vasyliūnas*, 2011, for a more details discussion]. The root of the disagreement clearly is the assumption in the Chapman-Ferraro model that pressure is the only force acting across the solar-wind/magnetosphere interface.

The concept of magnetic field lines from Earth being pulled back by the solar wind to form a (transient or permanent) magnetotail was suggested by *Parker* [1958] and *Piddington* [1960]; it acquired a concrete form with the proposal of the magnetically open magnetosphere [*Dungey*, 1961]. The more general concept of an (unspecified) tangential drag force across the solar-wind/magnetosphere interface was introduced by *Axford and Hines* [1961] and invoked to discuss a magnetotail by *Axford et al.* [1965]. A quasi-permanent (and very long) magnetotail created by internal hydromagnetic-wave or plasma pressure was proposed by *Dessler* [1964]. Before they could be developed into some reasonably coherent quantitative theory, these early theoretical ideas were soon overshadowed by the observational identification of

Earth's magnetotail [*Ness*, 1965] and subsequent detailed studies of its properties that continue, on the basis of ever-expanding data sets, to this day.

One consequence has been to deflect the attention of theorists from the basic problem of understanding what creates the magnetotail itself to the applied task of modeling and calculating its various aspects (such as local stress balance between plasma and magnetic field, dynamical developments, etc.), taking for granted that the magnetotail exists and has its empirically determined parameter values. The basic problem arises primarily as the result of two general properties of observed magnetotails:

1. To first approximation, magnetic fields are nearly aligned (in opposite senses on the two sides of the central current sheet) with the direction of solar wind flow, which is also, more or less, the direction of the magnetotail axis.
2. In the lobe regions, magnetic stresses are dominant over plasma mechanical stresses (pressure or flow).

1.3. GLOBAL STRESS BALANCE PROBLEM

The two properties listed above imply that across any cross section perpendicular to the magnetotail axis there exists a net magnetic tension force directed approximately along the axis. As pointed out explicitly by *Siscoe* [1966], this force must be exerted ultimately on the massive planet; moreover, something external to the magnetotail must be exerting this force. Understanding the origin of this global force constitutes the fundamental (and in my view still unsolved) problem that the magnetotail poses for magnetospheric physics.

1.3.1. Plasma Momentum Equation

Quantitative discussion of stress balance begins with the plasma momentum equation in standard conservation form (partial time derivative of density of conserved quantity plus divergence of flux density of conserved quantity equals zero):

$$\partial \rho \mathbf{V} / \partial t + \nabla \cdot (\rho \mathbf{V} \mathbf{V} + \mathbf{P} - \mathbf{T}) = 0, \quad (1.1)$$

where ρ , \mathbf{V} , and \mathbf{P} are the plasma mass density, bulk velocity, and pressure tensor, respectively, and \mathbf{T} is the total stress tensor: Maxwell stress tensor \mathbf{T}_M plus stress tensors of any other forces that might be present. Equation 1.1 has been written with the usual approximation of charge quasi-neutrality, nonrelativistic bulk flow, and Alfvén speed $V_A^2 \ll c^2$, neglecting electric field terms both in the momentum density and in the Maxwell stress tensor,

$$\mathbf{T}_M = \mathbf{B}\mathbf{B}/4\pi - \mathbf{I}(B^2/8\pi) \quad (1.2)$$

(Gaussian units, \mathbf{I} = unit dyad δ_{ij}). The divergence of any stress tensor equals the corresponding force density, in particular,

$$\nabla \cdot \mathbf{T}_M = \mathbf{J} \times \mathbf{B}/c \quad (1.3)$$

(\mathbf{J} = current density). Gravity can be treated by including in \mathbf{T} a gravitational stress tensor

$$\mathbf{T}_G = -\rho \mathbf{g} g / 4\pi G + \mathbf{I} (g^2 / 8\pi G) \quad (1.4)$$

(\mathbf{g} = gravitational acceleration, G = Newtonian gravitational constant), satisfying

$$\nabla \cdot \mathbf{T}_G = \rho \mathbf{g}, \quad (1.5)$$

but it is almost always simpler to just put the term $\rho \mathbf{g}$ on the right-hand (RH) side of equation 1.1. In any case, for most magnetospheric problems direct gravitational effects are so small that they need not be explicitly included.

1.3.1.1. Integrated Forces. The divergence term in equation 1.1 integrated over any fixed volume gives the net force acting on the contents of the volume, expressed as a surface integral over the boundary of the volume,

$$\mathbf{F} = \int d\mathbf{A} \cdot [\mathbf{B}\mathbf{B}/4\pi - \mathbf{I} (B^2/8\pi) - \mathbf{P} - \rho \mathbf{V}\mathbf{V}], \quad (1.6)$$

where $d\mathbf{A} = \hat{\mathbf{n}} dA$, with $\hat{\mathbf{n}}$ the outward normal to the boundary (throughout this chapter, \hat{a} designates unit vector); the force can thus be determined just from values of physical quantities on the boundary, without the need to inquire into what goes on in the interior. With the force taken as acting on the volume *interior* to the (closed) bounding surface, the surface integral in equation 1.6 contains *exterior* quantities, and vice versa. If $\hat{\mathbf{n}}$ is reversed (i.e., “interior” and “exterior” are interchanged), the force \mathbf{F} is also reversed; this is a statement of Newton’s third law.

The component of \mathbf{F} in a fixed direction $\hat{\mathbf{u}}$, assuming gyrotropic pressure, is

$$F_u = \int dA \left\{ [B_n B_u (1 - \xi) / 4\pi] - [\hat{\mathbf{n}} \cdot \hat{\mathbf{u}} (B^2 / 8\pi + P_\perp)] - [\rho V_n V_u] \right\} \quad (1.7)$$

where the first bracket $[\]$ is magnetic tension modified by pressure anisotropy $\xi \equiv 4\pi(P_\parallel - P_\perp)/B^2$, the second is total pressure (magnetic + plasma), and the third is bulk flow stress (“dynamic pressure,” which can also be described

as “negative tension”). If the direction of \mathbf{B} or \mathbf{V} or both is reversed, \mathbf{F} remains unchanged.

With the volume integral of the time-derivative term included, the integrated equation 1.1 becomes

$$\mathbf{F} = (d/dt) \int d^3r \rho \mathbf{V}, \quad (1.8)$$

i.e., force (applied to a given volume) equals rate of change of linear momentum (within the volume): Newton’s second law. With M the total mass enclosed within the volume and \mathbf{R} its center of mass defined by

$$M \equiv \int d^3r \rho, \quad M\mathbf{R} \equiv \int d^3r \rho \mathbf{r}, \quad (1.9)$$

the rate of change can be written as

$$(d/dt) \int d^3r \rho \mathbf{V} = M d^2\mathbf{R}/dt^2 + 2(dM/dt)(d\mathbf{R}/dt) + \int d\mathbf{A} \cdot (\partial \rho \mathbf{V} / \partial t)(\mathbf{r} - \mathbf{R}) \quad (1.10)$$

[Vasyliūnas, 2007a]. The last term can be shown to be $O(\delta \mathbf{R} d^2M/dt^2)$, where $\delta \mathbf{R}$ is a length sufficiently short to fit within the volume. For magnetospheric volumes of global scale, the enclosed mass in most cases changes, if at all, very slowly in comparison with time scales of interest; the terms in the second line of equation 1.10 can then be neglected, and equation 1.8 reduces to the more conventional form

$$\mathbf{F} \approx M (d^2\mathbf{R}/dt^2 - \mathbf{g}_{\text{ext}}) \quad (1.11)$$

where gravity has now been taken into account, with \mathbf{g}_{ext} the gravitational acceleration due to matter external to the volume (the enclosed mass cannot by self-gravity produce a net acceleration of itself).

The integrated equations (1.6)–(1.11) apply to any arbitrarily chosen volume, provided the integrals have been calculated over the corresponding volume or surface. An important distinction between volumes in the magnetosphere that do and those that do not include the planet follows from equation 1.11. Consider a magnetospheric closed surface 1 that surrounds the planet and nested inside it another closed surface 2 just outside the planet; the volume enclosed by surface 1 consists of the magnetosphere (or part thereof) plus the planet, and that enclosed by surface 2 is just the planet. The forces on the two volumes, calculated as integrals over the respective bounding surface, are

$$\mathbf{F}_{\text{PI+MS}} \approx (M_{\text{PI}} + M_{\text{MS}}) (d^2\mathbf{R}/dt^2 - \mathbf{g}_{\text{ext}}), \quad (1.12)$$

$$\mathbf{F}_{\text{Pl}} \approx M_{\text{Pl}} \left(d^2 \mathbf{R} / dt^2 - \mathbf{g}_{\text{ext}} \right), \quad (1.13)$$

Subtracting equation 1.13 from equation 1.12 gives the force on the magnetospheric volume with the planet excluded,

$$\mathbf{F}_{\text{MS}} \approx M_{\text{MS}} \left(d^2 \mathbf{R} / dt^2 - \mathbf{g}_{\text{ext}} \right), \quad (1.14)$$

which can be calculated from integrals on bounding surface 1 minus surface 2. Now $(d^2 \mathbf{R} / dt^2 - \mathbf{g}_{\text{ext}})$ is essentially the same for the planet and for the magnetosphere, hence the force on the magnetosphere is smaller than that on the planet by the ratio of the respective masses:

$$|\mathbf{F}_{\text{MS}}| / |\mathbf{F}_{\text{Pl}}| \sim (M_{\text{MS}} / M_{\text{Pl}}), \quad (1.15)$$

which is a very small number indeed (e.g., of order 10^{-21} for Earth). It follows that a net (nonzero) force can be exerted only on the massive planet; *the force exerted on any magnetospheric volume is transferred to the planet, and the net force on a magnetospheric volume that does not include the planet is essentially zero.* This principle was first explicitly enunciated by Siscoe [1966] and further discussed by Carovillano and Siscoe [1973], Siscoe [2006], and Vasyliūnas [2007a].

1.3.1.2. Linear Momentum Transport. An alternative view of the momentum equation 1.1 is in terms of transport of linear momentum. The stress tensor \mathbf{T} represents the flux density of linear momentum, i.e., the tensor component T_{un} is the amount per unit area of linear momentum component along direction $\hat{\mathbf{u}}$ being transported in the direction $\hat{\mathbf{n}}$ (or, equivalently, component along $-\hat{\mathbf{u}}$ transported in direction $-\hat{\mathbf{n}}$). The surface integrals in equations 1.6 or 1.7 represent the net flux of linear momentum (or specified component thereof) across the entire surface. The total linear momentum contained inside a volume can be changed only by transport across the enclosing surface, because linear momentum is a conserved quantity.

From this point of view, it is also meaningful to discuss partial forces, across a segment of a bounding surface, by applying equation 1.6 or 1.7 to an unclosed surface; the calculated \mathbf{F} is then the linear momentum flux through (or, equivalently, the force exerted across) that part of the bounding surface. In the special case $\hat{\mathbf{u}} = \pm \hat{\mathbf{n}}$, of particular interest for magnetotails (see section 1.3.2), equation 1.7 becomes

$$F_u = \pm \int dA \left\{ (B_n^2 - B_t^2) / 8\pi - P_{\perp} (B_t^2 / B^2) - P_{\parallel} (B_n^2 / B^2) - \rho V_n^2 \right\} \quad (1.16)$$

or for isotropic pressure

$$F_u = \pm \int dA \left\{ (B_n^2 - B_t^2) / 8\pi - P - \rho V_n^2 \right\} \quad (1.17)$$

where $B_t \equiv \sqrt{B^2 - B_n^2}$ is the magnetic field tangential to the surface; $F_u > 0$ represents a net tension force (outward through the bounding surface) and $F_u < 0$ a net pressure force (inward through the bounding surface). In the surface integrals, tension is contributed only by the normal magnetic field; all other terms (tangential magnetic field, plasma pressure, flow stress) contribute pressure.

1.3.2. Implications for Magnetotail

The force between the magnetotail and the dayside magnetosphere can be estimated most simply by choosing the bounding surface shown by the double vertical dotted line in Figure 1.2: cross section perpendicular to the magnetotail axis, located at a distance near the interface between the magnetotail and the dayside magnetosphere, where the magnetic field is still nearly aligned with the solar wind flow but is beginning to turn toward a dipolar configuration. With this choice of surface and with the force component of primary interest being that along the magnetotail axis (or solar wind flow direction or Sun-planet line), taken as $\hat{\mathbf{x}}$ sunward in standard solar magnetospheric coordinates, the surface normal $\hat{\mathbf{n}} = -\hat{\mathbf{x}}$ and the force direction $\hat{\mathbf{u}} = \hat{\mathbf{x}}$ are aligned, and hence equation 1.16 or 1.17 can be applied. The first of the two magnetotail properties listed at the end of section 1.2 implies that, over much of the cross-sectional area, $B_n^2 \gg B_t^2$; the second implies that $B^2 / 8\pi \gg$ plasma terms. The surface integral over the interface can then be estimated as $F_x = -F_{\text{MT}}$ with

$$F_{\text{MT}} \approx (B_T^2 / 8\pi) (1 - \delta) A_T, \quad (1.18)$$

where B_T is the magnetic field strength in the magnetotail lobes, A_T is the cross-sectional area, and δ is a correction term for plasma sheet contribution [Siscoe, 1972; Vasyliūnas, 1987; see the Appendix]. The global magnetotail force is thus a net tension force; this is a direct result of two magnetotail properties, the stretched-out magnetic field configuration (what is universally called a “tail-like” field), and the extended lobes where plasma stresses are very small in relation to the magnetic field magnitude.

A bounding surface that encloses a volume containing the dayside magnetosphere (and the planet) can be constructed by taking the magnetotail cross section at the interface shown by the vertical dotted lines in Figure 1.2 and joining it to a surface just outside the dayside magnetopause. Similarly, a bounding surface that encloses a volume containing the magnetotail can be constructed by taking the same magnetotail cross section (now viewed as